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Progress of Airborne Lidar of Ocean Chlorophyll Observations Including Algorithm and Instruments

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Abstract. Airborne lidar is widely used to measure water depth, organic matter, chlorophyll, seabed topography and seabed types et al. The water depth observation has been studied for many years by many scientists, while the Chlorophyll retrieval by airborne lidar is studied by a few scientists. In this paper, the progress of measurements of Chlorophyll by use of airborne lidar is discussed, which includes the progress of retrieval algorithm, international instruments, and Chinese instruments.

1. Introduction

Chlorophyll is the main element for photosynthesis of marine phytoplankton. According to its content, the concentration of marine phytoplankton can be retrieved directly. Chlorophyll-a is the ultimate conversion of light energy of other chlorophyll, so it is the most important parameter which represents the spatial distribution of marine phytoplankton.

For the vast area and rapid change of the ocean, it will take a lot of manpower, material, and financial resources to rely on field measurements alone. Besides, it maybe need a long period. However, airborne or space-borne optical remote sensing can solve this problem, and it can obtain chlorophyll concentration of a regional/global area in a short time.

Optical remote sensing of Chlorophyll-a mainly includes passive optical observation and active optical observation, while passive observation mainly includes ocean color remote sensing [1-2] and fluorescence spectrophotometry [3]. They play an important role in marine chlorophyll remote sensing, but only carried out in the daytime.

As an active optical detection method, lidar can measure Chlorophyll-a in day and night time. Besides, it can penetrate thin cloud and aerosol, which can obtain much more data [4]. Lidar is an efficient and practical ocean optical observation technology [5-6], which can simultaneously measure optical parameters through several bands such as Raman scattering and chlorophyll fluorescence signals of ocean water. Based on the optical parameters, the chlorophyll concentration can be retrieved exactly.

2. Progress of Chlorophyll-A Retrieval Algorithm

Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented.

2.1. Progress in Abroad

The fluorescence radiation of chlorophyll in seawater will be generated by laser irradiation. There is a linear correlation between the intensity of the fluorescence radiation and the concentration of chlorophyll. So the lidar fluorescence equation of chlorophyll is as follows [7]:

$$\mathrm{dP}_F = \frac{K_F n(z)\sigma\exp(-\int_0^z(\gamma_L(z)+\gamma_F(z)))}{(z+mR)^2}dz \tag{1}$$

Where R is lidar altitude, σ is the absorption cross section, γ_L is the effective attenuation coefficient of laser seawater, m is the refractive index of seawater, n(z) is chlorophyll concentration, γ_F is the effective attenuation coefficient of fluorescent seawater. The constant parameter of K_F includes instrument parameters, laser intensity P0, surface albedo, and atmospheric attenuation coefficient etc.

$$\mathrm{K}_F = \frac{P_0\xi A_R\Delta\lambda_D(1-\rho_L)(1-\rho_\mu)\exp(-(\beta_L+\beta_\mu)R)}{4\pi\Delta\lambda_F} \tag{2}$$

In equation (2), ξ if the signal receiving efficiency of the lidar instrument, A_R is the receiving area of the telescope, $\Delta\lambda_D$ represents the receiving wave width, ρ_L is the sea surface reflectivity of the laser, ρu is the sea surface reflectivity of the fluorescent, β_L is the extinction coefficient of the laser in the atmosphere, the extinction coefficient of the fluorescence in the atmosphere, and $\Delta\lambda_D$ represents the width of fluorescence light. Then, equation (1) can be integrated:

$$\mathrm{P}_F = \frac{K_F n(z)\sigma}{m^2R^2(\gamma_L+\gamma_F)} \tag{3}$$

According to equation (3), the intensity of chlorophyll fluorescence signal increases linearly with the increase of chlorophyll concentration and decreases linearly with the decrease of chlorophyll concentration. However, due to the disturbance of Raman scattering generated by water and instability of the instrument etc, the linear relationship will be changed, which will lead to the decrease of the inversion accuracy directly. Therefore, it is necessary to measure the Raman scattering signal of water by use of another band to eliminate its influence. In 1975, Fadeev et al [8] introduced firstly Raman scattering of seawater to chlorophyll fluorescence signal equation, and corrected the fluorescence signal. Then, Bristow [9-10], Poole [11] etc corrected the signal by Raman scattering respectively. The lidar Raman scattering equation is as follows:

$$\mathrm{P}_R = \frac{K_R n_W\sigma_W}{m^2R^2(\gamma_L+\gamma_R)} \tag{4}$$

The parameters in equation (4) are similar to those in equation (3), but the independent variable should be changed from chlorophyll to water. Therefore, the ratio can be derived from equation (3) and (4):

$$\mathrm{Ratio} = \frac{P_F}{P_R} = Cn_{Cl} \tag{5}$$

In equation 5, n_{Cl} is chlorophyll concentration, and C is correction coefficient. It shows that the chlorophyll concentration can be retrieved by use of Raman scattering assuming that the system and environmental parameters remain constant during the measurements.

