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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 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.nautilus-project.eu>.

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● EXECUTIVE SUMMARY

The observation of the oceans involves the deployment of a wide range of sampling platforms and the use of different sensing technologies that are able to collect an increasing stream of data. The complexity of this information and the need of merging complex datasets into global ingestion portals to join research efforts, call for the standardisation of these data.

A condition for the integration of datasets deriving from different sampling campaigns is interoperability of data and metadata. Interoperability is essential for enabling data to be reused, preserved, and integrated. A building block for a distributed system in which component systems can exchange and understand information is standardisation of data formats, distribution protocols, and metadata.

The present document outlines the standards and best practices on data formats, metadata and data services to be adopted during the NAUTILOS project implementation to ensure interoperability and harmonisation of the new observations generated with the already available data.

The NetCDF (Climate and Forecast Convention - CF) data format is going to be adopted together with the standards recommended by the specific platform networks (e.g. Argo Data Management Team). The ISO standards and SeaDataNet common vocabularies and directories are being implemented for metadata interoperability. The definition of vocabularies and best practices will be needed for specific parameters investigated by the NAUTILOS project.

ERDDAP and GeoServer are the core interoperability technology solutions implemented for ensuring data accessibility. More specifically ERDDAP is a data server that gives a simple, consistent way to download subsets of scientific datasets in common file formats and make graphs and maps, GeoServer publishes data from any major spatial data source using open standards. GeoServer implements several Open Geospatial Consortium protocols including Web Map Service (WMS), Web Feature Service (WFS), Web Coverage Service (WCS) and Web Map Tile Service (WMTS). Additional extensions are available for Catalogue Service (CSW) and Web Processing Service (WPS).

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- LIST OF ACRONYMS AND ABBREVIATIONS

Abbreviation	Definition
BODC	British Oceanographic Data Centre
CDI	Common Data Index
CF convention	Climate and Forecast convention
CMEMS	Copernicus Marine Environment Monitoring System
DAC	Data Archive Centre
DMP	Data management policy
EDMO	European Directory of Marine Organisations
EMODnet	European Marine Observation and Data Network
EOV	Essential Ocean Variable
FAIR	Findable, accessible, interoperable, re-usable
GOOS	Global Ocean Observing System
GTS	Global Telecommunication System
ICES	International Council for the Exploration of the Sea
INSPIRE	Infrastructure for Spatial Information in Europe
JERICO	Joint European Research Infrastructure of Coastal Observatories
MEDIN	Marine Environmental Data and Information Network
MSFD	Marine Strategy Framework Directive
NetCDF	Network Common Data Form
ODV	Ocean Data View
OGC	Open Geospatial Consortium
QC	Quality control
SOOS	Southern Ocean Observing System
TAC	Thematic Assembly Centre

1. INTRODUCTION

The goal of NAUTILOS is to fill in existing marine observation and modelling gaps through the development of a new generation of cost-effective sensors and samplers for physical (salinity, temperature), chemical (inorganic carbon, nutrients, oxygen), and biological (phytoplankton, zooplankton, marine macrofauna) essential ocean variables, in addition to micro- and nano-plastics, to improve our understanding of environmental change and anthropogenic impacts.

A specific technical objective of the NAUTILOS project is to appropriately collate, process, and archive all primary environmental data generated during the project to ensure that they are Findable, Accessible, Interoperable, and Reusable (FAIR). The achievement of this objective requires the development of an end-to-end information system and infrastructure for both data management (internal to the project) and data transfer towards well-established repository services and tools (e.g. National Oceanographic Data Centres and thematic and international data assembly repositories, EMODnet, SeaDataNet, Copernicus Marine Environmental Monitoring Services). It also requires the preparation of data and metadata following commonly agreed standards and FAIR principles, the establishment of mechanisms for integration and interoperability of heterogeneous data and production of open-access data and the processing of environmental data appended with the necessary sensor specification, validation, calibration data, and field operation details to, enable stand-alone data reuse.

The present document outlines the standards and best practices on data format and metadata adopted during the project implementation to ensure interoperability and harmonisation of the new observations generated with the already available data, disseminated through a range of portals and initiatives (e.g., EMODnet, CMEMS).

2. INTEROPERABILITY

Expansions in the scope and scale of ocean observations, as well as automated sampling and ‘smart sensors’, are leading to a continuously increasing stream of data. Ocean data are diverse in type, coverage, and extent. They include multi-variate observational data from near-real time in situ and remote sensing platforms, data from research cruises, and data from numerical models. This provides opportunities to transform the way we study and understand the ocean through more complex and interdisciplinary analyses, and offers novel approaches for the management of marine resources.

The data management of ocean observing systems is complex and scattered, and hence requires massive coordination effort. In this fragmented landscape, interoperability is essential to enable data to be used, reused, preserved, integrated, building a federated system in which components can be exchanged. To achieve this, standardisation of formats, distribution protocols and metadata is necessary.

Novel data management approaches have to start from enhancing data handling through more widespread adoption of community data standards and well-designed data management plans based on Findable, Accessible, Interoperable and Reusable (FAIR) principles so that data is machine-readable.

The ability to integrate across such a management landscape, in support of ocean research, depends critically on the widespread adoption of data interoperability standards. Interoperability can be defined as the “degree to which two or more systems, products or components can exchange information and use the information that has been exchanged” (ISO/IEC/IEEE, 2017). It is the ability by which coupled systems can communicate and exchange data via common formats and protocols and also meaningfully interpret and reproducibly act on exchanged data.

Although interoperability is not a characteristic of a single data file or dataset, enhancing interoperability means improving data sharing between scientists, industry and governments. Each of these players are interested, for instance, in obtaining data for scientific research, for assimilation into a numerical model, or to create a web-based visualisation tool. According to each specific use, it may be necessary to provide all the available data and extensive metadata to ensure that users understand as much as possible about how the data were generated, and make data accessible or downloadable by means of different data delivery channels (e.g. FTP, webAPI, etc.).

