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Ocean Lidar (BLOL) for Measuring Chlorophyll-a Concentration, Diffuse Attenuation Coefficient and Water-Leaving Radiance*

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Abstract　A shipboard multi-parametric active-passive blue-green light ocean lidar system (BLOL) was developed, which can be used for the validation of remotely sensed ocean color in the East China Sea. The BLOL can be used for passive measurement of water-leaving radiance L_w and active measurement of the diffuse attenuation coefficient k (532 nm) and chlorophyll-a concentration C. The lidar system was installed on the research vessel (about 2500 t) of Ocean University of Qingdao. The experiment was conducted at 21 stations. The experiment region is between Shanghai and west Okinawa. The results measured by BLOL were consistent with those obtained by using traditional method.

Key words　ocean lidar,　ocean color,　validation,　water-leaving radiance,　chlorophyl-a concentration,　diffuse attenuation coefficient。

1　Introduction

With the increase of population and decrease of usable land, more and more people turn their attention to ocean. Many countries put large capital into ocean research. Satellite detection can rapidly obtain ocean properties data in a large area, and is therefore one of the most effective ocean research methods. US launched successfully the Sea-Viewing-Wide-Field-Sensor (Sea WiFS) on August 1, 1997. It is a new generation of sensor for ocean color remote sensing. Sea WiFS will provide a series of data products. The level-2 data products include pigment and chlorophyll-a concentration C, diffuse attenuation coefficient k at 490 nm, normalized water-leaving radiance L_w, aerosol radiance and an error field. The ocean color satellite can provide estimates of the near-surface concentration of phytoplankton pigments by measuring the backscattering radiance from the water. In fresh water environment, high concentrations of chlorophyll-a indicate the presence of high levels of planktonic algae,

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suggesting, in turn, the existence of eutrophic conditions, a situation in which high concentrations of nutrients creat algae bloom. Such conditions can lead to malodorous and even toxic water conditions. Conversely, anomalously low chlorophyll-a levels might indicate the presence or influence of a source of toxic pollutants. Chlorophyll-a is also important in the marine environment. Phytoplanktons are a primary food source; their distribution and productivity are of considerable interest to fishing industry. The attenuation of light in seawater is also important because the energy in the 350 nm ~ 700 nm wavelengths varies strongly with depth and governs the primary production of nutrients by photosynthetic reactions. So three parameters, L_w, C, and k, are important to understand ocean.

The algorithms of the three parameters in application of remote sensing upwelling spectral radiance have, to date, been developed by using shipboard truth data[1]. Sensor response might degrade over time, so the calibration program must be carried out through the life of a mission. Direct calibration during the phase of the post-launch of satellife is done by using onboard source that is traceable to international ground-based standards. Indirect calibration can be done by making use of reference targets on Earth's surface or in the atmosphere and radiative transfer theory to compute the radiance measured at satellite altitude. For sensors without on-board calibration capabilities, indirect methods are the only methods available to monitor calibration coefficients while the instruments operate in orbit. So shipboard truth data must be obtained. Hoge[2] developed an active-passive system-Airborne Ocean Lider (AOL) for identifying ocean color algorithms. In 1997, NASA established an office for Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS). SIMBIOS project is an international cooperation program, and includes three parts: 1) sensor calibration, 2) data product validation, 3) data merging.

Specific areas related to data product validation include

1) detection and /or correction for strongly absorbing aerosols;

2) performance of bio-optical algorithms at high latitudes;

3) performance of algorithms in divers turbid waters;

4) quantification and correction for stray light electronic overshoot and bright target adjacency effects;

5) quantification and correction for whitecap of sea waves and sun glittering effects.

The East China Sea is a typical case-2 water area, which contains a great amount of suspended matter. So the bio-optical algorithms are very complicated. Lee and Cader[3] have developed a good remote sensing model for case-2 water. We need validating whether this model is suitable for the China Sea area.

An active-passive shipboard lidar system was developed in our university, which allows the validation of ocean color research in the East China Sea.

