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Turbidimeter and RGB sensor for remote measurements in an aquatic medium

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ABSTRACT

The present article describes a turbidimeter based on nephelometric scattering measurements, which operates with an infrared source. The device also includes an RGB sensor to obtain information about the color of the sample. The basis of operation and process of calibration of the device are described. The turbidimeter was tested during two months offshore in a bay of northwestern Spain obtaining a periodic turbidity daily signal from the water. On the other hand, the RGB sensor pointed out that the marine suspended particles were primarily green. These data demonstrated that the apparatus detected the diel vertical migration of phytoplankton.

1. Introduction

The measurement of water turbidity gives us insight into the way dissolved matter and suspended particles affect its optical clearness. The dispersed materials can be either microorganisms, organic matter or inorganic substances. Measurement of sea water turbidity accounts a great interest in biological marine studies and water-quality analysis. It has been demonstrated that the variations of turbidity strongly modify the aquatic ecosystems [1]. For instance, photosynthetic organisms can be blocked by shadows which prevent them from obtaining energy from the sun, and consequently the whole food chain can possibly result affected. As for what concerns fish, they can experience a vision reduction and may also find trouble to breathe. It is on this context where the turbidity measurement has gained its major interest.

There are few classical methods to measure turbidity, most of them based on transmission of light through water. Among them let us cite the Jackson candle turbidimeter [2] which works pouring water progressively into a tube under which there is a candle. The measurement is taken just at the moment when the candle stops being visible from the top. This is a low cost method and needs no calibration but it is unuseful to measure low turbidities and does not allow automatic nor remote measurements. Another method is the Secchi disk [3,4] which consists in immersing a black and white disk into the water up to a depth where the disk becomes invisible. This low cost method does not require consumables and needs no calibration. However, it is less accurate than the former, it cannot be used in shallow waters nor swift currents and it is not applicable to small samples. Additionally, it is unable to measure low turbidities and does not allow remote measurements either. A combination of the both methods described above is the so-called turbidity tube or transparency tube [5]. In this device, the disk is placed on the bottom of a tube and water is added up to the point where the disk becomes invisible from the top. Turbidity is then read as the level reached by the water on the tube scale. This makes the procedure useful for many water sources but it still has the drawbacks of the above

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described methods. Modern turbidimeters are based on transmission or scattering of light coming from a source like a bulb or LED and result more accurate, suitable for small turbidity measurements, and allow working with small samples. In the present work we describe one of these turbidimeters, specially designed to take remote measurements from natural environments.

When light encounters random irregularities in its propagation medium (such as small particles), rays are deflected in different directions. This phenomenon is known as scattering. Fundamentally, the monitoring of turbidity is based on optical methods such as backscattering measurements, 90-degree scattering, forward transmission and forward scattering [6,7]. Due to its low dependency on the particle size, the here described sensor is based on the 90-degree scattering also known as nephelometric method [8]. Nowadays, there is a wide variety of commercial sensors on the market, useful to control the turbidity of a sample. However, most of them lack a RGB sensor which could allow to obtain not only an estimation of the color of the liquids, but also may aid the identification of the immersed particles responsible for it. Possible applications of this device can be: pollutants detection [9] (e.g. oil), wastewater quality evaluation [10], filter monitoring in diverse processes [11], industrial waste treatment control and limnological studies [12,13].

In the following sections we will describe the operating principles of the device (Section 2), as well as its design and characteristics (Section 3). Subsequently, we detail the process of calibration for the turbidity and color scales (Section 4). Next, we present the measurements and analyze the results for the different tests carried out (Section 5).

2. Operating principles

When measuring the scattered light in a suspension we have to take into account that a number of factors can alter the received signal. For instance, the properties of the dissolved solid (like size, shape, concentration and absorbance) can play an important role. We are unable to control those factors, but we can choose an appropriate design so that their impact is minimized. Concerning the particle size, it modifies the distribution of the scattered light in the different directions. When the dimensions are larger or equal than the incident wavelength a larger forward scattering will be sensed, whereas the perpendicular scattering is barely changed [14]. This way, fixing the receiver at an angle of 90° respect to the emitter will reduce the effect of the particle size [see Fig. 1(a)].

