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NAUTILOS

Deliverable 2.2

Technical requirements required for sensors in WP3 and WP4

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DEM	Demonstrator	
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NAUTILOS

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NAUTILOS - New Approach to Underwater Technologies for Innovative, Low-cost Ocean observation is an H2020 project funded under the Future of Seas and Oceans Flagship Initiative, coordinated by the National Research Council of Italy (CNR, Consiglio Nazionale delle Ricerche). It brings together a group of 21 entities from 11 European countries with multidisciplinary expertise ranging from ocean instrumentation development and integration, ocean sensing and sampling instrumentation, data processing, modelling and control, operational oceanography and biology and ecosystems and biogeochemistry such, water and climate change science, technological marine applications and research infrastructures.

NAUTILOS will fill-in marine observation and modelling gaps for chemical, biological and deep ocean physics variables through the development of a new generation of cost-effective sensors and samplers, the integration of the aforementioned technologies within observing platforms and their deployment in large-scale demonstrations in European seas. The fundamental aim of the project will be to complement and expand current European observation tools and services, to obtain a collection of data at a much higher spatial resolution, temporal regularity and length than currently available at the European scale, and to further enable and democratise the monitoring of the marine environment to both traditional and non-traditional data users.

NAUTILOS is one of two projects included in the EU´s efforts to support of the European Strategy for Plastics in a Circular Economy by supporting the demonstration of new and innovative technologies to measure the Essential Ocean Variables (EOV).

More information on the project can be found at: http://www.nautilos-project.eu.

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Executive Summary

This deliverable outlines a set of technical requirements for 13 instruments to be designed and developed through the NAUTILOS project (WP3 and WP4). The objective is to ensure that the instruments developed in the project will be as compatible as possible with ocean observing platforms of the project, and also aligned with future European and global ocean observing efforts. Through a collaborative effort among 11 partners, recommendations for common technical requirements have been developed under seven main topics:

1. Form factor and construction material: cylindrical, fit-for-purpose material selection, standard O-ring size, Allen/hex hardware.
2. Anti-biofouling measures: various techniques implemented, all of them to be addressed by EU regulations.
3. Power requirements and communication protocols: Variable power input for instruments is preferred, but standard power input is also accepted. Data format should be in ASCII.
4. Cable types/connectors: wet-mateable rubber molded connectors (circular; 31 and 15.5 diameter) and cables shall be used.
5. Cost and scalability: The economies of scale and lower manufacturing costs are dependent on widespread use. Common technical specifications will promote this aim, but many external factors will influence this.
6. Metrological considerations: Measurement quality of data is a growing concern that must fit the needs of end users. For this purpose, metrological considerations will be addressed from the beginning of the project.
7. Special considerations: Some platforms have specialized requirements such as power supply, payload capabilities, and the need for miniaturization.

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List of Acronyms and Abbreviations

Abbreviation	Definition
ABS	Acrylonitrile butadiene styrene
ACT	Alliance for Coastal Technology
ASCII	American Standard Code for Information Interchange
AUV	Autonomous underwater vehicle
BR	Butadiene rubber
CommonSense	Cost-effective sensors, interoperable with international existing ocean observing systems, to meet EU policies requirements (FP7 project)
CSV	Comma separated value
CTD	Conductivity, temperature, depth sensor
EMSO-ERIC	European Multidisciplinary Seafloor and water-column Observatory
ESONET	European Seas Observatory NETwork (FP6 project)
EU	European Union
Euro-Argo	European contribution to the international Argo Program
FAO	Food and Agriculture Organization
FixO3	Fixed-point Open Ocean Observatories (FP7 project)
GNSS	Global Navigation System Satellite
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
JERICO-RI	Joint European Research Infrastructure of Coastal Observatories

Modbus	Data communications protocol originally published by Modicon
NBR	Nitrile
NeXOS	Next generation, Cost-effective, Compact, Multifunctional Web Enabled Ocean Sensor Systems Empowering Marine, Maritime and Fisheries Management (FP7 project)
NMEA 0183	National Marine Electronics Association Interface Standard 0183
OBPS	Ocean Best Practices System
PA6	Polyamide
PE	Polyethylene
PEEK	Polyetheretherketone
POM-C	Acetal copolymer
PTFE	Polytetrafluoroethylene
RS-232/422/485	Recommended Standard 232/422/485
TCP	Connection orientated transport layer protocol
UAV	Unmanned aerial vehicle
UDP	Connection-less transport layer protocol
UNEP	United Nations Environment Programme
USB	Universal Serial Bus
SCHeMA	Integrated in situ chemical mapping probes (FP7 project)
VAC	Volts alternating current
VDC	Volts direct current

I. INTRODUCTION

The Horizon 2020 NAUTILOS project will develop thirteen different types of cost-effective sensors and samplers to measure 70% of the biological and biogeochemical essential ocean variables, and eight of the Marine Strategy Framework Directives. In order to progress from instrument development (WP3/4) to platform integration (WP5), calibration (WP6), demonstration (WP7), and eventual exploitation of the data acquired (WP8/9), the NAUTILOS consortium must define sensor technical development requirements in task 2.2 to ensure compatibility, modularity, and durability during all phases of the project, as well as for scalability beyond the life of the project. Task 2.2 on sensor requirements is linked to task 2.1 that will address the political and societal drivers and requirements for sensors developed within NAUTILOS as well as task 2.3 that will address requirements for the integration of sensors onto selected platforms as part of NAUTILOS. Within task 2.2 the participating partners (NIVA, IFREMER, Aquatec, NKE, HESSO, SCT, UL-FE, SCEM, CNRS, DFKI, ETT) will address the following activities in this Deliverable:

- To review and evaluate existing technical requirements for marine sensor systems,
- To establish NAUTILOS technical requirements for shallow and deep sensor systems including, but not limited to, form factor, construction materials (i.e., durability), size, cost, scalability (both in terms of costs savings and manufacturing), attachment points/mechanism, anti-biofouling mechanisms, power requirements, communication protocols, and cable types and connectors.

