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Report on “Novel multi-platform cooperative network integration”

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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-h2020.eu.

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Executive Summary

This deliverable is the outcome of the work performed in Task 5.1, where the main objective was to integrate multiple physical platforms and vehicles in a "Novel multi-platform cooperative network" for future autonomous and integrated ocean observation and monitoring capabilities.

This deliverable, is organized in five main sections:

Chapter I: Introduction describes the state-of-the-art of underwater communications and protocols.

Chapter II: Choice of Communications and Protocol presents an overview of acoustic and optical communication protocol, and, in the first case, it compares JANUS protocol with that of DAMOCLES project. It also includes the motivations that led NAUTILOS' partners to adopt the DAMOCLES standard rather than JANUS within the project.

Chapter III: Ethical Considerations makes considerations about data protection, as environmental protection related to the batteries and all the electronic equipment that will be recycled, health and safety concerning pressure cases and protection of marine life related to the frequency band used by the acoustic modems.

Chapter IV: Implementation of the Communication Architecture presents the communication architecture between a Lander platform, an AUV and an ASV to create a multi-platform network.

Chapter V: Summary retraces the fundamental steps of this deliverable, starting with the description of the available technologies, moving on to the choice of communication protocols and then to the implementation of these protocols in order to realise a multi-platform network.

Chapter VI: Appendix: References and related documents with the updated version of DAMOCLES specification.

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List of Acronyms and Abbreviations

Abbreviation	Definition
ANCHOR	Acoustic Navigation and Communications for High-latitude Ocean Research
ASCII	American Standard Code for Information Interchange
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
CFRP	Carbon Fiber Reinforced Polymers
CMRE	Centre for Maritime Research and Experimentation
DAMOCLES	Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies
DCPD	Dicyclopentadiene
EM	Electromagnetic
FEPT	Free Error Period of Time
GCS	Ground Control Station
HF	High frequency
LoS	Line of Sight
MMS	Mission Management System
MTBF	Mean Time Between Failures
NMEA 0183	National Marine Electronics Association interface standard 0183
NMFS	National Marine Fisheries Service
NATO	North Atlantic Treaty Organization
NMEA	National Marine Electronics Association
NVRAM	Non-volatile Random Access Memory
RF	Radio Frequency
ROV	Remotely Operated Vehicles
RS 232	Recommended Standard 232
RT/NRT	Real Time/Near Real Time
SWiG	Subsea Wireless Group
TTL	Transistor-Transistor Logic
UOWC	Underwater Optical Wireless Communication
UUV	Unmanned Underwater Vehicle
UW	Underwater
UWSN	Underwater Wireless Sensor Network
WEEE	Waste from Electrical and Electronic Equipment
WHOI	Woods Hole Oceanographic Institution
WSN	Wireless Sensor Network

I. Introduction

The fundamental aim of Horizon 2020 NAUTILOS project will be to fill in existing marine observation through the development of a new generation of sensors and samplers (WP3/4), that will be integrated on different platforms (WP5). All these platforms will be integrated in a "Novel multi-platform cooperative network" for future autonomous and integrated ocean observation and monitoring capabilities.
A network of underwater communications will be established between the nodes of NAUTILOS program by using both optical and acoustic communication channels.
The underwater acoustic communications will be realized with modems from Aquatec, using the communications protocol developed during the DAMOCLES FP6 project. All NAUTILOS' acoustic system will be brought into sync with each other by defining a common frequency over which all systems can announce their presence.

1. State-of-the-art of Communications and Protocols

In scientific, industrial and military sectors the development of robust and efficient submarine wireless communication links is of enormous interest because underwater wireless information transfer plays an important role in pollution and climate change monitoring, oceanography research, tactical surveillance, oil control and maintenance and offshore explorations. In order to facilitate all these activities, there is an increase in the number of unmanned vehicles or devices deployed underwater, which require high bandwidth and high capacity for information transfer.

At this time the use of wireless communications is very common in a wide range of terrestrial devices, but underwater use is more ambitious. The biggest challenge for underwater wireless communication originates from the fundamental characteristics of ocean or sea water; addressing these challenges requires a thorough understanding of complex physio-chemical biological systems.

There are three wireless communications techniques currently in use in the ocean environment, illustrated in **Errore. L'origine riferimento non è stata trovata.**, which also shows the physical limits of data rate and range in ideal conditions.

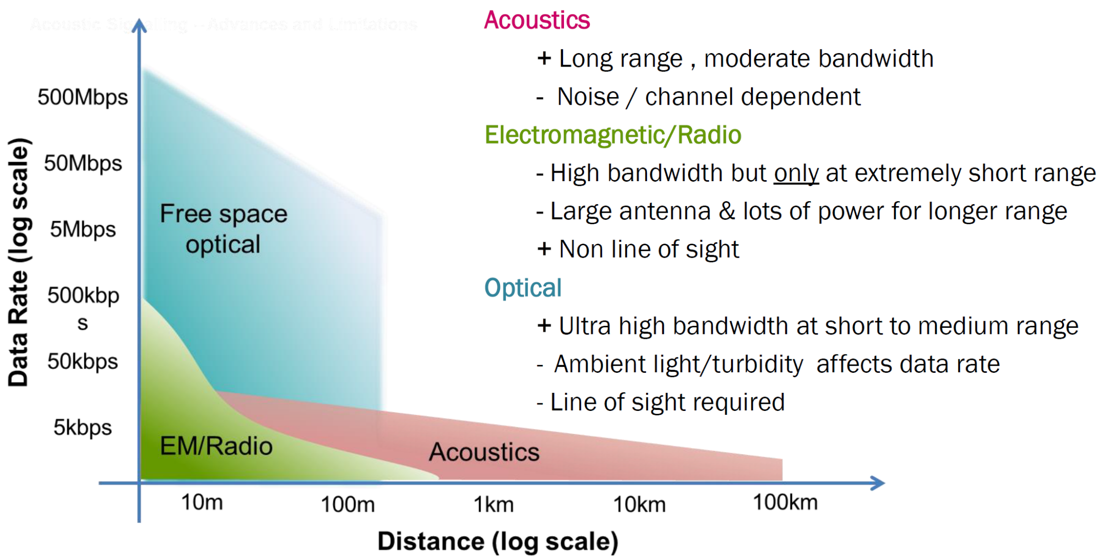

Figure 1. Underwater/Wireless communications options (SWiG, 2022)

The current available wireless underwater acoustic communication techniques can support data rate up to tens of kbps for long distances (ranging in kms) and up to hundreds of kbps for short distances (few meters). Depending upon the transmission distance, the acoustic link is classified as very long, long, medium, short and very short links. Table 1 provides a typical bandwidth for various underwater acoustic communication links with different ranges. However, various underwater vehicles, sensors and observatories require a communication link with data rates ranging from few to tens of Mbps. In these cases, for use with large and stationary devices, fiber optic or copper cables are used to achieve high data rates but they require significant engineering and maintenance issues and are not wireless. In case of moving platforms, a good alternative is a wireless link with high data rates.