Light scattering is also influenced by the absorbance of the solid, which depends on the wavelength of the incident light. In order to have a more accurate measurement we decided to use an 890 nm infrared (IR) emitter, avoiding in such a way the need of color compensation. This source is a light emitting diode (LED) with a radiation power of 1 mW and a spectral FWHM (full width at half maximum) of 80 nm. In order to get information on the color of the solid, also a triple (red, green and blue, RGB) LED source was installed on the device to get measurements on these three components. A unique phototransistor is used as detector for all IR and RGB sources oriented in such a way that it receives the scattered radiation into a 90-degree angle respect to the direction of both sources. For this, an arrangement as the one illustrated in Fig. 1(b)–(d) is used. Both sources and the detector are placed at the apexes of an equilateral triangle and properly bent to form the requested 90-degree angle between every source and the detector.

Regarding the mechanics of the equipment, sources and detector are attached to a copper piece. This material was selected in order to minimize the corrosion of salty water and the fouling. Fouling is the accumulation of organic or inorganic matter on a surface. It has a negative effect since it impedes the correct functioning of an underwater device [15]. It has been demonstrated that copper produces a film, composed of oxychloride, that diminishes this effect [16]. The copper piece was pierced to place the IR and RGB LEDs at the desired position, both forming a 90-degree angle respect to the phototransistor as explained above. The copper plate is integrated on the bottom of a commercial buoy to be placed offshore or into the water ecosystem to test (lakes, rivers or seas) in such a way that it lays

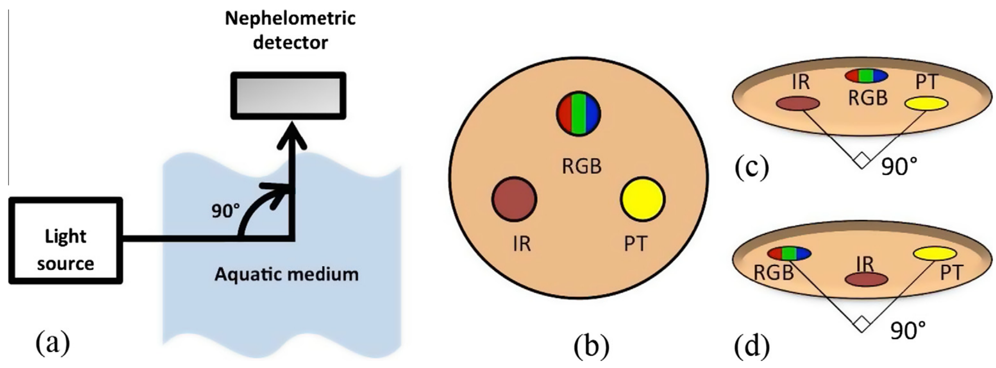

Fig. 1. (a) Scheme showing the operating principle of a nephelometric sensor, based on detecting the 90-degree scattered radiation. (b) Sketch of the arrangement of sources (IR and RGB) and the phototransistor acting as a detector on the copper piece attached to the bottom of the buoy. (c and d) Detail of the orientation of both sources and detector to fulfill the 90-degree angle layout. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

immersed to detect the turbidity and the color changes inside the water body. The buoy also contains the control electronics, batteries and solar panels on the top to charge the batteries.

3. Description and operation of the device

The electronics of the designed device (see Fig. 2) consist of an 8-bit microcontroller, an infrared (IR) LED, a triple red, green and blue (RGB) LED, a global positioning system (GPS) module, a wide response phototransistor, a negative temperature-coefficient resistor (NTC) used for temperature calibration, a 16-bit analog-to-digital converter (ADC) with several channels, and a modem for satellite communication. The phototransistor is biased to obtain a voltage response proportional to the incident light. To power-supply the device, a battery charged by means of solar panels is used.

A calibrated negative temperature resistor (NTC) is used to determine the temperature of the water. A voltage divisor was implemented for this purpose. This voltage is sampled with one of the channels of the ADC converter.