Due to the hardware/physical link between sensors and platforms, some topics in this Deliverable will be covered in more depth by Deliverable 2.3 on requirements for integration of sensors onto platforms including attachment points, communications protocols, and cable types/connectors.

While sensor technical requirements are not standardized across the oceanographic sensor manufacturers and community, a number of best practices related to sensor deployment, calibration, and operations have been developed in recent years as part of ocean observing projects and initiatives that include, but not limited to, JERICO-RI, EMSO-ERIC, FixO3, ESONET, NeXOS, CommonSense, SCHeMA, Euro-Argo, Alliance for Coastal Technology (ACT), and, as a repository of best practices across projects, the Ocean Best Practices System (OBPS). Rather than be a manual or document related to best practices, this deliverable is intended to provide guidance for all instrument systems (sensors and samplers) developed under NAUTILOS to provide standardization and interoperability between instrument systems and observing platforms.

II. Requirements and suggested specifications/guidelines

To assess requirements and suggested specifications for instrument systems (sensors and samplers) developed under the NAUTILOS framework, the partners reviewed the existing best practices concerning instrument-related requirements (see section 1) and requirements for instruments presently in use or under development by NAUTILOS partners. These aspects were taken into consideration together with: a) practicality and suitability based on the requirements of each instrument system itself as well as platforms that they were intended to be integrated with, b) minimum acceptable requirements to ensure compatibility and modularity, and c) future prospects for scalability in terms of costs and manufacturing and so-called "future-proofing" within a certain extent of possibilities.

The instrument requirements were divided into the following sections: form factor and construction material, attachment points/mechanism, anti-biofouling, power requirements, communication protocols, cable types/connectors, and cost and scalability. A follow-up section on instrument requirements that should be considered in the scope of specific platform types is also included in this chapter.

Briefly, the recommended requirements and suggested specifications for instruments systems that are covered in the following sections are as follows: cylindrical, fit-for-purpose material selection, standard O-ring size, Allen/hex hardware; various anti-biofouling techniques to be implemented, all of them to be addressed by EU regulations; variable power input for instruments is preferred, but standard power input is also accepted; ASCII data format; wet-mateable rubber molded connectors and cables; where possible, employ common technical specifications to promote an economy of scale and lower manufacturing cost; consider metrological aspects of the instruments from the beginning of the project; acknowledgement that some platforms have specialized requirements and limitations with regards to power supply and payload capacity.

1. Form factor and construction material

Based on a cursory review of instruments available through sensor manufacturers that are NAUTILOS partners (SubCtech, Aquatec, and NKE Instrumentation; see Fig. 1) and other major sensor manufacturers such as Sea-Bird Scientific, Chelsea Technologies, TriOS, etc., it is apparent that instrument form factor is dominated by the cylindrical form factor. This is for small and large sensors alike - ranging from several centimetres to 10's of centimetres in diameter. Some manufacturers also use a short cylindrical form factor referred to as a puck. The prevalence of the cylindrical form factor is in part due to sensors being designed for primary use and deployment on CTD rosette systems, the ability of a cylinder to withstand pressure when deployed to depth, the simplest and therefore least expensive form factor to manufacture/machine, and the most efficient shape for using commonly available O-rings, which is necessary for preventing water/moisture from entering housing. The deployment on CTD rosette systems and similar frame systems require a degree of customization related to design and placement, and cylindrical items are easily secured and removed for maintenance (or other reasons) using stainless steel hose clamps. Some cylindrical sensor housings will also have small recesses where hose clamps or brackets can be positively engaged and not allow a sensor housing to slide horizontally out when the clamps/brackets are not fully tightened. Because these instrument packages and sensors are often deployed to depths greater than several hundred metres, or in some cases 1000’s of metres, the pressure rating must be able to withstand the large pressures exerted on the housing that contains and protects the sensor’s electronics and optics. For use with above-water installations such as fixed platforms, ship railings, or aerial drones, radiometers and cameras also tend to be in a cylindrical form factor that also allow easy and flexible connections using hose clamps or other mounting systems. Spherical or hemispherical elements are sometimes used for extreme pressures or to provide optimum strength to weight ratio. An example is the Vitrovex glass spherical instrument housing line.