This active-passive system is a shipboard lidar system, which can measure:

1) water-leaving radiance L_w;

2) diffuse attenuation coefficient k (532 nm);

3) concentration C of pigment and chlorophyll-a.

The three parameters are important to bio-optical properties for ocean color validation of the case-2 water area.

2 Principle and method

The active-passive ocean lidar system (BLOL-Blue-green Light Ocean Lidar) can be used for passive measurement of water-leaving radiance and active measurement of the diffuse attenuation coefficient (532 nm) and chlorophyll-a concentration. The principles and methods are described as follows:

1) normalized water-leaving radiance L_w

L_w can be measured by a collecting optical system, which has a limited field of view, so that only the vertical upwelling radiance can be received. In our lidar system, Cassgrainian telescope (Fig. 1) is used for receiving upwelling radiance, then the spectrum of the received L_w can be measured by a spectrometer. Spectral distribution is detected by a 1024 photodiode linear array.

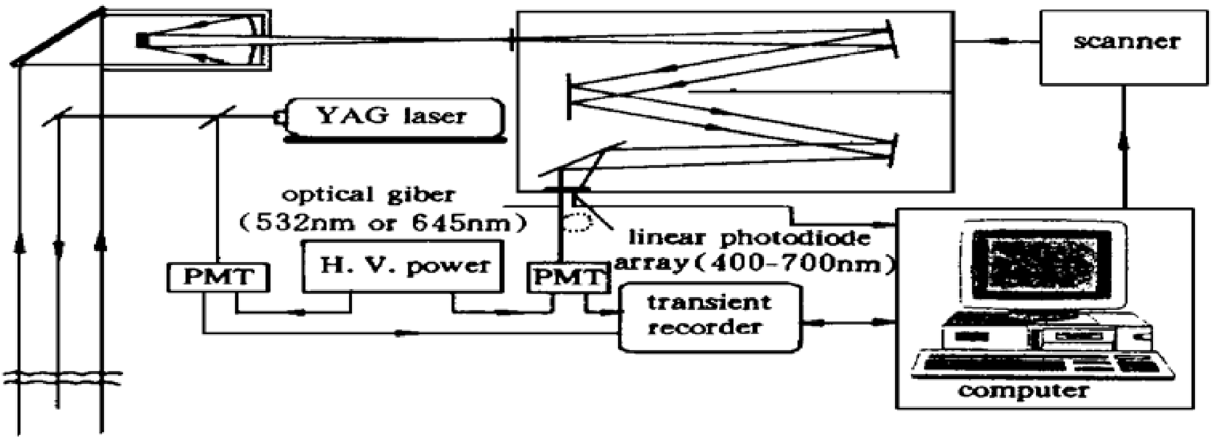

Fig. 1 The block diagram of the shipboard ocean lidar

2) diffuse attenuation coefficient k

In general, the up-and down-welling irradiance with different depths is measured by using an irradiance meter and k can be calculated from irradiance variation with water depths. k can also be measured by a lidar. We can measure the waveform of the return signals from different water depths with the lidar system.

The lidar equation is

$$P_R(r) = P_t\eta_1\eta_2 b_b\Delta r \frac{\exp(-2kr)}{(r+10)^2} \tag{1}$$

Where, P_t is the transmitted laser power; $P_R(r)$ is the return signal power; η_1, η_2 are the optical system efficiency and receiver quantum efficiency, respectively; k is the attenuation coefficient at the laser wavelength; Δr is the water depth resolution; r is the water depth; b_b is the backward scattering coefficient; $(r+10)$ means the lidar system is 10 meters above the water surface.

In the above equation, $(P_t\eta_1\eta_2 b_b\Delta r)$ does not change with r. After $P_R(r)$ was normalized, the variation of $P_R(r)$ is only caused by $\frac{\exp(-2kr)}{(r+10)^2}$ and is only related to r. $P_R(r)$ is a function of time, which is also a function of distance r ($r = vt$, $v = c/n$, where, v is the light speed in water, n is the index of refraction). If we assume that the seawater body is homogeneous, then the value of k is a constant, so we can obtain the value of k from the variation of the measured return signal. The waveform of return signal with different k is shown in Fig. 2. These signals $P_R(r)$ are variable with water depth, in other word, these signals are variable with return time.