Since the device will be working under ambient light, we need to subtract this background illumination from our measurements. This is done with both LEDs off. The response of the phototransistor under these conditions is sampled with the ADC converter and temporally saved in the microcontroller. Afterwards, the IR LED is turned on and the voltage response is sensed and saved. Subsequently, the previously measured ambient light value is subtracted from the latter. These steps are repeated five times. The final output is provided averaging the results obtained from those repetitions. The same process is followed for the RGB signal measurement. Measurements are taken every 30 min in principle, however this time step can be changed if necessary by means of a satellite telecommand.

Data (including time, GPS coordinates, charge of the batteries, NTC voltage, IR, R, G and B outputs) are sent as a character stream to a mail server through a satellite. A later processing of data will be carried out. For instance, to obtain data independent from temperature, a calibration is performed (see Section 4.1) in order to translate all the measurements to a fixed reference temperature.

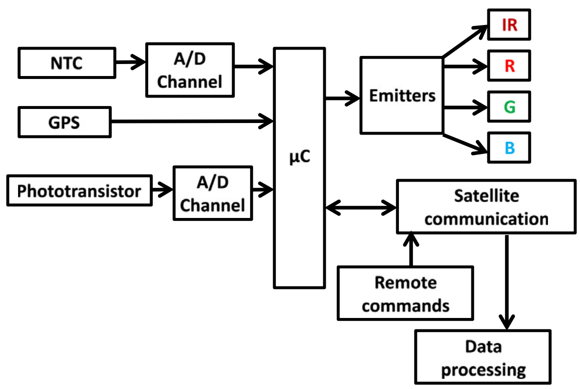

Fig. 2. Scheme showing the functioning and different parts of the system. The micro-controller is labeled as μC.

The most widely used units for turbidity are the NTU (nephelometric turbidity units). These units are based on primary solutions used as measurement patterns. Since a 90-degree (also named nephelometric) measurement is independent to the particle size, shape and reflectivity, the NTUs can be correlated to the total suspended solids (TSS) units, which in the international system are mg/l (milligrams per liter), being the relationship practically linear [17].

With the first version of the measuring-device, only operating with the IR sensor, we are able to obtain an approximation of the particle concentration in the liquid. The measurement is then complemented adding a RGB sensor that provides information about the sample color. This sensor uses the same receiver to measure the color components, also employing the 90-degree scattering configuration. This tool opens the possibility to a latter identification of the particles.

In order to obtain the relationship between the measured signals and nephelometric turbidity units (NTU), we used four different concentrations of a standard commercial formazine (white polymer broadly used in turbidity instrumentation). A calibration function was calculated for this purpose. The process is described in Section 4.2. A similar procedure was used to calibrate the color scale for the RGB sensor, using a formazine dissolution as well (Section 4.3).

4. Calibration process

A process of calibration is necessary to relate the scale of the output signals (digital voltages obtained from the ADCs into the microcontroller ports) to the real turbidity scale. Also, a temperature calibration is required since the device is going to operate under different temperature conditions affecting the response of the emitters.

4.1. Temperature calibration

Measurements depend on the temperature, specially because the LEDs emission power is strongly temperature-dependent. Since the device is intended to be installed outdoors, ambient conditions will vary daily and consequently a way to correct these measurements is required so that they become independent from temperature. In such a way, a temperature calibration process was followed. Using the RGB and turbidity (IR) sensors we performed a set of 930 measurements at different temperatures stepped about 0.026 °C, using a fixed white solid sample. The temperature was varied using a warm air stream directed to the copper piece where the LEDs, phototransistor and NTC sensor are placed. The output signal is plotted against temperature for every source in Fig. 3, showing a basically linear relationship. Data points were in this way fitted to a straight line $S = aT + b$, where S is the signal obtained at the ADC output and T is the centigrade temperature. Using the slope a of the corresponding line it is possible to relate the signal at any temperature T to the one at a reference temperature T_{cal}, that we

