Optical scattering property: spatial and angle variability in daya bay

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Received June 25, 2012; accepted October 10, 2012; posted online December 28, 2012

The optical data which collected *in situ* in inshore and offshore of Daya Bay in July 26, 2 010 is presented. The data is collected by using the instrument, which synchronously measured the volume scattering function in seven directions from 20° to 160°, the attenuation coefficient, and the depth of water. The analysis of the data indicates that in Daya Bay, in general, the scattering and attenuation increase with depths after 4 m below the surface, while it decreases with depths from near surface layer to 4 m. But not for the area near Daya Bay Nuclear Power Station due to the unique geographical environment of it.

OCIS codes: 010.4458, 010.4450, 290.5820, 290.5838.

doi: 10.3788/COL201210.S20101.

The volume scattering function (VSF), $\beta(\psi)$ (units of $m^{-1}sr^{-1}$), describes the angular distribution of light scattered from an incident unpolarized beam. Integrating the VSF from 0 to π radians (or 0° to 180°) yields the scattering coefficient, (units of m^{-1}), according to $2\pi\int\sin(\theta)\beta(\theta)d\theta$. Integrating the VSF in the backward direction (i.e., from 90° to 180°) yields the backscattering coefficient, b_b (units of m^{-1}). The VSF and the volume absorption coefficient a (m^{-1}), provide the most fundamental description of a medium's inherent optical properties (IOPs), and form the link between its biogeochemical constituents (phytodetrital material, and inorganic minerals) and the apparent optical properties (AOPs)[1−5].

Despite its fundamental nature, little is known about the variability of the VSF, this is largely due to the direct measurement of the VSF is an intractable problem. More than 30 years ago, instruments were developed for measuring the general volume scattering function of the ocean across a range of angles[6−10]. The typical instrument used is the general angle scattering meter designed by Petzold. Most researchers[3,11−13] still made their analyses on a relatively small VSF data set taken in three representative types of seawater. More recently, there are two representative types of these instruments: the multi-spectral volume scattering meter (MVSM), which measures the VSF at angles between 0.6°∼177.9°[3,13], and the multi-angle scattering optical tool (MASCOT) which measures the VSF between 10° and 170° at 10° intervals. With these instruments, some deeply research on the angular shape of the VSF and the relationship between VSF and the physical properties of bubbles and particles, such as size, refractive index, shape *et al.*, are underway.

This study examined the variability in the attenuation and the shape of the VSF in different space (including the different water and the different depth in the same water profile) using an *in situ* multi-angle VSF measurements in Daya Bay in July 2 010. The multi-angle scattering measurement instrument was recently developed by South China Sea Institute of Oceanology, Chinese Academy of Sciences and measures the attenuation coefficient and VSF of 650-nm light between 20° and 160° in seven different discrete angles.

Field measurements of optical attenuation and scattering were made with the multi-angle scattering measurement instrument in the Daya Bay of the South China Sea on July 26, 2 010. All *in situ* profile measurements were carried out in cruises on a 30 tons fishing-boat, using a manual winch lower and raise the VSF instrument through the water. The measurements data are *in situ* recorded continuously providing detailed VSF and depth information of the water column being tested. To investigate the variation of attenuation and the VSF with angle, depth, and space, the experiments were performed in areas with various water qualities from more turbid shallow sea water breeding area of the Dongshan quay of Nanao (near the National Field Station of the Marine Ecosystem at Daya Bay, Shenzhen) to the relatively deeper and clearer sea water offshore Daya Bay (near the Daya Bay Nuclear Power Station, and the water types (i.e. attenuation coefficient) is similar to Dan Diego Harbor[10]). Figure 1 shows the profile measurement locations of the multi-angle scattering measurement instrument (seven measurement locations from A1 to A7).

