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Toward the widespread application of low-cost technologies in coastal ocean observing (Internet of Things for the Ocean)

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Abstract

The ability to access user-friendly, low-cost instrumentation remains a limiting factor in coastal ocean observing. The majority of currently available marine observation equipment is difficult to deploy, costly to operate, and requires specific technical skills. Moreover, a harmonized observation program for the world's coastal waters has not yet been established despite the efforts of the global ocean organizations. Global observational systems are mainly focused on open ocean waters and do not include coastal and shelf areas, where models and satellites require large data sets for their calibration and validation. Fortunately, recent technological advances have created opportunities to improve sensors, platforms, and communications that will enable a step-change in coastal ocean observing, which will be driven by a decreasing cost of the components, the availability of cheap housing, low-cost controller/data loggers based on embedded systems, and low/no subscription costs for LPWAN communication systems. Considering the above necessities and opportunities, POGO's OpenMODs project identified a series of general needs/requirements to be met in an Open science development framework. In order to satisfy monitoring and research necessities, the sensors to be implemented must be easily interfaced with the data acquisition and transmission system, as well as compliant with accuracy and stability requirements. Here we propose an approach to co-design cost-effective observing modular instrument architecture based on available low-cost measurement and data transmission technologies, able to be mounted/operated on various platforms. This instrument can fit the needs of a large community that includes scientific research (including those in developing countries), non-scientific stakeholders, and educators.

Keywords: Internet of things; low-cost technologies; ocean observations.

Acronyms

ARGO-Global array of free-drifting profiling floats; AUV-Autonomous Underwater Vehicle; DBCP-Data Buoy Cooperation Panel; EOV-GOOS Essential Ocean Variable; EV -GOOS Essential Variable; GEOSS-Global Earth Observation System of Systems; GLOSS-Global Sea Level Observing System; GOOS-Global Ocean Observing System; GO-SHIP-Global Ocean Shipbased Hydrographic Investigations Program; GSM-Global System for Mobile; LoRa-Long Range; LPWAN-Low Power Wide Area Network; LoRaWAN-LoRa Wide Area Network; MPPRCA-Marine Plastic Pollution Research and Control Act; MSFD-Marine

Strategy Framework Directive; NB-IoT-Narrow Band Internet of Things; NTC-Negative Temperature Coefficient (thermistor); OceanSITES-A worldwide deep-water reference stations; OECD-Organization for Economic Co-operation and Development; OpenMODs-Open Access Marine Observation Devices; POGO -Partnership for the Observation of the Global Ocean; ROV-Remotely Operated Vehicle; SOOP-Ship of Opportunity Program; SOT-Ship Observations Team; TUV-Tower Underwater Vehicle; UNEP-UN Environment Programme; USV-Unmanned Surface Vehicle.

Introduction

Most global coastal areas are located in countries with low/medium GDP per capita. Although most human marine activities take place in the coastal zone, this area is seldom regularly observed. On the other hand, UNEP (2016) predicted that in the next 50 to 100 years, up to 70% of the world`s population will be living in the coastal zone, affecting and being affected by it. The concomitant growth of ocean-based economic activities will produce 2.6 trillion euros by 2030 according to OECD estimates (OECD 2017). Over past decades, the global ocean environment is changing rapidly because of natural and anthropogenic pressures. For all these reasons continuous monitoring of coastal and marine systems is becoming more and more important.

Within the Sustainable Development Goal 14 (life below water), in the Revised Roadmap for the UN Decade of Ocean Science for Sustainable Development (2021-2030) (Ryabinin *et al*. 2019) the need is felt to improve the observation capabilities in coastal areas, especially in developing countries. Similar recommendations can be found in Tsukuba (in 2016) and in Turin (in 2017) documents approved by G7 Ministers of Science and Research, as in the Charlevoix blueprint for healthy oceans, seas, and resilient coastal communities (Kirton, 2018).

To foster the ocean monitoring in the developing countries, the development of user-friendly and low-cost instruments is essential. However, the ability to access user-friendly and low-cost instrumentation is still a limiting factor in ocean sciences because the majority of marine observation equipment is difficult to deploy and costly to operate since it requires specific technical skills. A shortage of local skills in ocean observation and interfacing capacities with stakeholders further exacerbates the problem (Miloslavich *et al.,* 2018). Moreover, a harmonized observation program for the world coastal waters has not yet been established despite the efforts of the GOOS organization, which is coordinating the assessment of ocean observing requirements, observing system implementation, and innovation through GOOS Projects (Tanhua *et al.,* 2019). As highlighted by Tanhua *et al.,* (2019) and reported by the Panel for Integrated Coastal Observation of GOOS (Digiacomo *et al.,* 2012) many areas have too infrequent, sparse, inadequate, or imprecise ocean observations; moreover, many new technologies are under development or their implementation on regional to global scales is very limited. A large part of the GOOS existing programs (ARGO, DBCP, GO-SHIP, OceanSITES, SOOP) are focused on open ocean waters and do not cover at all the coastal and shelf areas while models and satellites require reliable and rich data sets for their calibration and validation in coastal zones – especially for biogeochemical variables. Yet even as the importance of coastal oceans continues to increase, our knowledge of these areas remains limited with obvious limitations in implementing informed management (e.g., Maritime Spatial Planning), fulfilling environmental regulations (e.g., European MSFD, Canada's Oceans Act, United States of America Shore Protection ACT, Japan's Basic Environment Law), and responsibly exploiting the marine resources. The lack of data and knowledge has an impact even more evident in the least developed countries and in small island developing states (SIDS) where the direct and indirect dependency on marine resources is often crucial for their survival.

Fortunately, technological advancements have recently led to novel improvements in sensors, platforms and communications systems that will enable a step-change in coastal ocean observations because of the lower costs of the components (while maintaining precision and accuracy sufficient for many applications), cheap housing availability, low-cost controller/data loggers based on embedded systems and low-cost LPWAN communication systems. The growing data availability in heterogeneous sources (e.g., citizen science), from sectors traditionally reluctant to share environmental data (e.g., fishing, fish farming and non-renewable energy) and the above-mentioned technological improvements will transform the observing philosophy in the coastal area. This will lead to the implementation of the Internet of Things paradigm in surface (Yang *et al.,* 2018; Wright *et al.,* 2016). and underwater applications (Kao *et al.,* 2017, Abdillah *et al.,* 2017). Previous reviews address *in situ* autonomous ocean observing methods and sensors both generic (Mills *et al.,* 2012; Crise *et al.,* 2018) and application specific (Danovaro *et al.,* 2016; Kumari *et al.,* 2019).

