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# The distances measurement problem for an underwater robotic swarm: a semi experimental trial, using power LEDs, in unknown sea water conditions

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## Abstract

An underwater swarm has the important task to know its geometric configuration; this can be computed from the knowledge of the relative distances between its elements and it is studied as a geometry distances problem. Typically, the distances are measured by ultrasonic devices but we want to propose a method based on light signal exchanged between the machines and the use of the unknown water adsorption coefficient. Aim of this paper is therefore to measure distance between underwater elements of the swarm using cheap power LEDs as light source and photodiode as receiver. The receiving photodiode produces a current we can correlate with distance and water adsorption coefficient; we can resolve the two unknown parameters by moving the robots and stressing the emission conditions of the LED diode. In a previous paper we have stressed work conditions of a power LED that we are using as optical modem in shallow water to change its emission characteristics; now, using these results, we can now perform a set of measurements leading to the knowledge of distances and adsorption coefficient  $a(\lambda)$ . The method we propose here can be a possible support to traditional ultrasonic devices

## Keywords

Power LEDs, Underwater robotic swarm, distance measurement, geometry distance problem.

## 1. Introduction

A robotic swarm presents many advantages with respect of a single Autonomous Underwater Vehicle (AUV). They are in the speed-up coming by the parallelism and in the increase of reliability by redundancy [1]; in fact, the lack of one member can be easily managed by redistributing the job among the others members like, in natural environmental, as usually done by the bees [2]. Moreover, it could limit the use of the expensive surface ships to the deployment phase, taking advantage of the parallel exploration to shorten times and have many other advantages [3], [4]. The human operator has the possibility to examine an object concurrently from more than one point of view (in general meaning i.e. with sensors working from different positions), leading to a better perception of the surrounding environmental and a deeper understanding of the context. A swarm have to interact with a human operator as a single object, without the problem of controlling a large number of individuals; job sharing between the elements is an internal swarm task. This has the meaning to reveal one disadvantage of the swarm: the control system needs one more layer to translate the commands from the operator to the swarm, interfaced as a whole creature, to its constituent elements. A swarm is able to perform tasks in a more fast and robust way with respect of a single machine; but the most important feature, we want underline, is its capability to span communication from out of the surface into the water. It allows us to realize a quasi-real time communication and to interact with the underwater system using a remote console that can be locate on the coast. Practically we can realize a multi-hop network with variable geometry. This because one element could be located on the water surface, to fix its position by GPS (localization of the whole swarm follows) and to communicate with the operator; in the meanwhile, it can distribute the received message to the other elements under the sea by other kind of modem (Ultrasonic or LEDs modem). The swarm has to adapt its configuration depending on the exploration mission and communication task.

ENEA is working in robotics since a long time (1961) and underwater robotics is a key topic of our laboratory [5]–[7]. Some years ago, (2006) we have addressed our studies from single AUV to a swarm of very low-cost cooperating robots. One of the most important tasks for an underwater vehicle is its localization into the sea; for a swarm there is also the need to know its geometric configuration. The configuration of the swarm is generated by flocking rules, recently used to determine the deformation of a continuous material [8] [9] A further extension of the problem concerning this topic can be performed by

considering the interplay between swarm robotics and newly conceived materials, the so-called metamaterials. Some examples of these materials can be found in [10]–[14] and [15], [16], [11], [17]. The knowledge of the configuration is a very important issue for many applications often depending by the assigned task that can also vary during the mission. Configuration can be computed from distance measurements [6], [7] that is the purpose of this paper. Usually it is done by ultrasonic measurements but our intention is to use absorption light coefficient as support to traditional measurements.