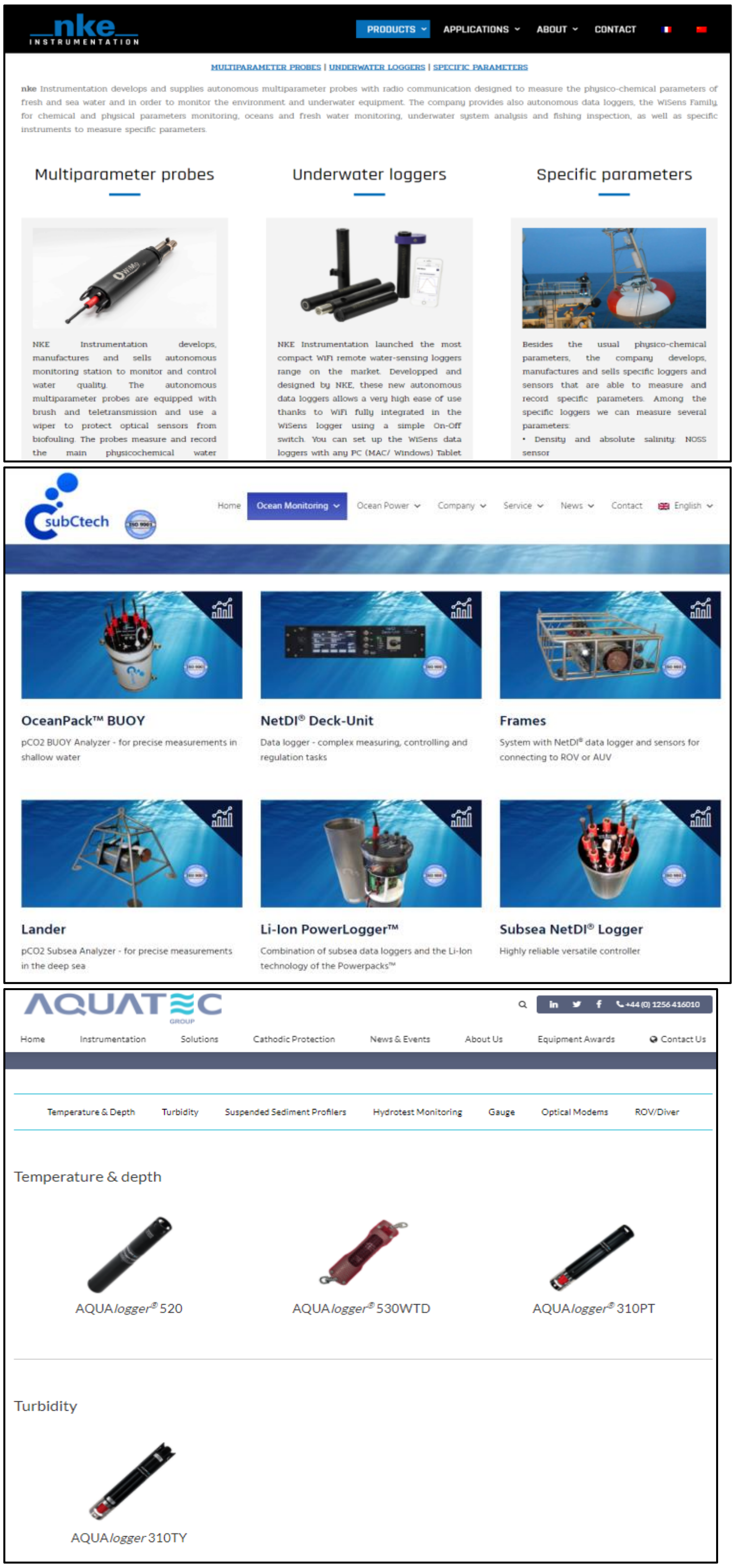

Figure 1. Sensors that are primarily of cylindrical design that were displayed on the websites of NKE Instrumentation, SubCtech, and Aquatec as of March 2021.

In terms of construction material, instrument housings generally fall into two categories: plastic and metal. Plastic housings, depending on the polymer (e.g., polyurethane, polyamide (PA6), ABS, PEEK, POM-C), thickness and construction, can typically withstand pressures up to many hundred metres. Metal housings made from aluminium alloys, stainless steel alloys, and titanium, again depending on thickness and construction, can generally withstand higher pressures that can easily extend to as deep as several 1000 metres or even 10,000 metres water depth. For applications requiring optical transparency, materials such as clear acrylic (e.g., Perspex) are used for applications up to a few thousand metres, while glass is used for housings capable of withstanding up to 10,000 metres depth. Sapphire windows are also used for low distortion optical instruments and cameras. The construction material also leads to some differences in impact resistance and corrosion. Epoxy resin and polyurethane have been used on some sensors and loggers in order to sustain pressure and minimize size. The sensors are cast into an epoxy resin or polyurethane under vacuum to prevent any air bubbles, and can be cast into various sizes and shapes, including hydrodynamic shapes that are important for animal borne platforms. Batteries can also be fitted into a metal cylinder before being cast in epoxy resin to prevent lateral compression.

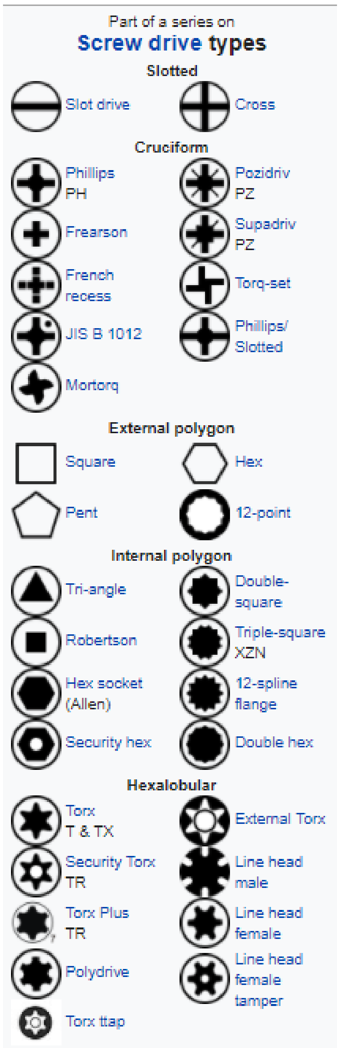

Figure 2. Commonly used screw drive types. Allen/Hex (external polygon subgroup), Torx (Hexalobular subgroup) and Philips (Cruciform subgroup) are recommended screw drive types. Reproduced from https://en.wikipedia.org/wiki/List_of_screw_drives.

In terms of durability, while plastic is generally resistant to impact, it could lose integrity with repeated impacts and susceptible to degradation due to exposure to UV light and absorption of water. Metal housings will generally be more impact resistant but could corrode, pit, and otherwise lose structural integrity, perhaps except for titanium. For underwater applications, sacrificial anodes (made with zinc or aluminium/indium) are often required to prevent and reduce corrosion of sensors made with metal housings by offering a preferential oxidation source. Even in the presence of sacrificial anodes, stainless steel enclosures may exhibit crevice corrosion in areas where the metal is confined to anoxic areas (around the clamps, in the mud, etc.). To limit oxidation in seawater, aluminium alloy enclosures can be treated with a hard anodization treatment. In certain anoxic muds, H_2S can be present, providing a highly corrosive environment. In such conditions, special corrosion resistant alloys such as Alloy 31, or plastics should be used. For above-water applications, construction material must be chosen carefully with respect to durability as conditions can also involve moisture from rain and condensation, and at worst, sea spray and partial submersion in very rough conditions. For aerial drones, weight must be prioritized over durability since payload capacity of drones is relatively limited compared to other ocean observing platforms in NAUTILOS.