Moreover, many important projects, such as NEXOS (Delory *et al.,* 2014; http://www.nexosproject.eu/), SCHeMA (http://www.schema-ocean.eu/), COMMON SENSE (https://www.commonsenseproject.eu/) and Sense Ocean (http://www.senseocean.eu/) contributed in the last years to implement ocean observing capabilities and to support policies also through the development of low-cost technologies.

Here, we report some examples of the existing available technologies for sensors, platforms and data transmission suitable for sustained coastal observing systems with specific attention paid to cost-effective fit-for-purpose technologies. We also propose a modular multi-platform architecture based on available low-cost measurements and data transmission technologies that can fit the needs of a large community that goes from scientific research in developing countries to operational use by non-scientists for educational purposes. However, its potential is not limited to the implementation of observing infrastructures for developing countries but also for applications in remote and poorly observed regions.

Many of the ideas and the analysis presented here stem from major achievements from the POGO's OpenMODs project (https://pogo-ocean.org/innovation-in-ocean-observing/activities/openmods-open-access-marine-observation-devices/) that produced the motivation and the background for this paper.

Needs and requirements for coastal observation for science and society

Concerning the priorities of variables to be observed, the GOOS Expert Panel has identified the Essential Ocean Variables (EOVs) based on the following criteria (Miloslavich *et al.,* 2018):

- Relevance: the variable is effective in addressing the general GOOS issues of climate, ocean operative services and ocean health.
- Feasibility: the observation or calculation of the variable on a global scale is technically feasible using proven and scientifically valid methods.
- Cost-effectiveness: generating and storing variable data is convenient and relies mainly on coordinated observation systems that use proven technology, exploiting, where possible, historical datasets.

Owing to the OpenMODs contexts and scope, a subset of the EOVs will be considered here based on the application requirements (sea temperature, salinity, pressure, chlorophyll *a*, turbidity and dissolved oxygen). However, an improving process of the EOVs led to include biogeochemical and biological variables (Muller-Karger *et al.,* 2018), so a general overview will be done since a small variety of cost-effective sensors are available (Wang *et al.,* 2019), as shown in Table 1.

The focus of the observational efforts on a limited number of EOVs (and companions EVs for the climate and the biodiversity) has also been recently proposed by Reyers *et al.,* (2017) to meet similar (but more ambitious) socio-economical goals.

OpenMODs proposes a way to respond to different operational scenarios and, according to the operational needs, to easily integrate different sensors in different platforms.

The general issue is to involve scientific institutes and universities from developing countries interested in implementing the OpenMODs infrastructure. This approach needs to co-design the functionalities and the operational mode of a coastal observing network working closely with the potential users to meet their requirements.

Another fundamental aspect is the production of a blueprint of the architecture of a modular platform capable of hosting the basic sensors to conceive/identify an easy-to-use, flexible, and affordable core set of ocean sensors and platforms, leveraging recent advances in telecommunications technologies particularly suited for coastal areas.

Advancement steps are to revise the requirements/progress in the preparation of the pilot studies that implement the OpenMODs philosophy in terms of education, science, and services and to pave the way for future initiatives.

Considering the above criteria, OpenMODs identified a series of general needs/requirements to meet the general objectives of the project. Here we report those related to the technological development:

- choice of essential ocean variables that meet socio-economic priorities (temperature, salinity, chlorophyll *a*, turbidity, currents) via a comparative market analysis of relevant low-cost sensors;
- definition of a simple modular design of autonomous platforms hosting multiple sensors for coastal ocean observations with cost-effective telecommunication capabilities.
- open science approach to remove the barriers for sharing/reuse any kind of output, resources, methods, or tools at any stage of the development process.

State of the art of cost-effective instruments

Many low-cost instruments and sensors have been developed with different characteristics in terms of measurement performance (accuracy and sensitivity) and use (Albaladejo *et al.,* 2010; Piermattei *et al.,* 2019). Some of them have been installed on buoys or fixed installations (i.e., on different measurement platforms); others have remained in an experimental laboratory phase. There are many shared initiatives towards the use of low-cost, modular, flexible and open source systems for marine-monitoring networks (Jiang *et al.,* 2009).

This requirement arises from the cost of commercial sensors and probes that limits the creation of extended monitoring observatories (Crise *et al.,* 2018; Beddows *et al.,* 2018). Thus, the scientific community has created cost-effective and open-source components to increase data availability. We acknowledge that the purchase cost of equipment is only one, yet in many cases significant, part of the overall cost incurred in operating in situ marine instruments. Deployment/installation, operation and data communication/handling are items which can have a substantial impact on the overall cost. The final impact of these items is however largely site and installation dependent. The installation costs for the same instrument changes dramatically if it is installed in front of your laboratory with a wi-fi connection or in an Antarctic base connected via Iridium. We therefore will not consider these costs since they are too much application - and site-dependent. The cost of calibration can be safely disregarded since the most effective way to maintain a sensor within the expected accuracy and precision is to regularly substitute it according with a carefully designed strategy of preventive maintenance (that can progressively be trimmed on the basis of the acquired experience and the impacts of local conditions.

In this section we will report some examples of sensors (commercial or non-commercial) and components, especially employed in marine environment, such as the Arduino microcontroller, which is a customizable, low-cost, and user-friendly platform for data collection (Lockridge *et al.,* 2016). This kind of technology supports the interface of a wide range of sensors to increase the observation potentiality and the resolution of the existing sampling efforts (Marcelli *et al.,* 2014; Lockridge *et al.,* 2016). This approach can be applied to a broad spectrum of purposes.

Sensors

Among the wide variety of sensors available, we prioritized the basic physical and chemical variables that are fundamental to describing the oceanographic processes.

Marine instruments for both physical and bio-optical measurements are extremely varied. A detailed and continuously updated catalogue of the available instrumentation applied to marine observation is reported by the Alliance for Coastal Technology (ACT: www.act-us.info), which is composed of research institutions, managers and private companies promoting the development of new effective and reliable sensors and platforms to be used in the ocean environment.

