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Executive summary

This best practice is based on variables generated by Eulerian platforms following the approaches of other global observing networks and programs (GO-SHIP, OceanGliders, etc.). This report includes recommendations on existing sensors, maintenance procedure and data processing for better data quality. It covers different types of variables provided by Eulerian platforms from the surface to the seafloor (physical, biogeochemical and geophysical).

1. Introduction

In integrated ocean observing systems, fixed Eulerian observatories form the backbone of the network, complemented by mobile platforms to extend Lagrangian observations. These fixed platforms allow long-term observation of the entire water column down to the seabed from autonomous sensors or connected by submarine cable. These platforms, equipped with fixed multi-sensors deployed on sites of environmental interest, allow high-frequency and multi-parametric observation of the different water masses, interactions between the atmosphere and the ocean (when equipped with surface buoys) and to observe the complex relationships between planktonic species and carbon export.

Due to the complexity of the measured variables through the Eulerian platforms (in particular for biogeochemistry and biology), the implementation of multi-disciplinary observation systems requires standardised sensor calibration procedures and harmonised data correction methods in order to provide high quality data necessary for science and stakeholders. These procedures also depend on technological progress and advances in correction methods, hence the need to be regularly updated, distributed and adopted by a large community. For this to happen, these procedures must become best practices.

A best practice is a methodology that has repeatedly produced superior results compared to other methodologies with the same objective. To be a best practice, a methodology must be adopted and employed by multiple networks (Simpson et al., 2018). Best practices can take many forms such as standard operating procedures (SOP) manuals or guides. However, they all share the common goal of improving the quality and consistency of processes, measures, data, and applications through agreed-upon practices (Pearlman et al., 2019). The development and deployment of best practices in observing systems plays an increasingly important role in supporting ocean observations. By their nature, best practices must be well adopted and reviewed to facilitate interoperability and reproducibility and to improve the quality of data and information products (Buttigieg et al., 2020).

In European seas, several organisations manage Eulerian observatories (OceanSITES, DBCP and EMSO ERIC) with different degrees of observing network maturity in terms of best practices, technical coordination, standards procedures (Coppola et al., 2016; Pearlman et al., 2019; OceanSITES 2020). Consistent use of best practice is an essential component of an effective ocean observing system. It therefore becomes essential in a future strategy for integrated observing systems to promote the improvement of existing best practices in methods and technologies.

2. State-of-the-art and objectives

Fixed-point time series observations at representative locations in a marine ecosystem are an essential component of an integrated global ocean observing system (Figure 1). Fixed platforms (or Eulerian observatories) are fixed with respect to their position on or above the seafloor. They may be part of a coastal feature such as a pier or jetty, or they may be located offshore. The long-term recordings collected by the fixed stations can provide evidence on the ocean state and ocean variability, allow a better understanding on the several processes that take place in the marine environment, support the calibration and the verification of the marine and weather forecasting systems but also to enhance the maritime safety and the efficient planning of marine infrastructures. Several types of systems can address these issues and the choice about the most suitable platform is related to the physical processes to be investigated, to the environmental constraints of the deployment area and to the expected monitoring period (in the medium or long term). In marine science, Eulerian platforms can provide a unique view of the complete temporal evolution of a system (ranging from diurnal to decadal cycles), accurate baseline data for adjusting Lagrangian platforms, and provide a full range of essential variables for observing from the seafloor to the atmosphere.

Efforts have been made, for example, to identify and promote best practices for the design and operation of ocean monitoring systems (Pearlman et al., 2019) and to foster the implementation of interoperable solutions between different RIs and develop new and innovative technologies to expand the range of EOVs measured in the water column. In the past, the different communities working on Eulerian observatories have produced several recommendations from different projects based either on data format (OceanSITES), platform technology (FIXO3 and EMSO) or data processing and sensor calibration (Van Ganse et al., 2019). The objective of the D3.11 is to improve the documentation of best practices for Eulerian Observatories in order to disseminate knowledge, and training activities specific to the ocean observation value chain. It will be based on the recommendations proposed for common variables acquired by the Eulerian observatories.

In 2015, FIXO3 European project (grant 312463) produced a Best Practices handbook to collect recommendations of mooring maintenance including all phases of the system covering the entire infrastructural chain of data acquisition (Coppola et al., 2016). It included recommendations on how to produce high quality data aiming towards common methodologies and protocols within the FixO3 network integrating open ocean moorings, surface buoys and deep cable observatories included in the ERIC EMSO. This work is a legacy of the EMSO European Research Infrastructure Consortium which was created in 2017. More recently, the OceanSITES consortium proposed a data format reference manual which has been endorsed by the GOOS Observation Coordination Group (OceanSITES panel of Experts) as a globally accepted best practice for the format of the files that are used to distribute OceanSITES data, and to document the standards used therein. In EuroSea D3.11, we propose new best practices for Eulerian observatories taking into account the recommendations of the three consortia (EMSO, OceanSITES and DBCP). It will be based on variable groups measured by the fixed platforms including sensor management, data QC and uncertainties estimations. Given the need to use data in the context of an integrated cross-platform environment, it is essential that all variable sections detail existing sensor performance, maintenance, and data processing procedures to improve data uncertainties for scientific applications.

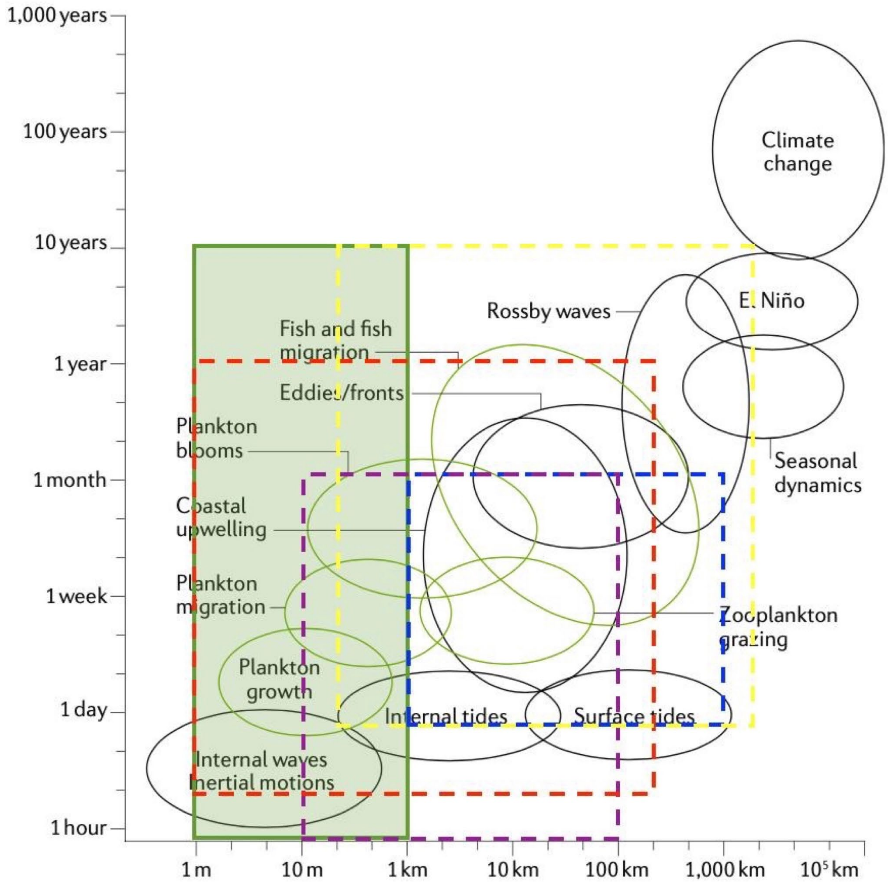

Figure 1: Place of the Eulerian platforms in the global ocean observing system. Spatial and temporal scales of marine dynamic and ecosystem processes, and the measurement capabilities of different observational platforms. The fixed platforms are indicated in green, ship in blue, glider/USV in purple, Argo floats in red and satellites in yellow (adapted from Chai et al., 2020).