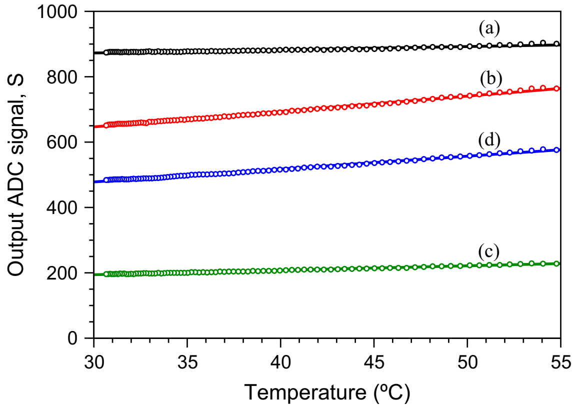

Fig. 3. Temperature calibration for the four used emitters. Line (a) corresponds to the IR LED, while (b)–(d) represent the calibration of the red, green and blue LEDs respectively. A sample of the experimental points are represented together with the fitted lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

established at $T_{cal} = 25\,^{\circ}\mathrm{C}$. In fact, the increment in the output signal between two different temperatures T_1 and T_2 is

$$S_{T_2} - S_{T_1} = a(T - T_1), \tag{1}$$

so that the signal variation rate from temperature T_1 to temperature T_2 is given normalising the slope by the signal at T_1,

$$\eta = \frac{a}{S_{T_1}} = \frac{S_{T_2} - S_{T_1}}{T_2 - T_1}\frac{1}{S_{T_1}} = \frac{S_{T_2}/S_{T_1} - 1}{T_2 - T_1}. \tag{2}$$

This factor can be obtained directly from the temperature calibration data and can be used to translate any particular measurement at a temperature T into a measurement at any other reference temperature T_{cal}, just adding the corresponding correction term,

$$S_{T_{cal}} = S_{raw} + \eta(T - T_{cal})S_{raw} = [1 + \eta(T - T_{cal})]S_{raw} \tag{3}$$

where S_{raw} is the initial measurement at temperature T. In Table 1 there are the fitted coefficients, the regression coefficient and the value of the translation factor η of the output signal into the established calibration temperature of $T_{cal} = 25\,^{\circ}\mathrm{C}$, for all the four sensors (IR, R, G and B).

As it can be seen in Fig. 3, the tendency is linear, except but for high temperatures where the behavior starts to fail to be linear, specially for the IR sensor. This is why the regression coefficient reaches a slightly smaller value for this sensor. Anyway, such high temperatures are never reached in practice and the behavior can be considered linear enough for practical use in the range of usual temperatures.

4.2. Turbidity calibration

To carry out the turbidity measurements the infrared LED was used. The output signal is a voltage proportional to the optical power reaching the phototransistor, and so it is proportional to the scattered power and ultimately to turbidity. A calibration process is necessary in order to relate this signal to a turbidity scale in nephelometric units (NTU). To obtain this correlation, we prepared four different concentrations from a standard commercial 4000 NTU formazine. The measurement process is described in the previous section. Fig. 4(a) shows the dependency of the phototransistor response with the formazine concentration (in NTUs). It is seen that points can be fitted to a straight line passing through the coordinate origin. The fitted slope of the line as well as the regression coefficient are given in Table 2. To calculate the turbidity in NTU we just multiply the output signal by this calibrated slope m following the equation,

$$IR_{NTU} = \frac{IR_{T_{cal}}}{m} = \frac{1 + \eta(T - T_{cal})}{m} IR_T, \tag{4}$$

where $IR_{T_{cal}}$ is the measurement translated to the reference temperature ($T_{cal} = 25\,^{\circ}\mathrm{C}$), IR_T the direct measurement at the actual temperature and IR_{NTU} is the final turbidity measurement in NTU.

4.3. RGB calibration

A similar process of calibration is followed for the RGB sensor in order to relate the output signal to the color of the sample. Formazine is also used for the RGB calibration, taking advantage of its white color and assuming that a 500 NTU dissolution corresponds to the top intensity, having the maximum red, green and blue components. According to an 8-bit range scale with its maximum set to 255 as is usual in computers and its minimum fixed at zero, a dense white color, indicative of a high radiation scattering at every component into the detector, would be described by chromatic parameters RGB = (255, 255, 255), while a complete transparency of the medium leading to a null radiation reaching the detector would be described as RGB = (0, 0, 0). This will allow us to know an approximation of the sample color. For each color we calculated a dependency line of the phototransistor response with different formazine concentrations. The different points shown on the curves in Fig. 4(b)–(d) were determined with the measurement process described in

Table 1
Values of the fitted coefficients ($S = aT + b$), regression coefficient and temperature calibration factor η to translate all the measurements to the reference temperature of $T_{cal} = 25\,^{\circ}\mathrm{C}$ for all four sensors. Values of η are rescaled for a neater presentation and should be divided by 10^3.