The data generated within the NAUTILOS project are meant to be highly complementary to the existing observing systems, and therefore all data and metadata need to be standardised and harmonised to meet the interoperability standards. The following sections describe the NAUTILOS strategies, plans and progress to implement interoperability.

Findable, Accessible, Interoperable, and Reusable (FAIR) data concept is key for adhering to interoperability standards.

Findable: Each dataset should be identified by a unique persistent identifier and described by rich, standardised metadata that clearly include the persistent identifier. The metadata record should be indexed in a catalogue and carried with the data.

Accessible: The dataset and its metadata record should be retrievable by using the persistent identifier and a standardised communications protocol. In turn, that protocol should allow for authentication and authorisation, where necessary. All metadata records should remain accessible even when the datasets they describe are not easily accessible.

Interoperable: Both metadata and datasets use formal, accessible, shared, and broadly applicable vocabularies and/or ontologies to describe themselves. They should also use vocabularies that follow FAIR principles and provide qualified references to other relevant metadata and data. Importantly, the data and metadata should be machine accessible.

Reusable: To meet this principle, data must already be findable, accessible, and interoperable. Additionally, the data and metadata should be sufficiently richly described that it can be readily integrated with other data sources. Published data objects should contain enough information on their provenance to enable them to be properly cited and should meet domain-relevant community standards.

● 2.1 COMMON ELEMENTS FOR INTEROPERABILITY

There are three main elements for implementing the interoperability, namely data format, metadata and data service.

○ 2.1.1. Data formats

NAUTILOS will deploy a set of sensors and samplers to measure a series of environmental variables and descriptors essential to understand the state of the ocean, its dynamics and properties, to quantify the forcing of the atmosphere-ocean boundary and to understand the role the oceans play in Earth's climate. These variables consists of 14 biogeochemical, biological and ecosystem essential ocean variables (EOVs), i.e. inorganic carbon, stable carbon isotopes, dissolved oxygen, inorganic macronutrients, suspended particulate matter, ocean colour, ocean sound, phytoplankton biomass and diversity, zooplankton biomass and diversity, turtles, marine birds, marine mammals abundance and distribution, live coral, seagrass cover, microbial biomass and diversity and invertebrate abundance and distribution, two deep ocean observing system (DOOS) specific EOVs, i.e. litter including micro-plastics, seafloor sponge habitat cover and eight MSFD descriptors (Table 2).

Therefore, NAUTILOS will collect, validate and process a huge amount of heterogeneous data that need dedicated tools and services to favour integration and interoperability. While data flows and standards exist for some platforms, such as animal-borne instruments and Argo floats, dedicated data management structures are being developed for new sensors (e.g. fluorescence imaging sensors and acidification sensors, Table 2).

Table 1 Data management organisation and standards references for NAUTILOS platforms

Platform	Data Management	Standard reference
Lander	<ul style="list-style-type: none"> • OceanSITES • EuroGOOS Fixed Platforms Task Team 	http://www.oceansites.org/docs/oceansites_data_format_reference_manual.pdf
Argo float	Argo Data Management Team	http://www.argodatamgt.org/Documentation
Animal-borne instruments	Argo Data Management Team	http://www.argodatamgt.org/Documentation
Ferry boxes, ships of opportunity, fishing vessels	EuroGOOS FerryBox Task Team https://www.ferrybox.org/	https://www.ferrybox.org/imperia/md/content/ferryboxusergroup/ferrybox_d-3-3-b_data_management_guidelines_r_2-0.pdf

Table 2 Data management organisation and standards references for NAUTILOS EOVs and their respective sensors

Sensor(s)	EOV	Data Management	Standard reference
Deep-ocean CTD	<ul style="list-style-type: none"> • Salinity • Temperature 	<ul style="list-style-type: none"> • OceanSITES • EuroGOOS Fixed Platforms Task Team 	http://www.oceansites.org/docs/oceansites_data_format_reference_manual.pdf
Silicate electrochemical sensors	Silicate (Inorganic macronutrients)		EMODnet Chemistry eutrophication
Phytoplankton and suspended matter sampler	<ul style="list-style-type: none"> • Phytoplankton biomass and diversity • Stable 		https://obis.org/manual/

	<p>carbon isotopes</p> <ul style="list-style-type: none"> • Suspended matter 		
Dissolved oxygen and fluorescence sensor	<ul style="list-style-type: none"> • Dissolved oxygen • Ocean colour • Phytoplankton biomass and diversity 	Argo Data Management Team	http://www.argodatamgt.org/Documentation
Surface multi-hyperspectral and laser-induced fluorescence imaging sensors	<ul style="list-style-type: none"> • Ocean colour • Phytoplankton biomass and diversity • Sea surface temperature 	To be defined	To be defined
Ocean acidification sensors	inorganic carbon	To be defined	To be defined
Submersible nano- and microplastics sampler	Litter, including nano- and microplastics	MSFD Technical Group on Marine Litter & EMODnet Chemistry	https://www.emodnet-chemistry.eu/repository/Proposal-EMODnet-TG-ML-Micro-Litter-Data-Gathering-03062020.pdf
Low-cost microplastic sensors			
Passive broadband acoustic recorder	<ul style="list-style-type: none"> • Ocean sound • Turtles, birds, mammals 	EC Task Group Noise	https://publications.jrc.ec.europa.eu/repository/handle/JRC88045
Passive acoustic event			

recorder	<p>abundance and distribution</p> <ul style="list-style-type: none"> • Sea ice 	<p>Marine Biodiversity Observation Network (MBON) and Ocean Biogeographic Information System (OBIS)</p>	<p>https://obis.org/manual/</p>
Active acoustic profiling sensor	<ul style="list-style-type: none"> • Litter and microplastics • Zooplankton biomass and diversity 	<p>MSFD Technical Group on Marine Litter</p>	<p>https://www.emodnet-chemistry.eu/doi/documents/Guidelines-Litter_Data_EMODnetChemistry3_rev_27072020.pdf</p>
Crowd-sourcing for visual marine image annotations	<ul style="list-style-type: none"> • Microbe biomass and diversity • Invertebrate abundance and distribution 	<p>Marine Biodiversity Observation Network (MBON) and Ocean Biogeographic Information System (OBIS)</p>	<p>https://obis.org/manual/</p>
Habitat mapping of key seabed habitats	<ul style="list-style-type: none"> • Live coral/hard coral cover and composition • Seagrass cover and composition • Sponge habitat cover 	<p>Marine Biodiversity Observation Network (MBON) and Ocean Biogeographic Information System (OBIS)</p>	<p>https://obis.org/manual/</p>