2.1. Which groups are involved in this deliverable?

OceanSITES

The OceanSITES programme is the global network of open-ocean sustained time series sites, called ocean reference stations, being implemented by an international partnership of researchers and agencies. OceanSITES provides fixed-point time series of various physical, biogeochemical, ecosystem and atmospheric variables at locations around the globe, from the atmosphere and sea surface to the seafloor. The program's objective is to build and maintain a multidisciplinary global network for a broad range of research and operational applications including climate, carbon, and ecosystem variability and forecasting and ocean state validation.

EMSO ERIC

The EMSO ERIC is a European marine Research Infrastructure (ERIC). It is serving marine science researchers, marine technology engineers, policy makers, industry, and the public. EMSO consists of ocean observation systems for sustained monitoring of environmental processes and their interactions. The variables address natural hazards, climate change, and marine ecosystems. EMSO observatory facilities have been deployed at key sites around Europe, from the North Atlantic, through the Mediterranean, to the Black Sea. EMSO ERIC provides power, communications, sensors, and data for continuous, high resolution, real-time and near-real-time, interactive ocean observations from polar to tropical environments, down to the abyss.

DBCP

The Data Buoy Cooperation Panel is an international program coordinating the use of autonomous data buoys to observe atmospheric and oceanographic conditions, over ocean areas where few other measurements are taken. Data buoys measure air pressure, sea surface temperature, ocean current velocity, air temperature, humidity, wave characteristics and wind velocity across all oceans. The DBCP aims to increase the quantity, quality, global coverage and timeliness of atmospheric and oceanographic data. These observations are relayed by satellite and used immediately to improve forecasts and therefore increase marine safety.

2.2. User engagement: who are the target users? Are there data formats and vocabularies that best serve the target users?

The main target is mainly the scientific users working on ocean process studies (experimental or model). Most of the data are in NetCDF (or ASCII equivalent) format with metadata information. These metadata are usable by data scientists who know this type of data. However, we learned from D3.12 that the current metadata is probably not completely suitable for integration into the OceanOPS portal and that several specific pieces of information are missing (ship name, list and location of sensors...).

2.3. How to build consensus on data best practices in a network?

The endorsement of GOOS is an example of achieving broad community consensus. Within GOOS, key best practices have been harmonised and adopted by components of the ocean observing system communities, e.g., the Observations Coordination Group (OCG) global ocean observing networks (such as Argo, GLOSS, GO-SHIP, and HF Radar), within the GOOS Expert Panels and Networks for Climate (OOPC), Biogeochemistry (BGC), or BioEco, and the Operational Ocean Forecasting Systems Expert Team (ETOOFS). These best practices have been developed within each of these GOOS components through a structured community review process and adopted as "global" methods by the relevant network or ocean observing community. To achieve this consensus, they have been widely adopted by the community to be considered as tested methods, fit for purpose and fully meeting the definition of a best practice. They have been recognized globally after undergoing a rigorous process of community review and consensus building for the specified application. These best practices mostly address essential ocean variables, observing platforms, and associated sensors.

2.4. Role played by the EuroGOOS Task Team Fixed Platforms

EuroGOOS FP TT started in 2021. It aims to integrate European fixed-point observatories, both in the open ocean and in coastal waters. The EuroGOOS FP TT should be one of the main communities of practice within EuroGOOS and its member institutes dealing with issues related to the planning, deployment, maintenance and sustainability of fixed platforms in European open and coastal seas. The TT FP can play a forum role, providing a platform for the exchange of expertise and the generation of advice in the field of the TT FP objective. Through this group, current eulerian best practices could be reviewed and adopted for fixed platform application by a broad European community. The consensus described above via GOOS should therefore be one of the goals of this TT in the coming years.

2.5. What are the main EOVs provided by the fixed platforms?

Long-term observations of the chemical, biological and physical properties, circulation intensity and patterns, and of the exchange of heat, freshwater, and momentum between the ocean and the atmosphere are essential to understand the ocean's role in the global climate (Cristini et al. 2016). Long-term marine observation is primarily aimed at acquiring Essential Ocean Variables (EOVs), for the assessment of their multiscale temporal variability (monthly to pluriannual).

Moorings and buoys remain at a single location for long periods of time (months to years), and demand longer operational lifetimes for the sensors, but often with less frequent measurements over limited temperature and salinity ranges. Here we will describe the different sensors most commonly used on moorings by group of EOVs and the recommendations proposed to obtain good data accuracy for scientific applications (Table 1).

Table 1: List of variables measured by Eulerian observatories.

Variables	Category	Maturity in best practices
Meteorological	Physical	mature
T/S/P	Physical	mature (see OceanSITES & IAPSO documents)
ADCP current profiler	Physical	mature (see OceanSITES documents)
Fluorescence	Biological	need more tests and validation (see SCOR group 154)
Dissolved Oxygen	Chemical	mature (based on Argo) but need global consensus
Nutrient	Chemical	need global consensus
pCO2	Chemical	need more tests and validation (link to ICOS)
pH	Chemical	need more tests and validation (link to BGC-Argo)
Irradiance	Physical	need more tests and validation (see SCOR group 154)
Organic matter flux	Biological	need more tests and validation (see SCOR group 154)
Zooplankton	Biological	need more tests and validation (see SCOR group 154)
Geophysics	Geophysical	need global consensus (see EMSO Science Service group)

3. Physical variables

3.1. Sensors characteristics

Temperature, Salinity (Conductivity) and Pressure (Depth) sensors

Moored Conductivity-Temperature-Depth (CTD) sensors are the most frequent instruments deployed in moored eulerian observatories. Accurate temperature and data from deep instruments allow the estimation of long-term trends of deep ocean water mass properties, and of heat and freshwater content. When deployed in an array covering the whole water column, temperature, salinity and pressure are also used to calculate time series of volume, heat and freshwater transports that can span thousands of kilometres in the ocean. All these estimates require highly accurate moored temperature, salinity and pressure data.

Temperature, salinity and pressure sensors are typically commercialised in different combinations of these sensors, but in most cases the sensors for the measurement of these independent EOVs are of similar characteristics.

Thus, for example, temperature sensors from different manufacturers consist in a high-speed external thermistor in a pressure-protected sheath for fast sampling. Temperature recorders are able to provide exceptional accuracy and stability during very long deployments and exist both as only temperature sensors or in combination with conductivity and/or pressure sensor in the same instrument. The most typical combinations of these sensors provide instruments for the measurement of: (1) only Temperature (T); (2) temperature and conductivity (TC); (3) Conductivity, temperature and pressure (Depth) (CTD); Temperature and Pressure (TP); and (5) only pressure (P).