Table 1. *Typical bandwidth for different ranges in underwater acoustic links (‘‘*’’ implies dependence on water type, range, horizontal/slant transmission) (UOWC, 2016)*

Distance	Range (km)	Bandwidth (kHz)	Data Rate*
Very long	1000	< 1	~ 600 bps
Long	10 - 100	2 - 5	~ 5 kbps
Medium	1 - 10	≈ 10	~ 10 kbps
Short	0.1 - 1	20 - 50	~ 30 kbps
Very short	< 0.1	> 100	~ 500 kbps

Acoustic systems have enjoyed great success underwater owing to their ability to communicate over many kilometers pushing the research in this field with the aim to further improve this technology.
Nevertheless, its performance is linked to the physical nature that limits the bandwidth, causes high latency, produces high transmission losses, time varying multi-path propagation and Doppler’s spread.

All this has led to the proliferation of underwater optical wireless communication (UOWC) that, due to its higher bandwidth, can support higher data rates at low latency levels compared to acoustic and RF counterparts.
The main disadvantage of underwater optical communication, which uses light to carry information, is that the water is a medium that highly absorbs optical signals; the second problem is optical scattering due to the particles present in the sea. Therefore, for short distance communications, UOWC can be a viable alternative to that achievable via acoustic waves.

Wireless communication via radio frequency (RF) waves is the most widespread technology in terrestrial communications. Unfortunately, this technology is not suitable for underwater applications. In water, radio frequency waves are strongly attenuated, especially in seawater where the propagation medium is highly conductive.

It has been observed that attenuation of RF waves increases with the increase in frequency and are heavily attenuated by seawater. Optical waves on the other hand have high bandwidth but they are affected by other propagation effects due to temperature fluctuations, scattering, dispersion and beam steering. Wireless underwater communication is limited to short distances due to severe water absorption at optical frequency band and strong back scatter from suspended particles.
A comparison between different wireless underwater technologies is presented in Table 2.

Table 2. *Comparison of different wireless underwater technologies (UOWC, 2016)*

Parameters	Acoustic	RF	Optical
Attenuation	Distance and frequency dependent (0.1 - 4 dB/km) [12]	Frequency and conductivity dependent (3.5 - 5 dB/m) [13]	0.39 dB/m (ocean) - 11 dB/m (turbid) [14]
Speed (m/s)	1500 m/s	$\approx 2.255 \times 10^8$	$\approx 2.255 \times 10^8$
Data rate	~ kbps	~ Mbps	~ Gbps
Latency	High	Moderate	Low
Distance	up to kms	up to $\approx$ 10 meters	$\approx$ 10 - 100 meters
Bandwidth	Distance dependent [8]: 1000 km < 1kHz 1 - 10 km $\approx$10 kHz < 100 m $\approx$ 100 kHz	$\approx$ MHz	10 - 150 MHz
Frequency band	10 - 15 kHz	30 - 300 Hz (ELF) (for direct underwater communication system) or MHz (for buoyant communication system)	10^{12} - 10^{15} Hz
Transmission power	tens of Watts (typical value)	few mW to hundreds of Watts (distance dependent)	Few Watts
Antenna size	0.1 m	0.5 m	0.1 m
Efficiency	$\approx$ 100 bits/Joules		$\approx$ 30, 000 bits/Joules
Performance parameters	Temperature, salinity and pressure	Conductivity and permittivity	Absorption, scattering/turbidity, organic matter

Due to the very wide-ranging environmental constraints and relatively small number of applications, standardization in underwater communication has been very limited. Over the last five decades, the development of commercial underwater communications technology, has generally been carried out by several individual small specialist companies, each producing their own proprietary designs. Ocean science and submarine defence have both contributed significantly to the need for underwater communication, while much of the commercial requirement has come from the offshore oil and gas sector.

During the EC-funded FP6 project DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies), the ANCHOR (Acoustic Navigation and Communications for High-latitude Ocean Research) international workshop was held in Seattle in 2006 (Lee and Gobat, 2008) to explore standardisation in acoustic communication and navigation for Arctic exploration at basin-, regional-, and local-scale.
Frequency bands and application areas were described in Figure 2.

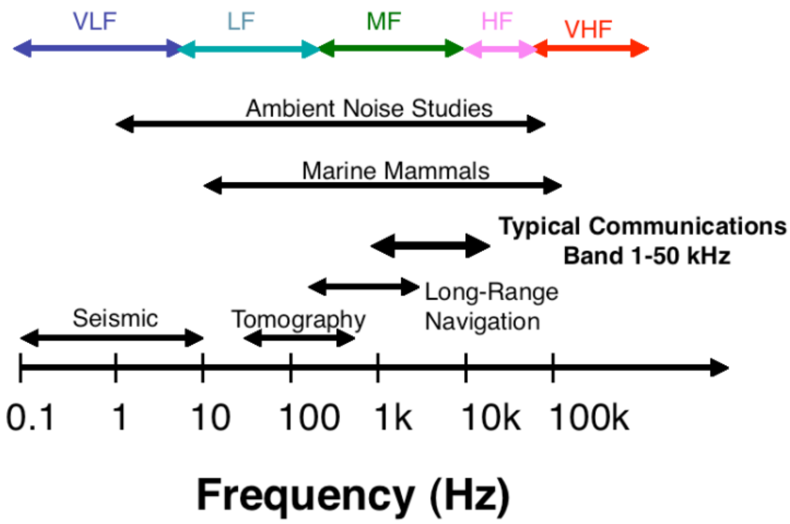

Figure 2. *Acoustic frequency bands and applications*

The report expressed a desire for standardisation of acoustic communications in the most commercially mature HF frequency band. However, most subsea communication systems are tightly integrated with other instrumentation manufactured by specialist acoustics companies serving niche markets, offering packaged products. Their acoustic communication technologies can differentiate them from their competitors, so there remained little motivation for manufacturers to move towards standardisation.

To address this problem, during the course of the DAMOCLES project, Aquatec Group developed an acoustic modem interface standard while retaining a proprietary acoustic communications protocol. The interface standard provided access to the modem functions via a serial data communications protocol based loosely on the Woods Hole Micromodem protocol, which itself was based on the NMEA 0183 standard. The protocol is described briefly in the next section, and detailed in an Appendix.

With the expansion of subsea oil and gas field developments, deep water intervention by Remotely Operated Vehicles (ROVs), and the increasing use of Autonomous Underwater Vehicles (AUVs) for automated inspection, vessel and vehicle operators need to equip their platforms with a growing range of acoustic systems to cover the various communication tasks. To address the problem of this increasing diversity of systems, the Subsea Wireless Group (SWiG) was formed in 2011 to promote interoperability between systems and develop open subsea communication standards. SWiG initially worked on the development of SWiG radio, a short-range electromagnetic signalling protocol, before turning its attention to an acoustic standard.

The discussions around standardisation of acoustic communications followed the same path as those of the ANCHOR workshop, a decade earlier, with modem manufacturers' intellectual property providing a barrier to developing a common protocol. However, NATO, who were seeking to develop a digital communications standard to coexist with the underwater telephones used for submarine through-water voice communication and first developed in 1945, was following a parallel path.

The JANUS acoustic signalling protocol was based on a superseded commercial communications protocol, and was designed to be used alongside underwater telephone transceivers in the same frequency band. It became the world's first published acoustic communication standard. The JANUS protocol is also described briefly in a subsequent section.