Acoustic communications are the standards in submarine environmental [18]. Unfortunately, reflections, fading and other phenomena make difficult and sometimes not reliable their measurements. The need to continuously exchange data among the nodes (the swarm elements) to get the distances represents a considerable burden for the network operation to calculate the network configuration, also using suitable algorithms, because it forces to frequent short messages that deoptimize the exploitation of the communication channel, mainly for the long times needed to switch from a message to another one [19]. A possible solution, which improves both the time allocation in the acoustical protocols and unloads the acoustical channel burden, is to couple the acoustic protocol with optical device [20], [21] with the intention to collect distance measurements between the robots more precise, using sensor data fusion. Optical methods are very powerful but their performances are affected by many strongly variable parameters like salinity, turbidity, the presence of dissolved substances that change the colour and the transparency of the water in different optical bands [22]. Moreover, the amount of solar radiation, in shallow water, heavily affects the signal to noise ratio. Our current approach uses a mixed strategy based on the variable exploitation of the optical channel depending on the environmental conditions. In favourable conditions the transmission protocol will freely decide which channel to adopt depending on the priority, i.e. distance-to-cover and dimension of the message itself. In less favourable conditions the optical channel will be limited to the fundamental synchronization task, generating a light lamp that will optimize the message passing through the acoustic channel. So far, we have realized an optical modem with cheap power LEDs that it is working together acoustic system. It must be outlined that only dense swarms can take advantage of such an approach because only in these situations, with internal distances ranging from few meters to a maximum of 20 meters, there are the conditions suitable to use light signals for sync and measurements. Moreover, backup solutions based on the “all acoustical” approach, must remain available because it is always possible to find dirty waters with no way to use light signals. In this paper we work about the problem to calculate distance using optical signals. In a previous paper we proposed the use of a cheap power led system to support acoustic devices in localization and configuration computation of an underwater robotics swarm [7]. The system was based on light signal exchanged between the machines and used power led, of different wavelength, to calculate distances between them. The unknown water conditions, affecting the light propagation, required a local measure of the absorption function  $a(\lambda)$  using a known distance. Moreover, we investigated as power supply and flash duration of the LEDs can be stressed to vary light emission spectrum. By this experience now we are able to measure distance without the local measure of the absorption function. In this paper we show as, modifying spectrum, we shall be able to measure  $a(\lambda)$  and, consequently, the distance  $d$ .

## 2. Our prototype

In Figure 1 and Figure 2 the swarm element, named Venus and realized in our laboratory, and the optical modem prototype are shown. The characteristics of the robot are the following: Max depth 100m; Max speed 4 km/hr; Weight about 20 kg; Autonomy 3hrs; Dimensions are 1.20mX0.20m diameter. Standard sensors include a stereoscopic camera, sonar, accelerometer, compass, depth meter and hydrophones. In the optical modem the LEDs chips and photodiode are visible; the system is repeated on three faces to cover quite 360°.



Figure 1 Robot prototype during test in Bracciano's lake



Figure 2 Optical modem

Note we are dealing with a system thought as to be a component of a swarm of about 20 objects. The distances between robots are between 3 and 50 m. Therefore, the maximum distance possible between two robots is about 1000 m, as a particular alignment case; the average value of the distances was considered about 10 m. Technology of dense swarms is an answer to these problems need larger acoustical bands and allowing other physical channels to be exploited.

### 3. Semi experimental results

In a previous paper [7] we were using cheap power LEDs to build an optical underwater modem; we have tried to stress power supply and flash duration to change its emission characteristics. This work was performed with the aim to get a complete characterization of the diode. In fact, LEDs technical specifications from data sheet were referred to the static work conditions and we need a more precise characterization of the diodes to evaluate the possibility to use them in signalling and communication. Typical emission of the white Led is shown in Figure 3 while one experimental result, concerning the peak emission value vs. power supply, can be seen in Figure 4.

