Submarine Cables as Precursors of Persistent Systems for Large Scale Oceans Monitoring and Autonomous Underwater Vehicles Operation

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OCEANS 2022, Hampton Roads | 978-1-6654-6809-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/OCEANS47191.2022.9977360

***Abstract*—Long-term and reliable marine ecosystems monitoring is essential to address current environmental issues, including climate change and biodiversity threats. The existing oceans monitoring systems show clear data gaps, particularly when considering characteristics such as depth coverage or measured variables in deep and open seas. Over the last decades, the number of fixed and mobile platforms for in situ ocean data acquisition has increased significantly, covering all oceans' regions. However, these are largely dependent on satellite communications for data transmission, as well as on research cruises or opportunistic ship surveys, generally presenting a lag between data acquisition and availability. In this context, the creation of a widely distributed network of SMART cables (Science Monitoring And Reliable Telecommunications) - sensors attached to submarine telecommunication cables - appears as a promising solution to fill in the current ocean data gaps and ensure unprecedented oceans health continuous monitoring. The K2D (Knowledge and Data from the Deep to Space) project proposes the development of a persistent oceans monitoring network based on the use of telecommunications cables and Autonomous Underwater Vehicles (AUVs). The approach proposed includes several modules for navigation, communication and energy management, that enable the cost-effective gathering of extensive oceans data. These include physical, chemical, and biological variables, both registered with bottom fixed stations and AUVs operating in the water column. The data that can be gathered have multiple potential applications, including oceans health continuous monitoring and the enhancement of existing ocean models. The latter, in combination with geoinformatics and Artificial Intelligence, can create a continuum from the deep sea to near space, by integrating underwater remote sensing and satellite information to describe Earth systems in a holistic manner.**

European Regional Development Fund (ERDF), Portuguese Foundation for Science and Technology (FCT)

***Index Terms*—submarine cables, ocean models, autonomous underwater vehicle, ocean monitoring**

I. Introduction

Climate change, ocean acidification, pollution, noise, loss of biodiversity and habitats, and increased frequency of extreme climate events are among a vast list of critical challenges that are in urgent need of additional ocean data, including new physical, biogeochemical and biological observations in the deep ocean [1], [2]. When analysing the currently available data sources, the horizontal coverage shows significant gaps, with large unmonitored areas between stations. Looking at the vertical coverage, data are particularly scarce at depths beyond 2000 m. Models of heat exchange and transport, as well as biogeochemical cycles, need more in situ data to generate accurate outputs and provide a better understanding of the dynamics of the planet. Thus, a network of sensors acquiring high spatial resolution data continuously in time, especially in the deep ocean where there is virtually no monitoring, would definitely help to cover a huge knowledge gap. Increased research into the deep ocean will enhance the capabilities of projection and adaptation to a new reality of fast global alterations, which are not fully understood.

While telecommunication cables cross the main oceans and form an ever growing intricate network of information highways, taking advantage of these infrastructures to form a network of sensors at the bottom of the oceans is quite attractive. SMART (Science Monitoring And Reliable Telecommunications) cables are seen as one of the main future assets for monitoring deep ocean zones [3], and will be important for a better temporal and spatial coverage of oceanographic measurements. Due to their characteristics, they are a potential source of data to extensively measure some of the EOVs (Essential Ocean Variables), especially in the deep sea, where the data gaps are the largest. Variables such as ocean bottom pressure, sea surface height, subsurface temperature and salinity, can be measured in a cost-effective way by SMART cables. However, full implementation of SMART cables is still challenging, and K2D aims exactly at helping to overcome some of these difficulties. There is an interest in measuring a large range of variables in the deep ocean, but the initial implementation of SMART cables should follow a conservative path, and start with a small set of sensors.

II. Current ocean in situ observing systems

Over the last decades, the number of fixed and mobile platforms for continuous in situ ocean data acquisition increased significantly, covering all ocean regions. However, there are still large areas lacking continuous and reliable monitoring, as well as sufficient historical support (Fig. 1).