Some examples of commercial instruments and their specifications are reported in the appendix and summarized in different tables organized by measure type (Appendix Table 1). The tables report a cost category classified as follows: very low € (€0 - 200), low €€ (€200 - 1,000); medium €€€ (€1,000 – 5,000); high €€€€ (€5,000 - 10,000). The cost of commercial high-end instruments may exceed €100,000 (Davis *et al.,* 2016), but this can be justified by the need for accurate and reliable observations for scientific purposes. On the other hand, extremely cheap commercial sensors can also be found, but these often have very low resolution and poor stability, which are inadequate for most marine applications.

Cost-effective sensors that still meet performance requirements often have small and low-cost components as well as modular technology; however, they are often reliable with an adequate resolution for marine applications. Examples can be found in the Internet platform of "Oceanography for everyone" where you can exchange ideas and propose projects and where you can find designs of a 100 m max depth CTD with components costs of about 260 € including a low-cost Niskin bottle (about 130 €) (Thaler *et al.,* 2013). Some examples of cost-effective marine sensors and probes combined with their main specifications are reported in Table 2.

Temperature sensors

Temperature is a fundamental parameter because it can affect other measurements such as salinity and density. It also influences pH, dissolved oxygen, and biogeochemical processes.

The choice of the sensing element is important for modularity, stability, and accuracy: The PT100 or PT1000 RTDs (platinum resistance temperature detector) offers good linearity and stability and can have different resolutions and increasing accuracy, meeting the modularity concept.

Commercial circuits with adequate quality can cost a few euros; sensing elements have variable costs depending on quality.

Thermistors are cheap and guarantee a fast acquisition, but they are not linear in their measurement performance and therefore require complicated electronics. Suitably conditioned and well calibrated thermistors can reach the level of accuracy and stability required. Sensor calibration and conditioning are essential to correct measurements.

Thermistors can be chosen at a cost ranging from about 15 - 30 € to hundreds of €. To achieve the high-level performances, NTC-type thermistors can be integrated into a Wien bridge circuit. If the circuit has very high technical characteristics, then high accuracy temperature measurements can be obtained. The cost obviously increases with the quality of the measuring circuit.

The market offers many low-cost (all the prices should be considered as purely indicative) and low-resolution sensor solutions, which seem to be sufficiently reliable for use in many applications. For example, ATLAS Scientific proposes a PT1000 temperature sensor with an accuracy of 0.15° C, and Adafruit offers both a pre-wired and waterproofed version of the DS18B20 digital sensor (Méndez -Barroso *et al.,* 2020) with an accuracy of ± 0.5° C (2€) as well as a PT100 AD converter and amplifier (13 €), and a three-wire PT100 sensor with an accuracy of ± 0.5° C (10 €) (Faustine *et al.,* 2014). These sensors require data management and transmission boards, but the vendors provide Arduino sample codes. Regrettably, almost none of the sensors on sale provide information related to the measurement stability, which is a fundamental parameter needed for long-term observations.

Salinity sensors

Salinity is the second fundamental variable for oceanographic and environmental applications. In regions of river influence, it can be also inversely correlated with other biogeochemical variables more difficult to be directly observed with automated instruments (e.g., nutrients, contaminants). A sufficient level of accuracy is supposed to be 0.1 PSU for some basic purposes. Currently, traditional methods based on conductivity and inductive cells seem to still be the best methods, but they require both a very good quality circuit and a system that prevents fouling. Although alternative approaches to salinity measurement have been trialed (tests based on optical properties), these approaches do not currently meet measurement and monitoring needs.

The measurement of conductivity by means of inductive cell seems to be a simpler and more robust solution, less subject to fouling problems since the sensing element is not in direct contact with sea water. Even in this case, the calibration is a critical factor. Many researchers approach the salinity measurement by experimenting with alternative methods or trying to integrate traditional sensors into low-cost technologies.

Some have proposed a salinity measurement based on the optical properties of seawater (Kumari *et al.,* 2016); other authors have proposed to measure salinity by inductive/conductivity cell sensors (Pham *et al.,* 2007), a very low-cost conductivity cell, a micro-USB cable (Carminati *et al.,* 2016), and even using a device to be applied to a smartphone to measure refractive index and absorption (Hussain *et al.,* 2017). Although these low-cost technologies can have a great potential, their sensitivities and accuracy are not yet sufficient for use in marine observations. Another progress is the conductivity sensor CTD-SRDL which is a novel device that can be deployed on marine mammals: it represents the first animal-borne instrument that provides temperature and conductivity profiles along the water column to 2000 m of depth (Boehme *et al.,* 2009).

Besides oceanographic data acquisition, these instruments can also record the environmental conditions where the tagged animals live and assess the impact of the environment on animal behavior.

Turbidity and Chlorophyll a fluorescence sensors

Different low-cost instruments for the measurement of both turbidity and fluorescence of chlorophyll *a* have been developed and tested but not yet field deployed. Due to the low resolution and sensitivity to low concentrations, not all the existing sensors are suitable for scientific applications. The resolution required for chlorophyll *a* measurement should be 0.05 µg/l, and 0.1 NTU for turbidity in coastal waters. The use of these sensors will require calibration against on-site samples in addition to laboratory evaluation.

In this section, we consider optical sensors to study light, turbidity, and photosynthetic pigments (mainly chlorophyll *a*). Several chemical variables can also be measured by optical sensors, but we will analyze these in the next paragraph together with traditional sensors.

In 2015, Murphy *et al.,* (2015) developed a low-cost optical sensor to continuously monitor turbidity in aquatic environments. The sensor was composed of an LED array source, two photodiodes, and a robust and modular electronic system, all controlled by a customized data logger. From the commercial point of view an example of low-cost sensors is the Atlas Scientific set, tested on both an onboard drifter and in moored applications. It was also compared with other commercial probes. These sensors are a valid option for marine observations despite not being fully reliable and accurate as top commercial probes (Lockridge *et al.,* 2016).

Thus, a turbidity sensor based on low-cost components (LEDs and photoresistors) was developed to monitor the different water inputs in aquaculture facilities; this is also suitable for many other applications (Parra *et al.,* 2018) as in the case of the fisheries management where the increase of turbidity can decrease fish catches.

ArLoc (Arctic Low-cost probe) is a cost-effective technology developed to acquire pressure, temperature, and fluorescence of chlorophyll *a* along the water column. This probe was developed to be modular and easily integrated onboard of different platforms with particular attention to Arctic applications (Piermattei *et al.,* 2019, Marcelli *et al.,* 2014).