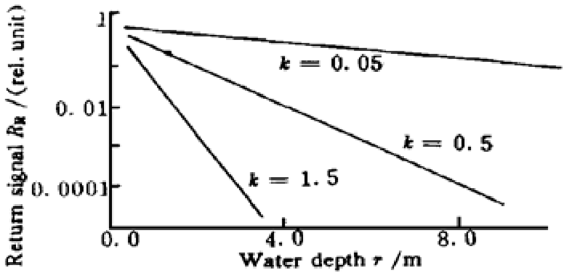

Fig. 2 The waveform of return signal with different k

3) chlorophyll-a concentration C

Since Hickman and Moore first suggested the chlorophyll measurements be undertaken using an airborne pulsed Neon laser at an altitude of 100 m, a series of lidar systems have been setup and used to detect the C of the sub-surface sea. This kind of lidar system has the ability to determine the C by measuring the chlorophyll-excited fluorescence using a short, intense laser pulse.

From a single fluorescence lidar equation, it is difficult to resolve the concentration of chlorophyll because of some uncertainties such as attenuation coefficients, optical efficiency, lidar power etc. So, a Raman channel is used to correct the chlorophyll fluorescence signals with different depths.

The fluorescence from the chlorophyll-a and other pigments is received at a band centered on the 685 nm wavelength. The signal is received from different water depths. Thus the received fluorescence signal can be written as:

$$P_f(r) = P_t \frac{A}{r^2} \eta_1 \eta_2 \Delta r \sigma_f N_f \exp(-2k_f r) \tag{2}$$

where P_t is the transmitted power; $P_f(r)$ is the return signal of fluorescence; σ_f is the fluorescence cross section of chlorophyll mole cules; N_f is the average number density of chlorophyll molecules within depth Δr; k_f is the effective attenuation coefficient at the fluorescence wavelength; A is the receiving area of the telescope.

In the above equation, k_f, η_1 and η_2 are hard to determine. So another channel is used to correct the power of fluorescence[4]. The Raman scattering is the best selection because it is the inherent properties of the water. Its scattering cross section is due to the OH stretch vibrational mode of liquid. In a similar manner as fluorescence, the Raman scattering signal observed at the Raman band (it is at 645 nm for 532 nm laser wavelength in this paper) can be written as:

$$P_R(r) = P_t \frac{A}{r^2} \eta_1 \eta_2 \Delta r \sigma_R N_w \exp(-2k_R r) \tag{3}$$

Where, P_t is the transmitted laser power; $P_R(r)$ is the return signal of Raman scattering; σ_R is the Raman scattering cross section of chlorophyll molecules; N_w is the number density of water molecules in Raman scattering in depth r; k_R is the effective attenuation coefficient at Raman scattering wavelength (645 nm).

We can assume $k_R \approx k_f$. Division of the fluorescence signal by the Raman signal eliminates uncertainties and fluctuations associated with η_1. η_2. P_t. and yields:

$$\frac{P_f(r)}{P_R(r)} = \frac{\sigma_f N_f}{\sigma_R N_w} \tag{4}$$

so

$$C = \sigma_f N_f = \sigma_R N_w \frac{P_f(r)}{P_R(r)} \tag{5}$$

In this equation $P_R(r)$, $P_f(r)$ are measured data, σ_R and N_w can be calculated theoretically, so the concentration C of pigment and chlorophyll-a can be obtained from the above equation.