Looking closer into the details of these observation systems, gaps in coverage and variables registered become more evident. Distribution maps of the platforms based on the type and number of measured variables show the lack of data at deep sea (Fig. 2), especially biogeochemical data in the deep North Atlantic.

III. Potential of submarine cables for oceans monitoring

In the 1980s the first fibre-optic cable was developed, and the first transatlantic cable was deployed by the end of the decade. The number of kilometres of cables becoming Ready For Service (RFS) had a large drop after 2001, but since then, it presents an increasing trend although with considerable variability among regions and time (Fig. 3). Currently, more than 1.1 million km of cable are operated

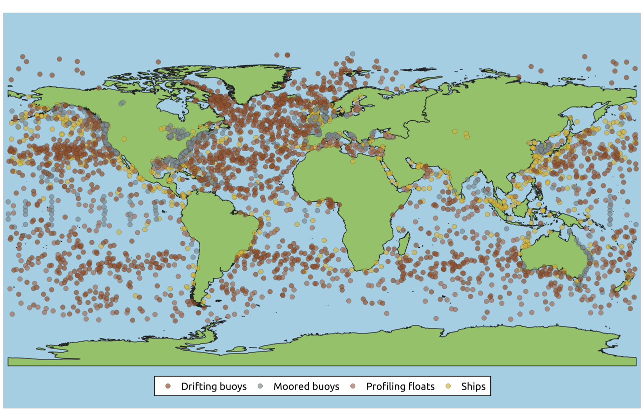

Fig. 1. Global Ocean Observing Systems (GOOS) data registered for the period between 01/09/2021 and 03/09/2021 (retrieved from https://www.goosocean.org/).

by telecommunications companies. Replacement or expansion of parts of this network occurs at intervals of up to 15 years, offering good opportunities to add sensors to the cables [3]. In 2022 more than 100,000 km of cables are expected to start operating worldwide. The EMEA region (Europe, Middle East and Africa) is the one presenting the highest investment in new cables in the forthcoming years, while considerably fewer kilometres of cable will be installed across oceans during the same period. The cable systems that will be deployed in the next three years will be located at an average depth of approximately 2,850 m.

If the potential of these new infrastructures is leveraged by installing SMART repeaters and implementing coupled AUVs monitoring, the extension of the oceanic area surveyed by AUVs can be drastically enlarged (Fig. 4). The AUV model used as a reference for the simulation is MBARI (Monterey Bay Aquarium Research Institute) Tethys, which has an autonomy of 1,000 km at a maximum speed of 1 m/s. If the autonomy for lower speeds is considered, the covered areas could be much larger.

The combination of SMART cables and AUVs allows the collection of data on a wide temporal and spatial scale, ranging from hours to decades, and from a few km to large ocean basins. This holistic perspective can provide essential information to study a range of marine phenomena, including physical oceanography or changes in biodiversity (Fig. 5). Some more specific applications could be:

- Cetacean monitoring. Cetaceans produce a wide variety of sounds to communicate and explore their surroundings. Acoustic monitoring with hydrophones distributed along subsea cables provide a great opportunity to collect data to complement cetacean visual surveys, also in areas and periods with little or none monitoring effort available. For example, in 2021, the CTBTO's technology, which aimed to detect nuclear bomb testing, allowed to record a new colony of pygmy blue whales in the Indian Ocean [5].
- Seismology and tsunami monitoring. Seismic activity detection and location could be largely improved by using accelerometers installed in the subsea cables. In addition, arrays of pressure sensors can be used to accurately assess a tsunami wave field as it propagates through the water layer [3].
- Habitat modelling for marine species. Environmental variables are needed to understand the ecological preference of any species and to predict their potential distribution. In the marine realm, many are the species living in high and deep seas, where in situ environmental data is often scarce or nonexistent [6]. Therefore, monitoring of deep-sea based on subsea cables could largely improve the quality of marine species distribution models.
- Plastic litter dispersion modelling. Microplastic physical, chemical, and biological properties change as a consequence of the environmental conditions, including temperature and sea surface height, availability of sunlight and salinity [7]. Additionally, its distribution is also highly dependent on external factors, resulting in