On the basis of Raman correction, Exton[12] et al improved the inversion accuracy of chlorophyll concentration by avoiding from the influence of atmospheric Mie scattering. The Mie scattering equation is as follows:

$$\mathrm{P}_S = \frac{K_S n_S\sigma_S}{m^2R^2 2\gamma_L} \tag{6}$$

Based on the equation (3), (4), and (6), we can obtain the following equations:

$$\frac{P_S}{P_R} = \frac{K_S}{K_R}\frac{n_S\sigma_S}{n_W\sigma_W}\frac{\gamma_L+\gamma_R}{2\gamma_L} \tag{7a}$$

$$\frac{P_F}{P_R} = \frac{K_S}{K_F}\frac{n_F\sigma_F}{n_W\sigma_W}\frac{\gamma_L+\gamma_R}{\gamma_L+\gamma_F} \tag{7b}$$

The ratio in equation (6) can minimize the disturbance of other factors, and it is not affected by laser intensity and chlorophyll height. Therefore, it can be better applied to chlorophyll inversion in shallow sea area (near land).

2.2. Progress in China

In 2007, Ocean University of China[7] independently developed the first Airborne Ocean Lidar System in China. Based on the system, the experiments were carried out nearby Yantai and Weihai. A new method was proposed to extract peak signal by use of least square fitting method. The concentration of chlorophyll-a was obtained based on Raman correction method. Besides, the attenuation coefficient of sea water was obtained. The retrieval results are consistent with the measurements of the same period in previous years.

In 2014, Ocean University of China [13] extracted and corrected underwater scattering signals based on CALIPSO satellite-borne lidar data. The correlation coefficients were obtained using the regression analysis between 532 nm backscattering signal and chlorophyll concentration. Then, the chlorophyll concentration was deduced based on the coefficients. The retrieval results were compared and consistent with MODIS chlorophyll concentration, and the averaged deviation is 0.052.

3. Progress of Instruments

3.1. Progress in Abroad

In 1970, Hickman et al. [14] used nitrogen laser to observe chlorophyll in laboratory. It was found that the fluorescence band of chlorophyll-a was near 680 nm. It was also found that chlorophyll concentration < 6 ug/L could be accurately measured. Then, Friedman et al. [15] found that algae species can be effectively distinguished by the fluorescence characteristics of laser echoes. Meanwhile, chlorophyll concentration below 1 ug/L can be obtained from 500 m distance by 100 KW laser. In 1973, Hongsuk [16] et al used the lidar to detect chlorophyll concentration. The laser system has a pulse energy of 0.25 J (within 300 nanoseconds) and a frequency of 2 pulses per minute. The system consists of two main parts: one part includes a control board, a converter, a signal processing and recording unit. Another part includes a laser transmitter, a photoelectric tube, and telescopes etc. In October 1972, the experiments were carried out using the laser system in Lake Ontario and other water areas, and the spatial distributions of chlorophyll concentration were obtained.

In the late 1970s, NASA and NOAA developed jointly an AOL (Airborne Oceanographic Lidar) system for chlorophyll concentration measurements. The AOL laser system is a double frequency Nd:YAG laser with an output wavelength of 532.1 nm. In June 1980, five experiments were carried out subsequently using AOL to observe and retrieve chlorophyll concentration at sea surface (5 m thick), and the distribution of chlorophyll concentration were obtained in these areas [17]. After that, the AOL system has been upgraded for several times, and up to the AOL-III system until now [18]. Compared with previous versions, AOL-III system mainly improves in weight, volume, and power consumption. Besides, much more new technologies were also applied to components of AOL-III system, such as optical fiber, spectrometer-detector optical chain, miniaturization of photomultiplier tube, dual-wavelength identical excitation source, and a new optical receiver. Finally, the main improvement of the system is the use of a dual-wavelength laser excitation source: one is 532 nm, the other is 355 nm (Table 1).

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Table 1. The receiving wavelength of AOL-III system

Excited wavelength	Receiving wavelength	
	Wavelength center	Wavelength width
355	355	--
355	402	7
355	450	50
532	532	7
532	560	12
532	590	17
532	650	20
532	685	25

In the early 1990s, the University of Germany Odenbao [19] measured hydrological parameters of the European coast using lidar, whose system used EMG 100 with a maximum energy of 10 mW and a laser pulse width of 12 ns at 308 nm. In addition, there was a 450 nm laser wavelength with a pulse width of 6 ns. The system can be also used with infrared/ultraviolet scanners to detect phytoplankton.