Conductivity sensors are based on two main principles -electrode or inductive conductometry- to obtain salinity measurements in the ocean. While electrode cells measure electrical resistance between the electrodes in direct contact with seawater, inductive cells function according to Faraday's law of induction (Relis 1947; Striggow and Dankert 1985; Nezlin et al. 2020). The measured conductivity is ultimately converted into practical salinity using the seawater equation of state (Fofonoff 1985; McDougall and Barker 2011).

Pressure is often used instead of depth to express the vertical coordinate in the ocean. Pressure can be precisely converted to depth and vice versa, using the local value of gravity and the vertical density profile. Pressure is now measured directly on most instruments, and very accurate pressure sensors can be made using a piezo-resistive silicon transducer, whose deformation depends on pressure. This technology is used in modern CTDs for mooring deployments.

The most current temperature, salinity and pressures sensors used in moorings are (Figure 2):

- for CTDs with Depth (Pressure being optional): SBE37 and RBR concerto.
- for TPs: SBE39 and RBR virtuoso & RBRduo
- for only T: SBE56 and RBRsolo & RBRduet.

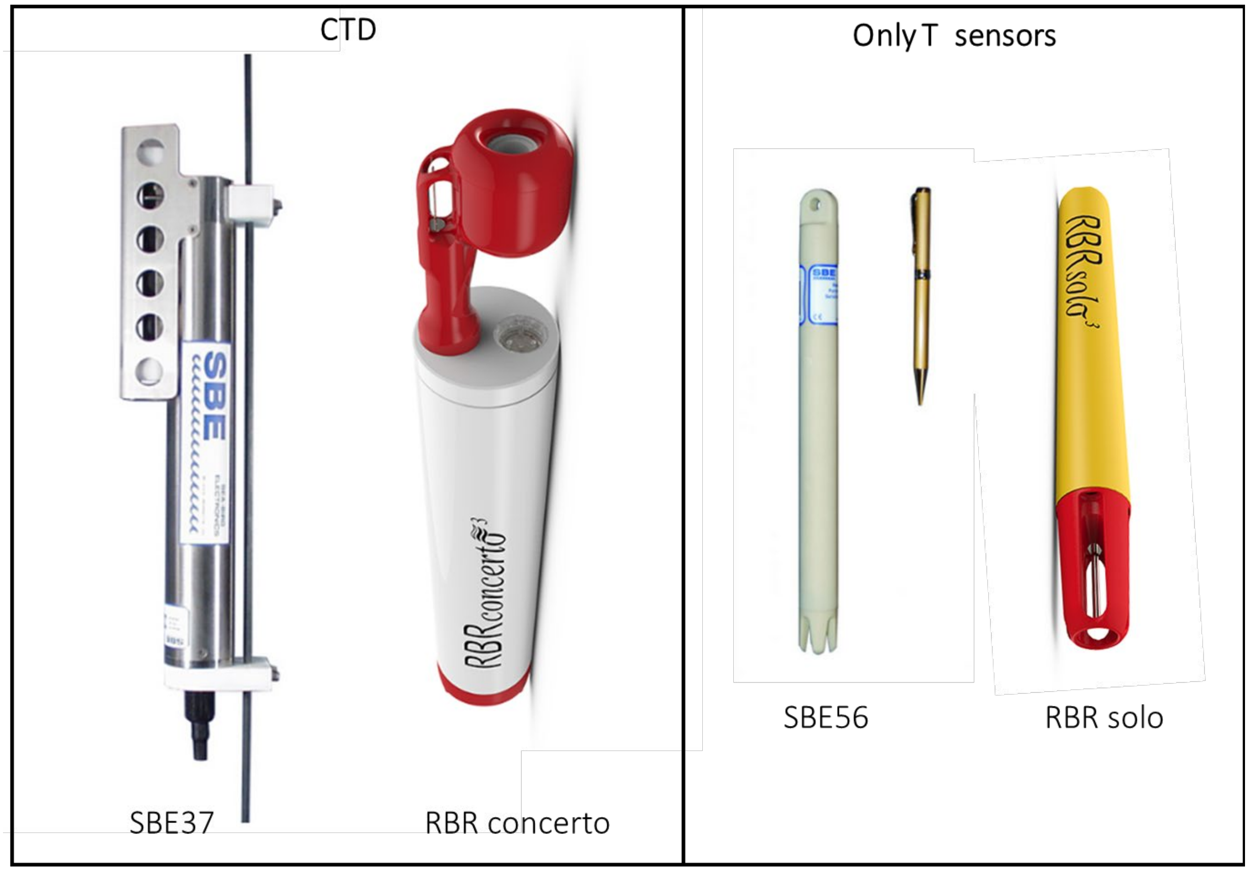

Figure 2: Examples of available sensors for temperature, salinity and pressure see webpages[1,2] for further information.

3.2. Delayed mode processing with uncertainties estimation

As previously mentioned, Moored Conductivity-Temperature-Depth (CTD) sensors are the most frequent instruments deployed in moored eulerian observatories, and highly accurate temperature, salinity and pressure data are necessary to derive from them deep waters temperature and salinity trends, and estimates of heat and freshwaters content, as well as volume, heat and freshwaters transports. It makes calibrations in pre and post deployment crucial for the data correction. Still, the methodologies for deployment and application of calibration procedures vary from group to group, and according to "Ocean Best Practices (OBPS)" repository (www.oceanbestpractices.org) there is not an extended bibliography of OBPS addressing standard Calibration procedures for Moored CTDs. Calibrations in pre and post deployment are important for the data correction. Regarding temperature and salinity data, apart from laboratory calibrations conducted ashore before and/or after deployment, other common procedures for temperature and salinity calibration include:

[1] https://rbr-global.com/
[2] https://www.seabird.com/

- Calibration profiles ('caldips') conducted at sea before and/or after deployment, in which mooring instruments are strapped on to a profiling CTD frame equipped with a high precision, calibrated CTD sensor (Karstensen, 2005; Cowley, 2022)
- Post-deployment calibration bath on board research vessels (Cowley, 2022).
- Comparison of in-situ data with nearby CTDs during deployment or visits with research vessels to the mooring location.
- Comparison with climatological data.

Salinity calibration also includes in situ sampling and laboratory analysis since salinometer determinations are still the reference to adjust the different sensors compared (e.g., calibration dips) with regular standard reference materials.

For the pressure sensors, the calibration includes pre and post deployment decks reading on pressure from which a linear correction in case of deviation between the pressure offset before and after the deployment can be applied to correct the data (see e.g., Karstensen, 2005).

4. The chemical variables

Chemical variables are used in oceanography through Eulerian observatories to estimate physical & biogeochemical processes playing a key role in the oceanic biological carbon pump (biomass production, net community production, carbon export), ocean ventilation, acidification and inorganic air-sea CO2 flux exchange.

4.1. Sensors characteristics

Dissolved oxygen sensors

For this category of variables, sensors are divided in two parts: electrochemical and optical sensors.