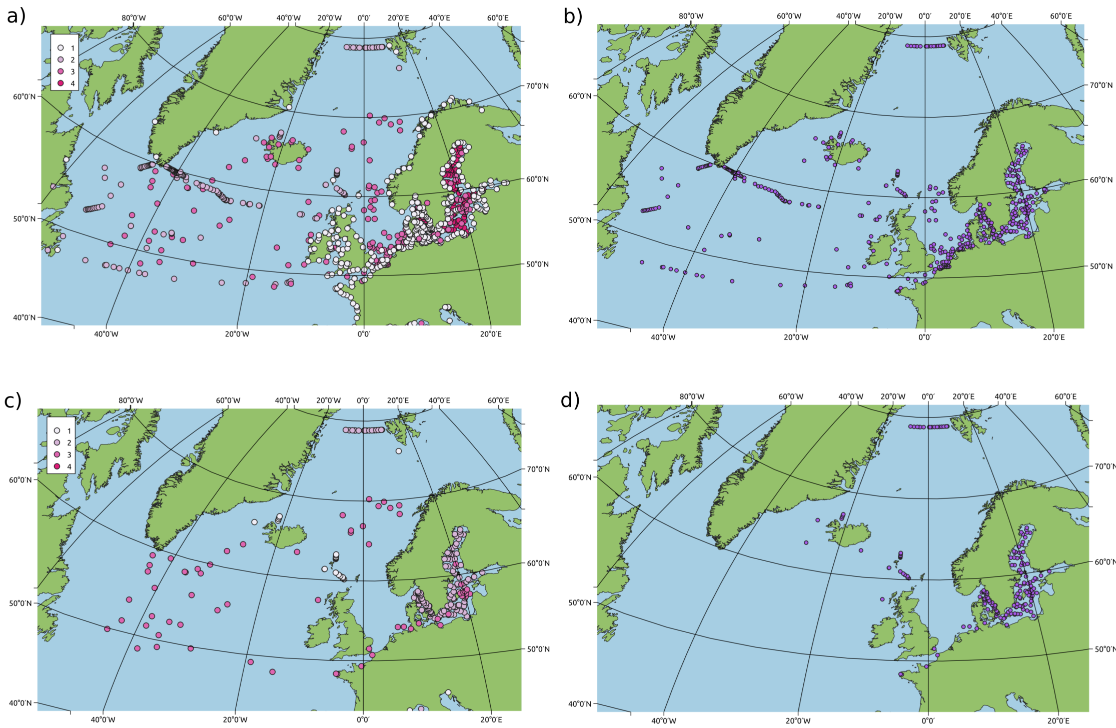

Fig. 2. Distribution of data acquisition stations in the North Atlantic. a) Physical variables not filtered by depth. Colour scale represents the number of categories of measured variables (categories are air-sea interaction, water properties, acoustics and ocean dynamics). b) Physical variables that reach the bottom of the ocean. c) Biogeochemical variables not filtered by depth. Colour scale represents the number of categories of measured variables (categories are water properties, nutrients, carbon, sediment characteristics and chlorophyll). d) Biogeochemical variables that reach the bottom of the ocean.