Dissolved Oxygen sensors

Electrochemical sensors with a variety of sizes and qualities and relatively low costs are commonly available. The main concern is the need for periodic calibration and maintenance.

DFRobot offers a galvanic oxygen sensor and related Arduino shield at about 140 €, with a precision of 0.05 mg/L, but there is no data about the accuracy (Glud *et al.,* 2000). The Atlas Scientific oxygen kit (shield, replacement membranes, calibration solutions, and circuit isolator) reports interesting characteristics and a cost of about 260 € (Table 2) (Demetillo *et al.,* 2019).

Commercial optical sensors for dissolved oxygen are based on luminescence properties of some complex molecules (DFRobot). These sensors could be integrated into cost-effective systems but unfortunately, they are still too expensive. Currently there are many experimental works and few commercial products, but these cannot currently be integrated into automatic measurement systems.

Nutrients

The measurement of seawater nutrients represents a big challenge because of the strong diversity in marine environments which reflects large concentration differences. This concern affects the *in-situ* measurement of nutrients that still need harmonization and standardization procedures (Daniel *et al.,* 2019). A variety of laboratory methods are commonly used to determine the concentration of most nutrients with a high accuracy, while in situ sensors have still some limitations connected to different issues such as local concentrations, type of deployment and monitoring target.

Many commercial sensors are available, as reported by ACT database, but many of them are characterized by high consumption, high costs, limits in the detection of low concentrations, low autonomy for long-term deployment. No low-cost nutrient sensors are still available but are under development.

pH and pCO_2

As already seen for the oxygen sensor, marine chemical sensing is very important, and some parameters can be easily measured with low-cost sensors. Regarding pH measurements, there are pH electrodes (DFrobot, Gravity: Analog pH Sensor / Meter Pro Kit for Arduino, sensor H-101) and related Arduino shields at a price of around 45 € with an accuracy of 0.1. Atlas also offers different pH tools at different costs depending on the construction and stability requirements (Méndez -Barroso *et al.,* 2020). An experimental lab-on-a-chip pH sensor for seawater measuring based on spectrophotometry was presented by Pinto *et. al.* (2019); it is characterized by a very low-cost (approximately 100 €) a strong miniaturization and low consumption.

In any case, most of low-cost sensors are not suitable for marine applications and the principal issue remains calibration and maintenance procedures for pH drift, which can be considerable after long-term time measurement. Alternative pH sensors are based on optical measurements, which use fiber optics based on a coating substance (in contact with seawater) via fluorescence (Martín *et al.,* 2006), as well as pressure compensating semiconductor (ISFET) electrodes (Johnson *et al.,* 2016), however most of these sensors still have high costs.

The pCO2 sensors are now moderately mature; some sensors can be deployed in marine environments but are limited in depth range and low acquisition rates. A lot of these sensors use membrane permeable to dissolved CO2 molecules whose partial pressure is determined by means of IR absorption or colorimetric spectrometry (Wang *et al.,* 2019). Many components are decreasing in costs; however, these sensors are still not typically cost-effective.

Low-Cost Technologies and Citizen Science

Citizen science can allow data acquisition in an efficient and cost-effective way, and many programs have been developed to study the marine environment via volunteers. In this model, scientists train lay people to apply the scientific method to study environmental processes and phenomena by collecting data (Lauro *et al.,* 2014). The connection with citizen science is two-fold: on one hand, the availability of cheap technology for ocean data acquisition can favor further engagement in a larger community of non-professional data producers; on the other hand, additional observations are made to complement scientific applications. In developing countries, this engagement is crucial, especially when fisher communities need to be involved because they can act as a source and destination of the data produced. This strategy has been already applied in some pilot endeavors such as the Fishery Ocean Observing System (Falco *et al.,* 2007).

These projects must be supported by the sustainability of available technology, and cost-effective sensors are key to this approach. A remarkable example of citizen science is the Smartfin realized to acquire temperature data through common surfboards. This can offer details on the time and space gap in surf zones (Bresnahan *et al.,* 2017). Aquatic recreational sports can be used as environmental platforms to host low-cost sensors; for example, sailing vessels can continuously cruise along the oceans and collect oceanographic data (Brewin *et al.,* 2017). Many citizen science projects collect data via miniaturized and low-cost sensors, especially temperature profiles in coastal areas (CMFRI 2018). Moreover, the usage of a smartphone applied to citizen science is challenging: an example is an easy-to-use, low-cost (approximately 50 EUR excluding smartphone) affordable fluorescence sensor (SmartFluo) based on smartphone elements, developed within the EU FP7 project CITCLOPS (Citizens' Observatory for Coast and Ocean Optical Monitoring (Friedrichs *et al.,* 2017).

Sensors and sampling can both make important data available. The NCCOS (National Centers for Coastal Ocean Science) of NOAA created a Phytoplankton Monitoring Network (PMN) for a better understanding of harmful algal blooms through volunteer monitoring. This initiative enhances the capacity to respond to and manage the growing threat posed by harmful algal blooms by collecting important data for species composition and distribution in coastal waters and creating working relationships between volunteers and professional marine biotoxin researchers' (Morton *et al.,* 2015).

Various citizen science initiatives were launched to monitor the jellyfish abundance (e.g., the Jellywatch Programme; Boero *et al.,* 2009) to preserve the coral reefs (e.g. Reef Check) (Hodgson 2001) or the coastal marine environment (e.g. Sea Search Koss) (Koss *et al.,* 2009). A recent report on the state and the advancement of citizen science in Europe has been published by the European Marine Board (Garcia-Soto *et al.,* 2017).

Observing platforms

The platforms for the ocean and marine observation cover a wide range of applications being operated at surface, on the bottom, onboard vessels, freely drifting, autonomous on planned tracks, sliding, towed by a ship, or remotely operated (Albaladejo *et al.,* 2012). The platform selection is based on the objectives of the research and monitoring activity and by the specific site characteristics.

Many commercial platforms currently measure parameters in an autonomous and continuous way; however, most of them are expensive and difficult to use.