The SBE43 is probably the most widely used electrochemical sensor in oceanography. Oxygen concentration is determined by the magnitude and diffusion of the current passing through a membrane. The diffusion coefficient inside the membrane varies according to the state of the membrane, which is itself sensitive to the presence of bacteria, requiring meticulous cleaning and regular calibration of the sensor (Denuault, 2009; Murphy et al., 2008).

Oxygen optodes are based on the principle of luminescence quenching by oxygen (Figure 3). The most current optodes used in moorings are SBE63 and AADI 4330. The measuring principle is based on the effect of the extinction of luminescence by molecular oxygen. The detection sheet is excited by a modulated blue light. The sensor measures the phase of the returned red light. For better stability, the optode also takes a reference phase reading using a red LED that does not fluoresce in the foil. The sensor has a built-in temperature thermistor that allows linearization and temperature compensation of the phase measurements to provide the absolute O2 concentration. The optode sensor technology has reached what is probably the highest maturity among all biogeochemical sensors. During recent years nearly all relevant characteristics of oxygen optodes have been studied intensively in view of their readiness for Argo float applications (Bittig et al., 2012, 2014, 2015; D'Asaro and McNeil, 2013; Bittig and Körtzinger, 2017). All these studies have provided knowledge on the possibilities and limitations for obtaining quality data, necessary for the development of protocols and recommendations for good practice (SCOR WG142, Bittig et al., 2016).

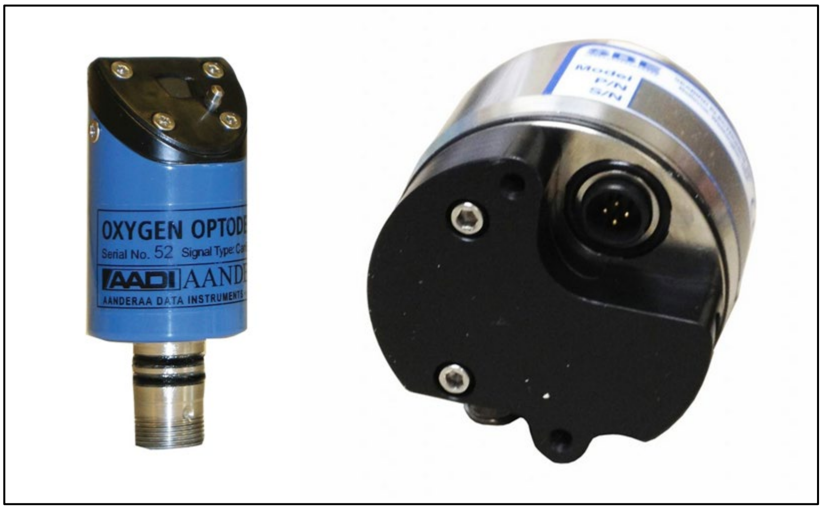

Figure 3: DO optode sensors from Aanderaa 4330 and Seabird SB63 (from left to right)

Nitrate sensors

Wet-chemical colorimetric analysers and ultraviolet (UV) optical sensor technologies are available for measuring nitrate in the ocean (Daniel et al., 2020).

Chemical sensors are based on the colorimetric reaction method where NO3 is determined using a copper cadmium column and in situ calibration using standard solutions. They allow for autonomous NO3 analysis on various platforms with high temporal and spatial resolution. However, their performance can be limited by analytical, biological, optical, and physical factors, including detection limit, reagent stability, biofouling, power consumption, and depth range. Wet chemical analyzers such as the WIZ probe (Systea, Italy; Vuillemin et al., 2009) and the Lab-on-Chip (LOC) sensor (NOC, UK; Beaton et al., 2012) have a measurement frequency of approximately 15 min, a detection limit of 0.025 µM NO3. These sensors are considered more suitable for long-term deployments on moored/buoy platforms.

Nitrate has a UV absorption band of 210-240 nm with a peak near 210 nm, which overlaps the stronger absorption band of bromide, which has a peak near 200 nm. In addition, there is a much weaker absorption due to dissolved organic matter and light scattering by particles (Ogura and Hanya, 1966). The background noise of the measurement may also include thermal effects on the instrument as well as slow changes in absorption due to soiling of the optics. All of these latter effects contributing to the background absorbance tend to combine to form a wavelength linear absorption spectrum over relatively short wavelength range.

The nitrate sensors optically (Figure 4) measure the amount of nitrate (NO3) dissolved in seawater by examining its absorption of ultraviolet (UV) light. The Sea-Bird SUNA V2 (Submersible Ultraviolet Nitrate Analyzer) is a chemical-free UV nitrate sensor based on the ISUS (In Situ Ultraviolet Spectroscopy) UV nitrate measurement technology developed at MBARI. These optical sensors provide fast response measurements, allowing for the sensor to be deployed on profilers, gliders, and AUVs (Johnson et al. 2013). UV optical sensors have been widely used on coastal platforms (Spectrolyser, Etheridge et al., 2014) and moorings (OPUS and SUNA; Collins et al., 2013; Sakamoto et al., 2017).

Figure 4: Nitrate optical sensors from Seabird (SUNA) and from TriOS (OPUS) (from left to right)

pCO2 sensors

Most measurement techniques for CO2 use one of 4 basic approaches: gas based, electrochemical, wet-chemical or fluorescent optode analysis (Clarke et al., 2017). Temperature cross-sensitivity is a problem for all sensors with respect to in situ CO2 analysis, and therefore temperature measurements alongside the CO2 measurements are required. Calibration of sensors is typically performed with reference gases, either through direct introduction into the detector or by bubbling the gases through seawater in which the sensor is positioned (at relevant temperatures).

In mooring/buoy platforms, the most common pCO2 sensors used the technique of NDIR (non-dispersive infrared spectroscopy) (4H JENA HYDRO-C, Pro-Oceanus CO2-Pro; Figure 5) and SPM (Spectrophotometry) (Sunburst SAMI-CO2, NKE-CARIOCA).

NDIR uses the characteristic vibration of gaseous CO2 upon absorption of infrared radiation. NDIR has a non-linear response over a wide measurement range (0-3000 µatm, Frankignoulle and Borges, 2001). To correct for detector drift, regular calibration with certified reference gases is required along with daily blank measurements. The seawater-equilibrated gas must be dried (to minimise band broadening) before entering the NDIR detector. In addition, for the best measurement precision and accuracy, the NDIR detector requires stable temperatures. At present, NDIR systems produce in situ pCO2 measurements at the highest accuracy and precision, and the alternative calibration and zeroing procedures facilitate in situ deployment of NDIR. However, the systems are typically large, require regular drift corrections and re-calibration to ensure long-term measurement stability, have high power requirements, which all make deployment on autonomous platforms challenging.

Spectrophotometric systems pump uses a colorimetric pH indicator into a CO2-permeable tube where it equilibrates with the seawater sample, before being propelled to the detection cell where the absorbance of the solution is measured at three wavelengths (absorbance of the acid and conjugate base forms of the indicator, and an independent reference wavelength). Seawater-only (blank) solutions are measured periodically to correct for fluctuations in light intensity and mitigate the effects of biofouling (Moore et al., 2011). There are several other potential challenges with in situ spectrophotometric deployments, such as light source instability, membrane or semi-permeable tube damage, and biofouling effects.