SWiG subsequently adapted the JANUS standard to suit the requirements of commercial underwater communications, leading to the generation of the SWiG acoustic protocol. The SWiG acoustic standard is soon to be released, and further advancements are also planned.

Through-water optical communication is far less mature than acoustic communication, and no standards currently exist. Again, the SWiG group is leading the way on standardisation, with SWiG optical standards currently under development for short range communication at rates from 115 kbps to 10 Mbps. However, for the optical communications used in NAUTILOS in the absence of any published standard, an Aquatec proprietary protocol has been used.

II. Choice of Communications and Protocol

1. JANUS protocol

As described above, the JANUS protocol is currently the only published acoustic communications standard, although the derivative SWiG acoustic standard is also close to final draft. The JANUS standard describes in detail how to convert a defined data structure into an acoustic sequence with specified frequencies and timings.

The baseline JANUS data packet shown in Figure 3 comprises 64 bits of information, of which 30 bits determine the packet characteristics, and the remaining 34 bits may be defined by different classes of user (256 possibilities, mostly different nations of the world) or application (64 options per user class). A JANUS transmission can also support further payloads of data cargo without the same overhead.

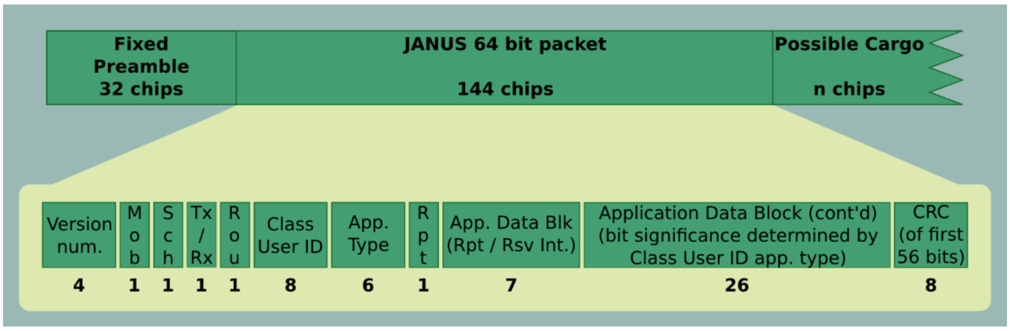

***Figure 3**. Baseline JANUS data packet structure*

The transmission may be preceded by a sequence of wake-up tones, followed by a fixed preamble for synchronisation. Each data or cargo packet is then encoded using a half-rate convolutional encoder and before being modulated using a frequency-hopped binary frequency shift keying technique for improved reverberation tolerance.

In the early stages of NAUTILOS development, it had been proposed to use the JANUS standard. However, it should be noted that the standard does not describe how to convert a received acoustic sequence back to the original data structure, nor more significantly, does it describe how to populate or break down that data structure.
From the user perspective, and particularly for the NAUTILOS partners, it was considered more important to be able to communicate between modems, instruments and platforms than for modems to be able to communicate with other modems, since all modems are supplied by one partner, and no JANUS compliant modems are yet widely available. This led to the adoption of Aquatec's modems, which use the modem interface protocol developed during the DAMOCLES project.

2. DAMOCLES project protocol

The acoustic modems used are Aquatec's AQUAmodem 1000 instruments, using the "DAMOCLES" modem interface protocol. The DAMOCLES protocol was established during the EC-funded FP6 DAMOCLES project. The last formal revision of the protocol was documented in 2013. An abridged and updated version of that protocol is attached in an appendix. Unlike the JANUS protocol, which describes acoustic interactions, the DAMOCLES protocol describes the command and data interface between the user and the modem.

The commands and data are transferred between the modem and connected host by a serial data interface, which may be RS232 or TTL logic level, depending on the configuration. All communications are in the form of ASCII sentences based on the NMEA 0183 format. Messages can incorporate the addresses of a message source and a message destination. Most exchanges involve a message being sent by the host to the modem followed by a response from the modem to the host. So, for example, the CCFSS command, described below, allows a short block of data to be sent from one modem to another in this form:

Table 3. *Commands*

$CCFSS, SRC, DEST, A, HH…HH*CS	
SRC	Source address 0 to 63
DEST	Destination address 0 to 63
A	Ack bit, if set to 1 then this command is acknowledged
HH…HH	Hex coded data up to 8 ASCII HEX bytes
***CS**	Hex coded checksum

So assuming we are connected with modem unit 1, *$CCFSS,1,2,1,0001020304050607*CS* will send the values {0,1,2,3,4,5,6, and 7} to modem unit 2. Once received, modem unit 2 will respond with an acknowledgment to modem unit 1 using the $CAFAK message, e.g., *$CAFAK,2,1,0000*CS* indicating that the message was received without error.

The modem infrastructure includes a non-volatile parameter storage area (NVRAM), which is used to store the current configuration of the modem. This includes settings for serial and acoustic communication. Commands are available to read and write the NVRAM.

The modem also includes memory banks, some of which can be accessed by the user. One bank of memory may be randomly read and written, while another acts as a 'store-and-forward' memory, which can be written by the attached instrument and read by interrogating modems.

The Aquatec modems use an acoustic transmission scheme that is proprietary to Aquatec. It includes an optional wake-up sequence that can be used to wake up sleeping modems. Data is then encoded into an acoustic message using 4-frequency shift keying. The original low frequency modem performance was described by A. Smerdon.

3. Optical communications protocol

The optical modems used are Aquatec's AQUAmodem Op2 instruments. They provide a transparent optical communications link between two devices typically via an RS232 serial communications interface. The full details of the optical modulation and demodulation are proprietary. However, the modems are designed to be operated without any form of command hierarchy, so communication across the optical link is indistinguishable from a wired connection.
The modems include an optional optical wakeup facility, whereby a modem can be woken up from a low power sleep mode by signalling from another modem. This mode is typically used on remotely deployed instruments.

4. Chosen communications system and protocol

During the early phases of work on WP5, AQUATEC noted that there were conflicting requirements between the descriptions for Task 5.1 and Deliverable D5.1, and the detail of Sub-task 5.1.1. The former made reference to the use of the JANUS international standard for acoustic communications, while the latter referred to AQUATEC's AQUAmodem 1000 acoustic modems, which were developed under the DAMOCLES FP6 project. The AQUATEC modems are not compliant with the JANUS protocol, but do use a user interface standard developed under the DAMOCLES project that is lacking in the JANUS standard.
The problem could be solved in three ways:

- Adopting the standard used by the AQUAmodem 1000, which provides interoperability between platforms and modems, but not between different acoustic systems;
- Adopting the JANUS protocol, which provides acoustic interoperability, but doesn't define an interface between modems and platforms;
- Combining the above approaches to define both the platform interface and the acoustic interface.