Thus, many projects use low-cost monitoring platforms for marine monitoring. One example is the SEMAT (Smart Environmental Monitoring and Analysis Technologies) project, that promotes the creation of a low-cost intelligent sensor network via different measuring platform prototypes, underwater communications, and alternative power management schemes with a cost of approximately 3500 € (Trevathan *et al.,* 2012). Albaladejo (2012) developed a cost-effective wireless sensor buoy system for shallow marine environment monitoring. This tool could acquire data at the surface, along the water column, and at the bottom. The miniaturized buoy acquired pressure and temperature at different depths. It could also collect meteorological data depending on the sensor availability and mission objectives. However, the buoy (without instruments) costs only €340.

Floats and drifters are the most cost-effective platforms. They can be equipped with many kinds of sensors enabling continuous and real-time monitoring of the surface and deep ocean. Argo floats primarily measures temperature and salinity of the upper 2000 m of the ocean. The Argo system has a wide spatial and temporal coverage and is a key element of the Global Ocean Observing System (GOOS), the World Climate Research Program (WCRP) Climate Variability and Predictability (CLIVAR) project, the Global Ocean Data Assimilation Experiment (GODAE), and Global Earth Observation System of Systems (GEOSS) (Roemmich *et al.,* 2009) allowing to acquire and make freely available a lot of data in a long period and in a cost-effective way (Rudnick, 2018), despite the cost which is about €17000. Similarly, drifters are used in many marine research fields such as climate studies, oil spill tracking, weather and marine forecasting, and search and rescue operations. Recently, the Global Drifter Program (GDP) was funded by the National Oceanic and Atmospheric Administration (NOAA) Ocean Observing and Monitoring Division of the Climate Program Office and mainly managed by the Lagrangian Drifter Laboratory (LDL) at Scripps Institution of Oceanography (SIO). Within this program, a series of drifters were developed to acquire currents, waves, temperatures, and conductivity at different depths, winds, and atmospheric pressures (Lumpkin *et al.,* 2017), and the price can vary between 1500€ and 5000€ depending on the additional sensors. Other examples can be found on the market.

Open source electronic boards and programming language

In the last decade, different technologies based on open-source electronic platforms have been developed and are characterized by common points including easy-to-use hardware and software for beginners. Among these, Arduino (started in 2003) is by far the most common. It has simple and open-source software (IDE) leading to a large open access community of Arduino users. A worldwide community of makers including students, hobbyists, artists, programmers, and professionals has joined this open-source platform helping novices and experts alike. In this way, thousands of projects have been developed from everyday objects to complex scientific instruments (https://create.arduino.cc/projecthub).

There are currently many small online companies that offer low-cost components. These can be combined in a modular way to obtain measuring instruments.

The strengths that today's technology allowing us to be able to develop instruments at low cost and good accuracy can be summarized as follows:

powerful embedded systems, cheap, widely used, easy to program and with low development costs, allow realizing the control, data storage and interface of the instrument. We can choose between very low power consumption systems without an operating system such as Arduino, programmable in C or Pyboard programmable in Micropython, or use real embedded computers with an operating system, such as Raspberry or Beaglebone that support Linux.

integrated circuits, developed for example in the medical field for portable systems, offer at very low cost as they are widely used, but with all the features that allow realizing the conditioning of the analog signal coming from the sensor and its conversion to digital with cost/accuracy performance unthinkable until some time ago bringing the computation toward the sensors (edge computing).

Data transmission technologies and Internet of Things of the Ocean (IoT-O)

Internet of Things allows objects to communicate with each other and to be remotely controlled. It combines existing internet infrastructures with optimized wireless communication systems to directly integrate the physical and digital worlds.

Several elements are fundamental to implement sustainable cost-effective IoT solutions: (i) low cost transmitting devices; (ii) low power consumption; (iii) availability of a network that can support a large number of connected objects; and (iv) a very wide geographic coverage reachable by as many elements as possible. The main impediments are related to: (i) network management costs; (ii) scalability and network organization; (iii) edge-nodes dimensioning and power efficiency; and (iv) coverage (Sanchez-Iborra *et al.,* 2016).

Sensors to be managed via an IoT approach must also be low cost with low power consumption. Therefore, an observing platform that can send data (hourly, daily, weekly or monthly) and that can be battery powered should consume as little as possible both in transmission and in reception. Network technologies that satisfy these needs of low power, good coverage, and network scalability are called Low Power Wide Area Networks, LPWAN.

Traditional cellular technologies have been widely deployed especially in densely populated spaces and are very good at meeting the needs of voice and high-speed data communications. Nevertheless they fall short at meeting the requirements of IoT for the following reasons: (i) the end device must periodically communicate with the base station even when it has no data to be transmitted – this can consume significant amounts of energy in the idle state: (ii) coverage is often lacking in areas of low population density that cannot normally offer an attractive business case for the operator; (iii) the recurring monthly costs for each device, while adequate for human users, are comparatively too high for objects with limited communication requirements; (iv) the coverage of a base station is limited to a few kilometers and cannot reach basements and cellars. These shortcomings have been addressed by several vendors who offer proprietary solutions specifically focused on the requirements of IoT in terms of low cost, low power consumption, and long range; these are achieved by limiting the transmission rate thus precluding its use for voice transmission.

Here, the best representatives are Sigfox and LoRa. They both use unlicensed frequencies, and thus do not incur spectrum usage fees, but are not protected from interference from other users and face limitations in transmission times. In Europe, a given device cannot transmit more than 1% of the time, while each transmission cannot exceed 400 ms in the USA. The maximum radio frequency power transmission is also specified by the regulator; it is therefore the same for both vendors.

Sigfox uses a transmission bandwidth of only 100 Hz, which is an order of magnitude less than that of cell phones. It can reach very long distances, but with very short and sparse messages. The Sigfox business case is oriented at partnership with cellular service providers, and their modules are quite inexpensive offering also low recurring costs per device.

LoRa uses a completely different strategy to achieve similar goals; it transmits modestly longer messages using a much wider bandwidth employing spread spectrum modulation. This type of modulation allows for the decoding of very weak signals so that they can also reach very long distances and achieve deep penetration in buildings. The main advantage of LoRa is that it can be installed by any interested party, and it can be deployed in areas not reached by cellular operators. The LoRaWAN alliance has produced an open-source protocol stack that can be freely used to provide a complete communication infrastructure for IoT.

Furthermore, a crowd-sourcing initiative, “The Things Network (TTN)”, has succeeded in installing freely usable “Gateways” that are connected to Internet application servers in many countries. Thus, anyone can register in the TTN web site, write an application for a specific purpose, buy a LoRa module, configure it to access TTN, and then leverage any reachable TTN gateway to transport the data to the specific application. Many users can connect to a given gateway, but the data streams are encrypted end-to-end so only the application owner can decode the data.