Projects on pCO2 optodes (Atamanchuk et al., 2014; Clarke et al., 2017) indicate that they are suitable for open ocean measurements and well suited for integration on autonomous platforms. They have low power consumption and do not require any reagent. Therefore, pCO2 optodes have a great potential for applications on moorings (in addition to Argo floats and gliders). To improve the performance of the pCO2 optode, it is suggested that more stable and sensitive sensor foil be used, reliable in situ calibration be performed, and a pump be added to accelerate the flow of seawater against the sensor foil for faster response time (Chu et al., 2020).

Figure 5: pCO2 sensors from 4H JENA (HYDRO-C), from NKE (CARIOCA) and from Pro-Oceanus (CO2-Pro CV)

pH sensors

The most commonly deployed pH sensor on moorings uses ion sensitive field effect transistor (ISFET) technology. The SeaFET is the most widely used. It was originally developed at MBARI (Martz et al., 2010) and has since been commercialised by SeaBird. This sensor has been deployed in numerous field studies and has been extensively reviewed to provide best practice for appropriate calibration and deployment procedures (Bresnahan et al., 2014; Hofmann et al., 2011; Kapsenberg and Hofmann, 2016; Martz et al., 2010; Matson et al., 2011; Yu et al., 2011). More recent studies have extended the scope of SeaFET accuracy, sensor variability, operator experience and multipoint calibration techniques (Gonski et al., 2018; Johnson et al., 2017; Kapsenberg et al., 2017; McLaughlin et al., 2017; Miller et al. 2018).

The SEAFET uses the ISFET technology (Figure 6) with an internal Honeywell Durafet and an external solid-state chloride selective electrode (Cl-ISE) along with an internal thermistor. SeaBird suggests that the external reference electrode provides the more accurate and stable pHt measurement given that chloride concentration can be precisely determined from accurate salinity measurements. However, Bresnahan et al. (2014) demonstrated that the internal electrode is of the highest quality and under most scenarios remains nearly as stable as the external electrode.

Figure 6: pH SEAFET sensor from Seabird alone (top) and mounted on SBE37-ODO instruments (SEAPHOX)

4.2. Sensors deployment & maintenance

Sensor calibration is an important process in order to acquire accurate data during the sensor's deployment. Most of the time, this calibration is performed by manufacturers or lab facilities able to provide certificates (ex. MINKE project, grant 101008724). In addition to the calibration procedure, best practices of sensors recommended in situ inter-comparison during the mooring/buoy maintenance and/or during regular ship visits (eg. fixed point time series) (Table 2).

Indeed, to estimate the sensor drift, in situ sampling and lab analysis are still the reference to adjust sensor dataset (Winkler for DO, spectrometry for pH, colorimetry for nutrients) with regular standard to qualify the lab measurements, evaluate the chemical blank and the instrument efficiency.

DO optodes are the most recommended sensor as they are robust with low power consumption and their behaviour and data correction have been studied for the last 10 years. DO optodes measure the seawater oxygen partial pressure, pO2, and they show an oxygen time response due to re-equilibration between sensing membrane and seawater (Bittig et al., 2018). Based on the ARGO community experiences, the calibration protocol for DO optodes using Presens foil has progressed for the last 10 years. It refers to the 7 Stern-Volmer coefficients to adjust the accuracy of the sensor coefficients. Recent papers established that the DO sensors after correction provide an accuracy around +/- 5 µmol/kg (Gregoire et al., 2021). Only DO optodes with multi-point calibration should be used as "foil-batch" calibrations perform worse in characterising the O2-temperature-response. As a good practice, Coppola et al. (2016) proposed a DO sensor maintenance procedure for fixed platforms. They suggested mounting the DO sensors on the CTD-rosette profiler before mooring deployment and to deploy the profiler at 2-3 different depth levels (avoiding the depth gradient) for 30 min to estimate the DO sensor offset and to reconstruct the 1D vertical profile. During this in situ inter-comparison, CTD-O2 sensors should be calibrated according to standard practice using Winkler bottle reference titrations (Uchida et al., 2010). In addition to inter-comparison procedures, they recommended sending the DO sensors to the manufacturers or laboratory calibration facilities every two years which implies having a pair of sensors to allow the sensor rotation.

For nutrients sensors, significant progress has been made over the last 10 years in improving data quality for seawater nitrate analysis using the ISUS and SUNA (Seabird Scientific, United States) optical sensors. Standardisation of sensor calibration and data processing procedures are important for ensuring comparability of marine nitrate data reported in different studies. For moored/buoy systems, CTD profiling, AUVs and FerryBox deployments, a discrete water sampler unit can also be set up alongside to the nutrient sensor deployment to collect samples for later laboratory analysis, especially in the case of UV optical and electrochemical sensors for which the sensitivity drift cannot be controlled *in situ*. This comparison of sensor and conventional nutrient measurement is the primary tool for control of trueness and accuracy of sensor-based field measurements (Daniel et al., 2020).

Table 2: List of sensors recommended to measure chemical the variables through Eulerian platforms (colour indicated the degree of robustness: green = robust, yellow = need more validation, red = need more deployment and test).

Variables	Recommended technique	Sensor 1	Sensor 2	Sensor 3	Sensor 4
DO	Luminescence lifetime optode sensor	AADI 4330	Seabird 63	JFE RINKO	RBR CODA
Nutrients	Ultraviolet spectrophotometer; wet chemistry	Seabird SUNA	Trios OPUS	Chemini, WIZ, …	
pCO2	NDIR, spectrophotometry	4H-JENA HYDRO-C	Pro-Oceanus CO2-Pro	Sunburst SAMi-CO2	NKE CARIOCA
pH	Ion-sensitive field-effect transistor	Seabird SEAFET	SAMI-pH	Chemini	Clearwater LoC

For oceanic carbon measurements, a best practice has been published from Dickson et al. (2007) but this concerns the analytical measurements for CO2 variables and not dedicated to the pCO2 and pH sensors for which their application to observing systems are more recent. However, some papers have been recently published for the application of pCO2 technology for marine observations (Clarke et al., 2017). NDIR pCO2 sensors are the most developed technology for in situ measurements but suffer from spectrometer drift. NDIR pCO2 sensors are suitable for use on moorings and buoys. Wet chemical spectrophotometric techniques have volume and pCO2 dependent response times and require minimal in situ calibration. Further development of appropriate reference materials is recommended, especially for the new generation of sensors that analyse pCO2 in the aqueous phase. Finally, regular in situ calibration with reference seawater materials during sensor deployment is the best solution and projects are ongoing to develop new DIC-TA reference materials for pCO2 calibration (other than Dickson DIC standards).

For pH sensors, Bresnahan et al. (2014) proposed best practices for the use of SeaFet sensor. They recommend to test the sensor during 5-10 days prior the sea deployment and to compare with in situ pH sampling in order to estimate any sensor drift (see EuroSea D3.6[3]). To limit biofouling of the sensor, an active flush flow pattern should be used to minimise the effect of light, with special antifouling paint and copper foil on the sensor. Where possible, frequent discrete samples should be taken in the vicinity of the sensor to establish an estimate of the error in the pH sensor data. It is also recommended to estimate pH values from other carbonate variables using the CO2SYS or SEACARB tools when direct in situ pH measurements are not possible or when the measured values are questionable (Van Heuven et al., 2011, Gattuso et al., 2021).