Transport format is one of the key elements for implementing data interoperability and having a common transport format is still an open issue. Some platform networks/operators agreed on common models. The most common transport format is NetCDF (Climate and Forecast Convention - CF) and the European marine data infrastructures apply the file models that are used to distribute OceanSITES data with some extensions to provide the user with more information, as defined the EuroGOOS DATAMEQ working group and the SeaDataNet technical working team. These extensions include common metadata on controlled vocabularies and data quality flags. Other data formats are txt, csv, odv4, (lately JSON and GeoJSON). In order to facilitate the ingestion/link process, it is recommended to use the CF convention (current version is CF-1.6) NetCDF format version 4.

In the NAUTILOS project, we adopt these data formats, namely NetCDF and txt/csv, and recommend to include as many descriptive attributes as possible. More specifically, given the different nature of the measuring systems, it is recommended to adopt the specific platform network recommendation on what attributes to use.

o 2.1.2. Metadata

'Metadata' refers to vital information about the data collection. Metadata describe a broad range of information that allows observations to be understood and evolved into knowledge. They provide a context for research findings, ideally in a machine-readable format, and are used by users to understand if data match their expectations. Metadata require the use of standardised sets of terms to solve ambiguities problems.

The collection and management of marine data and metadata is a complex step-wise process that includes the identification of the observing requirements, the configuration of the sensors, their deployment at sea and collection of the observations that are regularly transmitted to a shore receiving station. The receiving station reformats the data messages, possibly applying some automated quality control, and then distributes the data over one of the several communication pathways like the Global Telecommunication System (GTS). Data producers (*i.e.* NAUTILOS partners) collect these data and develop added value reanalysis products. Each step produces information associated with the given observation, hence generating a huge volume of metadata information.

In order to implement the interoperability, NAUTILOS metadata have to be primarily designed to provide users with pieces of information identifying a collection of files as a thematic and coherent dataset, to support discovery of that collection using keywords, spatial, and temporal searches, to give information of and links to the processing history of the observations (source, version, quality assessment and control) and provide links to document sensors and platform characteristics associated with the observation.

As we refer to the ISO standards for cataloguing the information, the key references are:

- ISO 8601 Representation of date and time
- ISO 19108 Temporal characteristics of geographic information
- ISO 19113 revised by 19157 standards for geographic information
- ISO 19115 Geographic information metadata
- ISO 19119 Taxonomy of services
- ISO 19139 Geographical information metadata implementation specification.

ISO 19113 defines quality principles, which are applied in ISO 19115 (geographic metadata). The metadata records in the current GEOSS use the ISO 19115 data model and its companion XML encoding (ISO 19139). ISO 19115 Standard requires a basic minimum number of metadata elements that are essential for the data presentation:

- Dataset or dataset series on specific challenges ('what'),
- Geographic bounding box ('where'),
- Temporal extent ('when'),
- Contact point to learn more about or order the dataset ('who').

Obviously, additional elements increase interoperability and usability.

The adoption of ISO standards and the use of shared controlled vocabularies are a key prerequisite towards consistency and interoperability.

Controlled vocabularies consist of lists of standardised terms that cover a broad spectrum of disciplines of relevance to the oceanographic and wider community. A key outcome of the past ICES/IOC Study Group on the Development of Marine Data Exchange Systems was the establishment of a combined SeaDataNet and MarineXML Vocabulary Content Governance Group (SeaVoX). This set of common standards for the marine domain is updated and maintained by SeaDataNet partners.

NAUTILOS is adopting many of the SeaDataNet common vocabularies and directories, and integrates additional metadata elements which are of particular use for the marine data community to have marine data findable, accessible, interoperable, and reusable.

Examples are the use of CF conventions for parameters (*i.e.* parameters standard name) that are mapped versus the NVS P01-P02. These metadata are defined as a global attribute in the transport file format.

The global attribute section of a netCDF file describes the overall contents of the file, and allows for data discovery. All fields should be human-readable and use units that are easy to understand. Global attribute names are case sensitive.

The European common data and metadata model for real-time data divides data global attributes into three categories: Mandatory Attributes, Recommended Attributes and Suggested Attributes. The Mandatory Attributes (M) include attributes necessary to comply with CF-1.6 and OceanSITES conventions. The Recommended Attributes (R) include attributes necessary to comply with INSPIRE and Unidata Dataset Discovery conventions.

The Suggested Attributes (*i.e.*, all others) include attributes relevant for describing the data, whether they are part of the standard or not. All of these attributes should be used as they contain meaningful information, unless there are technical reasons making this impossible.

Attributes are organised by function: discovery and identification, geospatial- temporal, conventions used, publication information, and provenance. Attributes that are part of the Attribute Convention for Data Discovery (ACDD) or CF standard, or that appear in the NetCDF Users Guide (NUG) are so indicated, as are those that are used by GDAC inventory software.