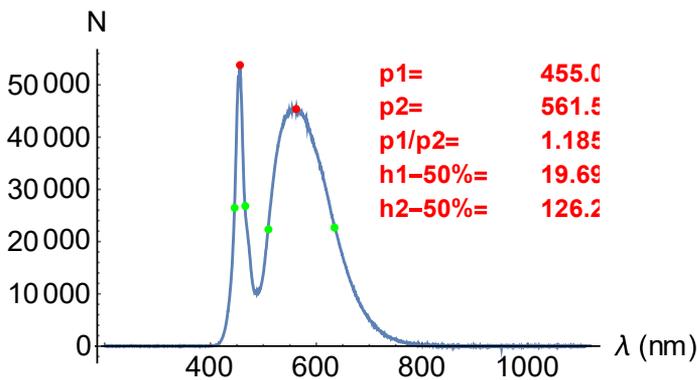


Figure 3 White Led diode emission

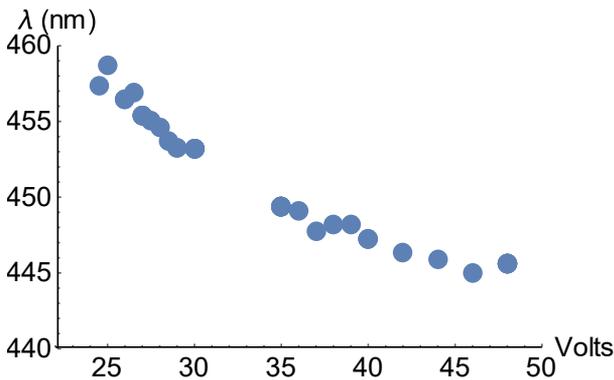


Figure 4 White Led first peak wave length shift value vs tension

The measurements have been performed with a resolution of 0.5 nm wavelength and similar results have been obtained with a blue LED. The reason to attempt to vary the LED's emission characteristics is economic: owing to the large number of swarm elements the use of complex variable frequency system is not sustainable. Therefore, we modify the function emission of the diode by the power tension and perform distance measurements based on water light adsorption. The water adsorption is generally unknown so, in the previous work, we performed a local measurement of the attenuation coefficient by a measure on the known distance head-tale of the robot. Unfortunately, this implies we have LEDs emission on the head of the torpedo-like robot and photodiode on the tale. This determines constructive problems of the optical modem. Our intention is to get rid of this architecture looking for another solution. The idea is that stressing LED emission we get some information useful to model water attenuation coefficient and, consequently, the distance. Practically we vary the spectrum emission of the LED, varying power supply, and perform an attempt to model absorption coefficient. In this paper we propose a theoretical way to compute it; we have not yet experimental data but simulating how could be the collected current from the photodiode using a simple equation. Only the data concerning the emission of the Led are experimental and this is the reason we use in the title the word semi-experimental. Later we try to match the current using some water categories, or linear combination of them,

from the literature. The high number of deformed emission function in a non-linear way allow us to avoid degeneracy solution so we get the right solution.

Light absorption by a medium, as a function of distance from the source is a well-studied phenomenon. In a first approximation, for a spherical wave, we can assume an exponential law for the decay of the signal intensity. So, we can write

$$I = f(\theta, \varphi) \frac{I_0 e^{-a(\lambda)d}}{d^2} \quad (1)$$

Where  $I$  is the measured intensity signal,  $I_0$  the emitted intensity,  $a(\lambda)$  the absorption function,  $f(\theta, \varphi)$  a shape factor and  $d$  the distance. We do not consider here the shape factor, known for the characteristics of the LED and of the photodiode leading to a modify of the spherical shape. Typically, you should consider an emission diagram of  $60^\circ \times 60^\circ$  therefore the energy is spread on this solid angle. The  $a(\lambda)$ , describing how the signal is attenuated as function of the wave length  $\lambda$ , is strongly affected by the water conditions as can be seen in Fig. 5 due to the courtesy of [23]. We are assuming that water characteristics do not vary in the volume containing the robots.

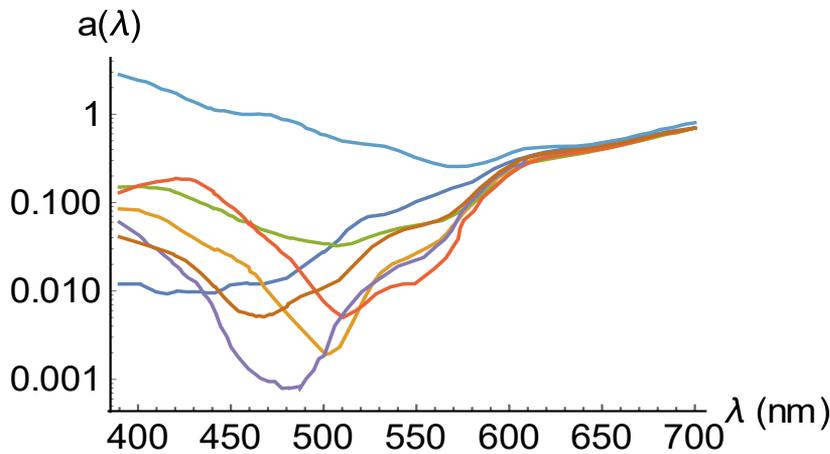


Figure 5 Light absorption in sea water in different condition [14]

Just to have an idea about the orders of magnitude of the attenuation in our case of interest we consider a distance of 10 m, a radius of receiving photodiode of 0,02 m and the case of clear water ( $a(\lambda)$  about  $0.02 \text{ m}^{-1}$ ) we get a signal attenuation of 20%; We have considered 1/3 as shape factor for the spherical wave because the LED emission diode is not omnidirectional. In case of turbid water ( $a(\lambda)$  about  $0.2 \text{ m}^{-1}$ ) the attenuation was about 90%.