	IR	R	G	B
a (1/°C)	0.984 ± 0.009	4.71 ± 0.11	1.366 ± 0.043	3.9390 ± 0.0095
b	843.19 ± 0.35	505.26 ± 0.41	153.19 ± 0.17	359.94 ± 0.38
r^2	0.929	0.996	0.991	0.995
$\eta \times 10^3$ (1/°C)	1.150 ± 0.011	6.07 ± 0.17	5.816 ± 0.091	6.62 ± 0.11

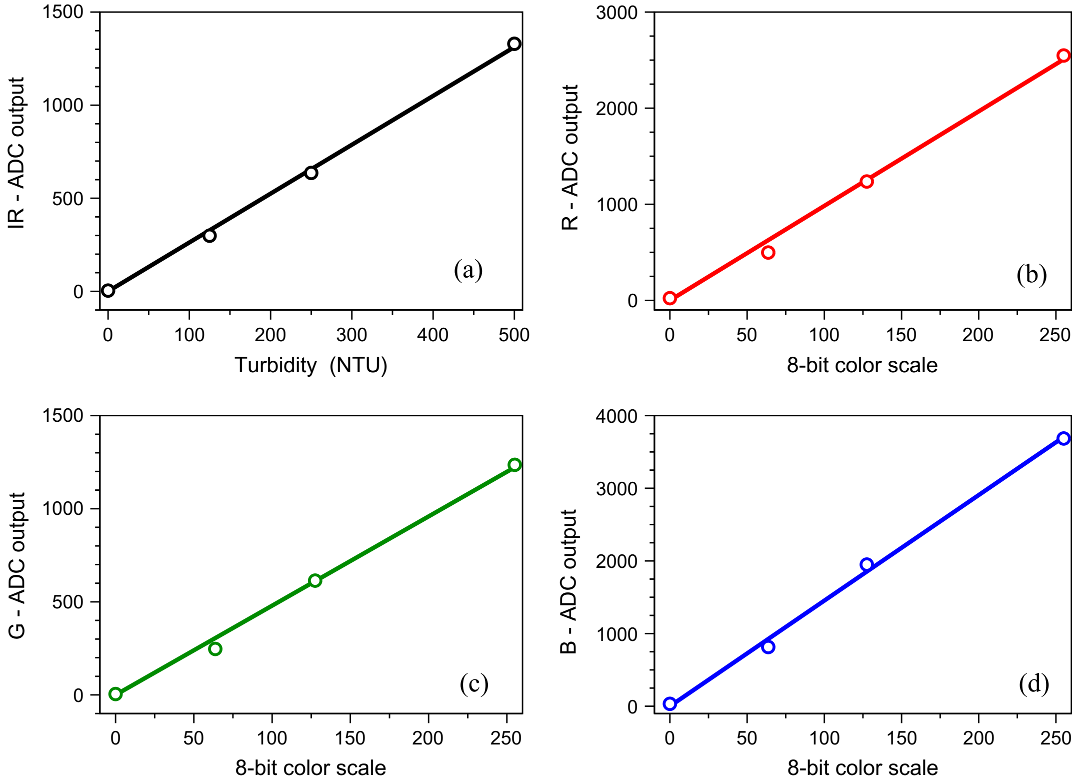

Fig. 4. (a) Relationship between turbidity and the IR 90-degree scattering detected by the sensor. (b)–(d) Color calibration for red, green and blue illumination respectively, using a 8-bit scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Values of the fitted coefficients and regression coefficient for the translation of the sensor outputs into the real units: NTU for the infrared sensor (turbidity calibration) and adimensional 8-bit scale units for the color components.