Finally, for all BGC sensors, a common recommendation is to perform regularly an inter-laboratory comparison exercise to evaluate the performance of the BGC sensors and to assess the accuracy of the sensors with each other and with in situ sampling data collected in controlled environments (e.g., ICOS pCO2 sensors, SapHTies and MINKE pH sensors, ...). These exercises between end-users and experts will also provide a list of "recommended" sensors by order of performance (precision, reliability...) which will be useful in particular for the new existing BGC sensors offering a new technology.

4.3. Delayed mode processing with uncertainties estimation

The delayed mode (DM) procedure is to provide the best quality data for science including realistic error estimates. It includes more sophisticated data adjustment and quality control procedures. In other words, the delayed mode data set suggests adjustment of variables after sensor acquisition. It suggests estimating any sensor drift and offset during and after deployment using a regular in situ intercomparison exercise ("in situ correction") during platform maintenance and a regular calibration procedure for adjusting sensor coefficients (see section 4.2). Obviously, this procedure is more suitable for fixed platforms operating near the time series stations or in coastal areas where regular ship visits are possible, but it remains the best way to constrain and to estimate sensor drift and limit the effect of biofouling on sensor data. The DM procedure should be performed by the platform PI as soon as the sensors on the mooring have been collected (once per year in general for open sea sites). For BGC variables, only Argo produces different cookbooks including sample parameter data processing code and meta-data population examples for a wide range of BGC sensor types and model configurations (Bittig et al., 2019). These different cookbooks should also serve the Eulerian platforms community. As for Argo Data Team, this requires to identify existing DAC to perform QC control and data file formats and staff to perform DM processing for BGC data (platform PI or experts). To propose this DM procedure as best practice, an operational workflow must be established such that any data adjustments resulting from DM efforts are effectively fed back into DAC and accessible for end-users.

In this context, a new procedure can also be proposed for Eulerian platforms: the application of artificial neural networks to predict BGC variables from baseline input variables after a number of training and testing validations. Today, we have learned that artificial neural networks in oceanography can efficiently model eventual non-linear relationships among input variables and to predict accurately nutrients and CO2 variables (eg. CANYON models from Sauzède et al., 2017; Bittig et al., 2018; Fourrier et al., 2020, 2022). Thus, the predicted variables could be used as a reference dataset to adjust in situ sensor data when in situ sampling is not possible. In some cases, reconstruction of the adjusted dataset can be used to fill the gaps in the time

[3] https://eurosea.eu/deliverables/

series and thus limit the impact of sensor drift or failure during the mooring deployment. This approach is already used by the Argo community for automatic data quality control.

Regarding the DO optodes, a strong DO sensitivity drift (order -5% per year between calibration and deployment) has been observed, independent of the type of calibration, which should be corrected with a factor on the pO_2 (Bittig et al., 2018). This “storage drift” can be easily estimated during the mooring deployment when in situ sampling is performed. Secondly, a smaller “in situ drift” can occur over the sensor deployment (-0.5% per year) and it could be estimated during regular calibrated CTD-O_2 profiles near the mooring position (Bittig et al., 2018). For DM data processing, more information can be found in BGC Argo data management documents (Thierry et al., 2021).

For nitrate, the optical SUNA sensor has a stated accuracy and precision of 2 and 0.3 µmol/kg, respectively, for raw data. After data is adjusted, as described by Johnson et al. (2017), accuracy improves to an order of 0.5 µmol/kg. The correction of nitrate data requires co-located measurements of pressure, temperature, and salinity from the CTD sensor. Despite careful calibration in the laboratory, these sensors can suffer from an initial calibration offset once deployed and a calibration drift over time. One recommendation from the Argo community is to estimate the offset to reference estimates for nitrate at 1500m where temporal changes in concentration are minimal. For fixed platforms, it is also possible to validate this approach with a profile of discrete water samples collected near the mooring and/or to mount the nitrate sensor on CTD-rosette profiler with discrete sampling prior to mooring deployment. For nitrate, it is also possible to compare with artificial neural networks such as CANYON-B or LINR (Locally Interpolated Nitrate Regression from Carter et al., 2018). It requires accurate oxygen values measured directly with T & S. For this approach, a regional neural network (eg. CANYON-MED for the Mediterranean Sea) is strongly recommended for fixed point observatory to better capture the BGC variability such as nitrate (Fourrier et al., 2020).

For pH data, SeaBird Scientific claims an initial stated accuracy of ±0.05 pH and a stability of 0.036 pH/year which could be reduced after data adjustment (up to 0.005 pH from Jonhson et al., 2017). The pH calculation requires co-located measurements of salinity, temperature and pressure from the CTD. Similar to nitrate, the raw calculated pH should not be considered “science quality” until it has been inspected/corrected for offsets and drifts. As for nitrate, we recommend using: 1) discrete sampling near the mooring position, 2) neural network predictions for comparison at the sensor depth and to estimate the pH sensor offset once the mooring has been deployed. More information on pH data processing can be inspired from the BGC Argo data management document: Processing BGC-Argo pH data at the DAC level (Johnson et al., 2018).

5. Geophysical variables

5.1. Sensors characteristics

Seismic sensors are arguably the most common type of geophysical instruments deployed on eulerian observatories worldwide to record ground motions over the bandwidth from Earth tides (10^{-5} Hz) to teleseismic body waves (> 10 Hz) (Table 3; Havskov & Alguacil, 2016). Pan-European seismological initiatives like ORFEUS (Observatories and Research Facilities for European Seismology) have long promoted the use of digital broad-band seismometers to cover at least part of this frequency range and a displacement dynamic range of ~10^9 (from 1 nm to 1 m). The underlying concept is that best practice in seismology is driven by the need to integrate records from the largest possible number of seismometers to reliably determine the origin time, location, magnitude and depth of an earthquake or other sources of seismic waves such as imparted by volcanic tremors or landslides. Yet, due to technical limitations, a broadband seismometer is considered as good for local and global studies when it covers at least the 0.01-100 Hz frequency band and ground motions ranging from 1 nm to 10 mm (Havskov & Alguacil, 2016).

Table 3: Typical frequencies generated by different seismic sources (from Havskov & Alguacil, 2016).

Frequency range (Hz)	Type of measurements
0.00001-0.0001	Earth tides
0.0001-0.001	Earth free oscillations, earthquakes
0.001-0.01	Surface waves, earthquakes
0.01-0.1	Surface waves, Compressional and Shear waves, earthquakes with Magnitude> 6
0.1-10	Compressional and Shear waves, earthquakes with Magnitude > 2
10-1000	Compressional and Shear waves, earthquakes with Magnitude < 2

In order to record ground motion in all directions three separate seismic sensors are assembled together in so-called "three-component seismometers". Inertial seismometers measuring ground motion relative to an inertial reference (seismic mass) are generally more sensitive to earthquake signals so they stand as the most common type of seismic sensors used for long-term monitoring offshore (Monna et al., 2005; Roset et al., 2018; Hello et al., 2019; Courboulex et al., 2020 and references therein). Broad-band seismometers of this type are built according to the force-balance principle such that vibrations of the seismic mass detected by capacitive, inductive, optical or electrochemical means are counteracted by the control electronics. Any change of the required electrical force is recorded as an output voltage proportional to ground acceleration which is turned into an output binary number using a digital-to-digital converter. In the lack of published offshore trials addressing the performance of co-located broad-band seismometers, those relying on capacitive transducers are the most advisable choice. This stems from the proven high sensitivity and large dynamic range that the intrinsically noiseless capacitive transducers afford. In this regard it is worth stressing that the careful selection of a broadband seismometer should be guided by the assessment of its response function as a means of evaluating to which extent its dynamic range and/or sensitivity might be frequency dependent and thus best suited for a narrower frequency band. Even if the sensitivity expressed as the gain of the instrument in V/m/s is a useful comparison parameter, Havskov & Alguacil, (2016) recommend to assess sensitivity from the sensor acceleration power spectral density curve equivalent to the sensor noise against the New Low Noise Model proposed by Peterson (1993) (Figure 7). Additionally, Havskov & Alguacil, (2016) pointed out that a good sensor should have a linearity better than 1% though this parameter is not always specified.

