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Development of a low cost optical sensor and of a drone system for the monitoring of cyanobacteria in freshwater ecosystems

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Abstract

Cyanobacterial blooms frequently disturb the functioning of freshwater ecosystems and their uses, due to the harmful toxins that cyanobacteria are able to synthesize. Therefore, many countries have implemented monitoring programs aimed at reducing the risk of human exposure to these toxins. The main limitation is related to the heterogeneity of the spatial distribution of cyanobacteria. In the vertical dimension, these organisms can stay in different layers in the water column and in the horizontal scale, the cells may accumulate in some area of the water body, under the action of winds or currents. In an attempt to improve monitoring, many research projects have been undertaken in order to develop new tools, like buoys equipped with various underwater sensors. This tool is highly relevant but it does not allow assessing the horizontal distribution of cyanobacteria and its cost remains expensive. Moreover, if satellite remote sensing can be considered very useful for estimating biomass and horizontal distribution of cyanobacteria in a water body, the cost of this technology and the limited availability of satellites make it unaffordable for routine monitoring. In this context, our project named OSS-CYANO (Development of optical sensors and drone system for the survey of cyanobacteria) aims in a first time to develop and validate a new, low-cost aerial sensor. In this goal, we developed a framework for sensitive and selective estimation of phycocyanin concentration using a set of reflectance measurements over controlled mixes of phytoplankton cultures. The next part of our work aimed at developing an inexpensive passive optical sensor to selectively track phycocyanin, and which could be used for both high-frequency monitoring and drone-based measurements.

Keywords: Cyanobacteria, monitoring, optical sensor, drone system

Introduction

Blooms of cyanobacteria are a growing issue in inland waters due to eutrophication and to climate changes (Jöhnk et al. 2008; Pearl and Huisman 2009; Markensten et al. 2010). Adverse effects of these cyanotoxins on human and animal health have been described (eg. Kuiper-Goodman et al. 1999, Carmichael et al. 2001, Briand et al. 2003, Codd et al. 2005). The prevention of these effects requires frequent monitoring which currently involves regular field sampling followed by laboratory analysis, and identification and enumeration of phytoplankton. The cost-efficiency of such methods is limited by the spatial and temporal heterogeneity of cyanobacteria (Porat et al. 2001, Welker et al. 2003, Cuypers et al. 2011; Pobel et al. 2011).

Remote-sensing could be a suitable tool to address this issue, and several methods have been developed in order to track cyanobacteria-specific pigments (Li et al. 2015). Semi-empirical remote-sensing approaches are particularly promising as they explicitly tackle the issue of overlaps in pigments spectral features (Dekker et al. 1991; Simis et al. 2005). The major drawbacks of these approaches are that they require expensive instrumentation, extensive calibration and heavy computations. Most of the currently used optical sensors are active sensors (measuring signals transmitted by the sensor that are reflected, refracted or scattered by the Earth's surface), which are expensive and perform badly in turbid water.

To answer these issues, the OSS-CYANO project aimed at developing a framework and inexpensive sensor for quantitative passive optical detection of cyanobacteria. The main issues which needed to be addressed are the following:

- Deriving selective metrics using a limited number of bands.
- Limiting the effects of environmental factors in order to provide sensitive metrics in a wide range of conditions
- Providing an inexpensive and scalable way to measure the developed metrics.

A framework using mixes of phytoplankton cultures to derive selective metrics has been published (Hmimina et al. 2019) and was used to define a set of 6 spectral bands which could be used to selectively track concentrations in chlorophyll-a, phycocyanin and phycoerythrin. This work focuses on the development and validation of a sensor platform designed to accurately measure this spectral information.