	IR	R	G	B
Slope m (NTU^{-1})	2.625 ± 0.041	9.83 ± 0.28	4.79 ± 0.12	14.53 ± 0.30
r^2	0.999	0.998	0.998	0.999

Section 2. Again, points are seen to fit quite well to straight lines passing through the coordinate origin. Fitting parameters (slope) are given in Table 2. In this way, to calculate the color components in the 8-bit scale we followed the equation,

$$(R,G,B)_{8bit} = \frac{(R,G,B)_{T_{cal}}}{m} = \frac{1+\eta(T-T_{cal})}{m}(R,G,B)_T, \qquad (5)$$

where $(R,G,B)_T$ are the output of the three sensors and $(R,G,B)_{8bit}$ are the final measurements in the 8-bit color scale. The factor η is introduced to translate measurements into the reference temperature (25 °C), and m is the slope of the correspondent calibration function.

5. Results

We tested the designed instrument during two months (from August to October 2013) at the port of Baiona (NW Spain). As it was explained above the device was placed on the structure of a commercial buoy, which maintains the sensor immersed 30 cm below the water surface. The exact GPS coordinates of its location were 42°07′46″N, 8°50′77″W. Fig. 5 shows the variation of the turbidity during the mentioned dates. As one can see, the turbidity level is kept low most of the day, below 10 NTU. This means that water surrounding the turbidimeter was clear. However, a periodic turbidity variation is observed. In fact, peaks over the mean arise daily around 12:00 GMT (see Fig. 6). Since our measurement is independent from both the ambient light and from temperature, this daily repetitions can be attributed to the diel vertical migration of phytoplankton. This type of microorganisms modulate their position as a response to environmental factors. According to the studies of Figueroa et al. [18] light-quality controls phytoplankton migration, stimulating or inhibiting the cell movements. Another aspect that we can highlight from the results is the attenuation of the peaks throughout the measuring time. This effect can be ascribed to the

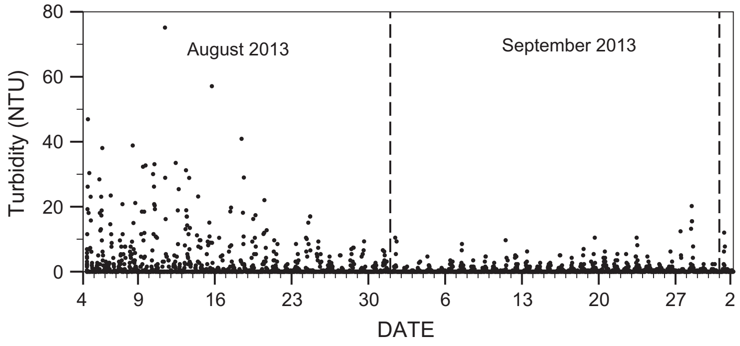

Fig. 5. Periodic variation of the turbidity in the port of Baiona during a two-month lasting measurement. Daily peaks are located around 12:00 GMT.

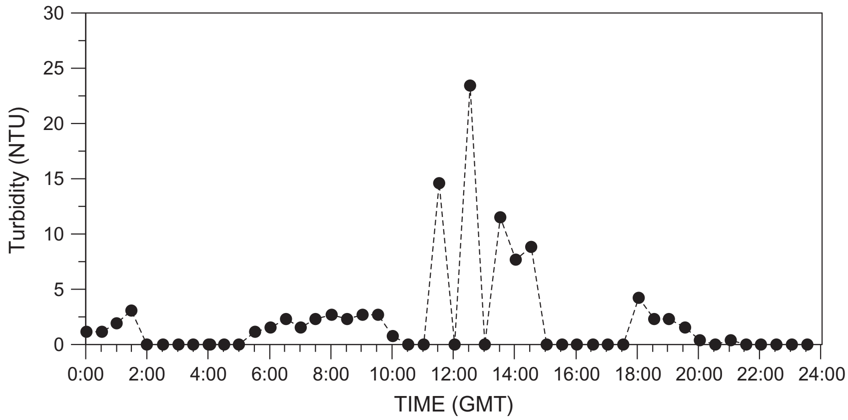

Fig. 6. Example of the variation of the turbidity during one day (6th August 2013). Dashed lines connecting points are placed for a better seeing and do not represent interpolated values.