To support fast integration into these international ocean data management infrastructures (*e.g.*, GDAC, EMODnet, etc), NAUTILOS also adds some requirements to the CF-1.6 standard:

- Time: is specified as a string, the ISO8601 standard "YYYY-MM-DDThh:mm:ssZ" is used; this applies to attributes and to the base date in the 'units' attribute for time. UTC must be used, and specified.
- Latitude and longitude follow WGS84
- Implement Global attributes from - Attribute Convention for Data Discovery (ACDD)
- Use GEMET-INSPIRE theme
- Use CF standard names, CF short names and SeaDataNet (SDN) P02/P09 for variable names and P06 for units.
- Use Platform types from SDN L06 and/or CMEMS INSTAC bigram
- Use Intuition codes: EDMO (European Directory of Marine Organisations)

Table 3 Metadata vocabulary

Metadata field	Vocabulary exists (Y/N)	Reference	Vocabulary governance
platform	Yes	http://vocab.nerc.ac.uk/collection/L06/current/	BODC
Platform short diagram	yes	CMEMS INSTAC – EMODnet Physics	EuroGOOS DATAMEQ
contributors_role			NAUTILOS
naming_authority	Yes	https://edmo.seadatanet.org/	SeaDataNet
institution	Yes	https://edmo.seadatanet.org/	SeaDataNet
rtqc_method	No		
platform_type	Yes		INSTAC SeaDataNet
ICES_code	Yes	https://ocean.ices.dk/codes/ShipCodes.aspx	ICES
sensor_model	Yes	http://vocab.nerc.ac.uk/collection/L22/current/	BODC
data_mode	Yes	RT/DM/REP	EuroGOOS DATAMEQ
phase	No		
variable names	Yes	http://vocab.nerc.ac.uk/collection/P02/current/	BODC
time	yes	ISO8601	ISO
Date	Yes	WGS84	ISO
taxon	Yes	LSID	WoRMS

Special parameters

Special attention needs to be paid to some of the parameters of interest to this project.

Ocean sound

Hosting continuous sound data requires storage and organisation of large amounts of data. The data formats HDF5, Wav and NetCDF are both well suited for this purpose and technically widely supported. There is a high level of compatibility between both formats and an abundance of technical support for format conversion and write/read support.

The HDF5 format provides objects called groups, datasets and attributes. A group is comparable to a folder in a file system. Datasets can be e.g. matrices or single values/strings. Attributes can be used to store metadata of datasets.

SeaDataNet and IOOS controlled vocabularies are used for the description of hydrophone metadata, including data streams, algorithm configuration, description, identification, contacts as well as technical information, providing unambiguous meaning for each term.

Marine Litter, micro- and nanoplastics

EMODnet Chemistry has developed and is maintaining a Marine Litter Database (MLDB) gathering datasets from existing monitoring projects, setting guidelines for data formats to ensure data harmonisation. The new formats, based on existing monitoring protocols and data reporting formats, allow to process heterogeneous datasets while keeping the main information and metadata. EMODnet Chemistry MLDB gathers data of floating micro-litter from EMODnet partners (e.g. Regional Sea Conventions, EU members, etc.) and external research projects. Floating micro-litter data are gathered in the system using a specific version of ODV format (for more details see: <https://www.seadatanet.org/Standards/Data-Transport-Formats>), where relevant characteristics are codified using [common vocabularies](#), such as:

- [ICES vocabularies](#) includes all terms used to describes seafloor litter data in EMODnet format;
- [SeaDataNet Common vocabularies](#) includes all terms used to describe micro-litter data in EMODnet format.

Table 4 Terms used to describe micro-litter in water bodies

ID	Description
MLDWWD01	Dry weight of micro-litter particles collected from the water body by categorisation using EMODnet chemistry reporting protocol
MLITCNTW	Count of micro-litter particles in the water body by categorisation using EMODnet chemistry reporting protocol
MLITCOLW	Colour class of micro-litter particles in the water body by categorisation using EMODnet chemistry reporting protocol
MLITPOLW	Polymer type of micro-litter particles in the water body by categorisation using EMODnet chemistry reporting protocol
MLITROPW	Transparency class of micro-litter particles in the water body by categorisation using EMODnet chemistry reporting protocol
MLITSHPW	Shape class of micro-litter particles in the water body by categorisation using EMODnet chemistry reporting protocol
MLITSIZW	Size class of micro-litter particles in the water body by categorisation using EMODnet chemistry reporting protocol
MLITTPW	Type class of micro-litter particles in the water body by categorisation using EMODnet chemistry reporting protocol
MLITVOVO	Count of micro-litter particles in the water body by filtration, ultrasonication extraction and microfluidic flow capillary raman spectroscopy and holography and categorisation using EMODnet chemistry reporting protocol

Animal-borne instruments

The sea mammals netCDF data formats, currently used to store and distribute data in the MEOP databases (<http://www.meop.net/database/format/>) has been adapted from the Argo data profile and trajectory formats. The Argo data management group develops and maintains such formats (<http://dx.doi.org/10.13155/29825>), with data files written with the netCDF format following the standardized Climate and Forecast (CF) specification.

The NASA/JPL Oceanographic In-situ data Interoperability Project (OIIP) has progressed interoperability for marine animal tagging data through their development of the netCDF electronic tag data template specification (nc-eTAG, Tsontos et al. 2020). These templates are applicable to a broad spectrum of data types and sensor measurements. A parallel data standardisation initiative is being run through the proposed Global Ocean Observing System Animal Research and Tracking Initiative (GOOS-ARTI), which could inform an expansion of the OIIP-led standard to encompass satellite-based location (Argos and GPS), ocean observing tags that are more commonly deployed on air breathing species such as seals, seabirds, and sea turtles.

The OIIP standard includes rich geospatial metadata, encompassing the following information: device type (e.g., manufacturer, model, serial number), ownership (e.g., country, program, PI, contact details), device programming (e.g., firmware version, sampling rate), platform deployment (e.g., species, life history characteristics, deploy location, date, attachment method), sensors (e.g., type, accuracy, precision, calibration), recovery (e.g., location, date). Each category has sets of required, recommended and optional attributes classed with groups conforming to the above categories.

