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Chlorophyll-a Profiling in Fresh Surface Waters by Fluorescence-Raman Lidar

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Abstract: We have developed a portable LD fluorescence-Raman lidar system providing quantified Chl-a profiles of *Chlorella vulgaris*. Based on the lidar observations and estimated Chl-a concentrations, we studied SCM characteristics at varying biomass concentrations. A positive linear relationship between the fitted curve and the lidar Chl-a data ($R^2 = 0.96$) is observed, which enhances accuracy and efficiency in chlorophyll-a monitoring. The developed system showed significant importance in Chl-a profiling in fresh surface waters affected by domestic effluents, and agricultural runoff.

1. Introduction

Phytoplankton biomass estimation through chlorophyll-a (Chl-a) concentration is commonly measured for water quality monitoring [1]. In aquatic systems, vertical distributions of Chl-a are commonly heterogeneous which contributes to the trophic status of the water column and primary productivity estimation. This underestimation is due to the occurrence of subsurface chlorophyll maxima (SCM), and overestimation due to the maxima of Chl-a near the water surface [2]. Observations of the Chl-a profiles is important in algal growth monitoring [3], estimating trophic status, phytoplankton biomass and primary production in freshwater systems [4].

Previous measurements were implemented through grab sampling method, in situ measurement, fixed-point sampling, and passive satellite remote sensing. With the limitation in sampling methods, insufficient information on the heterogenous distribution of Chl-a in regional scales. Passive satellite remote sensing is commonly used in estimating Chl-a concentrations [5], however, limitations on SCM features are omitted [6]. To further understand the effects from agricultural runoffs, domestic and industrial effluents, in-situ monitoring is needed.

In this study, we propose the use of a laser diode fluorescence-Raman light detection and ranging (LDFR-Lidar) technology in understanding Chl-a concentrations in fresh surface waters. Chl-a concentrations retrieved from Lidar measurements showed positive correlation with spectroscopic analysis.

2. Materials and Methods

The schematic diagram of the developed LDFR-Lidar in Figure 1. In this study, we developed a portable LDFR-Lidar system with excitation wavelength at 405 nm with maximum power of 20 mW and an assembled telescope for the receiving system. The specifications of the LDFR-Lidar system are presented in Table 1.

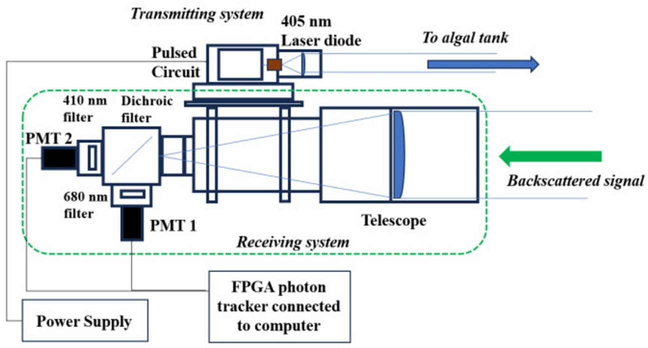

Figure 1. Schematic diagram of the LDFR-Lidar System

Table 1. LDFR-Lidar specifications

Components	Parameter	Value
Pulsed LD	Central wavelength	405 nm
	Pulse width	11 ns
	Divergence angle	0.5 mrad
Telescope	Diameter	75 mm
Detection device	PMT: Hamamatsu H11901P-10	185-870 nm
Dichroic lens	Reflectance	400-450 nm
	Transmittance	500-700 nm
Filters	Water Raman	410 nm
	Chl-a	680 nm
Photon counter	FPGA photon tracker	
	System clock:	550 MHz
	BIN Width	5 ns
	BIN length	50

Preliminary measurements were conducted using excitation-emission matrix (EEM) spectroscopy for chlorophyll-a measurements and water Raman signal [7]. From the EEM results, LDFR lidar measurements were conducted for water at 410 nm, and chlorophyll-a at 680 nm from the surface water (0 – 1 m) by optical filters. A photomultiplier tube (Hamamatsu H10721P-04) was used to measure light detection at weak signals with an FPGA-based high-speed photon counting board. A detailed discussion was reported previously [3]. The measurements were conducted in a dark environment at room temperature. The system was upgraded from an elastic lidar and was validated by Monte Carlo simulation and analytical model [8,9]. The bio-optical model was constructed to connect diffuse attenuation coefficient (Kd) for the retrieval of Chl-a as previously discussed [10]. The Chl-a concentrations can be derived after calibration at the water surface using the Raman and fluorescence signals. All in-situ measured fluorescence profiles were subjected to curve fitting by an exponential power distribution function [11] as shown below:

$$Chl(z) = a + b\left[\frac{\alpha}{2\sigma\Gamma(\frac{1}{\alpha})} e^{-\left|\frac{(z-\mu)^{\alpha}}{\sigma}\right|}\right] \quad (1)$$

where Chl(z) is the Chl-a at a depth z, a is the background Chl-a, b is the scale factor to adjust the SCM depth (μ) and thickness (2σ), α is the peak shape. If α = 2, the curve is a Gaussian distribution. Γ is the gamma function dependent on background Chl-a concentration. The root mean square error (RMSE) was utilized to verify the accuracy of the Lidar-retrieved Chl-a concentration and its linear dependence on SCM.

3. Observations

Lidar Measurements

In this study, powdered samples of *Chlorella vulgaris* at varying concentrations were prepared in an algal tank. The feasibility of LDFR-Lidar system was estimated for both detection accuracy and penetration depth. Figure 2 shows the curve fitting based on the eq. (1) for the Chl-a profile at 120 μg/L *C. vulgaris* concentrations. The SCM depth used is 9 with peak shape of 1.3.

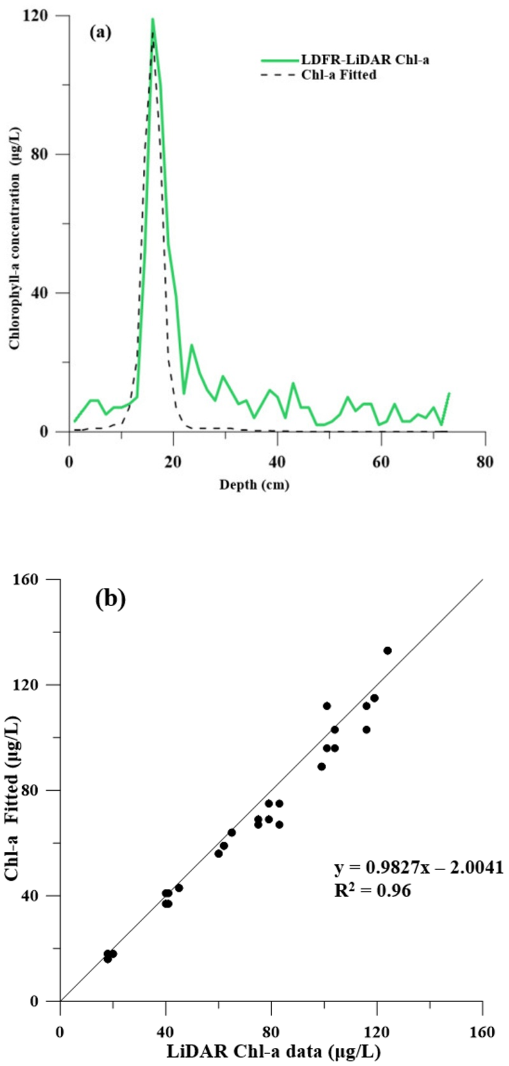

Figure 2. (a) Curve fitting of fluorescence profile over Chl-a profile measured through LDFR-Lidar system; (b) linear correlation between Chl-a derived through curved fitting and Lidar Chl-a data.

The linear relationship between the fitted curve and the Lidar Chl-a data using linear regression (R^2 = 0.96) is shown in Figure 2(b). However, measurements above 80 µg/L concentrations showed overestimations with 4-10 µg/L range error with RMSE of 22 %. This is due to the overestimation of Kd caused by possible multiple scattering effects on lidar retrieval [12]. This is validated by measuring the estimated Chl-a concentration as provided previously [3].

Applications to Water Quality and Pollution Monitoring

Water quality and pollution monitoring through Fluorescence-Raman Lidar systems is necessary. Pollutants such as plastic litter, domestic and industrial effluents, and agricultural runoffs affect water quality in rivers, oceans, lakes and other bodies of water [13]. With the emerging seasonal algal blooms and water quality problems, the developed LDFR-Lidar systems help provide real-time Chl-a profiling in surface waters. It displays a promising tool to observe vertical Chl-a distribution and can provide complementary data to satellite passive remote sensing data. This study aids in water quality monitoring affected by domestic effluents, and agricultural runoffs.

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