Some of the key features of the two standards are illustrated in the diagram below:

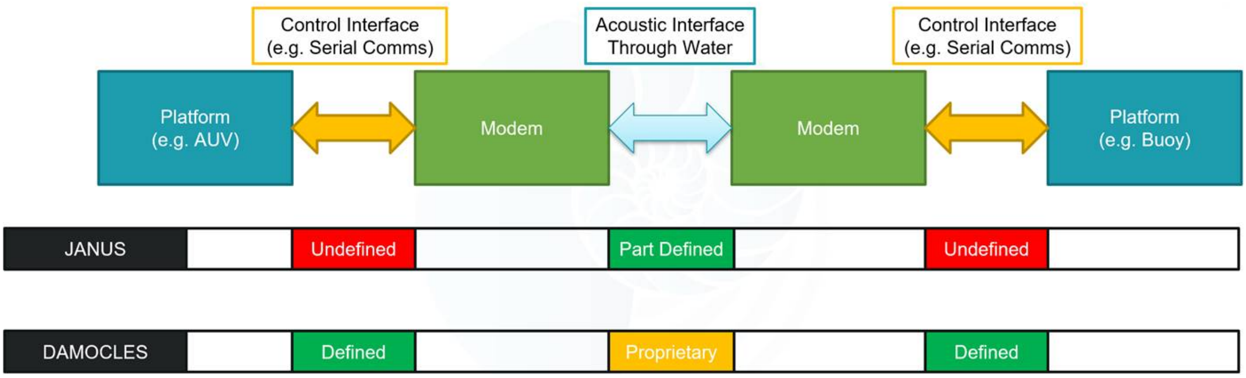

Figure 4. *Comparison between JANUS and DAMOCLES*

The JANUS standard, developed by NATO, was intended to replace the use of the analogue underwater telephone technology developed for submarines during the second world war. It includes a number of features that relate to its military origins. The standard defines the steps needed to convert a specific binary dataset into a modulated acoustic signal. It does not, however, describe any acoustic handshaking protocol between communicating devices. Nor does it define how a modem user – for example an AUV or a subsea instrument – should communicate with that modem.

The DAMOCLES AQUAmodems produced by Aquatec incorporate the DAMOCLES control interface standard, meaning that other users within the consortium can interface to the modems using an existing standard. The acoustic communications between modems include handshaking protocols, but are a proprietary Aquatec protocol.

The table below compares the two standards:

Table 4. *Comparison of JANUS and DAMOCLES standards*

	Standard JANUS	Standard DAMOCLES	
Originator	NATO (CMRE) for Submarine Communications	DAMOCLES European FP6 project	
Based On	Historic Teledyne Datasonics Technique	WHOI Micromodem command set & NMEA protocol	
Acoustic Signaling	Covered by standard	Aquatec proprietary	
Acoustic Technique	Frequency-Hopped Binary Frequency Shift Keying	4-Frequency Shift Keying	
Command Interface	Not specified	Covered by standard	
Acoustic Handshake	Not specified	Aquatec proprietary	
Interoperability	Modem to Platform not specified Modem to Modem implicit in standard	Modem to Platform implicit in standard Modem to Modem only Aquatec modems	
Minimum Information Rate	57 bps (basic packet, 34 bytes)	53 bps (short packet, 8 bytes, 25 symbols/s)	
Maximum Information Rate	107 bps (data cargo packet, 64 bytes)	290 bps (long packet, 1000 bytes, 100 symbols/s)	
Centre Frequency	11.5 kHz	10 kHz	22 kHz
Maximum Range	> 5000 m	> 5000 m	> 1500 m
Export License Required	Yes	Yes	No

The various partners have considered adopting the DAMOCLES standard rather than JANUS within the NAUTILOS project, thus using technology already developed in an EU-funded project.
The main benefits of this choice will be:

1. The command interface is already defined in the standard, and does not need to be developed by the project partners,
2. The acoustic handshaking protocol is already integrated in Aquatec's proprietary protocol, and does not need to be developed by Aquatec,
3. The maximum information rates are higher, which means that data can be transferred faster,
4. Data packets do not include unnecessary NATO-related overhead,

5. A version of the DAMOCLES modem is available that does not require an export licence for dual-use technology (see also Deliverable D13.6, in the Appendix).

This decision has no impact on the quality, objectives, budget and description of action of the project, it doesn’t change anything in the deliverable and it doesn’t require additional work (person/month) compared to what was agreed.

III. Ethical Considerations

1. Data Protection

The ethical questions related to data protection when exchanging several information may arise. In this sense and having in mind that more information lead to a more valuable understanding of the underwater world to monitor climate changes is important to have a process of safeguarding information from corruption, compromise or loss. The information and data acquired in the scope of the project doesn't follow the applicable procedures of data protection and they will be used only in the scope of this project.

2. Environmental Protection

WEEE Directive for Commercial Users: For commercial users of Aquatec products and accessories, including the batteries contained therein, at the end of product life, Aquatec will provide free recycling of all electronic equipment once the user has returned the equipment to an Aquatec designated collection point and where a replacement product is being supplied by Aquatec. Where a replacement product is not being supplied, recycling services can be provided on request at additional cost. A certificate of disposal will be supplied by Aquatec. Where national legislation dictates that other services should be offered, we will adapt our service to be compliant. This service is offered in the European Union, UK, Switzerland and Norway.

3. Health and Safety

The following health and safety issues should be considered when using the AQUAmodem instruments.
Pressure Cases: WARNING – Please follow the guidelines below when handling pressure cases

- If a case leaks, it can be hazardous when brought to the surface.
- If a hissing noise is heard, wait for it to cease before carefully opening the case.
- It is advisable to allow the cases to reach ambient temperature before opening.
- A cold case may have an internal pressure below the outside pressure which can cause water to be sucked in. Carefully dry the area near the end cap to be opened.

Battery Charging: Where instruments are fitted with rechargeable batteries, precautions should be taken to avoid internal gas pressure build-up as a result of accidental overcharging or battery fault. If automatic vents are not fitted, this can be achieved by opening manual vents or by opening the pressure housing.

4. Protection of Marine Life

As can be seen from Figure 2, the frequency band used by the acoustic modems overlaps that used by marine mammals. In particular, it overlaps echo-locating odontocete species – the toothed whales that include dolphins, porpoises, and killer whales, which have very sensitive auditory responses.

Short duration high energy impulsive sound, and sustained use of lower energy sound can be detrimental to marine mammals, with effects ranging from disruption of feeding, mating and migration patterns through to temporary or permanent hearing threshold shift. The potential association of military sonar use with mass whale and dolphin strandings has drawn public attention to this, and methodologies for the environmental impact of the marine piling activities associated with offshore windfarm construction have led to the development of methodologies to conduct environmental impact assessments.

In assessing the potential effects of any anthropogenic sound, it is normal to consider both the sound power level and the duration of sound at that power. It is also important to consider the hearing sensitivity of species that are potentially affected by the sound. Finally, the sound propagation from the source to the potentially affected species should be considered.

The US National Marine Fisheries Service (2016) has produced recommendations for sound levels that may result in temporary or permanent hearing threshold shift. The most sensitive species may experience temporary threshold shift at a 24-hour cumulative sound exposure level of 153 dB re 1 µPa2s for frequencies within their hearing range.

A typical AQUAmodem 1000 message could last 1 second at a maximum sound exposure level of 185 dB re 1 µPa2s-m2 RMS. The range at which a single transmission would not exceed the temporary threshold shift for a high frequency cetacean is therefore 10(185-153)/20 or 40 m.

On the basis of an intensive period of interrogation, one might assume up to 30 minutes of transmissions in a 24-hour period, providing a cumulative sound exposure level of (185 + 10 log (1800)) dB or 218 dB re 1 µPa2s-m2 RMS. Thus, the range beyond which the temporary threshold shift sound exposure level would not be exceeded for sustained presence is 10(218-153)/20 or 1.8 km on the basis of spherical spreading, and ignoring sound attenuation.