It is also possible to buy a LoRaWAN gateway and install it wherever it might be needed. The only requirements are Internet connectivity and a power source since the gateway must be always on and cannot rely only on batteries; a small photovoltaic panel can fulfill this need.

In addition, the 3GPP alliance – the organization that establishes the protocols for the cellular industry – has also addressed the needs of IoT in its most recent releases by means of two different protocols: Narrow Band IoT (NB-IoT) and LTE-M. Both considerably reduce the power consumption of the end device by allowing much longer “sleeping times” and increase the range by reducing the bandwidth and therefore the throughput. NB-IoT employs a technique of sending several replicas of the same message which are combined in the receiver allowing deep penetration into buildings and very long transmission distances. The big advantages of the 3GPP solutions are that they use a protected spectrum and are better sheltered from interference. The disadvantage is its dependence on an operator to deploy service in a given area.

Another interesting approach applies a LoRaWAN communication system to a low-cost CODE-like drifter (Gerin *et al.,* 2018). This drifter represents a cost-effective solution for coastal use due to the current limited distance range of alternative communications technologies. This outperforms the standard CODE in terms of sampling frequency and reusability (recovering the drifter at the end of its mission and replacing the battery pack when needed).

Feasibility of a new multipurpose platform

For the sake of clarity, we will hereafter use the hierarchy sensor-instrument-platform-observing infrastructure proposed by Bermudez *et al.,* (2009). They describe the sensor or transducer as an entity capable of observing a phenomenon and returning an observed value, the instrument as a device hosting multiple heterogeneous sensors, the platform as a vehicle carrying multiple instruments, the observation infrastructure as the *in situ* multi-platform infrastructure. Not all the hierarchy is always applicable: simple surface drifters equipped with GPS only can be considered both as instruments or platforms.

In OpenMODs, we proposed the architecture of a platform that meets a series of requirements such as: the needs identified during the Mindelo OpenMODs meeting (https://pogo-ocean.org/about/pogo-meeting/pogo-20/); the use of components with sufficient technical features, low cost, and readily available; deployable from small boats (i.e. fishing boats); to be supported by an adequate training and information programs also via communication tools available and accessible to all (e.g. YouTube, Instagram).

Architecture of Low-cost Effective Ocean-observing (LEO) instrument

The OPenMODs proposed solution is a Low-cost Effective Ocean-observing (LEO, Fig.1) instrument as a single instrument that can be easily integrated into multiple platforms. Its technical specifications should meet the requirements of strong miniaturization, low consumption, and easy integration into all types of oceanographic platforms, and could be a valid example.

The system architecture involves the construction of a modular apparatus (Fig.2) able to be used individually or integrated into the greatest number of measurement platforms:

- the sensors must be easily interchangeable (i.e., better to change old sensors with new ones than re-calibrate them).
- the control electronics must be based on “open” systems such as Arduino or other embedded systems with different analog and digital inputs.
- LEO can operate in an on-line mode as a cabled instrument (direct acquisition of data in a PC) or in delayed mode by recording data internally and sending data (possibly after a preprocessing step) by using different data transmission methods (mainly LoRa and NB-IoT but also GSM).
- LEO will guarantee the proper interface of the sensors with the network, e.g., LoRa can provide access to an observational network including sensors tagged

as IoT objects.

- an interface will be provided for a GPS receiver.
- LEO will be equipped with batteries and internal memory so that it can operate in stand-alone mode.
- the housing must be made with low-cost components adapted from other uses such as to withstand the corrosion of seawater.

Additional requirements concern the operational details:

- the launching and recovery must be as simple as possible.
- LEO will operate between the surface and depths of 200 meters (extendable in case of need);
- LEO will be made as compact as possible and with particular attention to the weight out of the water to make it easy to manage during transportation.
- LEO will be assembled in different ways depending on both the use and the different platforms to which it could be interconnected; so that the weight, buoyancy, and electrical interfaces can be managed.
- the assembly of the sensors into the electronic management and power supply system, the data transmission system, and the assembly inside the pressure hull or the protection box must be easy and manageable even without special equipment.

The LEO flexibility can facilitate its use in different autonomous operational modes (Fig.3) such as:

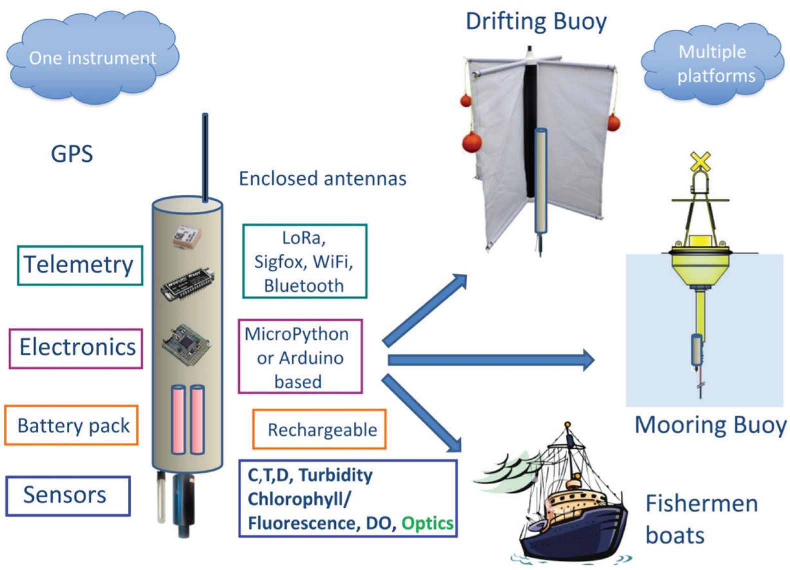

Fig. 1: LEO architecture showing the main electronic components of the instrument and their specifications (left) and its integration in different platforms/operational modes (brown: examples of different data transmission; green: second stage improvements).