3 The BLOL System

The schematic diagram of the BLOL system is shown in Fig. 1. A doubled Nd∶YAG laser with 100 mJ per pulse is the laser transmitter in the system. The laser pulse repetition rate is 40 Hz. A small partition of the laser power is used to monitor the fluctuation of the laser power. The output pulse is directly fired into the water by a prism, which is mounted at the center of the receiving mirror, so the transmitter and receiver can be kept coaxial. A Cassegrainian telescope of 120 mm aperture and 668 mm focal length receives the return signals. A monochrometer for measuring the k constitutes the 645 nm channel (Raman scattering signal), the 685 nm channel (fluorescence signal) or the 532 nm channel. The light signal from monochrometer is received by a PMT and a linear photo-diode array. The signals are digitized by a transient recorder of two channels, 8 bits and a 100 MHz sampling rate. The real time display and analysis was done by a PC automatically.

4 Experimental Results

The lidar system was installed on the Dongfanghong research vessel of 2500 tons (Ocean University of Qingdao). The experiment was conducted during October and November of 1994. The route is showed in Fig. 3. The experiment region is between Shanghai and Okinawa. At every station, the ship was anchored. The laser was starfed when the white caps disappeared. The lidar data of twenty-one stations were obtained.

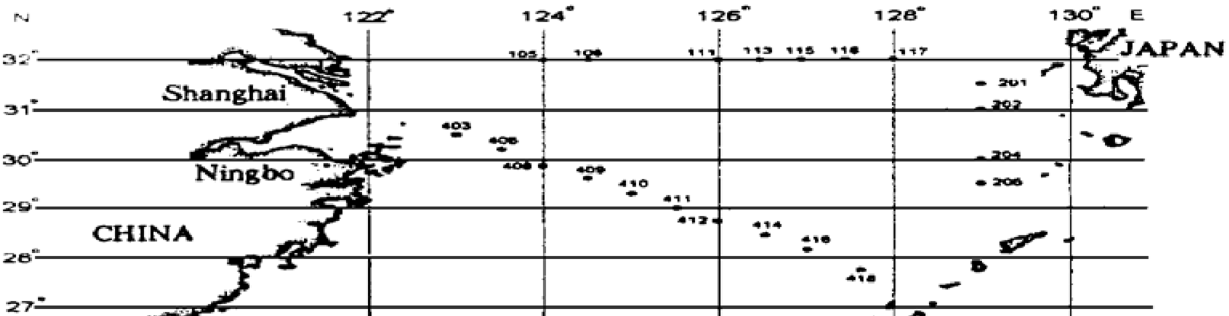

Fig. 3 Natural chart of the East China Sea area and the experiment station distribution

Fig. 4 shows the results of measured water-leaving radiance at four different stations. The measurement of chlorophyll absorption shows that chlorophyll has a strong absorption at about 450 nm, which leads decrease of L_w with the increase of chlorophyll concentration around 450 nm. The concentration of inorganic particles (e.g. sand) is relatively high near shore. So upward radiance by inorganic particles because of scattering in near shore sea area is larger than that in off shore sea area. Inorganic particles do not have significant spectrum characteristics, and the chlorophyll absorption between 550 nm and 460 nm is weak. Under synthetical effect of chlorophyll and inorganic particles, the nearer it is to the shore, the larger value of L_w we have between 550 nm and 640 nm.

Fig. 5 shows the comparison between chlorophyll-a measured by the lidar and the sampler for sub-surface water. The x-axis of Fig. 5 shows the station numbers, which are 105, 106, 111, 113, 115, 116, 117, 201, 202, 204, 205, 403, 406, 408, 409, 410, 411, 412, 414, 416, 418 in turn. We analyzed the measured values of chlorophyll concentration with both different methods, one by analyzing water sample and another by lidar, we obtained the correlation coefficient between the both measured data is 83%.

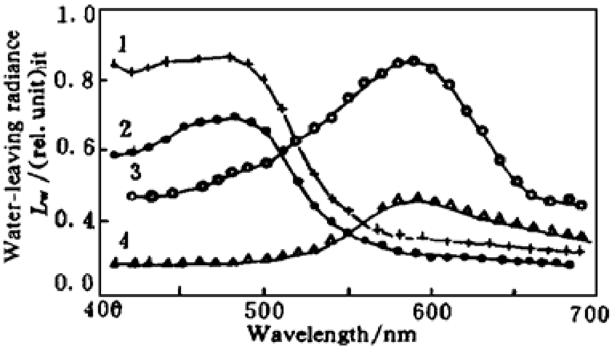

Fig. 4 The results of measured water-leaving radiance L_w at 4 different stations. 1, 2, 3, 4 represent stations 418, 416, 412, 410, respectively