High frequency cetaceans are highly mobile, and unlikely to remain in the presence of a disturbing signal for long. Any marine mammal outside of a radius of 40 m from a modem transmitting at maximum power should not experience any temporary threshold shift. The intended range of the acoustic transmission system is also the radius beyond which temporary threshold shift would occur with 24 cumulative exposures. However, and animal experiencing sustained transmission would most likely move away.

5. Dual Use Potential

Dual use category 5A001.b.1.a covers underwater untethered communications systems with an acoustic carrier frequency outside the range 20 kHz to 60 kHz. The AQUAmodem 1000 acoustic modems supplied for this project operate within the band 20 kHz to 60 kHz, and are therefore not considered dual use.
The AQUAmodem Op2 has been the subject of a specific rating request from UK Export Control and is deemed to be “not dual use”.

IV. Implementation of the Communication Architecture

Tests of sensors and platforms will be performed during the duration of the NAUTILOS project in order to demonstrate the functionality of NAUTILOS sensor and platform systems in end-user specific environments.

During the first phase of the project, test activity will be carried out independently by each group involved. Test activities will be done through the evaluation of both:

- performance parameters like response time, detection limits, drift and necessity of calibration, long term stability of the response function etc. (sensors); mechanical performance, buoyancy and trim, waterproofness, communications (platforms);
- handling/maintenance parameters like ease of motion parameter setting, single point calibration capability, sensing element and spares replacement, low operational cost, etc.

After that, sensors and data acquisition/logging/transmission systems will be subjected to integrated functional tests in a simulated environment, to offer proof for:

- correct two-way operability and communication link,
- readout functionality.

NAUTILOS data will be tested in user-relevant environments, and eventually, testing of systems in different sea scenarios will be performed, in order to assess device performances in different environmental conditions and to offer valuable technical information and feedbacks to technology developers since each sensor/platform will be operated close to their environmental parameter threshold condition.

During the final activity phase, closing tests will be carried out on all integrated platforms/sensors and systems as well. These tests will be effectuated in open waters (either coastal or off-shore), and will be focused on the definition of:

- Free Error Period of Time (FEPT),
- Mean Time Between Failures (MTBF),
- measurement precision,
- maintenance needs,

by evaluation of the measurement reliability in time under the effects of working environment changes.

A typical underwater wireless sensor network (UWSN) consists of various sensor nodes (modems) that collect, store, and share data wirelessly below the water surface. The working range, data rate, cost and power consumption of these nodes vary, depending on the applications for which they are deployed. In underwater (UW) communications, water is the transmission medium. Electromagnetic (EM) waves in water suffer from excessive absorption in the communication link. To achieve high-speed data communication, optical waves are a good choice with the constraints of scattering, absorption, limited to short distances and require line-of-sight (LOS) alignment of agents. As compared to electromagnetic and optical waves, acoustic propagation is better in water and it can cover far greater distances, in the order of several kilometers. Compared to a terrestrial wireless sensor network (WSN), designing a UWSN is more time consuming and expensive due to harsh conditions of the aquatic environment.

Integration of sensors within foreseen NAUTILOS platform, and creation of a communication network of the same, will be pursued by a two-fold approach:

Firstly, front-end electronics will be integrated and developed for each sensor. Those elements contain amplifier, AD converters, and filters and provide the sensor element (transducers) with power. This approach, so called "*Standard approach*" will optimize the compact and energy efficiency aspect. A standard approach is to put together sensors that each separately include necessary electronics for signal conditioning and, in some cases, also microcontrollers to do the job.

In conjunction with the Standard approach a "Reduced approach" will be used in which a computer with data acquisition capabilities will be used. This will facilitate the development of measurement procedures as well as parameter extraction algorithms with open-source approach.

With this approach we will connect a multitude of sensor elements (transducers) to a single computer with minimal additional signal conditioning circuitry that will be "borrowed" from the Standard approach. This approach will give us capabilities of rapid prototyping and testing of measurement procedures as well as parameter extraction algorithms. These procedures and algorithms will be transferred and adapted to a microcontroller based Standard approach sensors.

Applications requiring low power consumption will be based on the Standard approach but will profit from rapid prototyping results gained with the Reduced approach.

The low power and maintenance free design is one of the main aspects, which will enable a small, lightweight thus cost-efficient system. Moreover, equipped with a novel telemetry for environmental monitoring systems, NAUTILOS' proposed platforms will be able to form a self-healing mesh network, thus enabling environmental monitoring with high spatial resolution.

Envisaged optional modules are:

- AD converter module, offering several analogue I/O with a programmable amplification and resolution
- Module for electrochemical sensors
- Digital I/O module, for control and readout of external components
- GPS Module, equipped with a SIRF III receiver allowing accurate position detection
- GSM/GPRS/UMTS modem, used for data uplink
- Satellite Uplink board
- Additional battery packs if, for example, a sensor system has a higher power consumption or a longer autonomous operation is required
- Solar panel controller, in cases where sensor systems require higher currents and long maintenance free autonomous operation is required, an alternative power supply can be solar panels that are used to recharge platform's batteries

This modular design allows NAUTILOS platforms to be equipped according to the present needs.

The modular approach in integration of sensor elements (transducers) with front-end electronics and parameter extraction microcontroller is implemented, with positive fall out on simplified integration procedures. In this approach same or similar front-end electronics will be used for signal acquisition and data transfer from sensors to platforms (see below Lander, AUV and ASV) and the sensor elements would be easily replaced by new ones in cases of failure of operation or if novel and improved technology is used.

NAUTILOS activities are focused on the deployment of the following platforms:

- A Lander platform with these characteristics:
    - Autonomy up to 6 months, allowing long timeframe missions
    - Maximum rated depth of 3000 meters
    - Deployable by crane
    - A modular design approach allowing the flexibility to accommodate diversified configurations and updated instrumentation

Regarding power, data management and mission electronics, the development will be joint with observing platforms.

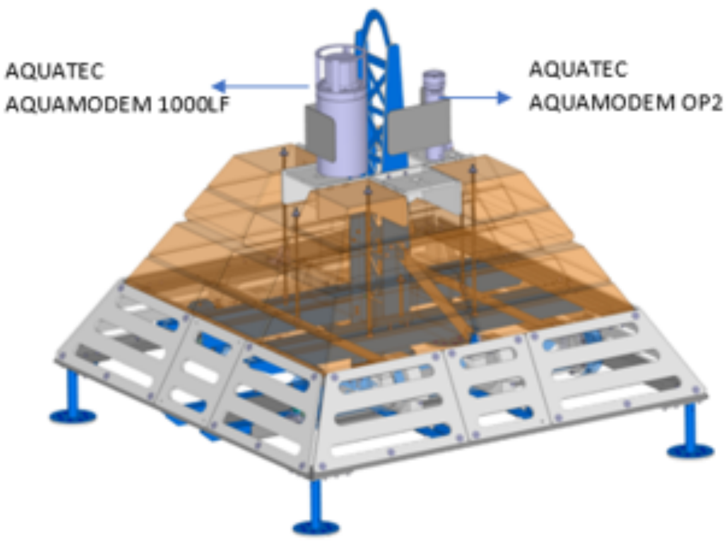

Figure 5. *Lander platform*

- An AUV with these characteristics:
    - low-cost sampling-enhanced AUV
    - capable of carrying out systematic surveys of the seabed as part of its self-selection sampling process
    - aided by model forecasts for identifying best locations or objects
    - rapid descent and ascent capabilities so that their mission time at sea will be biased toward actual working time