Materials and Methods

Evaluation of the stability of optical indices in a changing light environment

A mesocosm experiment was run from July to November 2015 at the Foljuif CEREEP-Ecotron station (Ile-de-France, Equipex Planaqua,St-Pierre-les-Nemours). Three wave tank mesocosms (Blottiere et al. 2016) were coated with a fast-cure black silicon elastomer (Sylgard 170, Dow Corning, USA, Midland MI) and equipped with a set of four spectrometers (ASEQ, LR1-T spectrometer, 300–1000 nm, 0.6 nm resolution, thermoelectric cooler (TEC) module, Vancouver, Canada). Each tank was equipped with a nadir-looking spectrometer installed 50 cm above the water (FOV: 44 degrees, 40 cm diameter). The fourth spectrometer was equipped with a cosine corrector (CCSA1, Thorlabs, USA, Newton NJ). The four spectrometers were synchronized to acquire data simultaneously, and their integration time was optimized in order to obtain a constant signal versus noise ratio. The acquired spectra were used to derive six 10 nm wide gaussian bands centered on 450 nm, 515 nm, 610 nm, 676 nm, 696 nm and 750 nm. A phycocyanin index was then computed as:

$$PC = \frac{R_{610} - R_{515}}{R_{610} + R_{515} - 2 \times R_{750}}$$

Following the Figure 1, with R_x the reflectance within the band x.

One mesocosm was kept free of phytoplankton while the two others were primed with a cyanobacteria culture (*Microcystis* sp. PMC 816.12) the 26 August. The spectrum of the mesocosm exhibiting the highest growth as measured with a BBE Fluoro Probe spectro-fluorometer (bbe Moldaenke GmbH, Schwentinental) was computed knowing that this probe allowed to estimate the cyanobacterial biomasses (expressed in µg L^{-1}) (e.g. Leboulanger et al., 2002).

Sensor design and validation

A passive optical sensor was designed to quantify the reflectance in the previously mentioned bands. Six 10 nm FWHM optical bandpass filters (Beijing Bodian Optical Tech, China, Beijing) were placed within a 4 cm diameter white silicon integrative sphere, on top of six photodiodes (TEMD5080X01, Vishay, USA, Malvern PA) whose signals were amplified (OPA2380, Texas Instruments, USA, Dallas TX) then converted into digital signals and stored every second. The gain was continuously increased following a saw-tooth function using an adjustable potentiometer (AD5206, Analog Devices, USA, Norwood MA), and the measured radiance was computed using the slope between the gain and resulting signal after calibration in an integrative sphere.

The sensor PCB was designed using KiCad EDA (http://www.kicad-pcb.org), the mechanical parts were designed under OpenScad EDA (http://www.openscad.org) and 3D printed. The optical parts were molded in optical silicon (Sylgard 184 and MS-2002, Dow Corning, USA, Midland Mi).

One sensor was installed over a water body in Champs-sur-Marnes, Ile de France, France in 2017, along with a BBE Fluoro Probes spectrofluorometer (bbe Moldaenke GmbH, Schwentinental).

Results and Discussion

Evaluation of the stability of optical indices in a changing light environment

The spectrum of the measured reflectance over one of the mesocosms as a function of the wavelength is shown in Figure 1.

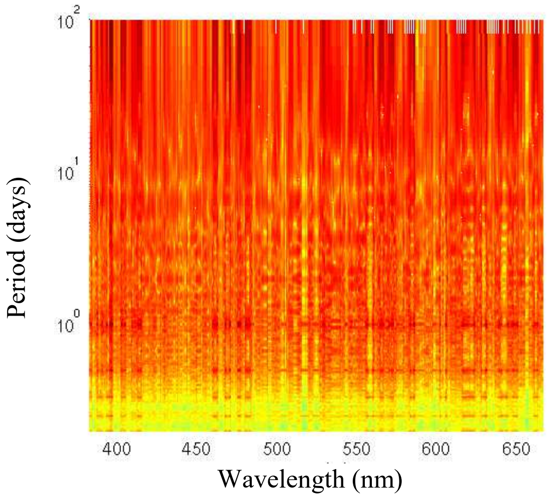

Fig. 1. Power spectral density of reflectance as a function of wavelength (x axis) and temporal scale (period in days, y axis).

Lines of high power densities can be seen for low periods (between 5 min and 1 day), indicating that the reflectance is sensitive to a high frequency phenomenon which affects all wavelength, with varying intensity. This can be explained by angular effects resulting from the interaction between waves and the solar angle.

Figure 2 shows the spectrum of the phycocyanin index.