The multi-angle scattering measurement instrument measures the attenuation coefficient and the VSF in an open volume from 20° to 160° at 6 Hz. Its source beam is a 650±5-nm semiconductor laser, which provides approximately 50-mW peak power output. The

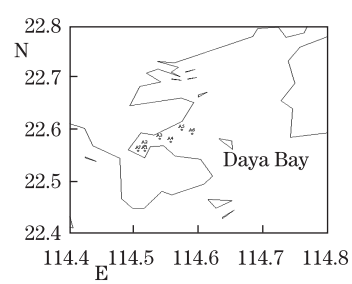

Fig. 1. *In situ* profile measurement locations.

laser passes through a beam expander that enlarges it to 10 mm and reduces the beam divergence to less than 0.02 mrad, generating a collimated beam. And then, the laser beam is directed through a depolarizer in order to scramble the beam to a continuous range of polarization states that are evenly distributed throughout the beam cross-section. After depolarization, the beam enters a half-transparent and half-reflective mirror that reflects 10% of the beam to a reference detector while 90% of the beam is transmitted to the plane of the aperture and is output through the optical glass as the light source of instrument $\Phi_i(0,0)$. The output signal of the reference detector is used to normalize the measured signals and compensate for variation in the laser's output. The laser is modulated at 400 Hz, and the transmission and scattering receivers are synchronized to the modulating signal to distinguish between scattered light and the solar background. The VSF measurement principle of this instrument is based on the array detection principle, viewing a common volume to measure the VSF at discrete angles (20°, 50°, 71°, 90°, 126°, 140°, and 160°) between 0° to 180° and a specific attenuation coefficient c (0°). Eight receivers are mounted on a semicircle with a diameter of 50 cm. The detectors and light sources are coplanar. The instrument is self-contained and automatically controlled by depth underwater, and the data can be easily downloaded via wireless communication (the transmitting distance is no less than 200 m). The above structure arrangement makes the instrument can quickly and synchronously measure the attenuation coefficient, the angle distribution characteristics of the VSF, and water depth information in profile *in situ*. Figure 2 is a photo during *in situ* work.

Details of the multi-angle scattering measurement instrument use and calibration can be found in Ref. [1]. Briefly, calibration test based on precise estimation of the scattering volume and optical radiometric calibration of the detectors in the optical laboratory in the air and $\beta(\psi)$ can calculated from

$$\beta(\psi) = \frac{\Phi_s(r_d,\psi)S}{\Phi_i(0,0)\exp[-c(r_s+r_d)]\Omega V(\psi)}, \tag{1}$$

Fig. 2. Photo of *in situ* work of multi-angle VSF instrument.

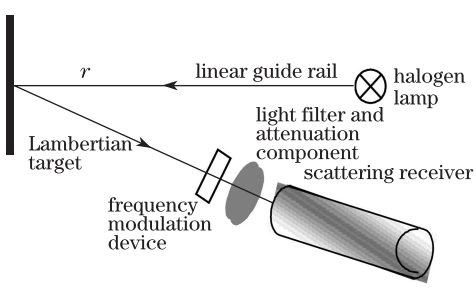

Fig. 3. Volume scattering calibration equipment.

where

$$0° < \psi < 180°,$$
$$V(\psi) = V(90)/\sin(\psi). \tag{2}$$

In Eq. (1), r_s, r_d, $V(\psi)$, and Ω are directly or indirectly computed theoretically from the geometrical parameters of the multi-angle scattering measurement instrument. Using an optical radiation calibration system (Fig. 3), the scattering light flux Φ_s and transmission light flux Φ_t can be determined by the photoelectrical signals DN_s and DN_t, which received by the scattering light detector and the transmission light detector. That is

$$\Phi_\mathrm{w} = DN_\mathrm{p} F_\mathrm{i}(\lambda) C_\mathrm{s}, \tag{3}$$

where C_s is the radiometric calibration coefficient in air. Φ_w is the light flux received by the receiver in seawater, DN_p is the photoelectric signal of each receiver in seawater, and $F_\mathrm{i}(\lambda)$ is the immersion factor.