Marine Biodiversity Data

The Ocean Biodiversity Information System (OBIS) provides a mechanism for integrating and making accessible standardised marine biodiversity data, including abundance and associated environmental data. The OBIS 2.0 includes a workbench for scientists to process data and for the data to be kept “private” (e.g., data can be kept by the eventual provider but still be checked using OBIS quality control services such as outlier detection). The system is based on a Darwin Core Extension which supports exchanging rich datasets containing a variety of measurements and facts linked to community-developed vocabularies.

This system is being adopted by EMODnet Biology, Fisheries and Oceans Canada (DFO), the US Integrated Ocean Observing System (IOOS), and the Integrated Marine Observing System (IMOS) in Australia.

New terms

The use of shared controlled vocabularies in metadatabases and data formats is an important prerequisite towards consistency and interoperability. Towards SeaDataNet projects the SeaDataNet community has developed and is maintaining controlled vocabularies consisting of lists of standardised terms that cover a broad spectrum of disciplines of relevance to the oceanographic and wider community. In SeaDataCloud NERC-BODC, in partnership with Marine Institute (MI) and CSIRO, has updated the NVS (NERC Vocabulary Server) in order to facilitate a wider adoption by a wider community. Expansion of domain expertise is an ultimate goal for the governance of the vocabularies as they become increasingly diverse and specialised and maintaining user trust in content therefore becomes more challenging. To this end the governance is now based on:

1. GitHub repositories for key NVS vocabularies, which would capture discussions and decisions relating to those vocabularies and be public visible
2. Extension of the NVS database to include formal links to these GitHub accounts
3. Exposure of the extended NVS infrastructure by means of NVS RESTful, SOAP and SPARQL public services.

GitHub organization was set up (github.com/nvs-vocabs) and repositories created for individual vocabulary collections to preserve governance decisions and record contact details for those providing steer for the collections

o 2.1.3. Data services

The focus of the interoperability services to the users is on making it easier for users to get scientific data.

Simply ensuring that data are freely and openly available is not enough to effectively improve data interoperability, though of course this is necessary. In order to reach a more diverse set of users, including domain and non-domain experts, it is also critical to provide effective data services that are easy to use and support both human and machine interaction.

Therefore, to facilitate the data harmonisation and operate as integrator and data translator for facilitating the data use and interoperability, NAUTILOS has adopted a data interoperability infrastructure that is based on ERDDAP, GeoServer and GeoNetwork.

The **ERDDAP** data server is open-source software written in Java that provides a platform through which data can be shared between partners and also published more widely. Developed out of NOAA's Monterey Laboratory, the platform-agnostic ERDDAP, or the Environmental Research Division's Data Access Program, builds upon the open-source ideals of the OPeNDAP, WCS, SOS and OBIS standards. It offers a consistent, yet an easy-to-use way of downloading or viewing scientific data in a variety of formats. Through all of this, ERDDAP also provides the ability to generate RESTful web API links in a relatively straightforward manner, which makes the process of integrating data into web-based applications simple. ERDDAP data server supports several common data file formats (html table, netcdf, csv, txt, mat, json, etc.) and output files are created on-the-fly in any of this format. ERDDAP implements FGDC Web Accessible Folder (WAF) with FGDC-STD-001-1998 and ISO 19115 WAF with ISO 19115-2/19139.

The GOOS Observation Coordination Group (OCG), coordinating the activities of the global ocean observing networks, it is working to improve data interoperability between and within the various observing networks. The OCG is actively promoting the use of ERDDAP as a key tool towards interoperability of global ocean datasets.

The second core data interoperability technology in NAUTILOS is **GeoServer** that implements several Open Geospatial Consortium protocols including Web Map Service (WMS), Web Feature Service (WFS), Web Coverage Service (WCS) and Web Map Tile Service (WMTS) and that was lately updated with the INSPIRE module.

o 2.1.4. Data quality

The end users of the NAUTILOS project will be provided with information about the quality of data and about the applied quality check procedure, to facilitate data usage. The quality control procedure will follow the recommended best practices on data quality control procedures.

Table 5 List of best practices on data quality procedures relevant to NAUTILOS project (Source: oceanbestpractices.org)

Reference	DOI
Davies, C. and Sommerville, E. (eds) (2020) National Reference Stations Biogeochemical Operations Manual Version 3.3.1 . Hobart, Australia, Integrated Marine Observing System, 66pp.	DOI:10.26198/5c4a56f2a8ae3
Becker, S.; Aoyama, M.; Woodward, E.M.S.; Bakker, K.; Coverly, S.; Mahaffey, C. and Tanhua, T. (2020) GO-SHIP Repeat Hydrography Nutrient Manual: the Precise and Accurate Determination of Dissolved Inorganic Nutrients in Seawater, Using Continuous Flow Analysis Methods . <i>Frontiers in Marine Science</i> , 7:581790, 15pp.	DOI: 10.3389/fmars.2020.581790
Daniel, A.; Laës-Huon, A.; Barus,; Beaton, A.D.; Blandfort, D.; Guigues, N.; Knockaert, M.; Muraron D.; Salter, I.; Woodward, E.M.S.; Greenwood N. and Achterberg E.P. (2020) Toward a Harmonization for Using in situ Nutrient Sensors in the Marine Environment . <i>Frontiers in Marine Science</i> , 6: 773, 22pp.	DOI: 10.3389/fmars.2019.00773
Möller, K.O.; Petersen, W. and Nair, R. (2019) Report on Best Practice in the utilization of sensors used for measuring nutrients, biology related optical properties, variables of the marine carbonate system, and for coastal profiling , JERICO-NEXT Deliverable D2.5.Version 1.0. Brest, France, IFREMER, 65pp. (JERICO-NEXT-WP2-D2.5-100919-V1.0),	DOI: http://dx.doi.org/10.25607/OBP-898
Bushnell, M.; Waldmann, C.; Seitz, S.; Buckley, E.; Tamburri, M.; Hermes, J.; Heslop, E. and Lara-Lopez, A. (2019) Quality Assurance of Oceanographic Observations: Standards and Guidance Adopted by an International Partnership . <i>Frontiers in Marine Science</i> , 6:706, 12pp.	DOI: https://doi.org/10.3389/fmars.2019.00706
GESAMP (2019) Guidelines for the monitoring and assessment of plastic litter and microplastics in the ocean (eds Kershaw P.J., Turra A. and Galgani F.), London, UK, GESAMP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, 130pp. (GESAMP Reports and Studies, No. 99).	DOI: http://dx.doi.org/10.25607/OBP-435
Venkatesan, R.; Ramesh, K.; Kishor, A.; Vedachalam, N. and Atmanand, M.A. (2018) Best Practices for the Ocean Moored Observatories . <i>Frontiers in Marine Science</i> . 5:469, 17pp.	DOI:10.3389/fmars.2018.00469
Fielding, S. (2018) Report of acoustic processing routines & quality checking methods. France, Collection Location Satellites (CLS) 9pp. (MESOPP-18-0003 [D.1]).	DOI: http://dx.doi.org/10.25607/OBP-442