There is no way to obtain,  $a(\lambda)$  and  $d$  separately by a simple measure if the intensity  $I$  because the two objects are linked by multiplicative way into the exponential function

In a previous work [20] we used monochromatic sharp peak blue Led to stress so we can measure the derivative of Eq. 1 respect to  $\lambda$  that give us the product  $a'(\lambda) * d$ . Computing it for two, unknown, distance  $d_1, d_2$  we can obtain the ratio  $d_1/d_2$  that is what we need. So far, considering the ratio of Eq.1 for the two distances, we can obtain the product  $a(\lambda) * d_1$ . Now, considering the Log of Eq.1 we have  $a(\lambda) * d_1 + 2 \text{Log}(d_1)$  and consequently  $d_1$ , without any model of  $a(\lambda)$ .

This was very nice but we are now using real white LEDs so we use, in this case, a semi-experimental procedure. Therefore, we use experimental stressed emission curves of the white LED together with the, furnished by the factory, responsivity of the photodiode to calculate the collected current at different, unknown, distance. The collected current is computed by the integration of the product of the experimental emission curves, the responsivity of the photodiode and Eq.1.

$$C = \int_{390}^{700} R * \text{EmLed}(\lambda) * \text{Eff}(\lambda) * f(\theta, \varphi) \frac{I_0 e^{-a(\lambda)d}}{d^2} d\lambda$$

Where EmLed is the emission curve of the Led (Figure 1) in 40 different stress conditions and Eff is the efficiency response of the photodiode; we have also introduced a random noise  $R$  of about 10%. We use, as  $a(\lambda)$ , the eight curves of Figure 5 to build a database. If we stress our LED emission on different unknown distances we obtain a set of curves like Figure 6 and Figure 7, depending on water quality. We now use the eight curves of Figure 5 as preliminary database, so we have 8 plots like

Figure 6. Now we perform our measurements in unknown water and distances, stressing the LED in 40 different ways, obtain 40 points set. These points are a vertical line on one of the 8 plots like Figure 7 posed at unknown distance; the points must coincide on all the curves. We repeat the operation for some other unknown distances to confirm our water quality hypothesis. We have to match our 40 points set into one of the 8 plots at a certain distance. One measurement could be present ambiguities leading to multiple choices so we repeat the measure at other distances as well as at the same one. At the end will be only one possible solution to match all. As “match” we mean a procedure concerning the minimization of the distances of our set of points from the curves, through optimization procedure. We are assuming the water behavior can be described by Figure 5 or by a combination of its curves; this could be reasonable because the figure is considering a very large water conditions case. If, as usual, our water is not comprising into the eight curves we generate it from linear combination of them losing in precision.

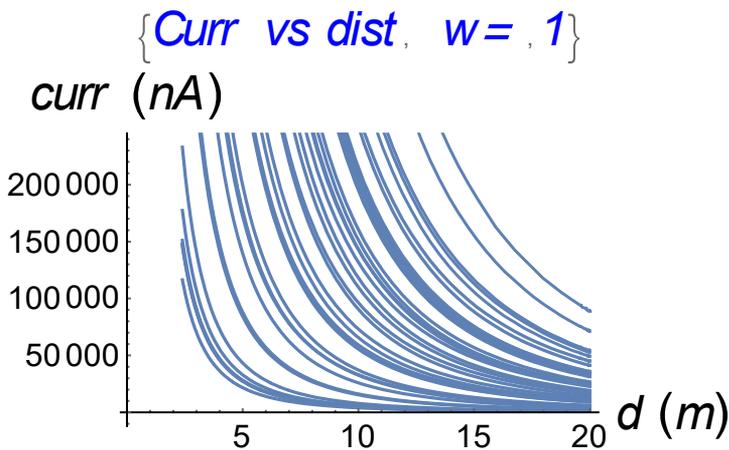


Figure 6 Collected current by photodiode for different Led power supply vs distance in clear water ( $w=1$ )