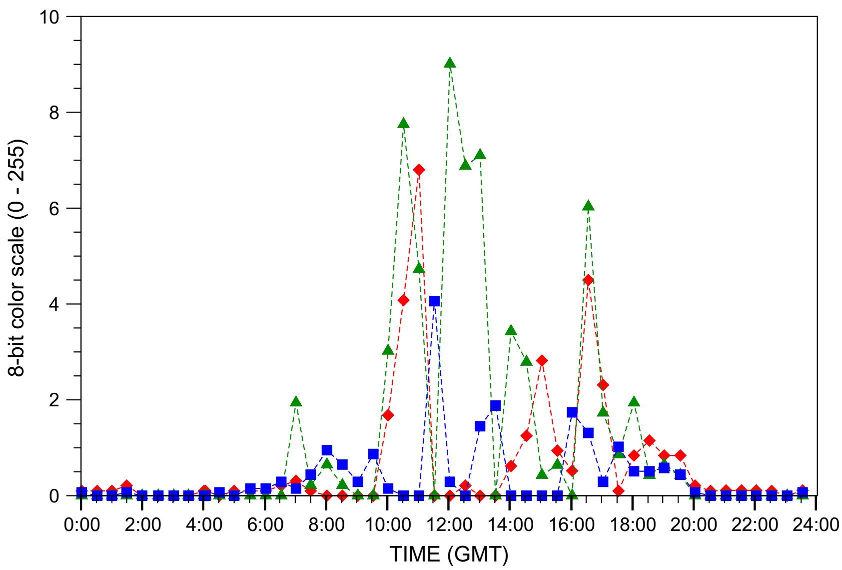

Fig. 7. RGB variation of the color components during a day (6th August 2013). Diamond, triangle and square shaped points correspond respectively to red, green and blue measurements. Dashed lines connecting points are placed for a more comfortable seeing and do not represent interpolated values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increasing presence of fouling. In fact, the emitter and receptor of the device are gradually blocked by the accumulated organisms.

Measurements obtained from the RGB sensor show similar results. Fig. 7 depicts the fluctuation of the red, green and blue color components of the water during one day of exposure. The axis showing the 8-bit scale was zoomed due to the fact that the present components were relatively low. Likewise the turbidity results, this indicates that the water maintained its optical clearness. Nonetheless, it is evident that the green color thrives over the rest. This is congruent with the assumption that the turbidity is caused by phytoplankton, because those autotrophic (photosynthetic) organisms contain chlorophyll-a. Well known algorithms for remote chlorophyll-a detection use the blue to green reflectance ratio (B/G) to estimate the concentration of this substance [19], being such concentration inversely proportional to that relationship. Our data show a low blue response whenever the green signal reaches its maximum, indicating an increment in chlorophyll-a concentration. We also see an increase in the reflectance of the red component respect to the blue one, though red peaks are lower than green ones, and again this verifies the presence of phytoplankton. In fact, Colored Dissolved Organic Matter (CDOM), also known as marine humus, is a product from the photosynthetic activity of these microorganisms [20] and the concentration of this yellow substance varies linearly with the red to blue (R/B) reflectance ratio [19]. As a matter of fact an increase in CDOM appears in our measurements at the same times as phytoplankton arises.

To improve the overall performance of the device the use of pulsed light (IR, R, G and B) together with FFT (fast Fourier transform) analysis or lock-in amplification could be implemented in future prototypes. Also further improvements, such as the inclusion of a wiper or the use of ultraviolet light, can be carried out to reduce the presence of fouling and decrease its negative impact on the operation of the system over time.

6. Conclusions

In the present work a turbidimeter together with a RGB sensor was designed and implemented. The turbidimeter operates in a 90-degree scattering configuration (nephelometric measurement) and uses infrared illumination. Nephelometric scattering was also used to develop a RGB sensor to provide information on the sample color. A calibration was performed to fix the measurements to a constant reference temperature. On the other hand a turbidity calibration was made to use standard NTU units. A GPS device and a satellite modem were included so that the device can transmit the data worldwide and receive remote telecommands to change its configuration. The apparatus was tested 30 cm under ocean water during two months. The results show that the water clearness is high and the concentration of particles is below 10 NTU most of the day. However, peaks above this level appear daily around 12:00 GMT revealing a vertical migration of phytoplankton.

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