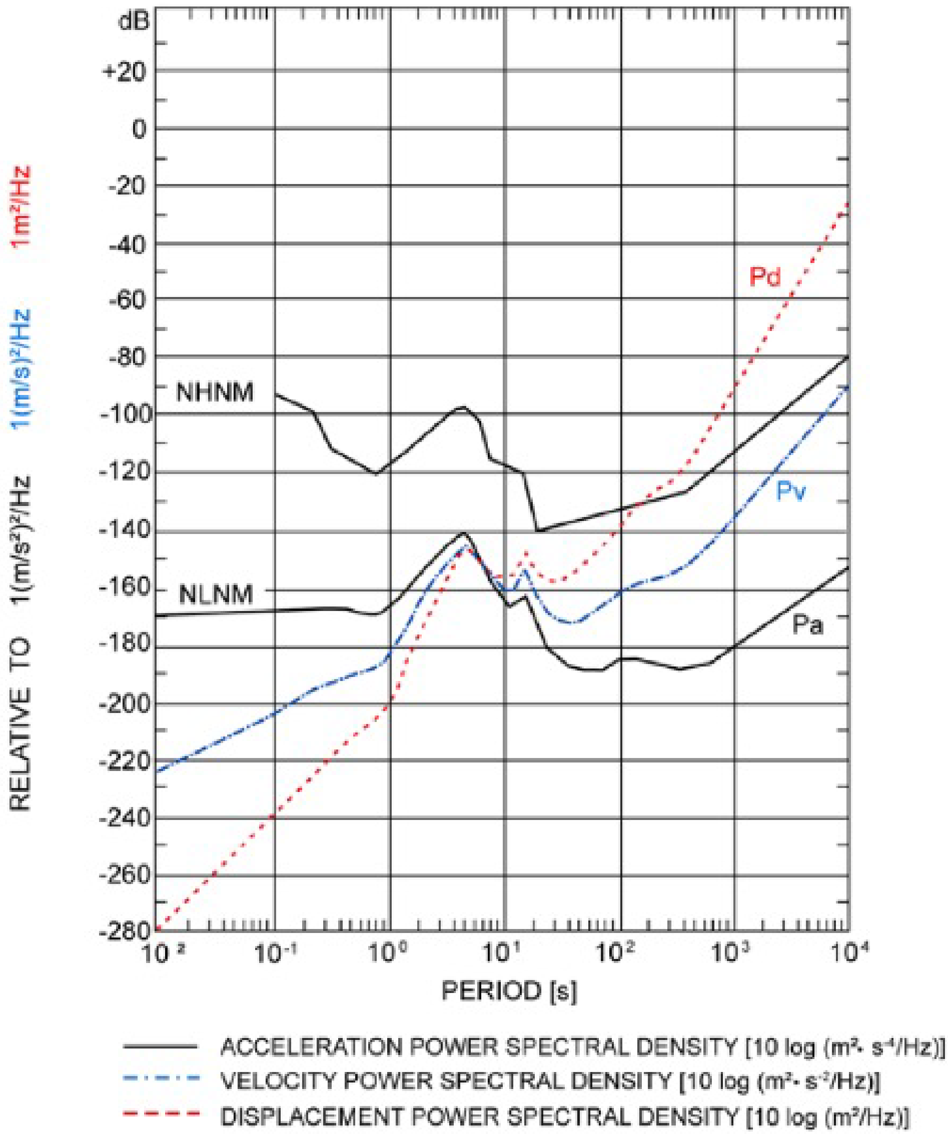

Figure 7: Envelope curves of acceleration noise power spectral density Pa (in units of dB related to 1 (m/s2)2/Hz) as a function of noise period (according to Peterson, 1993). They define the new global high (NHNM) and low noise models (NLNM) which are currently the accepted standard curves for generally expected limits of seismic noise. For the NLNM the related curves calculated for the displacement and velocity power spectral density Pd and Pv in units of dB with respect to 1 (m/s)2/Hz and 1 m2/Hz are given as well (Taken from Bormann & Wiedlandt, 2013).

As a transition to the following section Landschulze (2019) pointed out that unwanted relative motion of a seismometer on the seafloor can be minimised with a careful housing design. This means that coupling can be improved by installing instruments as small as possible in a housing with a density and weight similar to the surrounding seafloor and the lowest possible wave field impedance.

In order to record ground motion in all directions, a triple set of seismic sensors oriented towards North, East and upward (z) has been the standard for a century (Wiedlandt, 2012). In the underwater realm, such a conventional practice is fraught with technical challenges bringing emphasis to seismometer deployment by divers or Remotely Operated Vehicles depending on the water depth (Figure 8; Monna, et al., 2005; Frontera et al., 2010; Bompais et al., 2019; Hello et al., 2019). As an alternative to portable compasses to achieve proper orientation, Güralp and Nanometrics companies have developed offshore seismometers equipped with orienting capabilities (Hello et al., 2019). These instruments also have tilt measurement and levelling capabilities as a prerequisite to offset the projection of the gravity vector onto the sensing axes. Seismometers without auto-levelling systems have to be remotely levelled providing real time access can be achieved via a cabled observatory or a surface buoy. In any case, rough primary levelling must be envisaged as part of the subsea interventions to bury or trench the instrument into the seafloor. Indeed, in line with the theoretical model developed by Landschulze (2019), comparative analyses of real-time data from offshore cabled seismometers proved burial to be critical to ensure good coupling to usually soft seafloors and, in turn, to reduce noise level (Hello et al., 2019). In circumstances when burial is too much of a task, placement of a fiber-glass protective cover can be a practical alternative to impede noise from convective or bottom currents (Hello et al., 2019). Note that such a cover is strongly advised to prevent damages to the instrument in areas of fishing activity. In order to reduce noise caused by water column fluctuations on the vertical sensing axis Webb and Crawford (1999) stressed that any deployment of broad-band seismometers offshore should include one or more pressure sensors to record changes in the 0.001 to 0.04 Hz frequency band. Although absolute pressure sensors like the accurate (but expensive) Paroscientific one can be used for that purpose, differential pressure gauges as developed by the SCRIPPS are preferable since they allow very small pressure fluctuations to be detected no matter the water depth (Frontera et al., 2010; Hello et al., 2019). As first shown by Webb and Crawford (1999) bottom pressure measurements provide an efficient means of removing the noise signal due to deformation under wave loading during the processing phase of the seismological data.