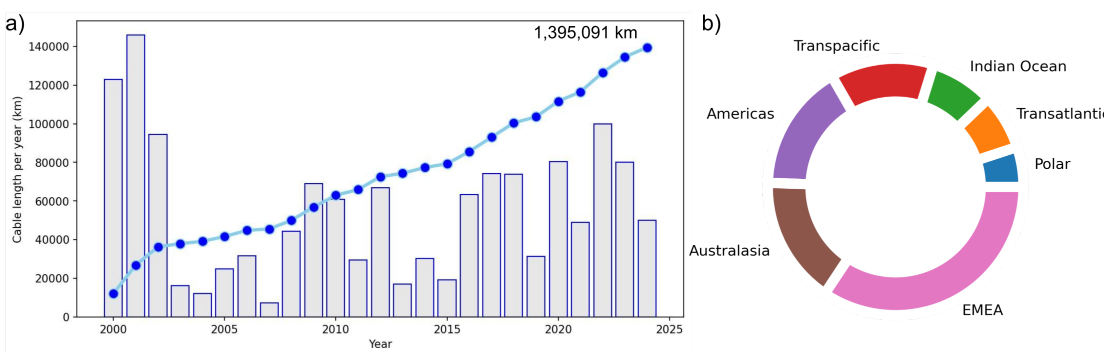

Fig. 3. a) Time series of submarine telecommunications cables length deployed by year, plus cumulative length that became ready for service between 2000 and 2024 (data obtained from TeleGeography's Telecom Resources). b) Planned systems by region from 2021 until 2026 (adapted from [4]).

an uneven distribution over the seafloor [8]. Within this context, considering updated oceanographic parameters (e.g., sensors located in subsea cables) becomes relevant when carrying out numerical simulations of microplastics' dispersion in water using Eulerian and Lagrangian models.

- Marine Protected Areas (MPA) management. The stability of marine communities can be altered by several chemical and physical parameters of the sea water column, such as salinity, dissolved oxygen concentration, presence of organic and inorganic nutrients, chlorophyll-a concentration or turbidity. For instance, increased uptake of CO2 emissions by the ocean is changing seawater chemistry and leading to a decrease in the pH. This ocean acidification process has the potential to significantly affect shell and skeleton formation in many marine organisms. Therefore, long-term monitoring of environmental variables must be recommended as part of MPAs management strategies to assess potential changes in species distribution as a response to environmental conditions [9].
- Ocean warming and sea level rise. Global surface temperature over the ocean was around 1ºC higher in 2011-

2020 than in 1850-1900 [10]. In the Atlantic, the warming ocean and the increasing ice melting in high latitudes have drastically decreased surface salinity causing the weakening of the Gulf Stream [11]–[13]. This is part of the AMOC (Atlantic Meridional Overturning Circulation) response, which is projected to weaken under warmer climatic conditions. In addition, ocean warming is enabling some existing species to spread into other areas, and creating welcoming conditions for new exotic species to become invasive [14]–[16]. Hence, monitoring certain variables such as temperature and salinity at a large scale and long term, and even in real-time, may allow for early detection of changes.

IV. Existing submarine cabled observatories

Over the years, several cabled observatories have been deployed in the marine environment, aiming to attain different objectives and apply different monitoring sensors. Most of these observatories are based on fixed stations connected to the cables and adapted to specific objectives, areas, or conditions, which may hinder the scaling up to broader scales. Some of these observatories and their main characteristics are summarised in (Table I).

The K2D project differs from previous cabled observatories in two main aspects. First, an effort is being put together with industry partners, to develop the nodes with a configuration compatible with signal repeaters used by telecommunications companies in their submarine cables. This is essential to enable modular and desirable 'plug-and-play' future deployment of submarine telecommunication cables with customised sensors attached, and therefore, to scale up and universalise the monitoring system. Second, the combination of fixed sensor nodes and AUVs increases the vertical (in depth) and horizontal scales of the data acquisition. These characteristics are key for the future development and deployment of persistent monitoring networks in areas of interest, covering deep sea habitats, such as hydrothermal vents, deep-sea MPAs, and thermohaline circulation essential monitoring regions, among others.