A central component of all the construction materials mentioned above includes O-rings and other seals and bolts used to seal access panels that prevent water and moisture from entering the sensor housing. Most sensors require access panels for maintenance checks, replacement of batteries, etc., however some newer generation sensors are designed to be sealed and charge inductively and transfer data wirelessly. O-rings can be made of several different materials (PTFE, FFKM, PE, BR, etc.) depending on the environment and application they are used in. The most commonly used material for O-rings for underwater applications is NBR, due to its high resistance to temperature, abrasion and chemical changes, as well as its moderate price. The cylindrical underwater housings are closed by removable end caps. The end caps are sealed by at least one O-ring (two O-rings are also common as double protection), and bolts hold the end cap in place. Bolts used for securing access panels onto the sensor housings are typically stainless steel, of relatively high thread density, and with an Allen/hex key, Torx, Phillips or other standard screw drive types (Fig. 2). Anti-seize compounds are also recommended for removable screws.

Recommendations: Oceanographic instrument systems have been designed over the last decades using a cylindrical form factor for several reasons that are detailed above. For these reasons, when possible and applicable, we recommend that NAUTILOS sensors and samplers are designed with a cylindrical form factor. In cases where attachment to a frame or other platform structure is not required, and where withstanding pressures at great depths is not required, an alternative form factor could be considered especially for above water applications where sensors may be more likely to be attached via a bracket rather than hose clamps (on aerial drones, for example). In terms of sensor construction material, we recommend that material selection meets basic durability and pressure needs, especially when it comes to the costs of less expensive plastic and aluminium compared to relatively more expensive stainless steel and titanium. And the price benefit of stainless steel is moderate compared to its low durability in confined areas. However, for applications and deployments to extreme depths (e.g., deep profiling CTDs or floats), titanium will be required despite being more costly. For above water applications, lower density materials can be used where weight considerations are important. Where possible, we recommend the use of O-rings with standard numbers (metric; DIN) for denomination for easy reordering, and standard screw drive types with a preference for metric Allen/hex key due to prevalence and easy accessibility to these tools, however Torx is also preferable.

2. ANTI-BIOFOULING MEASURES

Due to the preference for organisms to grow on substrate, and in some cases in the proximity of light emitted from some sensor systems, the growth of autotrophic and heterotrophic single cell and multicellular organisms is a common issue on sensors and other instruments deployed in the ocean (Fig. 3). Biofouling can be composed of microfouling, including the formation of biofilms of bacteria or phytoplankton, and/or of macrofouling which can include larger organisms such as macroalgae, bivalves, or tunicates. Biofouling of surfaces is generally understood to begin with organic molecule adhesion, followed by biofilm formation, and then followed by secondary macrofouling organisms (which are the only organisms that are generally visible to the naked eye in Fig. 3) (e.g., Kerr et al., 1998).

Figure 3. Example of biofouling of a Mclane Phytoplankton Sampler (photo from www.mclane.com).

Many instruments are dependent on clean and clear optical windows, acoustic sensors, or electrical contacts to perform properly, and biofouling, even as a thin biofilm, can compromise the function and eventually the structural integrity (of moving parts including bolts, shackles, or other articulating mechanisms) of some sensor and sampler systems. For most sensors, the most basic and effective anti-biofouling measure is to recover, manually clean with wipers, brushes, solvents, or other cleaning agents, and then re-deploy. However, from the perspective of ocean observations and cost/time related to sensor deployment and recovery, other anti-biofouling measures are often used. In order to prevent biofouling, a number of strategies are often employed including: biocides, low friction coatings, and physical cleaning.

Biocides are chemicals that are toxic to mostly all organisms, but often the amount and type used is designed to prevent microorganism growth on sensor surfaces that are necessary to be clean and clear for adequate operation. Biocides that are commonly used for ocean sensors include metals copper and tin in the form of mesh, nubs, and/or coatings (e.g., Manov et al., 2004). Copper can in some cases precipitate on optical windows and affect performance of sensors (Fig. 4). Tin, in the form of bis(tributyltin) oxide, is used for some sensor systems, but tin is presently banned in the EU according to the Rotterdam Convention for marine antifouling (UNEP/FAO/RC/CRC.11/3/Rev.1, 2015). Low friction coatings can be used to reduce the adhesion of marine biofouling, including clear polymers for optical windows, and


Figure 4. Example of copper precipitations from Cu on optical window. The sensor was enveloped by a copper net to avoid biofouling on the optical window. It turned out that the optical window was blinded by the Cu precipitations.

the ClearSignal coating (Severn Marine Technologies, LLC) for acoustic transducers. Wipers including rubber blades or brushes, and at times in combination with copper, are also used to mechanically wipe clean optical windows. These systems can be effective and at times the only solution in productive systems where biofouling is expected to be high. Here it should also be mentioned that UV irradiation can be used to prevent biofouling, but UV sources tend to have high power requirements and are therefore not often used in marine sensor settings.

A technique that can be used to produce a biocide in seawater as close as possible to the transducing interface is electrolysis of seawater. Hypochloric acid is produced at the working electrode that surrounds the transducing area of the sensor. Figure 5 shows such a protection scheme on an *in situ* turbidimeter after an 80-day deployment (Delauney et al., 2015). This technique can be used on sensors without modifying its design and can be used on existing instruments. This technique does require power, so there could be challenges for long-term deployment and when power supply is limited (e.g., on a deep sea un-cabled observatory). In the specific case of optical sensors (based on a "transparent" optical window), cameras, or lights, the electrode, where the biocide generation takes place in case of seawater electrolysis, can be a conductive and transparent coating based on tin dioxide and sprayed directly on the optical windows of the device.