The attenuation calibration test was performed in a clean black water tank that is filled with high-purity water. After the calibration it is easy to calculate the attenuation of the water:

$$c = \frac{1}{(r_\mathrm{d}+r_\mathrm{s})}\ln\left[\frac{(DN_\mathrm{ib}-DN_\mathrm{ib-d})}{(DN_\mathrm{tb}-DN_\mathrm{tb-d})}\frac{(DN_\mathrm{tm}-DN_\mathrm{tm-d})}{(DN_\mathrm{im}-DN_\mathrm{im-d})}\right] + c_\mathrm{w}, \tag{4}$$

where DN_tm, DN_im, $DN_\mathrm{tm-d}$, and $DN_\mathrm{im-d}$ are the transmission detector and light source signals and dark current in the measurement water, respectively; DN_tb, $DN_\mathrm{tb-d}$, DN_ib, and $DN_\mathrm{ib-d}$, which are the transmission receiver and light source signals and the dark current in a pure water standard, respectively; c_w is the attenuation of the pure water standard.

To estimate the accuracy of the VSF and the attenuation coefficient measured by this instrument, a series of comparative experiments on polystyrene beads were performed in the water tank in the laboratory. The observations of the VSF of these beads compared well to theoretical Mie calculations. For particles with two different central diameters (3.0 and 4.91 μm) and same refractive index (1.615), the average error is less than 0.12.

Since direct measurements of the full VSF from 90° to 180° are very difficulties, the backscattering coefficient b_b estimated based on measuring the VSF at 140°. The VSF for pure seawater was subtracted from the measurements of the total VSF through application of the coefficients provided in Refs. [14,15].

$$b_\mathrm{bp} = \chi_\mathrm{p}(140)[\beta(140) - \beta_\mathrm{w}(140)]$$
$$\chi_\mathrm{p}(140) = 1.18sr, \tag{5}$$

$\beta_\mathrm{w}(140)$ is obtained from the relationship.

$$\beta_\mathrm{w}(\psi) = 1.38(650/500)^{-4.32}(1+0.3S/37) \times 10^{-4}(1+\cos^2(\psi)(1-\delta)/(1+\delta)), \tag{6}$$

where δ is depolarization ratio and S is salinity:

In order to ensure the highest accuracy possible in the

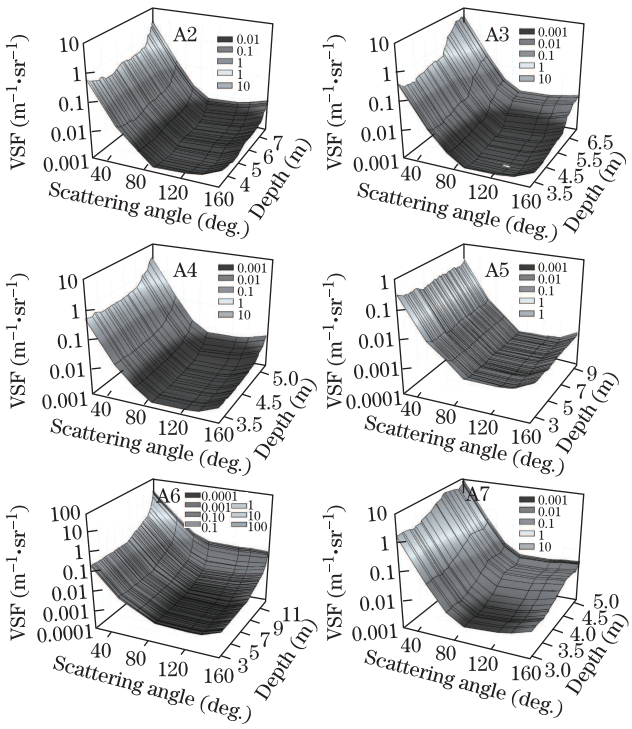

Fig. 4. Distribution of the profile and the angle of the VSF from station A2 to A7 (include the shallow sea water breeding area of the Dongshan quay of Nanao and the relatively deeper sea water offshore Daya Bay).