- reactive procedure: data and samples will be offloaded during a short interval on the surface and new programme instructions loaded, with possible transit to another area for reimmersion
- charging process simple to use and cost-effective on-board solution

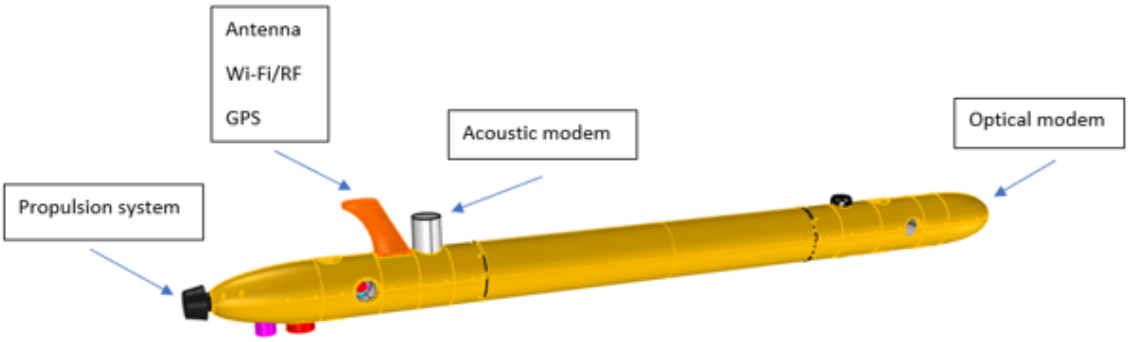

Figure 6 *AUV*

- An ASV with these characteristics:
  - Payload capacity of up to 100 kg
  - Endurance up to 24 hours
  - Maximum operational speed of 5 knots
  - Integrated mission planning and control software
  - Modular design approach allowing the flexibility to accommodate diversified configurations and updated instrumentation
  - Efficient smart power supply system
  - Charging process simple

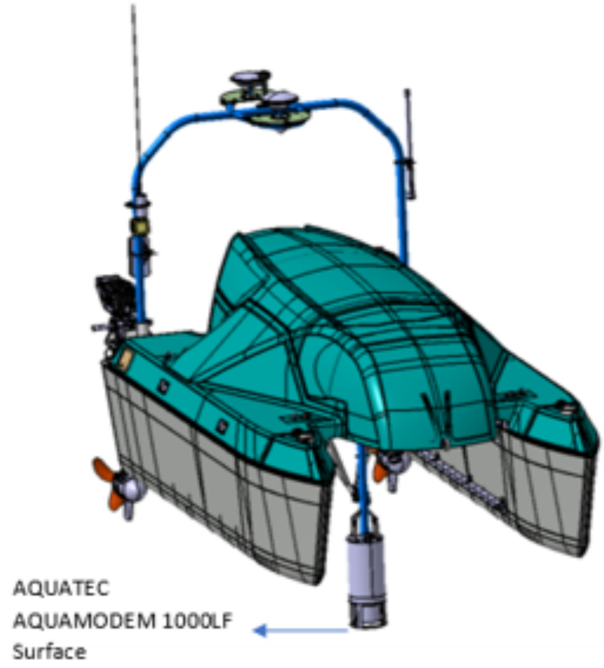

***Figure 7**. ASV*

With the aim of improving the capacity of the NAUTILOS instrument network and implementing RT/NRT (Real Time/Near Real Time) data transmission, integrating the resulting data with other biological and physical measurements to give a more complete picture of biology in the ocean with respect to the biogeochemical and physical environment, they have on board an acoustic and an optical modem:

- the AQUAmodem 1000, a fully bi-directional acoustic modem, with capability to transmit up to 10 km in its long-range configuration. It is not available as a stand-alone instrument, but provided as a component in custom engineered solutions, and is tailored to customer specific applications to optimise performance, e.g., the OEM version for the AUV.

  The modem provides a bi-directional command and data telemetry link, capable of sending and receiving commands, and communicating data over long range and in deep water. This system allows up to 16 uniquely identified transceivers to initiate or receive command and data transmissions.

  The transceivers include a substantial data storage capability, so that attached equipment can pass data to them in a 'store and forward' mode, for onward transmission when a transmission channel is available. The data can also be recovered later when the modem is retrieved.

With a flexible command and data architecture, including data validation and automatic retransmission requesting, the system can be configured to suit many different commanding, data acquisition and data transmission applications.

Figure 8*.* *AQUAmodem 1000, AQUATEC acoustic modem*

- the AQUAmodem Op2, an advanced optical modem, that provides a seamless interface between the user and any subsea instrumentation with RS232 serial interfaces. It features individual unit addressing and automatic optical or serial data wake-up, to conserve the life of the external battery pack and prolong the service of the device. The instrument permits short-range interrogation, commanding, and data download for the subsea monitoring equipment, providing a cost-effective and efficient solution to subsea communication needs.

  Users can benefit from having access to data subsea, which can be particularly useful at times when it is impractical to retrieve the monitoring instruments. The AQUAmodem Op2 has real-time capability (depending on the monitoring instruments), which can save time and money in the field, and allows for prompt analysis of data.

  Once installed, the AQUAmodem Op2 will wirelessly transfer your information ready for analysis.

Figure 9*.* *AQUAmodem Op2, AQUATEC optical modem*

The lander, the AUV and the ASV are connected wirelessly and monitor various events of interest collaboratively. The objective is achieved by having a set of autonomous devices in a network which can self-organize and adapt to deep-sea conditions. Data communication between various heterogeneous underwater and surface-based communication nodes has been required by the growth of underwater operations.

1. USE CASES

Following this plan, the development of platforms will be performed by pursuing a modular approach, e.g., AUV can perform a complete area coverage by easily replacing changing on-board sensor modules.

The networks would be constituted by static nodes (i.e., lander, a seafloor-mounted system), and nodes with controlled motion (AUVs and ASV). This creates a demand for allocating and complementing observational resources, to maximize the information content of the collected data.

Optimum sampling strategy will be implemented by design, to achieve compatibility between the observing capabilities of the different nodes.

These sampling strategies will adapt to the evolution of the environment, considering the motion capabilities of some of the sensor nodes of the network.
Adaptability of the network topology requires continuous feedback of information between the nodes and a data processing unit.

In the frame of sensors-platforms integration, the objectives will be twofold:

1. Research will be conducted to implement NAUTILOS sensors into a various set of vehicles and buoys. This will result in efficient platforms able to provide information about the concentration of substances of interest in the water column with a high spatial-temporal resolution. Navigating platforms (AUV and ASV) will be suitably modified in order to carry out autonomously long-term patrol missions.

2. To investigate the optimum design and exploitation of NAUTILOS heterogeneous monitoring network to characterize the environment area in a timely manner. Meanwhile, techniques will be implemented to find a correct synergy between the different monitoring technologies involved (buoys, controlled vehicles, satellite, etc).