Gago, J., et al (2018) Standardised protocol for monitoring microplastics in seawater . Deliverable 4.1. JPI-Oceans BASEMAN Project, 33pp.	DOI: http://dx.doi.org/10.25607/OBP-605
Linders J. and Willstrand Wranne, A. (2017) Best practices for quality control of sensor based biochemical data . Version 1.3. [Deliverable 5.11]. Issy-les-Moulineaux, France, Ifremer for JERICO-NEXT Project, 70pp.	DOI: http://dx.doi.org/10.25607/OBP-16
Karlson, B.; Artigas, F.; Créach, V.; Louchart, A.; Wacquet, G. and Seppälä, J. (2017) Novel methods for automated in situ observations of phytoplankton diversity . WP.3, D3.1, Version 9. IFREMER for JERICO-NEXT, 69pp. (JERICO-NEXT-WP3-D3.1).	DOI: http://dx.doi.org/10.25607/OBP-219
Pensieri, S.; Bozzano, R.; Schiano, M.E.; Ntoumas, M.; Potiris, E.; Frangoulis, C.; Podaras, D. and Petihakis, G. (2016) Methods and Best Practice to Intercompare Dissolved Oxygen Sensors and Fluorometers/Turbidimeters for Oceanographic Applications . Sensors, 16, 702 [pp.1-25]	DOI: http://dx.doi.org/10.25607/OBP-19

● 2.2. CATALOGUES

The ability to access and search metadata for marine science data is a key requirement for answering fundamental principles of data management, making data FAIR. In order to address the requirements of the Findable aspect of FAIR data, a dataset needs to be described by rich metadata in a searchable resource and the dataset must be assigned a clearly labelled persistent, unique identifier. Additional requirements include meeting domain-specific, community defined standards and legislative requirements placed on data publishers, for example maintaining semantic heterogeneity in cross-disciplinary domains, such as Marine Spatial Planning (MSP). Therefore, the need for a modular approach to data cataloguing which is designed to meet a number of requirements has been demonstrated. Modularity is required in order to represent datasets, projects or programmes and other data resources within the catalogue system in other cross-disciplinary topics.

NAUTILOS catalogue is going to be based on the GeoNetwork application. **GeoNetwork**, based on an open source (GNOS) project, is a free and open source (FOSS) cataloguing application for spatially referenced resources. GeoNetwork provides an easy to use web interface to search geospatial data across multiple catalogues. The search provides full-text search as well as faceted search on keywords, resource types, organizations, scale, etc. The catalogue is able to describe geospatial layers, services, maps and also non geographic datasets.

Geonetwork implements WxS, OGC, ISO standards. The metadata editor supports ISO 19115/119/110 standards used for spatial resources and also Dublin Core format usually used for open data portals. Online editing of metadata is based on a powerful template system and directories of information (eg. contacts, thesaurus).

● 2.3. NAUTILOS DATA INTEGRATION SCHEME

A schematic representation of the NAUTILOS data management flow is given in the diagram below (Figure 1).

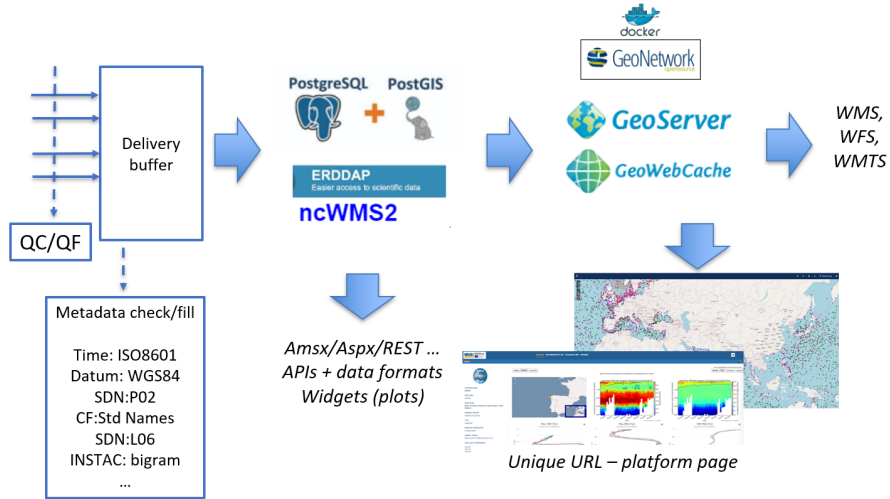


Figure 1 Schematic representation of NAUTILOS data management flow

3. INSPIRE IN NAUTILOS

○ 3.1. INSPIRE

The Infrastructure for Spatial Information in the European Community (INSPIRE) directive aims to create a European Union spatial data infrastructure for the purpose of EU environmental policies. This European spatial data infrastructure will enable the sharing of environmental spatial information among public sector organisations, facilitate public access to spatial information across Europe and assist in policy making across boundaries.

INSPIRE is based on the infrastructures for spatial information established and operated by the Member States of the European Union. The directive addresses 34 spatial data themes needed for environmental applications.