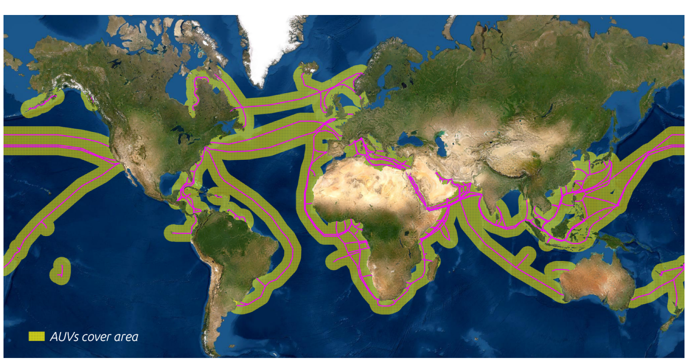

Fig. 4. Areas that could be surveyed by MBARI Tethys AUVs, if in combination with the cables that will be RFS in the next three years (2022 - 2024) when equipped with SMART repeaters. The areas were calculated considering a maximum distance of 500 km from the cables.

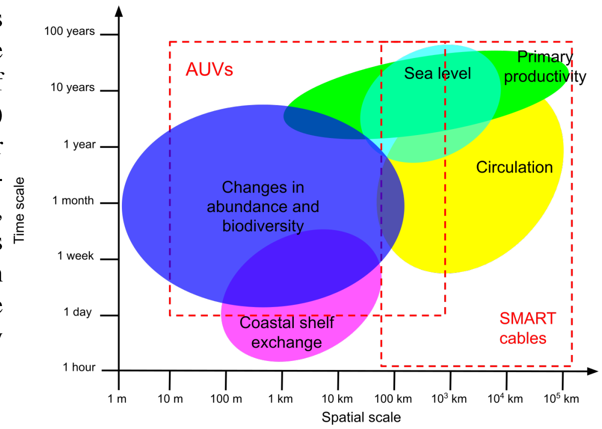

Fig. 5. Comparison of spatial and temporal scales of different phenomena and of the observations provided by SMART cables and AUVs.

TABLE I
Some of the existing cabled observatories worldwide and their main characteristics

Name	**Size (km)**	**Location**	**Sensors**	**Focus**
S-net	5700	Japan	Seismometres and pressure sensors	Seismic
VENUS	50	Canada	CTDs, oxygen and cameras	Oceanography
NEPTUNE	800	Canada	Current meters, hydrophones, pressure sensors, seismometres and plankton samplers	Oceanography
MARS	52	USA	Hydrophones and DEIMOS system	Oceanography
RCA	900	USA	ADCP, benthic fluid flow meters, bottom pressure, oxygen, fluorometre, among others	Seismic, volcanic and hydrothermal processes
KM3Net	100	Mediterranean	Seismometres, CTD, oxygen, turbidity, ADCP, bottom pressure and camera	Oceanography and physics

V. K2D demonstrator, a pilot test for future SMART cables

Within the K2D project, demonstrators are being developed to test critical components and show the potential of combining the use of submarine cables and AUVs. The planned project demonstrator (Fig. 6) will have multiple nodes simulating the positions of the repeaters in telecommunication cables. There would be two possible types of nodes according to the sensor configuration: (1) nodes with a simple sensor configuration, including, for example, pressure, seismic and