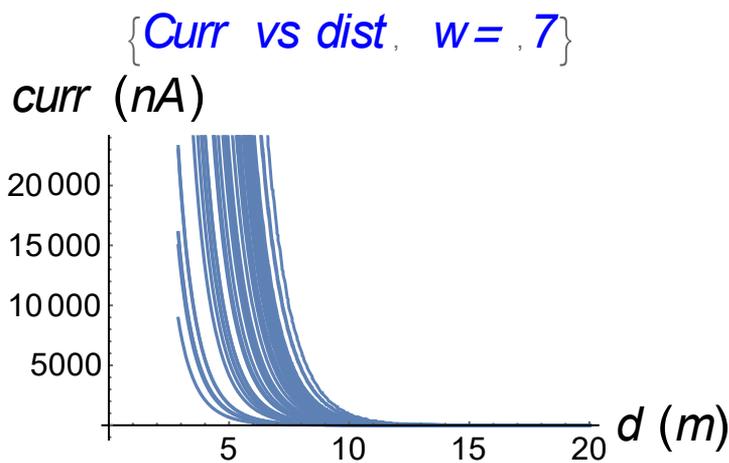
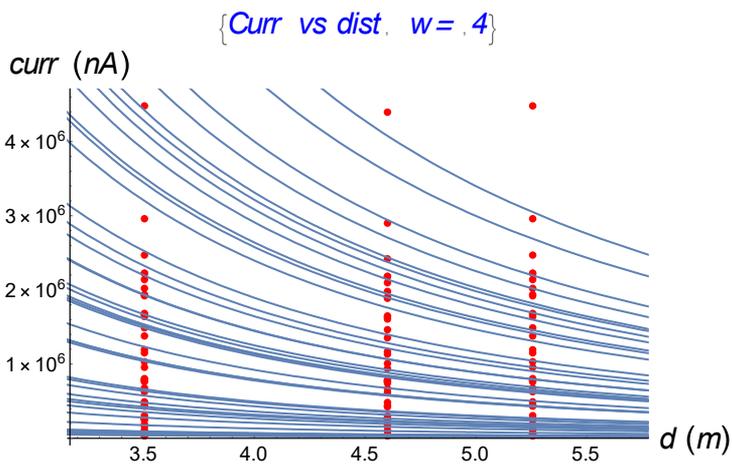


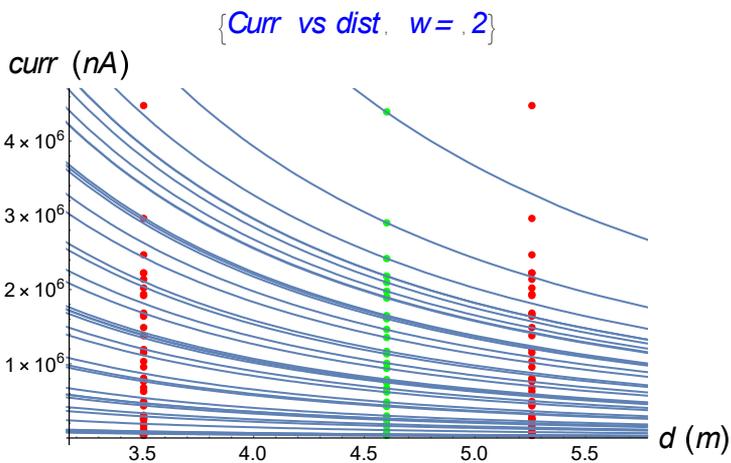
Figure 7 Collected current by photodiode for different Led power supply vs distance in turbid water ( $w=7$ )

Practically the steps are the following. 1) Simulate the collected data. We choose one of the eight kind of water (2 in our example or linear combination of them) and a distance  $d$  (7.1 in our example). 2) Compute the current  $C$  form the photodiode. 3) With this data we try to match, for each picture like Figure 7 and Figure 6 (or linear combination of them) the set of 40 points until we find the distance  $d$ .

An example can be seen in Figure 8 and Figure 9. Our measurements are the vertical points and there is just one distance, in a particular kind of water, to minimize the distances of the points from the curves; we move the vertical lines to find the distance for the best match between the curves and the points.



**Figure 8** Collected current by photodiode for different Led stress vs distance in water ( $w=4$ ) and distance= $7.1\text{m}$ . The red points are our, simulated, measurements. We try to match the curves without success



**Figure 9** Collected current by photodiode for different Led stress vs distance in water ( $w=2$ ) and distance= $7.1\text{m}$ . The red points are our, simulated, measurements. We try to match the curves: best result is for  $d=7.26\text{ m}$

Simulation computing can be seen in Table 1 where the simulation for ten different distances are shown. Therefore, we perform 40 flashes for each distance and 50 measurements with random errors, stressing the LED in different conditions, for ten unknown distances. The results are quite good. Take in account that each simulated measurement is affected by a random 10% noise generate to make more realistic the computing. In Table 2 we report the results of mixed water conditions (Linear combination of water of kind 2 and 4). The results are less accuracy, especially at low distances, but still useful.