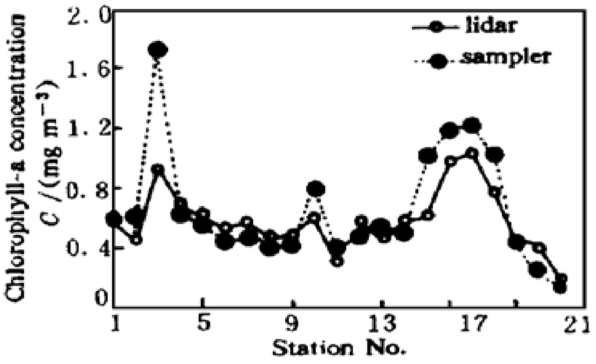

Fig. 5 The comparison of results of sub-surface water measured by lidar and sampler

From Fig. 5, we can see the measured data from the lidar and sample data for chlorophyll-a are in good agreement.

Fig. 6 shows the comparison of the results of k measured by the lidar measured by an irradiance meter. Table 1 is the data of k measured by the lidar and the irradiance meter. The data measured by using two kinds of instruments have a good consistency.

Table 1. Data of k measured by the lidar and an irradiance meter

station	irradiance meter	lider
1 (403)	1.68	1.500
2 (406)	1.06	1.000
3 (105)	0.450	0.500
4 (106)	0.230	0.200
5 (411)	0.120	0.100
6 (111)	0.100	0.070
7 (412)	0.100	0.100
8 (113)	0.100	0.100
9 (414)	0.085	0.100
10 (115)	0.073	0.070
11 (205)	0.060	0.050
12 (204)	0.049	0.050
13 (201)	0.050	0.040

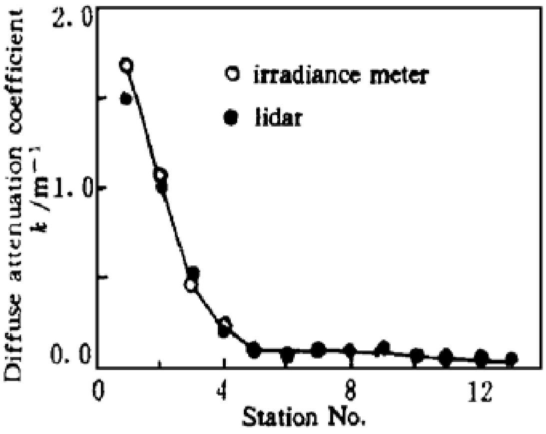

Fig. 6 The results of diffuse attenuation coefficient k measured by the lidar in comparison with the data measured by an irradiance meter

Conclusion The BLOL is a active-passive ocean lidar system, which can be used for measuring pigment and chlorophyll-a concentration, diffuse attenuation coefficient at 532 nm, normalized water-leaving radiance. The results measured by the BLOL were consistent with those by the traditional method. So the BLOL is suitable for the validation of satellite ocean color products.

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测定叶绿素 a 浓度、漫散射衰减系数和离水辐亮度的海洋激光雷达*

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摘　要　研制了一台多参数的主被动船载蓝绿光海洋激光雷达系统(BLOL)，它可用于我国东海海域的海色遥感印证。该海洋激光雷达系统能被动地测量离水辐亮度 L_w，主动测量漫散射衰减系数 k 和叶绿素 a 浓度 C。雷达系统安装在青岛海洋大学的调查船上(约 2500 吨位)，曾在 21 个站位进行了实验。实验的区域从上海东开始到冲绳岛附近。用该海洋激光雷达系统测量的结果与用传统的方法测量的结果符合的很好。

关键词　海洋激光雷达，　海色，　印证，　离水辐亮度，　叶绿素 a 浓度，　漫散射衰减系数。

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