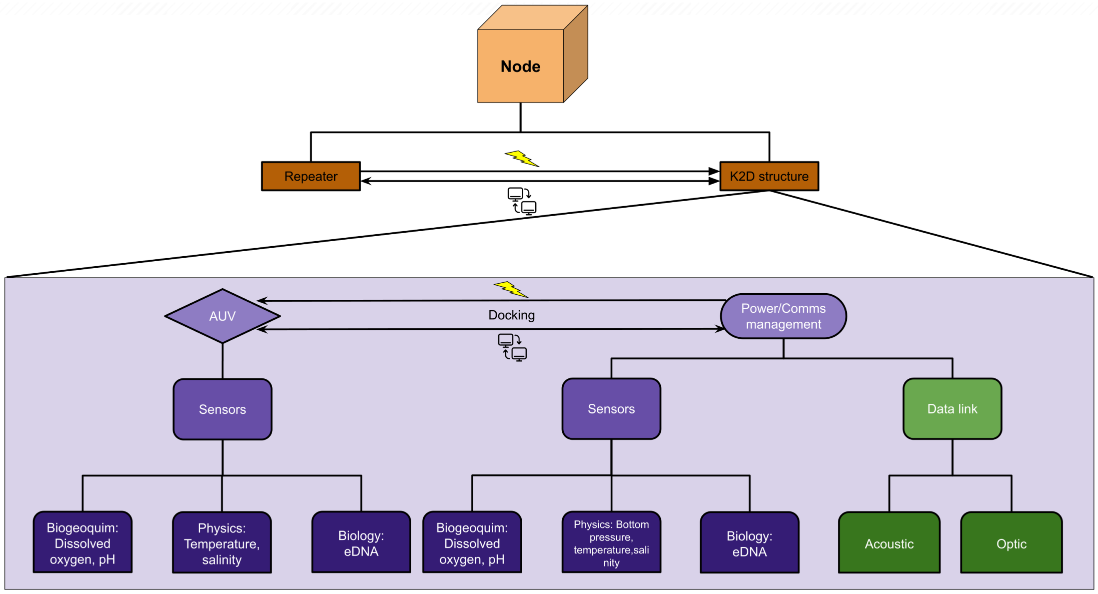

Fig. 6. Representation of the components of the K2D demonstrator.

temperature sensors; and (2), nodes with more specific sensors, including hydrophones or pressure inverted echosounders.

Internally, the node will be composed of: a) a processing unit with computational capabilities; b) interfaces for peripheral devices; and c) a power management subsystem to supply energy to the attached devices and convert voltage levels. For internal status logging and diagnosis, a set of internal sensors (depth, Attitude and Heading Reference System -AHRS- and a camera) will be added to the node. For local observations, a set of environmental sensors, such as temperature and bottom pressure, will be attached to the node and will be responsible for supplying power and communication bus.

The AUV that will be used for the K2D demonstrator will integrate the following three subsystems:

- Communication. The middle- and long-range acoustic communication system will use low frequencies and high-power acoustic sources for distances up to 25 km with a low data rate communication. These will maintain the AUV connected when it bounces between nodes. The short-range high-speed acoustic communication system will use frequencies up to 1 MHz at distances of up to 200 m. This connection will allow acquiring data and controlling the AUV in real time. The very short ultra-high-speed optical communication system will be used for ranges up to 10 m and for the acquisition of large volumes of data.
- Multi-range navigation. It will help AUVs to communicate with the nodes and improve navigation efficiency. AUVs' localisation module will have acoustic transducers and optical artificial markers. The acoustic transducers will enable ranging and bearing estimates for relative localisation of the AUV allowing the vehicle to navigate with bounded uncertainty. For ranging purposes, a time synchronisation scheme will be adopted. It will either rely on a two-way travel-time scheme or on explicit synchronisation of the time base shared between the node and the AUV. Additionally, artificial active optical markers will be attached to the node structure for optical detection, by means of an optical camera in the AUV. Under adequate visibility conditions, these markers will enable complementary measurements at a high-rate (>10 Hz) ensuring relative pose estimation.
- Energy and payload. A power transfer module will enable battery recharging for the AUV when it is docked.

The use of the bottom nodes and the AUVs will generate data that, combined with remote sensing data, will enable the development of deep learning (DL) models with different layers feeding each other. DL models are novel tools that tie different data sources and create more accurate and holistic models of marine areas, allowing for the development of new frameworks for ocean data analysis (Fig. 7). Additionally, geostatistical tools will be applied to filling data gaps in 2D and even 3D datasets, offering a more complete perspective and joining data from different sources. A DL regression model can then be trained and applied as a forecast model based on environmental and biological data collected, for example, by SMART cable systems. One example of a DL model is the Digital Twin Ocean, which is a consistent, high-resolution, multi-dimensional and near real-time virtual representation of the ocean, combining ocean observations, artificial intelligence and advanced modelling accessible to all (https://digitaltwinocean.mercator-ocean.eu/).