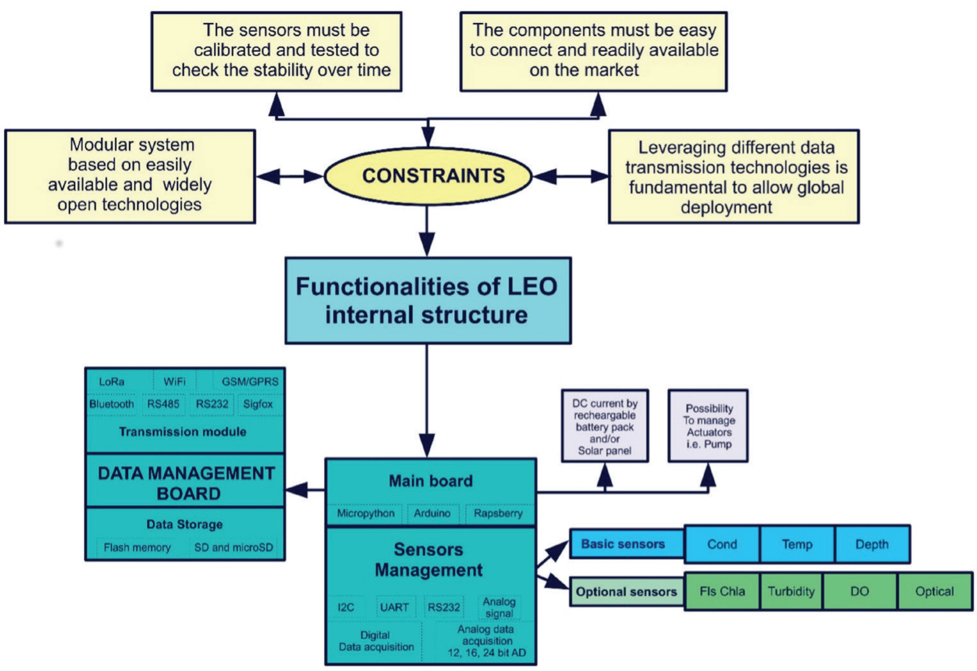

Fig. 2: LEO modularity reflects internal main electronic components distribution and assemblage.

- **Self-recording/RT vertical profiler.** It is operated by a boat with both electromechanical cables (connection with a PC) and mechanical cables (acquisition on internal memory).
- **Stand-alone fixed installation.** This would use a FerryBox, fixed station of coastal measurement, and/or be on a platform. This would have autonomous data acquisition, storage, transmission, and power supply (solar panels or battery packs).
- **Hosted onboard different platforms** (AUV, USV, Glider, ARGO, Lagrangian Buoys, TUV and ROV). In this configuration, the instrumentation may be integrated and adapted to different existing measurement platforms and may include a serial interface (RS485-RS232).

As a side comment, we suggest that a sustainable observational network based on low-cost technology (such LEO) should include (when available) top-quality instruments and sensors to consolidate the operational confidence and roughly estimate the uncertainties of instruments of LEO class. The optimal use of LEO instrument network simultaneously with top-class instruments meets the IoT heterogeneity and represents the state-of-the-art in observational oceanography. Involving as many actors as possible, and operating on different time scales at different resolutions, IoT heterogeneity will allow us to add value to all the observation by verifying and certifying the process of implementation, calibration, and effectiveness of the whole network.

Operational guidelines and capacity creation

The calibration and standardization processes of different technologies are important. The possibility of using different sensors coming from different origins is a great advantage but also a considerable risk. Besides the accuracy and resolution of each sensor, one should also follow the guidelines that allow the comparability of observations obtained from different instruments and sensors.

Another essential aspect related to the calibration process is the long-term stability of the sensors which will have to be addressed and verified by an experimental phase. Stability is often a missing component in low-cost sensors.

Additional considerations to be considered in the applications follow:

It is more convenient to change sensors, platforms, and ancillary materials before their performance degradation occurs instead of using a costly and time-consuming in loco calibration phase.

An in-house accurate comparison with high-quality instruments will help to identify possible malfunctions or evident drifts in the low-cost sensors. This in turn implies that some of the high-end equipment and related expertise should be made available locally.

Thanks to the simple design and system modularity, assembly, sensor testing, and inter-comparison can bring students (at various levels) closer to the scientific method (Solomon, 1980).

It is worth noting that the training is one of the most promising LEO application fields. The educational value of the OpenMODs approach goes well beyond the oceanographic domain. It can lead to curious, rigorous, and quantitatively oriented minds (Hodson, 1988).

Conclusions

This paper aims to call for additional interest toward sustained observations in the global coastal ocean (including the waters belonging to developing countries), define the architecture that will lead to LEO, the first prototype of a new generation of cost-effective multifunction instruments. LEO takes advantage of the sensors and components on the market that can be easily integrated into open architectures that meet the objectives of OpenMODs. These modular measurement platforms will be adaptable to different operating modes. In addition, the availability of low-cost transmission methods, such as LoRa, increases the possibility of managing these platforms by inserting them in shared systems such as IoT-O. These can be integrated via an optimized data architecture ready to be explored, (re)used, and exploited to help leverage the novel opportunities offered by AI technologies.

The use of open sensors and electronic platforms will certainly require more calibration and maintenance work on the instrumentation. The community must develop new protocols and adopt best practices to verify the system functioning; local staff is needed to operate

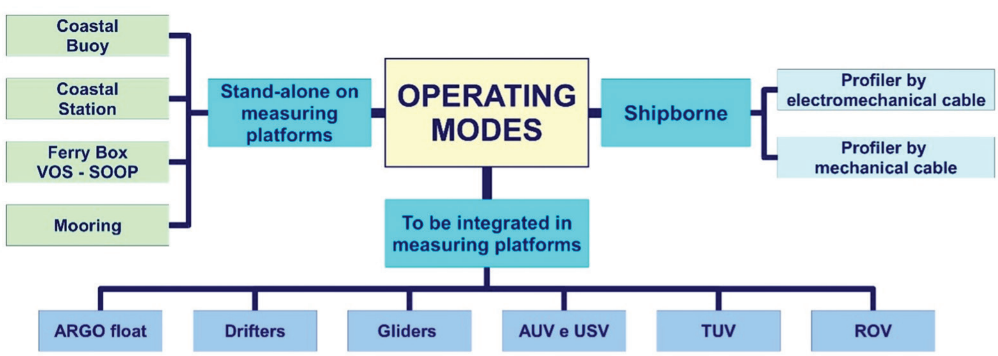

Fig. 3: LEO Operating scheme. These operating modes require a modular development capable of being adapted to different needs, to different communication systems, as well as to different supply possibilities.

them. Capacity-building initiatives in this field will receive a big boost by modern communication platforms (e.g., YouTube videos on basic training courses). These also involve international organizations committed to capacity creation in the marine sector (e.g., UNESCO IOC).