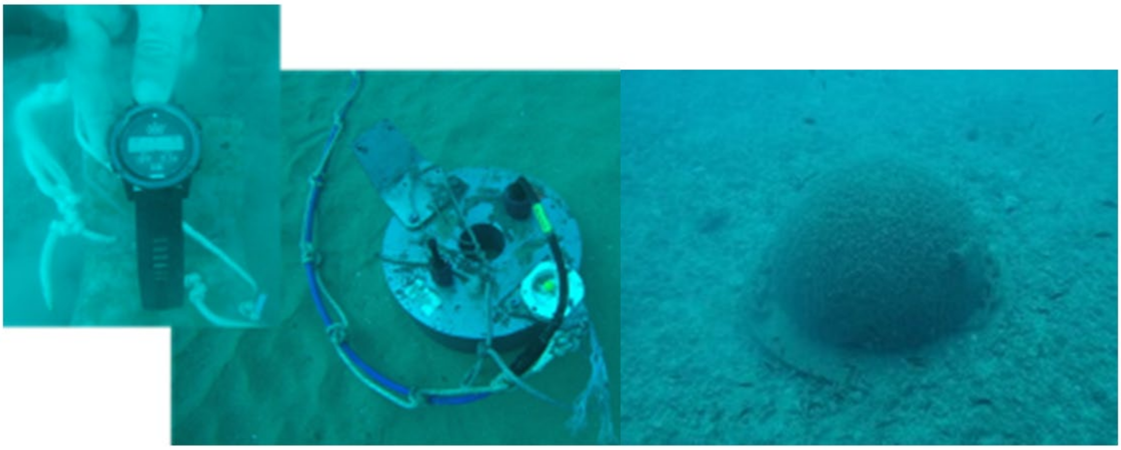

Figure 8: Broad-band seismometer (CMG 3T 360s) trenched into the seafloor and oriented with a portable compass before its connection to the cabled EMSO Ligure Nice observatory. Right: Fiber glass protective cover above the seismometer shown to the left.

5.2. Delayed mode processing with uncertainties estimation

Following up on the previous section, delayed mode processing may first be oriented towards the assessment of the precise orientation of the north axis of a seismometer with respect to geographical North and its coupling to the seafloor. As shown by Frontera et al., (2010) the first of these assessments can be achieved by means of polarisation diagrams using data from both local and teleseismic events. Besides, Monna et al.,

(2005) relied on the recordings of the high frequency content associated with local events to infer good coupling to the surrounding sediments of a broad-band seismometer partially buried with a ROV. They draw this conclusion based on seismic noise analysis with reference to the New Low-Noise and New-High Noise models from Peterson (1993). Under the umbrella of the International Federation of Digital Seismograph Networks[4] such an analysis reached standard status for seismic data quality assurance. As shown in Figure 9 it relies on the plot of the Probability Density Function (PDF) of the Power Spectral Density spectra (PSD as previously presented in Figure 1). Figure 9 illustrates that this method is an effective means of spotting a "dead" sensing channel and its "recovery" following servicing and calibration. Beyond the identification of data problems and the planning of maintenance operation, this method is particularly useful to derive a range of metrics with practical relevance to the selection of seismological data from local to global networks. As detailed in the reference manual of Standard for the Exchange of Earthquake data, a range of other parameters can be used to obtain quality indicators and guide the selection process from national and international data centres and web services. Complying to this standard to contribute to data archives like ORFEUS comes as a strong recommendation as it implies benefitting from long-term archival, state-of-the-art quality control, improved access, increased usage, and community participation (Haslinger, 2022).

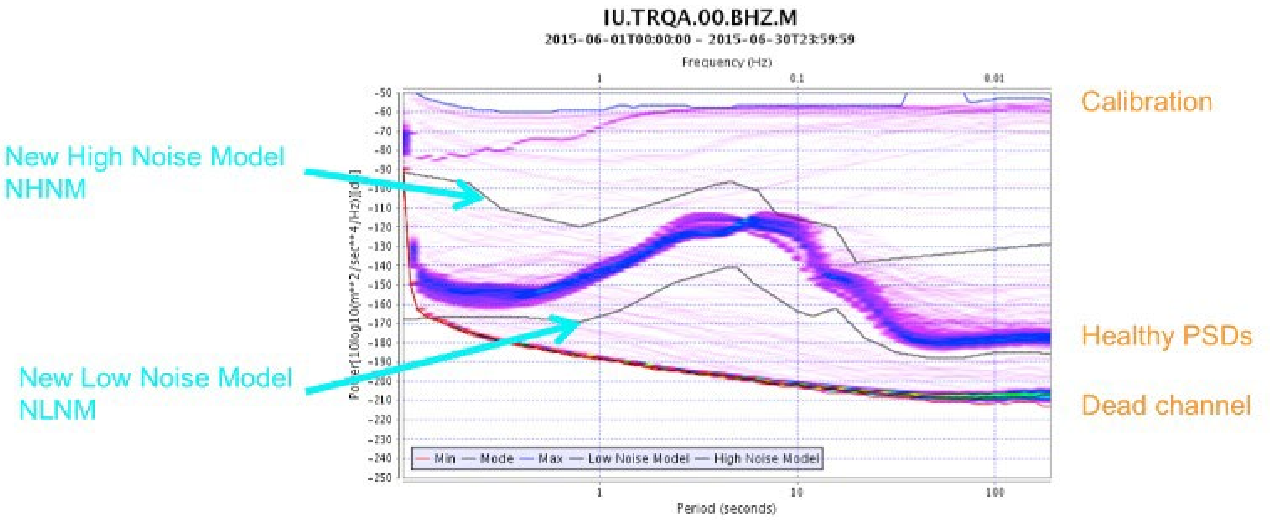

Figure 9: Example of a Probability Density Function (PDF) plot of PSD spectra showing the signature of a dead channel which was subsequently serviced, calibrated before becoming functional again[5]

[4] https://www.fdsn.org/

[5] https://www.iris.edu

Conclusion

The variables discussed in this deliverable cover several areas ranging from physics to geophysics for water column and seafloor observations operated by Eulerian platforms. Most of these recommendations raise the fact that variables measured automatically at high frequency cannot do without measurements at sea and thus the presence of research vessels that have a financial and environmental impact on the nations and programs in charge of these platforms. Without doubt other alternatives should be considered such as the presence of drone ships or the application of neural networks to estimate the accuracy of dataset and to allow a correction of data but this will require a reflection on a larger community. Also, it can be assumed that progress on marine technologies (e.g. microfluidic systems, chips…) capable of collecting and analysing seawater will provide better opportunities to constrain and estimate the performance of autonomous sensors deployed on mooring.

Finally, the objective of this report was to propose best practice guidelines for the variables measured by the different fixed platforms. It is rather a synthesis of recommendations for the measurement of the different variables, the maintenance of the associated sensors and the current data correction procedures. Finally, to constitute a best practice guide, the proposals described in this deliverable should be accepted by a large community using fixed platforms for observations in order to obtain a general consensus. This should be the next step and probably reviewed by a community beyond EuroSea and represented by the EuroGOOS task team on fixed platforms.

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