VI. Conclusions

Long-term and consistent monitoring of ecosystems have become essential to address current oceans environmental challenges, including climate change and biodiversity threats. At deep and open seas, in situ data is still very limited,

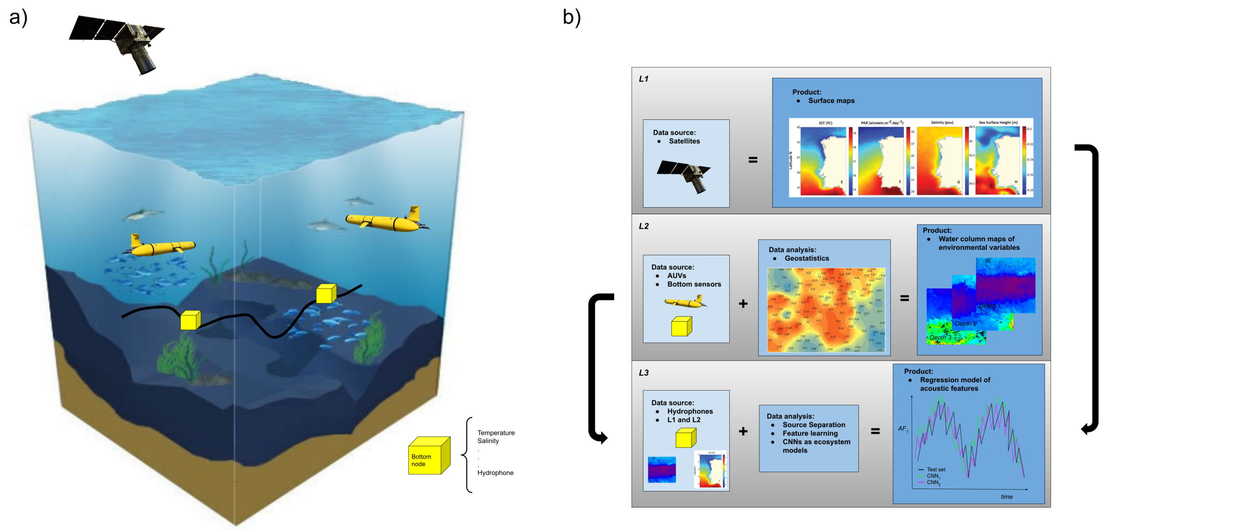

Fig. 7. Representation of the model which will be developed in the context of K2D, with an illustration of the data acquisition sources (a), and the layers and how they interact with each other (b).

and novel technologies and monitoring approaches such as SMART cables are promising. However, there are still great challenges to overcome, not only regarding the initial implementation of SMART cables, but also in the development of joint initiatives with academia, the industry and the companies involved in the deployment of the cables. In this context, K2D proposes the development of a scalable system for ocean monitoring taking advantage of the existing subsea cable infrastructures, combining fixed bottom nodes with AUVs to extend the horizontal and vertical data coverage. It is totally unpredictable the plethora of potential applications of submarine cables for ocean science, since the large scales involved and the possibilities in terms of continuous data acquisition are unprecedented. New paths for studying and understanding the oceans are yet to be unveiled, based on new in situ information previously unavailable, which is expected to enhance novel ocean models and increase our knowledge about Earth's most critical systems, the oceans.

Acknowledgment

This work was supported by the project K2D: Knowledge and Data from the Deep to Space with reference POCI-01-0247-FEDER-045941, cofinanced by the European Regional Development Fund (ERDF), through the Operational Program for Competitiveness and Internationalization (COMPETE2020), and by the Portuguese Foundation for Science and Technology (FCT) under the MIT Portugal Program.

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