For instruments that pump seawater through flow cells or other fluidic circuits, the use of a prefilter and/or periodically pumping freshwater or cleaning solutions like H_2O_2, dilute acid, or other cleaning agents/detergents through the tubing/sensing compartments can also be used. When possible, especially for some types of cleaning agents, a recirculation or other system to capture and recover the waste is preferable compared to discharge to the environment.

With regards to sensors that spend the majority of time at depth (below the euphotic zone) on deep Argo floats or diving animal borne platforms, for example, biofouling has not been identified as a major issue. Biofouling phenomena are very rarely observed, if at all, on the sensors mounted on Argo floats. The floats are at the surface for limited timeframes for the transmission of data to satellites which limits the opportunity for biofouling to form. For animal borne sensors, in addition to not spending much time in the euphotic zone, their swimming speed appears to prevent organisms from settling and growing.

Recommendations: Instruments developed in NAUTILOS and in future ocean observing initiatives must either be designed to not be affected by biofouling or incorporate anti-biofouling measures that are environmentally-sound and with consideration of EU regulations regarding the use of toxic elements and chemicals. In many cases, wipers are effective at keeping sensor surfaces clean, but only for sensors that have relative flat sensing surfaces. For other sensor types/contacts, biocides or other coatings could be required to sufficiently keep sensors clean in between regular service intervals. The development of instruments in NAUTILOS should, where possible, also include some degree of evaluation of how biofouling affects instrument performance and the precision/trueness of the variable that is measured.

3. POWER REQUIREMENTS AND COMMUNICATION PROTOCOLS

Most instruments will require power to operate, and power is typically provided from an internal battery (as part of the instrument system), an external battery, or the platform that the instrument is coupled to. Input voltages for sensors provided via battery packs can be flexible (e.g., 9 to 35 VDC; volts direct current) or standard (e.g., 5, 9, 10.8, 12, 24 VDC), while some platforms such as cabled observatories or FerryBoxes tend to supply power at standard 220 VAC (volts alternating current) and therefore require conversion to DC power (to be covered in detail in Deliverable 2.3). Due to the variability in power supply from different platforms, and since some power drops occur with long power cables, the most versatile sensor power requirements would be a variable power input such as 9-48 VDC or provide their own power supply that can take into account variable power input. However, the flexibility of sensor input voltages means that voltage regulators must be incorporated on the sensor side, and this makes the hardware layer more complex and restrictive in terms of sensor miniaturization. Platform-specific power delivery will be expanded upon in Deliverable 2.3, and sensor design must take this into account. Power cable and connection options are discussed in section II.4 of this deliverable.

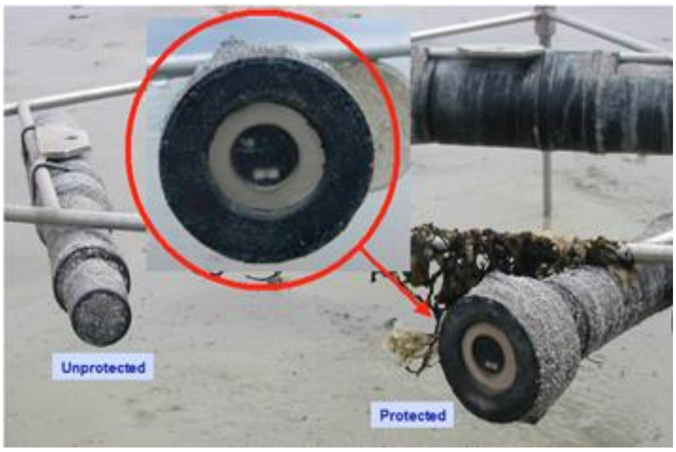

Figure 5. Biofouling protection by seawater electrolysis on turbidimeter Mont St Michel Bay – March to May – 80 days. On the left side, the unprotected turbidimeter shows significant coverage of barnacles after deployment. The protected turbidimeter, that uses a flat washer as a working electrode shows a clean transducing interface after the same deployment. Photo: Ifremer - L. Delauney.

Power management systems in more complex sensors are necessary to allow for smart sensing capability and rapid availability. Rather than apply power and trigger a complete reboot, instruments can be provided with a continuous power supply that maintains a very low power 'sleep' state. An external trigger is then used to initiate sampling with very low latency. Triggers are typically simple electrical signals. They can be provided by a host platform as part of a master data acquisition programme. They can be provided from other sensors that emit a trigger when they start or stop acquiring data to allow for synchronisation or interleaving of data acquisition (to avoid cross-instrument interference). They can also be provided by sensors that have reached a pre-programmed threshold signifying an event of interest. Permanent power also allows autonomous sensors to schedule a pre-programmed or adaptive burst sampling regime.

Instrument systems also require communication protocols to receive commands for setup and configuration, or auxiliary data from platforms/sensors or other connected peripherals. While some sensors are equipped with internal loggers for storing all their data and metadata locally (including the critical metadata of time of measurement), some sensors are linked to external logger units or other connected peripherals (e.g., PC or Raspberry Pi). A link between sensors and loggers/control units would also allow for data backups and avoid losing acquired data with the internal logger in the case of technical failure (e.g., flooded sensor chamber). Sensors should be designed, when possible, for real-time or near real-time data provision, with an exception for devices generating very large amounts of data. Real-time availability of data from sensors can be crucial for observing and monitoring the evolution of in situ events and to detect and quickly fix technical issues. The availability of real-time data will be important for some sensor and sensor/sampler systems that will be demonstrated in NAUTILOS together with event detection/AI data analysis and “smart” sampling.