The directive is defined in a generic manner, providing overall requirements towards metadata and data provision, together with a short description of the data themes encompassed. Based on the framework defined within the directive, implementing rules have been formulated detailing explicit requirements that must be adopted by the Member States. In addition, technical guidelines have been developed that help Member States to comply with these implementing rules.

○ 3.2. Compliance requirements

INSPIRE requires that the data being made available for specific INSPIRE themes includes all concepts specified within the data specifications for the relevant themes, and laid down in the Commission Regulation regarding the interoperability of spatial data sets and services (1253/2013/EU). That document formalises which spatial objects are to be made available for a specific theme, together with which attributes are to be provided for each spatial object type.

In order to facilitate the provision and sharing of data falling under INSPIRE, the data specifications have been designed in UML, which was subsequently transformed into XML Schema documents (XSD) made available by the European Commission Joint Research Centre (JRC) at <http://inspire.ec.europa.eu/schemas/>. Whilst providing data falling under INSPIRE in accordance with the XSDs is not mandatory, this is recommended to allow for better interoperability of data stemming from different sources. In the case where the INSPIRE schemas are not followed, the data provider must specify how the concrete data model being used for data provision correlates with the concepts stipulated within the Commission Regulation.

○ 3.3. Relevant INSPIRE themes

Based on the analysis of data being collected and administered within SeaDataCloud, the data specifications for the INSPIRE Themes Environmental Monitoring Facilities and Oceanographic Geographical Features apply.

The INSPIRE Themes Environmental Monitoring Facilities (EF) is comprised of the following feature types:

- Environmental Monitoring Activity
- Environmental Monitoring Facility

- Environmental Monitoring Network
- Environmental Monitoring Programme
- Observing Capability
- Operational Activity Period

In addition, observational data are to be provided in accordance with the observational model from the Generic Conceptual Model (GCM) and specified in the INSPIRE deliverable *D2.9 Guidelines for the use of Observations & Measurements and Sensor Web Enablement-related standards in INSPIRE*. This model is extended from the Observations and Measurements (O&M) data model formalised in ISO 19156, providing specialised feature types as required for various types of observational or measurement data falling under INSPIRE. Of specific relevance are the specialised observation types, defined for the provision of various types of observational data; the specialisation pertains to various constraints on the observation such as the type of object being measured or the type of result to be provided:

- pointObservation
- pointTimeSeriesObservation
- multiPointObservation
- profileObservation
- trajectoryObservation
- gridObservation
- gridSeriesObservation
- specimenObservation
- specimenTimeSeriesObservation

Within the INSPIRE Theme Oceanographic Geographical Features (OF), the specification is devolved to various packages stemming from the observational model, including:

- Specialised Observations
- Processes
- Observable Properties
- Observation References

In addition, it is stated that “The process used to derive Oceanographic Geographical Features will involve one or more Environmental Monitoring Facilities (e.g. a ship).”

○ 3.4. OF, EF, O&M data models

As shown in the section above, there are strong interlinkages between the INSPIRE Themes OF, EF as well as the Observational Model from the GCM. The OF Theme specifies which of the specialised observation types are to be utilised, while stressing the importance of the relationships to additional themes, such as EF and the Observational Model defined in the INSPIRE Deliverable D2.9. The EF Theme specifies how the facilities (various platform types, i.e. vessels, buoys, aircraft) are to be described.

The observational model describes the various specialised observation types as well as the feature types to be utilised for the provision of information on the measurement process as well as the properties being observed.

Within the Oceanographic Geographical Features data specification, in addition to mentioning the relevance of the coupled environmental monitoring facilities for the provision of information on the

process used to derive the data on physical conditions, the INSPIRE Theme Sea Regions (SR) is considered to be of importance, as these provide the spatial context of OF feature.

- 3.5. INSPIRE compliance implementation plan

Given the NAUTILOS implementation plan, the relevant information in relation to the requirements for INSPIRE compliance are the metadata on Environmental Monitoring Facility:

- Platform
- Sampling Point

OF/Observations:

- Time Series Observations
- Profile Observations
- Trajectory Observations

EF/OF:

- Feature of Interest
- Process

NAUTILOS ERDDAP catalogue makes available XML/GML encoded files and this information is going to be available within the ERDDAP fields following the recommendations and conventions described in this document.

4. DATA LICENSING

The interoperability of data across initiatives also depends on data usage licensing. Licences facilitate the accessibility and legal re-usability of data. Data with restricted or protected usage cannot be freely used or shared, unless explicit authorisation is granted.

International best practices recommend the use of open licences that contain attribution clauses as these clauses help trace data provenance and can enhance trust in the data. Digital Object Identifiers (doi) are used to cite data and acknowledge data sources.

The data generated by this project will be licensed under CC BY 4.0, to allow sharing and redistributing without restrictions.

5. STAKEHOLDERS ANALYSIS

In the effort to identify potential data management challenges and ensure NAUTILOS data 'FAIRness', we have carried out an analysis of the existing ocean data integration projects and initiatives that may have a potential interest in using or integrating the data produced within NAUTILOS. Below there is a non-comprehensive list.

EMODnet

The European Marine Observation and Data Network (EMODnet), is a long-term initiative implementing mechanism of the European Commission's Marine Knowledge 2020 strategy to unlock the potential of Europe's wealth of marine data. EMODnet is a network of organisations linked by a data management structure. These organisations work together to facilitate the discovery and access to marine data and data products.

EMODnet provides access to European marine data across seven discipline-based themes. The data generated within the NAUTILOS project are of interest to Physics, Biology, Chemistry and Seabed Habitats domains.

SeaDataNet

SeaDataNet is a pan-European marine data infrastructure for the management of large and diverse sets of data deriving from in situ of the seas and oceans. It addresses the need to ease the access to marine data measured by the countries bordering the European seas.

Professional data centres, active in data collection, constitute the network providing on-line integrated databases of standardised quality.