Framing this technological development in the perspective of the IoT-O, a step-change in the way we obtain information from ordinary objects offers an alternative way to use instrumentation. The ability to use open sensors and open electronic platforms could be the first step towards the implementation of IoT-O.

The development of a system whose modular architecture allows the deployment of different low-cost platforms – including the development of the data transmission system, calibration protocols, and stability test – is in line with the strategies for global ocean observation (e.g., GOOS, POGO, GEOSS) and can dramatically improve the observation of coastal waters worldwide.

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APPENDIX

Summary table for the most popular marine sensors/probes

Many commercial probes for oceanographic measurements can be reported and discriminated on the basis of price, but sensor accuracy is the most important. SBE 37 MicroCAT is an expensive probe whose cost is justified by very high-resolution sensors used also for open ocean applications; YSI 600OMS is a moderately expensive probe equipped with lower quality sensors; Idronaut Ocean Seven has very high sensitivity sensors with a cost comparable to YSI. It is rather difficult to find cheap commercial optical sensors. These usually range between €2,000 and €10,000: Cyclops-7F Turner Design, ECO FL Wetlabs, SeaPoint, UniLux Chelsea, MicroFlu TriOS (Hodson, 1988; Piermattei *et al.,* 2019).

Appendix Table 1. Main state-of-art specifications of commercial and cost-effective marine sensors/probes.

	Sensor - Probe	Measure	Accuracy	Resolution/ MDL*	PRICE Category
CTD SENSORS/ PROBES	SBE 37 MicroCAT	Temperature Conductivity	± 0.002 °C ±0.003 mS/cm	0.0001 °C 0.0001 mS/cm	€€€€
	YSI 600OMS	Temperature Conductivity	± 0.15 °C ± 0.5 mS/cm	0.01 °C 0.001-0.1 mS/cm	€€€€
	Idronaut Ocean Seven CTD	Temperature Conductivity	± 0.002 °C ± 0.003 mS/cm	0.0002 °C 0.0003 mS/cm	€€€€
	Underway CTD Teledyne Oceanscience	Temperature Conductivity	± 0.004 °C ±0.005 S/m	0.0002 °C 0.0005 S/m	
	MIDAS CTS Valeport	Temperature Conductivity	± 0.01 °C ±0.01 mS/cm	0.002 °C 0.005 mS/cm	
	MINOS CTD AML Oceanographic	Temperature Conductivity	± 0.005 °C ±0.01 mS/cm	0.001 °C 0.001 mS/cm	
	CTD350 Greenspan Analytical	Temperature Conductivity	± 0.2 °C ±1%	-	
	CTD Aanderaa Data Instruments	Temperature Conductivity	± 0.1 °C ±0.15 mS/cm	0.05 °C 0.075 mS/cm	
	Castaway-CTD SonTek-Xylem Brand	Temperature Conductivity	± 0.05 °C ±0.25% ±5 S/m	0.01 °C 1 S/m	€€€
	Van Essen CTD	Temperature Conductivity	± 0.1 °C ±1%	0.01 °C ±0.1%	€€
	OTT CTD Hach Environmental	Temperature Conductivity	± 0.1 °C ±1.5%	0.01 °C 0.01 mS/cm	€€€
OPTICAL SENSORS/ PROBES	Cyclops-7F Turner Design	Chla Fls Turbidity	0.03 µg/l 0.05 NTU		€€
	ECO FL Wetlabs	Chla Fls	0.02 µg/l		€€-€€€€
	SeaPoint	Chla Fls	0.02 µg/l		€€€
	UniLux Chelsea	Chla Fls	0.01 µg/l		€€
	MicroFlu-chl Trios	Chla Fls	0.02 µg/l		€€
	6025 Chlorophyll Sensor YSI	Chla Fls	0.1 µg/l		
	C-STAR WET Labs	Transmittance			€€€-€€€€
	EXO Turbidity YSI	Turbidity	0.3 FNU		€€€

	Sensor - Probe	Measure	Accuracy	Resolution/ MDL*	PRICE Category
	Hydroscat-4 HOBI Labs	4-Wavelength Backsc. and fluorometer			
	OCR-500 Series Irradiance Satlantic	Wavelenght 400 – 865 nm			€€€€
	PRR-2600 Radiometer Biospherical Instruments	Irradiance, Reflectance, PAR			
CHEMICAL SENSORS/ PROBES	2710 OxyGuard probe Rickly Hydrological	Dissolved Oxygen	± 0.5 ppm		€
	SBE 43 Sea-Bird Electronics	Dissolved Oxygen	2% of saturation		€€€€
	Oxygen Optodes Aanderaa Instruments	Dissolved Oxygen	< 5%	0.4%	
	WQ401 Global Water	Dissolved Oxygen	± 0.5% of full scale		€€
	EXO Optical DO YSI	Dissolved Oxygen	0.1 mg/l		€€
	CS511 Campbell Scientific	Dissolved Oxygen	± 2%		€
	DO AMT	Dissolved Oxygen	± 2% of saturation	± 0.1% of saturation	
	N510 Nexsense	Dissolved Oxygen	± 0.2 mg/l		
	WQ-FDO Optical DO Global Water	Dissolved Oxygen	± 0.2 ppm	± 0.01% of saturation	€€
	SBE 18 Sea-Bird Electronics	pH	± 0.1 pH		€€€€
	WQ201 Global Water	pH	± 2%		€
	6589 Fast Response YSI	pH	± 0.2 pH	± 0.01 pH	
	Hydrolab HACH Environment	pH	± 0.2 pH	± 0.01 pH	
	Deep-Water pH AMT	pH	± 0.05 pH	± 0.01 pH	
COST-EFFECTIVE SENSORS/PROBES	**Cost-Effective**				
	Atlas Scientific	Temperature	± 0.15 °C	-	€
		Conductivity	± 2%	-	€
		pH	± 0.002	-	€
	Smartfin	Temperature	± 0.1 °C	-	€
	‘Leeuw’ sensor	Chla Fls	0.3 μg/l	-	€
	CTD-SRDL	Temperature	± 0.005 °C	-	€
	ArLoc	Temperature	± 0.01°C		€
		Chla Fls	0.01 μg/l		€

* Minimum Detectable Limit