The most commonly used communication protocols include serial RS-232/422/485, USB, UDP and TCP. In general, USB should be avoided as a subsea control interface as it is generally less stable, although it is one of the most power- and time-efficient ways to transfer instrument data once it has been retrieved. TCP is more reliable than UDP in the sense that successful package transfer is checked on both ends. However, TCP requires additional implementation for handling situations where packages are not completely transferred. This can be a problem if sensors dedicated for gathering data should suddenly use resources for solving communication issues. Therefore, serial and UDP are probably the best choices.

For underwater instrument deployment, the two alternative methods for communications are acoustic telemetry and inductive modem technology as described in the FixO3 Handbook of Best Practices (FixO3, 2017):

“Acoustic telemetry is a substitute for direct cables. However, acoustic methods pending of the platform/sensor specifications can result in an even more costly and complex system; additional battery packs are required, depth is restricted due to limited transmission range, and they are subject to a multitude of error sources and failure modes.

Inductive modem technology provides a convenient, economical, and reliable solution while still maintaining flexibility (ref. Seabird application note n.92) The Inductive Modem (IM) System (or 'Inductively Coupled Modem') employs the mooring cable as its transmission medium, eliminating the need for additional conductors. An Inductive Modem Module (IMM) transmits sensor data to the surface by applying a signal to the internal winding of a cable coupler. This system induces a signal in the single-turn secondary winding formed by the mooring cable passing through the coupler. The signal is retrieved at the surface by a similar configuration. Each coupler is made up of two halves, allowing it to simply clamp around the cable as opposed to having to thread the cable through the unit."

Regarding format protocols, the American Standard Code for Information Interchange (ASCII; IANA, 2021) format in the form of either CSV data or NMEA 0183 like sentences are very common and easy to implement. They also have the advantage of being very easy to use for testing and checking the configuration of sensors, and can be accessed and read by many different types of programs including common text editors, Microsoft Excel, and scientific programming languages such as Matlab, R, Python, etc. Other protocols such as ModBus are very reliable and robust but require more knowledge about the protocol itself and data cannot be visualized without special software. Moreover, sensors generating a larger amount of data may have to choose a binary format in order to reduce the communication load. In these cases, a dedicated software tool to visualize the transferred data and communicate with the sensor should be provided in addition to documentation explaining the data format. Several sensor manufacturers use specialized or otherwise proprietary data formatting/output - this is acceptable as long as there is software available to convert proprietary data to ASCII format. Any data output that would effectively "lock" data availability would be counterproductive to the aim of "democratizing" ocean observation supported by NAUTILOS and other European and global ocean observing initiatives.

Recommendations: Power supply to instruments can vary depending on the source of power. Ideally, instruments should be designed to accept variable power input (9-48 VDC), but standard power requirements are also acceptable especially in the case of specialized or miniaturized instruments. Great care should be paid to the sensor energy consumption necessary for the data acquisition but also the on-board processing of the collected data in relation to the absolute sensor precision in a way to identify the best possible compromise. The developed instruments should integrate a community-friendly communication protocol which allows to control the sensor parameters, its acquisition frequency among others, and also to preferably send its data in real-time, or at the very minimum requirement, to download the data from its internal memory. However, in both cases it is of eminent importance that the measurements are stored with a timestamp that represents most adequately the time of the measurement (which can be different from the time when the data arrives at the main computing unit of the platform). With this in mind, it is recommended that ASCII data format should be used whenever possible, and if another format is used because of technical limitations, software should be provided to convert the data to ASCII format.

4. CABLE TYPES/CONNECTORS

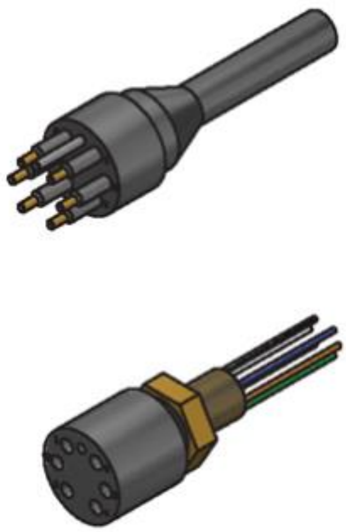

Figure 6. An example of a 6-pin (male and female) SubConn circular 31 mm diameter wet-mateable connector (www.mcartney.com).

The connection of power to/from external batteries or platform-supplied power (described in section II.2), and the transfer of data to/from data loggers or control units (described in section II.3) require a physical or wireless connection. At this time, physical cabled connections are the most commonly used connections for these types of connections. For underwater applications, SubConn- or Seacon-type wet-mateable 31 mm connectors are considered the industry standard (Fig. 6). The connectors are rubber molded with male pin connectors, which are connected and sealed with female pins using electrically conductive grease. These types of connections are typically rated to depths of 8000 m, rated for voltages up to 600 VAC/VDC, with a maximum amperage of 10 A per pin with a maximum of 50 A per connector. The connection is temperature rated to -4 to 60 deg C (water) and -40 to 60 deg C (air). The SubConn circular 31 mm diameter connector can be configured with 6, 8, or 10 pins. These types of wet-mateable connectors also use dummy plugs to allow for deploying sensors without cables attached, and only attach cables when charging or transferring data. There are also other circular and square connectors available on the market (such as the SubConn micro circular 15.5 mm diameter or micro low-profile 25.5 mm rectangular connector) which are smaller and are preferred for smaller instruments and when miniaturization is a priority in instrument design. Above water sensor systems for oceanographic deployment on ships or buoys, for example, also tend to use the same type of wet-mateable connectors described above since these installations require moisture- and water-proof connections due to foul weather and sea spray. But the use of M12 type connectors is suitable for relatively low-moisture environments. M12 connectors are circular connector with a 12-mm locking thread and are available with 3, 4, 5, 8, and 12 pins. For FerryBoxes and stationary platforms, an artificial intelligence-based computing module will be used as a peripheral device that processes data and provides triggering signals for certain instruments. For these devises a high bandwidth connection is required and a wired ethernet connection with RJ-45 connectors is preferred here.