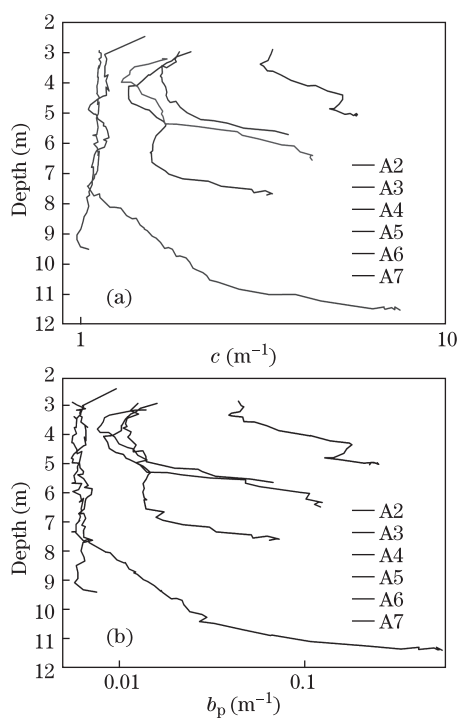

Fig. 5. Profile distribution of attenuation coefficient and the particulate backscattering coefficient from station A2 to A7.

final data, *in situ* determinations of dark counts were made, as *in situ* field dark count values might reflect specific instrumental configuration and environmental conditions during deployments, though dark counts were determined in the laboratory. *In situ* dark counts for the multi-angle scattering measurement instrument were determined by covering the laser source with black electrical tape and leaving all detectors exposed. The laser's output was compensated by the reference light.

The profile measurements of attenuation coefficient c and $\beta(\psi)$ were starting at 9:14AM Beijing Time on July 26, 2 010, from station A1, the sea water breeding area of the Dongshan quay of Nanao near the National Field Station of the Marine Ecosystem at Daya Bay, Shenzhen to station A6, the relatively deeper sea water offshore Daya Bay (near the Daya Bay Nuclear Power Station), and finally go back near station A1(i.e. station A7 in Fig. 1) to finish the last profile measurement at 12:19 PM Beijing Time. Starting sample depth was approximately 2.5 m relative to mean sea level, and that the maximum measurement depth is the seafloor. Sampling process is unidirectional, and it only occurs during the instrument lower through the water.

In Fig. 1, since A1 and A7 are very close in latitude and longitude, here, we select A7 to represent the inshore water near Dongshan quay of Nanao.

Figure 4 shows the vertical and angular variability of VSF for various waters from inshore to offshore in Daya Bay. Since A7 represents A7 and A1, there are six stations in Fig. 4, from inshore to offshore, the VSF present the gradual step-down trend. In the same direction and depth (excludes the near-bottom layer), the VSF of the inshore waters is far greater than that of the offshore waters. This result may be due to the contributions of the silt injection from the seacoast and the plankton and other suspended particles, such as the excreta of creatures, all of which will affect the inherent optical properties of inshore water. It is worth noting that the maximum measurement depth is the seafloor. As can be seen from Fig. 4, in all of these stations except A5, when the instrument contacts the seafloor, the sediment and some particulates could be stirred up, the VSF values of the water near the seafloor could increase, and the maximum at the seafloor might be reached, and in above stations, the VSF and attenuation increase with depths after 4 m below the surface, while it decreases with depths from near surface layer to 4 m. In station A5, there is little change in VSF in vertical profile, this is mainly due to the unique geographical environment of A5, A5 is near Daya Bay Nuclear Power Station, it is a mouth of the Daya Bay and the seafloor is mainly composed with rock, the mineral and particulate is exchanged in vertical profile and washed into ocean constantly by sea wave and cannot deposited on rock seafloor, the bio-optical properties in this velocity profile are similar. In the same vertical profile, the angular variability of VSF is very significant, the difference between forward 20° and backward minimum value (between 90° to 120°) exceeds two orders of magnitude, the closer to the inshore, and the more significant difference is obtained.

The optical beam attenuation coefficient and backscattering scattering coefficient profiles for various water (from station A2 to A7) are shown in Figs. 5(a) and (b). The backscattering scattering coefficient was calculated form Eq. (5). Due to unique composition of various waters, there are some minor differences in variation trend of attenuation and particulates backscattering coefficient, although, the general variation trend of them is similar and just like VSF.