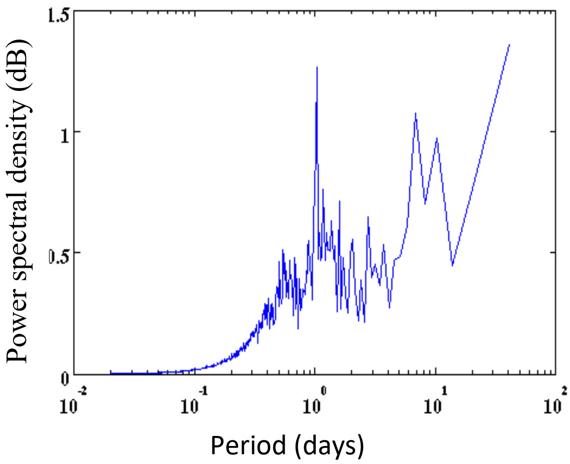

Fig. 2. Power spectral density (dB) of the phycocyanin index as a function of temporal scale (period in days, y axis).

High spectral densities can be seen for periods equal and lower than one day, and account for around one third of the total signal, indicating that the computation of a normalized optical index does not suppress the noise due to angular effects. To answer this issue, the high-frequency noise due to waves need to be filtered, and the high-frequency noise due to angular effects need to be addressed using observations made under comparable light conditions.

Sensor design and validation

The resulting sensor and its component are shown in Figure 3.

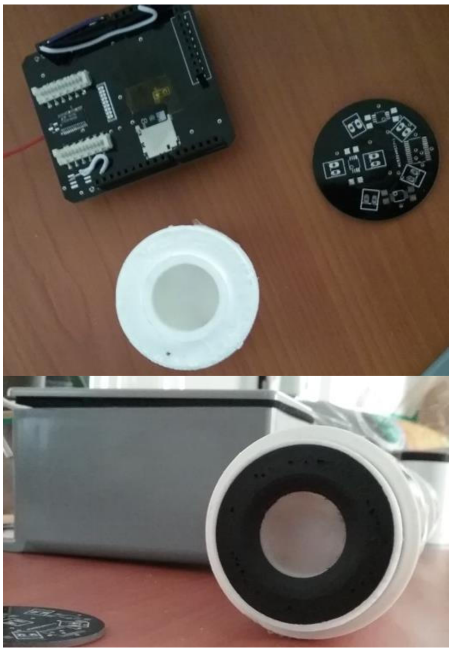

Fig. 3. Components and assembled optical sensor.

It was designed as a fully integrated sensor and datalogger, able to record water reflectance over a wide range of gain. The final production cost was lower than 500$ per unit, and it was able to continuously record series of incident and reflected radiances in six spectral bands over a range of 256 gain values spanning 5 min each. The use of a gain versus radiance linear relationship fitted over a moving window spanning more than 5 min enable an automatic filtering of high-frequency noise due to waves ad sudden changes in light environment.
The obtained measurements of the phycocyanin index were related to cyanobacterial biomasses estimated by using the BBE-Spectrofluorometer as shown over the course of 12 days in Figure 4.

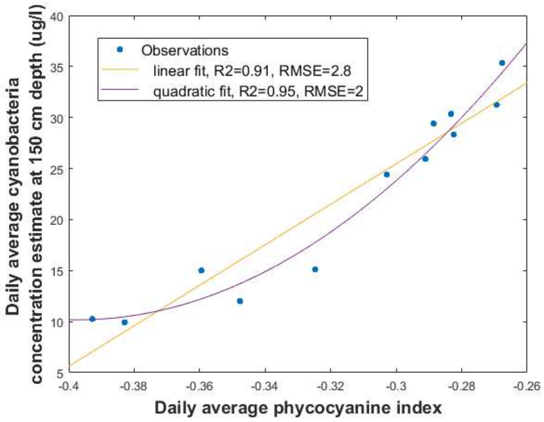

Fig. 4. Relationship between daily average phycocyanin index measurements and daily average

phycocyanin concentration derived from BBE measurement over the course of one of 12 days.

Significant relationships were obtained, indicating that the new passive sensor can provide a reliable estimation of phycocyanin concentration. Future efforts will focus on testing the sensor suitability for spatial sampling, and its ability to track phycocyanin concentration over a wider range of different aquatic ecosystems.

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