Real distance	Estimated distance	Standard deviation
0.9	0.9	0.2
1.1	1.2	0.2
3.5	3.4	0.1
4.1	3.9	0.4
4.6	4.4	0.6
5.1	5.0	0.4
8.3	7.8	1.3
14.0	12.4	2.3
16.6	15.1	3.0
17.6	16.7	2.1

**Table 1** Estimation of the unknown distance  $d$  using one of the eight water of Figure 5

Real distance	Estimated distance	Standard deviation
0.9	0.9	0.2
1.1	1.2	0.2
3.5	3.4	0.6
4.1	3.8	0.5
4.6	4.3	0.7
5.1	4.8	0.7
8.3	7.5	2.1
14.0	13.4	2.6
16.6	15.2	3.2
17.6	16.6	3.1

**Table 2** Estimation of the unknown distance  $d$  using mix of the eight water of Figure 5

Many objections can be moved to this methodology. As example we can consider that our database can be valid only for one diode, because its chromatistics can change. Therefore, we have tried to work not with the original emission but with the ratio of the 40 emission with one of them. The results are the same and by this way we avoid the problem to be linked to a particular diode. Moreover it is possible to use more than one LED, with different frequency emission, to increase precision [7]. Working on the ratio intensity at the different frequencies we can enhance our measurements owing to the increasing stability of the photodiode current, with respect of that of a single source. Practically we increase the sensitivity of the signal to the measured distance, by enlarging the responsivity dynamic. It should be noted as we obtain similar results also if we consider the same emission curve varying its amplitude because the integral in the collected current introduce a non-linear operation (owing the emission curve shape) and this is what we need to separate we product  $a(\lambda) * d$ . We have tried, of course but remember that, as proof by experimental data when you change power you obtain non-only a different amplitude but also a different emission function, so we have worked directly with experimental data. The same job was performed by using a quite monochromatic blued diode (see Figure 10) obtaining similar results with a better degree of precision.

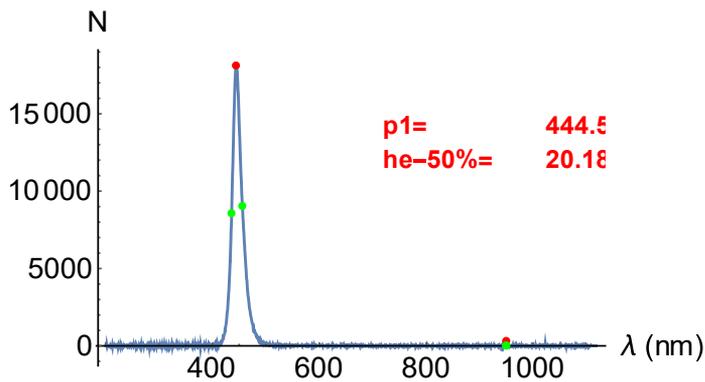


Figure 10 Blue Led diode emission

## 5. Conclusions

We have built an optical modem by using cheap commercial LEDs and modifying power tension we are able to modify emission peak. Working around it in this paper we proposed semi- experimental results to measure distances between light source and photodiode in unknown water conditions based on adsorption coefficient. The emission curve of the LEDs is stressed by power source getting information on the water adsorption function. We talk of semi-experimental because while the emission peak is experimental the collected current form the photodiode is simulated by a simple equation. Simulating these collected current we use a database of water condition, or its linear combination, to match the data. Varying the unknown distances, we can build a set of compatibility to identify the extinction coefficient of the water. The method could be a support for standard acoustic measurements and can be used to calculate configuration of an underwater robotic swarm that we are developing in our laboratory.

Experimental measurements are in progress to validate the concrete possibility to estimate water extinction coefficient  $a(\lambda)$  by this method. Errors sources are many. This method must be considered as an iterative method whose precision is increasing with many measurements. These measurements must be integrated with some other source like acoustic, as usual in robot science. The use of more than one LED, with different frequency emission, suddenly increase precision. The work is in progress in our laboratory with experimental campaign into the Bracciano Lake, close to our laboratories.

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