As shown in the Figure 10, there are several possible cases of interaction:

- Acoustic communication between Lander and ASV: Lander pings to ASV to communicate presence and position and to confirm operation of Lander systems. There is also the possibility of two-way communication, i.e., the ASV pings the Lander to activate the weight release.

- Optical communication between Lander and AUV, with a higher bandwidth to allow data to be collected from the Lander at shorter intervals than would normally be the case if data were only collected when the Lander resurfaces. There is also the possibility of two-way communication by updating the lander software or by devising an alternative solution to activate the lander weight release via a command from the AUV.

- Wireless communication between AUV and ASV, ASV can act as relay to ground or space of data collected by the AUV from the Lander. There is also the possibility of two-way communication, as the ASV can act as a scout to confirm the exact position of the Lander to the AUV so as to minimise the time it takes the AUV to find and communicate with the Lander.
- Wireless communication between ASV / AUV and Ground Station and/or Satcomms. The data collected by the Lander are transferred to the operators through the autonomous vehicles ASV / AUV, in particular the ASV is useful for long-range data transmission to the ground station or satellite while the AUV is useful for short-range communication on the ground. There is also the possibility of two-way communication: operators can send commands to the ASV/ AUV.

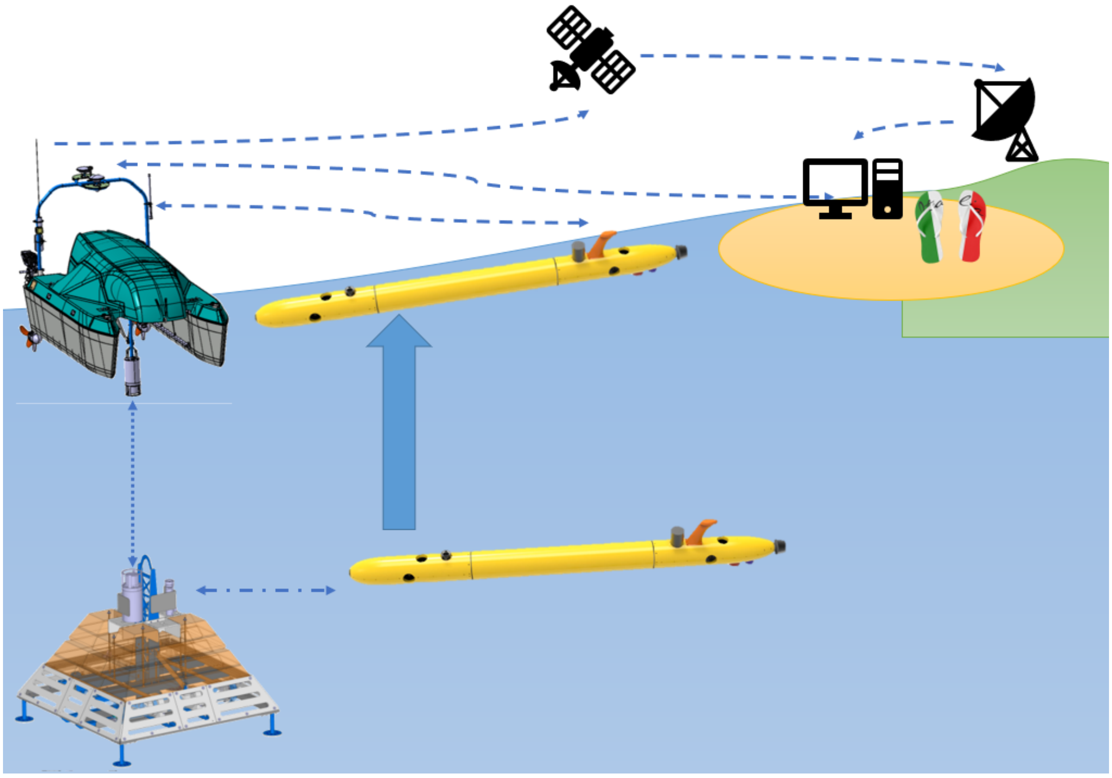

***Figure 10**. Multi-platform network*

There is also the possibility of introducing a situational awareness scenario based on Edgelab's JDeMon GUI. It serves to represent all the data collected by LANDER, AUV and ASV in the mission in a single planning, visualisation and control platform.

The GUI enables monitoring, communication and data sharing.

• Setting-up: A key aspect of the strategy relies on the ability to coordinate the actions between the different technology functions and monitor the operations, especially over long period of unattended activity. A Ground Control Station (GCS) will be implemented for that purpose with the aim of interfacing each technology. The GCS will be equipped with a server for basic processing, navigation data and sensors, necessary for automatic system operations, ICT cloud data transfer technologies. The GCS will extract the data provided by each technology, translate it into a common language and send it to the cloud.

• Use: Sharing the data from each device will allow the populating of a common database, providing a comprehensive view of the operating status (energy consumption, alerts, faults and other important device-specific parameters).

For devices on the move, such as the AUV and ASV, navigation information and the status of various sensors can also be displayed. The database will be updated in real time on the cloud and integrated with available information on environmental and marine weather conditions. Additional tools such as decision support algorithms, data visualisations, statistical probability maps of the correlation of pollution phenomena will be implemented. Finally, all data, sensors and platforms will be geolocalised.

Edgelab's JDeMoN Graphic User Interface (GUI) will include graphical interfaces to allow:

- Mission planning, (optional) monitoring, and post-mission analysis with chart underlay.
- Control setting of Optical and Acoustic Data Link with the platforms.
- Mission Management System (MMS) allows:
    - Mission Modification decided by operator.
    - Mission adaptation to environmental changes detected by AUV or external sensors (user defined).
    - Mission re-planning.

Mission control software is composed of a man-machine interface that presents a tactical map of the operational area, a series of data to give the operator feedback on vehicle behaviour and a set of buttons that allow an operator to set up, initiate and abort a mission.

Each mission pattern is identified by a series of waypoints associated to real geographical positions and depth or altitude (distance from the bottom), that the AUV/ASV needs to reach with a defined speed and heading. To facilitate mission planning task, a set of configurable pre-defined patterns may be selected from a dedicated list.