Recent advancements in wireless technology have enabled some sensors to be wirelessly inductively charged and to wirelessly transfer data via IEEE 802.11 or Bluetooth (formerly IEEE 802.15.1) network protocols (e.g., Xu et al., 2014). Wireless charging is typically only useful for sensors that are deployed with internal batteries or battery packs that otherwise would require charging via cabled connections, and could reduce issues related to opening and closing sensors to replace batteries - such as stripping bolts, damaging O-rings, water ingress, etc. Wireless logging could be useful for a wide range of sensors and can make data transfer both easier and can reduce strain on connection points that are sturdy, but not indestructible. For example, SubConn connectors have a wet mating rating upwards of 800 times but can and will eventually fail upon overuse. Another clear advantage for wireless charging and technology is the case of citizen science, where sensors need to be more robust, easy to maintain, and user-friendly. For citizen science it is also preferable for data to be transferred from a sensor to a smartphone with WiFi and Bluetooth capabilities. While there are some advantages, wireless charging and data transfer are limited by the construction material of the sensor, and this often can restrict the pressure rating of the housing. For example, power loss can occur with metals like aluminium and stainless steel, and wireless charging will result in heating of the housing and ineffective charging rates.

Recommendations: Oceanographic instruments are typically equipped with SubConn- or Seacon-type wet-mateable rubber molded connectors and cables, which are the industry standard in terms of keeping electrical connections dry and secure in subsea applications. The 31 mm diameter circular and 15.5 mm diameter micro circular connectors are the most commonly used, and these types of connection systems must be used to avoid sacrificing the durability and dependability of the instrument system. Smaller and different shaped connectors of a similar wet-mateable configuration are also available for sensor systems that require smaller dimensions for miniaturization. Above water sensor systems are also recommended to use similar types of wet-mateable connectors due to the proximity to seawater and weather.

5. Cost and scalability

An important objective of NAUTILOS is to develop instruments that can be scaled up in support of future widespread ocean observing initiatives that we require for understanding and managing the impacts of climate change and other anthropogenic impacts on the oceans. Therefore, the cost and scalability of sensor production must be accounted for so that ocean observations can be expanded in a reasonable and achievable manner. In terms of cost, the aim here is to minimize production costs while still maintaining the precision and accuracy required of the variable(s) measured by a specific sensor system. In terms of scalability, the aim here is to select designs/components that allow for efficiency of manufacturing to allow for more units to be made in a shorter amount of time and lower cost, and also ease of use, maintenance, and repair (to allow for sensor systems to stay in operation for a longer period of time). The issues of cost and scalability are interlinked, and they will be discussed in the paragraphs below.

For facilitating deployment and usability of data from oceanographic instruments, the ideal situation would be a low cost sensor with high precision and trueness. However, higher precision and trueness, especially under harsh conditions of long-term deployment in the ocean or in high-pressure deep sea environments will also mean higher costs. This is both from the standpoint of the costs related to the detection technology of a sensor and their regular data quality control (metrology) as well as the costs related to the construction materials (as described in section II.1). Without large advances in material science, the costs related to construction material and machining are likely limited to what is covered in section II.1 - the most economical construction materials/techniques can be chosen to meet the requirements of pressure rating and durability for any given application. But when it comes to detection technology of a sensor, because the relationship between costs and precision/trueness are typically positively correlated, the requirements of precision/trueness of the sensor application will be the main determining factor for cost. For example, precision/trueness is very important for most research and monitoring applications where instruments are used to observe relatively small changes over time. Here, high costs are justified to support high precision/trueness of measurements in these types of activities. However, the case could be made that for observing strategies that involve a network of sensor measurements (e.g., 100's of sensors deployed for high density observations, or a widespread citizen science observing initiative; e.g., Ripoll et al., 2019), a larger number of lower cost sensors with lower precision/trueness requirements could be acceptable, especially if there are several concurrent "reference" measurements being made. This is only the case when trying to improve the trueness of the average, and not the trueness of individual measurements. Similarly, in a budget-limited observing effort, a cost-benefit analysis needs to be made in order to decide on whether a lower cost sensor system that sacrifices precision/trueness is more beneficial when compared to fewer observations.

It is clearly important that observing efforts should not compromise on precision/trueness of sensor systems, and to a certain degree the costs of high precision/trueness systems could be reduced by increasing the number of units manufactured and used by the observing community - the so-called economies of scale, when production efficiency is achieved through increased production and lower cost per unit. The economies of scale, related to ocean sensor systems, is therefore also dependent on the ocean observing community adopting certain sensor technologies for widespread use. This is usually, but not always, related to several factors that include: high precision/trueness of the measurement (as described above), reliability, ease of use, and maintenance/repairability. This means that sensor systems need to be affordable (or at least the cost-benefit needs to be justifiable), they need to be durable in terms of the electronics, software, hardware, and construction material, they need to be easily deployed and operated, and they need to be easily maintained/repaired and metrologically controlled for reasonable expected lifetimes. Generally speaking, the recommendations in the sections above should lend to the various user-related requirements mentioned here. Due to the open market for oceanographic sensors, sensor manufacturers must design and manufacture sensors that are durable, easy to use and maintain, and metrologically sound in order to stay competitive and in business.

This implies that scalability of sensor production and widespread ocean observing is dependent on good communication and interaction between the sensor manufacturing community and the ocean observing community. The needs and requirements of the ocean observing community need to be made clear for sensor manufacturers, and the limitations of technological advancement and production costs also need to be made clear from sensor manufacturers to the ocean observing community. An external factor that is outside the scope of this deliverable is the available funding from national and international funding agencies to support and stimulate sensor development, production, and acquisition for ocean observing efforts.

Recommendations: Cost and scalability of instrument production are important factors that can influence how future ocean observing efforts can be improved. These factors are linked to limiting costs to the required degree of construction and precision/trueness for certain applications, as well as reducing costs through economies of scale. This means that instruments should be designed and produced with improved standardization and interoperability, and therefore more widespread usability with a variety of ocean observing platforms (as opposed to instruments that only fit specialized niches within ocean observing).