In 1995, Barbini [20] in Italy observed the distribution of chlorophyll-a, CDOM in Lake Xiehu of Venice, and phytoplankton in Antarctic waters based on a triple-frequency Nd:YAG pulse laser. The 355 nm laser is mainly used to observe CDOM and chlorophyll, whose pulse energy is 30 mJ and pulse length is 10 ns. While the 266 nm laser is mainly used to observe organic matter and oil spill, whose pulse energy is 10 mJ and pulse length is 2 ns (Table 2).

Table 2. The lidar for chlorophyll-a in Italy

Parameters	Value
Excited wavelength	355 nm
Pulse width	10 ns
Receiving wavelength	402\450\650\690
Pulse energy	30 MJ

In 2002, Korea [21] detected the concentration of chlorophyll-a and CDOM in the ocean surface based on a marine fluorescence lidar system. The system mainly consisted of a flip mirror, a telescope, a polychromatic instrument, a CCD detector, a laser cooling system, a laser light source, and a double and triple frequency Nd:YAG etc. The laser had 8 ns pulse width, 25 Hz repetition rate. The energy of the 1064 nm laser pulse is 600 mJ, that of the 532.1 nm laser pulse is 280 mJ, while 354 nm laser pulse has 100 mJ energy. The system can be installed on aircraft or ships to monitor sea water, oil spill, and land vegetation. Besides, due to the similar laser spectral characteristics, the system can be used not only for pollution monitoring in coastal waters, but also for monitoring global forests or urban parks.

Figure 1. Radar System on Helicopter Developed in Korea

3.2. Progress in China

To date, the study of marine chlorophyll measurements based on Airborne Radar started in early 21st century, and just a few studies had been carried out. Ocean University of China [22-23] has developed the first airborne marine lidar in China, which was mainly used to measure the chlorophyll-a concentration of the ocean surface. It has been carried out for observation experiments in many areas. The excitation wavelength of the airborne marine fluorescent lidar is 355 nm, the single pulse energy is 80 mJ, the pulse width is 8-10 nm, and the telescope aperture is 200 mm. The receiving wavelengths are 404 nm and 685 nm. The 440 nm is mainly used to measure Raman scattering of sea water, while 685 nm is mainly used to obtain chlorophyll fluorescence signal.

Then, a new three-channel Ocean Lidar System TOLRSS (Three-channel Oceanographic Lidar Remote Sensing System) was built by the Ocean University of China and Ludong University [24]. The system used a double-frequency Nd:YAG pulse laser with a maximum single pulse energy of about 5 mJ and a pulse width of about 7 ns. It used 685 and 650 nm to measure the chlorophyll fluorescence signal and Raman scattering respectively, and then the chlorophyll concentration was retrieved using the signal of the two bands. Besides, the system also acquires elastic scattering signal using 532 nm, and retrieves suspended matter concentration combining with 650 nm Raman channel (Table 3).

Table 3. TOLRSS parameters of the Ocean University of China

Parameters	Value
Excited wavelength	532 nm
Pulse width	<10 ns
Receiving wavelength	532\650\685
Power	<400 W
One pulse energy	<5 MJ

4. Discussion

The research of marine chlorophyll detection by airborne lidar has been carried out for decades. Compared with the traditional field measurements, it can detect a wide area in a short time. Besides, it can observe continuously in day and night time. However, there are still some problems to be solved:

(1) It is greatly influenced by sea water floating matter, sea water pollution, and sea water transparency, especially for case-ii water area. The retrieval accuracy of chlorophyll will be reduced greatly due to more suspended substances and complex bottom topography and types of sea.

(2) It is greatly affected by waves. The size and shape of wave will greatly affect the echo signal of lidar, especially the peak information. To some extent, this will seriously interfere with the accurate extraction of chlorophyll echo signal, and then affect the retrieval accuracy of chlorophyll concentration.

Although there are still some problems to be solved urgently, the retrieval accuracy of chlorophyll concentration has been improved gradually with the continuous innovation of engineering technology and inversion algorithm. So the lidar has been used more frequently for remote sensing of marine chlorophyll. Besides, the active technology of lidar can also combined with other detection methods (such as multi-spectral passive remote sensing) to obtain much more remote sensing data and observation parameters, which can realize the complementarity of various data, and to improve the accuracy of chlorophyll observation.

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