To characteries our data set, we compared our VSF and phase function with Petzold measurements, Sokolov measurements, Lee measuremtns, and Fournier-Forand (F-F) theoretical functions.

Figure 6 shows the VSF in the same depth profile in station A2 to A7, along with the VSF in San Diego Harbor (measured by Petzold), while the phase functions (similar B_b, near 0.018) derived from Lee measurements in New Jersey coast[16], Petzold measurements in San Diego Harbor[10], Sokolov measurements in Black Sea[4], and the (F-F) analytical phase functions were shown in Fig. 7. As we can see in Figs. 6 and 7, the shapes of all volume scattering functions and phase functions are in general similar; nevertheless some difference also can be noticed. The phase function near 90° is below and the phase function near 150° is higher than that was measured by Petzold in San Diego Harbor. The phase function shapes near 90° or 150° are probably mainly due to high proportion of suspended calcium carbonate mineral like particles with high refractive index in Daya Bay. Mie calculations of VSF for particles (for example refractive index greater than 1.55) showing a prevailing composition of highly refractive particles were performed and confirmed that such type of particles can lead to these occurrence; in addition, low resolutions of the angles inevitably also lost some information VSF.

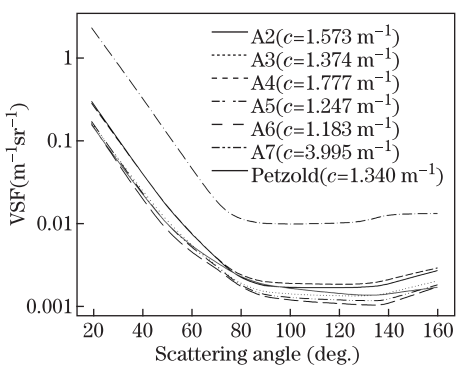

Fig. 6. Comparison of VSF in 4 m in Daya Bay from inshore to offshore with VSF of the Petzold in approximate same attenuation coefficient in San Diego Harbor.

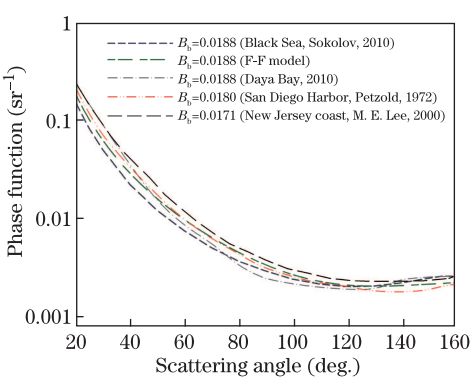

Fig. 7. Comparison of Daya Bay 2010 phase function with phase function derived from Lee measurements in New Jersey coast, Petzold measurements in San Diego Harbor, Sokolov measurements in Black Sea, and the F-F analytical phase functions.

In conclusion, the variation characteristics of the attenuation coefficient and VSF with angle, depth and water quality in the Daya Bay are simultaneously measured and analyzed by an *in situ* volume scattering function instrument developed by ourselves for the first time, and the particle backscattering coefficient was calculated from the VSF in 140°. The *in situ* results indicated the VSF of the inshore waters is far greater than that of the offshore waters. This result may be due to the contributions of the silt injection from the seacoast and plankton and other suspended particles. We also find that the phase functions proposed by Fournier-Forand, measured by Petzold in San Diego Harbor, Lee in New Jersey coast, and Sokolov in Black Sea do not fit with our measurement in Daya, these could mainly due to the high proportion of suspended calcium carbonate mineral like particles with high refractive index. Due to the unique geographical environment near Daya Bay Nuclear Power Station, the variation characteristics of the attenuation coefficient and VSF of this sea water is different from the others. All these experiment revealed that different seawater environments have unique regional bio-optical properties, and this is one reason why study of regional bio-optical properties is important.

This work was supported by the National Natural Science Foundation of China of China (Nos. 41176083, 0606011, 40906022, 40906021, U0933005, and 41076014) and the National "863" Program of China (No. 2007AA092001-2).

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