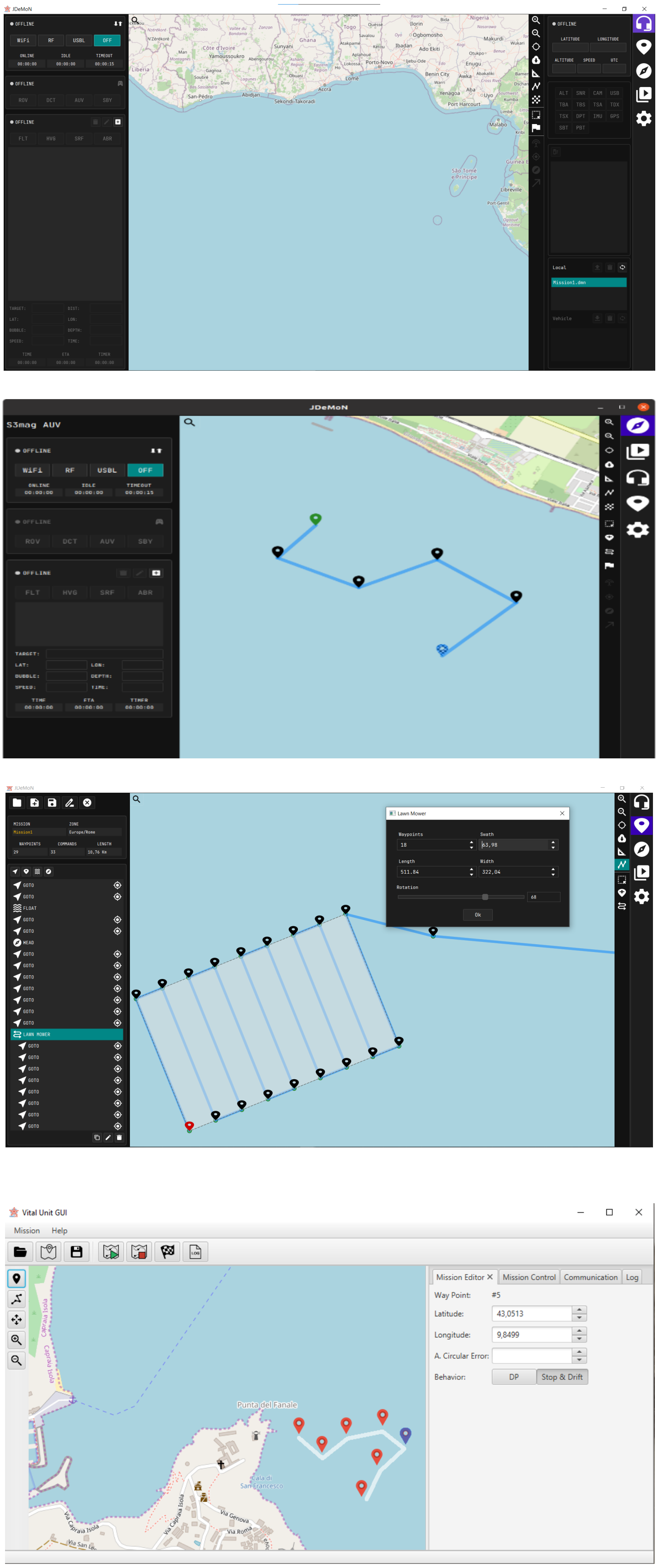

Figure 11. *GUI (from top to bottom): Interface communication panel with chart mapping; Mission planning panel; Lawn-mower path selection; Waypoint path selection*

Regarding waypoint insertion, once the mission planning is complete with depth, speed, etc. and the target models are established, the operator can load the mission into the vehicle, using a dedicated cable or wireless connection.

During the mission loading phase, the vehicle is on the bridge or on the surface while its geographical position is acquired by means of the available satellite positioning systems.

The position of the vehicle is represented by a red arrow (others on request), with the same orientation measured by the vehicle's compass, together with its latitude and longitude which are indicated next to the arrow. At this stage the position of the vehicle and the predicted model (a blue line or other colour) are associated.

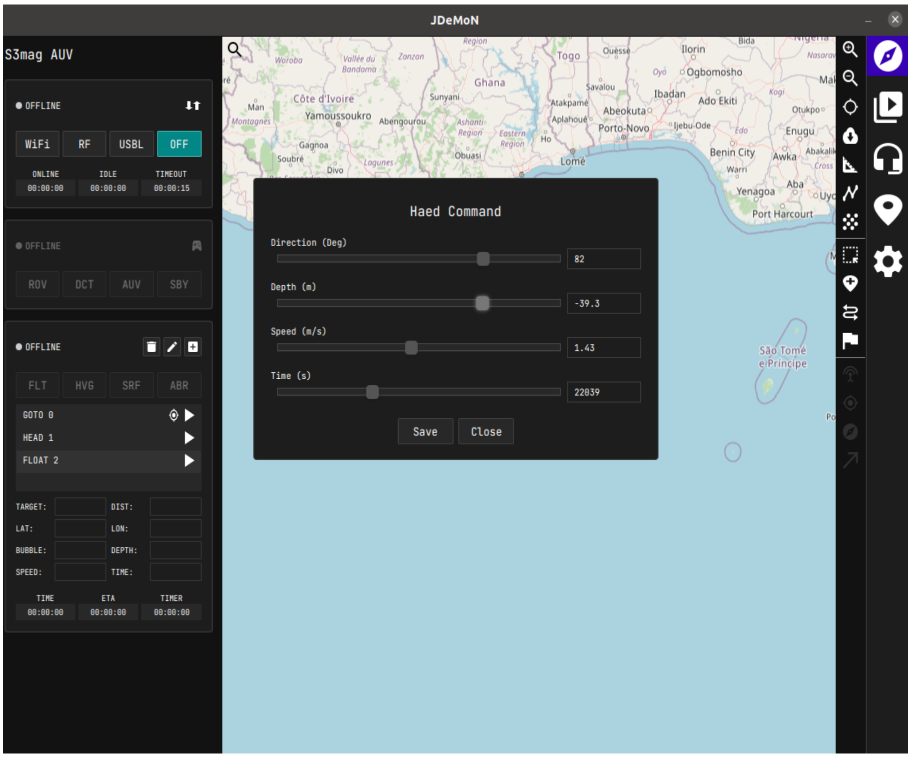

Figure 12. *Vehicle communication interface*

The essential data to be sent to/ from the AUV/LANDER/ASV via optical or acoustic link will be:

- Status sent to surface by AUV/LANDER/ASV of:
    - Vehicle position and depth
    - Speed
    - Ancillary and required status for monitoring the health and other parameters
    - Software status
    - Battery Capacity

- Status sent to AUV/LANDER/ASV from surface/data link of:
    - Mission abort
    - Mission start
    - Mission change
    - Redirect Commands
    - Latitude, Longitude, Depth
    - Payload Control
    - Emergency surface commands

V. SUMMARY

This deliverable concerns the realisation of a “Novel multi-platform cooperative network” through the interconnection of multiple physical platforms and vehicles.

It contains a description of the state-of-the-art in the field of underwater communications and a comparison of various communication protocols and channels. After a preliminary evaluation of available choices, it was decided to implement DAMOCLES based procedures instead of JANUS standard as stated in the Grant Agreement. Advantages of that choice are analysed for implementation in future deliverables (e.g., D5.2).

Use cases are described as established by pursuing a modular approach where networks will be composed by static nodes (i.e., lander, a seafloor-mounted system), and nodes with controlled motion (AUVs and ASV). The objective is achieved by having a set of autonomous devices (Lander, AUV and ASV) connected wirelessly in a network which can self-organize and adapt to deep-sea conditions.

This creates a demand for allocating and complementing observational resources, to maximize the information content of the collected data.

Eventually a Graphic User Interface (GUI) is proposed for realization of situational awareness scenario where all the above nodes will be identified and tracked during execution of missions and deployments.

VI. Appendix: References and Related Documents

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ID	Reference or Related Document	Source or Link/Location
1	DAMOCLES Deliverable D8.1-4 (Modem Specification) Rev2.09	*DAMOCLES Project Archive*
2	D13.6. DU - Requirement No. 9_27.04.2021_v3	*NAUTILOS Project Archive*