6. METROLOGICAL CONSIDERATIONS

For any measurement device, the metrological characterization is key in order to have confidence in the obtained measurement result. To this extent, it should be clear to specify for each instrument type:

- the quantity to be measured (also called the measurand in the sense of the VIM (BIPM et al., 2012),
- the measurement technology,
- the measurement range,
- the expected measurement quality (expressed if possible as an uncertainty, but any other partial information – trueness, precision, accuracy, tolerance, … - can be valuable).

In order to be able to interpret the measurement data, an analysis of the measurement processes will be made for each instrument type. Such an analysis will allow for identification of the errors that may impact the measurement result. Two kinds of errors are typically considered:

- The systematic errors are errors that remain constant or vary in a predictable manner in replicate measurements.
- The random errors are, in the opposite, the errors that vary in an unpredictable manner.

While the random errors can be reduced using an increasing number of replicate measurements and getting their average, the systematic ones cannot. As a result, a large network of sensors may be useful for the minimization of such random errors, provided that they operate in an area where the ambient conditions (salinity, temperature, ...) are presumed to be constant and that the associated collected data is the mean of these sensors data. Such a large network might or might not have an impact on the reduction of systematic errors depending on the way measurements are post-processed and collected; it does, however, imply a deeper analysis of these measurements. Traceability and the definition of calibration protocols should be used for characterization and quantification of these systematic errors.

7. Special considerations for some platforms and instrument types

Within NAUTILOS and the ocean observing community, there are several platforms and instrument systems which may not be able to meet the requirements set forth in the sections above, or have requirements that are uniquely specific. This is in part due to platform-specific differences such as power supply or form factor, and also due to specific requirements for collecting or detecting certain variables included in NAUTILOS such as particle samplers or acoustic sensors.

Related to platforms (which will be covered in depth in Deliverable 2.3), Argo/AUVs, UAVs, and animal-mounted sensor systems all generally have requirements for sensors to be relatively lower in power consumption since power supply (battery) is generally limited due to payload limitations. And for the same payload limitation rationale, the size and weight of instrument systems must also be reduced for Argo/AUV's. This contrasts with fixed platforms and ships of opportunity that are generally not power or payload-limited. Fixed platforms can be equipped with solar panels and are always at the surface for generating solar-based energy, or ships of opportunity that have virtually unlimited power supply from shipboard generators. Power supply is especially relevant for NAUTILOS instrument systems such as the phytoplankton/suspended matter sampler, microplastics sampler, and microplastics sensor (NAUTILOS Tasks 3.5, 4.3, and 4.4) that will rely on filtering large volumes of water to adequately sample the water column. This translates to a requirement of a pump to push water across filters/sieves and therefore relatively large power requirements.

Power and payload limitation are also important for instrument systems used in conjunction with UAVs where weight in air can drastically limit sensor systems that can be mounted. For UAVs, most sensor systems are designed to be fully integrated with GNSS, IMU, logger, etc., with the only external requirement being a battery pack. This means these types of sensor systems operate independently of the UAV platform, and only weight and attachment to the platform need to be considered.

In addition, a standardized communication port is important for some instruments considering event-based triggering of activities is of high relevance for some platforms and instruments. For example, several instruments will be designed to accept commands from an artificial intelligence algorithm and change sampling frequency or trigger additional sampling in regions of interest. The artificial intelligence algorithms must run on either a separate device connected via Ethernet to such instruments or platforms and will require a reliable 230 V power supply, or this can be installed on the central computing unit of an instrument/platform if it can provide high performance computing capabilities.

In terms of data format protocols, some sensors will not be able to meet requirements of simple ASCII format for ease of use and accessibility. NAUTILOS acoustic sensors (Tasks 3.3 and 3.4), for example, generate large amounts of data that are stored using custom binary data formats that are designed to minimise data storage demands. In these cases, as described in section II.3, software is provided to extract significant information into commonly used data standards (e.g., ASCII) for use with conventional data processing packages. For example, the sound recorder processing software (Task 3.3) can output data in WAV format, which is a common sound file format, while the acoustic profiler processing software (Task 3.4) can output data in both ASCII format and the compressed Matlab data format.

III. Summary

The NAUTILOS project will develop 13 sensors and samplers in WP3 and WP4 of the project. This deliverable outlines requirements and suggests specifications and guidelines under which these 13 instruments should be designed and developed under for use on various ocean observing platforms. The instruments and platforms will ultimately be operated together in WP7 demonstration activities in a variety of European seas. The objective of this deliverable is to form a basis of common design and operating specifications to ensure that the instruments developed through the NAUTILOS project will be compatible with a variety of ocean observing platforms to support future prospects of scaling up European and global ocean observing efforts. The guidelines are provided for five categories related to instrument design and interoperability. The recommendations described above are summarized as follows:

- Cylindrical form factor, fit-for-purpose material selection, standard O-ring size, standard screw drive type for hardware with a preference for Allen/hex.
- Some degree of anti-biofouling measures should be used, but techniques are varied and can be different depending on instrument type. EU regulations related to toxic substances must be adhered to.
- Variable power input for instruments is preferred, but standard power input is permissible for specialized or miniature instruments. Data format should be in ASCII or easily converted to ASCII.
- Wet-mateable rubber molded connectors (circular; 31 and 15.5 diameter) and cables are industry standard and should be used. Unfortunately, there are no “open-source” connectors that are presently recommend for use.
- Adhering to the common design and operating recommendations above will result in instruments that will be relatively modular and adaptable for widespread use. This will take advantage of the economies of scale and result in lower manufacturing cost per unit.
- Instruments designed for some platform types such as Argo floats, AUVs, animals, and UAVs may have specialized requirements related to power supply and payload capabilities, and the need for miniaturization.

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