CMEMS, Copernicus Marine Environment Monitoring Service

Copernicus is a major European programme for Earth Monitoring and is the main European contribution to the GEO/GEOSS programme. CMEMS has set up a pan-European service for ocean monitoring and forecasting for the global ocean and specifically the European seas. In-situ and satellite observations are routinely assimilated in ocean models to provide integrated descriptions and short-term forecasts of the ocean physical and biogeochemical state.

International Council for the Exploration of the Sea (ICES)

ICES is an intergovernmental marine science organisation, whose mission is to provide impartial evidence on the state and sustainable use of our seas and oceans. Their goal is to advance and share scientific understanding of marine ecosystems and the services they provide and to use this knowledge to generate state-of-the-art advice for meeting conservation, management, and sustainability goals. ICES also collects and makes available a set of biological and physico-chemical datasets.

JERICO

The Joint European Research Infrastructure network for Coastal Observatory is a long-term EU-funded project providing operational services for the timely, continuous and sustainable delivery of high quality environmental data and information products related to the marine environment in European coastal seas. Jerico seeks to provide a simple access to a large set of validated crucial information to understand the global change in coastal areas, and to send data and information in an operational mode to European data systems, with dedicated service access.

PANGAEA

PANGAEA is an information system aimed at archiving, publishing, and distributing georeferenced data from Earth science research.

Global Ocean Acidification Observing Network (GOA-ON)

GOA-ON is a collaborative international network to detect and understand the drivers of ocean acidification in estuarine-coastal-open ocean environments, the resulting impacts on marine ecosystems, and to make the information available to optimise modelling studies. GOA-ON makes data available through a data portal.

Marine Biodiversity Observation Network (MBON)

The Marine Biodiversity Observation Network (MBON) is a global initiative composed of regional networks of scientists, resource managers, and end-users working to integrate data from existing long-term programs to improve our understanding of changes and connections between marine biodiversity and ecosystem functions. It provides biological and environmental data collected by multiple independent programmes in an integrated web-based tool that informs scientists, resource managers, educators, and all stakeholders about the state of marine biodiversity and how it is changing.

HIMIOFoTS

HIMIOFoTS is a large-scale national infrastructure aimed to apply an interdisciplinary management approach through the implementation of state-of-the-art technologies and techniques together with innovative solutions in order to support the sustainable development and the provision of relevant services to the society. The main objective of HIMIOFoTS is to provide open access to data from marine and inland waters monitoring networks as well as to related forecasting products that may lead to the development of added value products and services.

LifeWatchGreece

The national node of LifeWatch in Greece has been established since 2012 and is aiming to address the precise cataloguing of the different Greek ecosystems and the biological species occurring therein, along with the continuous monitoring of species distribution changes through time which are of paramount importance for studying the rich Greek terrestrial and marine biodiversity. LifeWatchGreece hosts the following virtual laboratories: micro-CT vLab, the MedOBIS vLab, the RvLab and the Ecological Modeling vLab. The Mediterranean Ocean Biodiversity Information System (MedOBIS) is a distributed system established in 2003 which constitutes the Mediterranean node of OBIS and includes multiple taxon-based biogeography datasets for marine organisms (both recent and historical) with a link to satellite environmental data.

POSEIDON

POSEIDON is a marine observatory research infrastructure of the Eastern Mediterranean basin, for the monitoring and forecasting of the marine environment, supporting the efforts of the international and local community and replying to the needs and gaps of science, technology and society. The POSEIDON general aims are: (a) to establish a sustainable marine observing network in the Eastern Mediterranean, (b) to provide quality and validated forecasts of the marine environment, (c) to provide scientific knowledge and support on the study of the ocean mechanisms and their variability, as well as to address the sensitivity of marine ecosystem and biodiversity to combined natural forcing

factors and anthropogenic pressures, and (d) to provide a technology test bed and services to marine policy-makers and society. The system is being developed in accordance with the policy frameworks suggested by IOC/GOOS, EuroGOOS, MonGOOS and GEO while it maintains a balance between the operational and research character of the infrastructure through the integration of methodologies and tools developed in relevant EU initiatives and projects.

Integrated Carbon Observation System (ICOS-ERIC)

The ICOS-ERIC integrates terrestrial, oceanic and atmospheric observations of atmospheric greenhouse gas concentrations and fluxes at various sites into a single, coherent, highly precise dataset.

● APPENDIX 1: REFERENCES AND RELATED DOCUMENTS

ID	Reference or Related Document	Source or Link/Location
1	Use of Observations & Measurements and Sensor Web Enablement-related standards in INSPIRE. INSPIRE Maintenance and Implementation Group (MIG), 2016.	https://inspire.ec.europa.eu/id/document/tg/d2.9-o%26m-swe
2	F. Galgani, A. Giorgetti, M. Vinci, M. Le Moigne, G. Moncoiffe, A. Brosich, M.E. Molina Jack, M. Lipizer, N. Holdsworth, R. Schlitzer, G. Hanke, D. Schaap, M.D.M Chaves Montero, 2020, Proposal for gathering and managing data sets on marine micro-litter on a European scale, 03/06/2020, 34 pp., DOI: 10.6092/8ce4e8b7-f42c-4683-9ece-c32559606dbd	https://www.emodnet-chemistry.eu/repository/Proposal-EMODnet-TG-ML-Micro-Litter-Data-Gathering-03062020.pdf
3	Underwater Soundscape and Modeling Metadata Standard (Version 1.0), Atlantic Deepwater Ecosystem Observatory Network (ADEON): An Integrated System for Long-Term Monitoring of Ecological and Human Factors on the Outer Continental Shelf.	https://doi.org/10.6084/m9.figshare.6792359.v2
4	Proposal to form the GOOS network, Animal borne ocean sensors, 2020. AniBOS	
5	Tsontos, V. M., C. Lam, and S. C. Arms. 2020. netCDF templates for electronic tagging data. JPL URS CL:19-6563	6510.6084/m6569.figshare.10159820