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SPACE AND UNDERWATER PNT FOR CLIMATE CHANGE MONITORING

Luca Andolfi[1], Mirko Antonini[2], Stefano Binda[3], Paolo Braca[4], Luciano Bozzi[2], Sandro Carniel[4], Nicola Forti[4], Giorgio Ioannou[4,5], Elizabeth Laier English[3], Margherita Lenoci[1], Leonardo M. Millefiori[4], Alfredo Renga[5], Aniello Russo[4], Giuseppe Tomasicchio*[1]

[1]*Telespazio SpA, Rome, Italy*

[2]*SpaceExe srl, Rome, Italy*

[3] *ESA/ESTEC, Noordwijk, The Netherlands*

[4]*CMRE, Centre for Maritime Research and Experimentation, La Spezia, Italy*

[5]*University of Naples Federico II, Italy*

* Corresponding Author

Abstract

Global warming affects the whole Earth's climate, particularly on polar regions, where large ice volumes are continuously melting at unprecedented rate. These phenomena are also monitored by satellite-based Climate Change Monitoring (CCM) methodologies contributing to depicting the global climate evolution. However, although remote sensing satellites are very accurate in monitoring the melting glaciers, they provide scarce or no information about under-ice water characteristics. The latter ones represent a challenge for CCM, as currently only handful Ice Tethered Profilers (ITPs) provide sustained monitoring of the upper Arctic Ocean water column. Mobile platforms would represent a substantial integration of the ITPs, which move slowly with the sea ice without possibility to select the specific area where the data are collected. In this context, this paper aims at giving an overview on how capabilities provided by underwater Positioning, Navigation and Timing (PNT) technologies can support CCM. Underwater PNT is intended to be integrated with Global Navigation Satellite Systems (GNSSs) and complement CCM solutions. The main challenge in the underwater is that no standard procedure is available, especially in the case of under-ice PNT, since GNSSs are unsuitable for any underwater application due to the electromagnetic wave dissipation in the water. Autonomous under-ice navigation is then complicated by some challenges, for instance the presence of floating ice. Nonetheless, the contribution of under-ice data to the CCM methodologies is of paramount importance. The role of GNSSs is still crucial in underwater missions, indeed the absence of underwater PNT can be mitigated by leveraging on GNSS surface references. Moreover, the data, collected during underwater missions, need to be georeferenced and integrated with satellite information to improve the CCM capabilities. In this way, satellite ranging observations become key enablers for the underwater exploration, asset tracking and management and data set collection. The polar ices position measurements, based on space and underwater reference assets, represent valuable data sources, which can be correlated with satellite earth observation data to improve CCM capability. This paper provides a review of the underwater PNT technologies in terms of sensors, instrumentations, and platforms, including moored beacons, remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs), and highlights the technical challenges and possible solutions. Finally, a particular focus on environmental friendly assets such as gliders and bioinspired robots will be presented, with an analysis of the possible use cases.

Keywords: (Climate Change Monitoring, Space and Underwater PNT, Autonomous under-ice navigation, gliders and bioinspired robots)

Acronyms/Abbreviations

AI: Artificial Intelligence
AUV: Autonomous Underwater Vehicle
BW: Bandwidth
BL: Baseline
CCM: Climate Change Monitoring
CMRE: Centre for Maritime Research and Experimentation
CSAC: Chip Scale Atomic Clock
CTD: Conductivity, Temperature, Depth
DR: Dead Reckoning
DVL: Doppler Velocity Log
ECV: Essential Climate Variables
EM: ELECTROMAGNETIC
EU: European Union
FLS: Forward-Looking Sonar
GCOS: Global Climate Observing System
GHG: Greenhouse Gas
GNSS: Global Navigation Satellite Systems
KPI: Key Performance Indicator
INS: Inertial Navigation Sensor
ITP: Ice Tethered Profiler
LB: Long Baseline

MUV: Manned Underwater Vehicles
NOC: National Oceanography Centre
OCXO: Oven Controlled Crystal Oscillators
PIG: Pine Island Glacier
PNT: Positioning, Navigation and Timing
RD: Reference Document
ROV: Remotely Operated Vehicle
SBL: Short Baseline
SLAM: Simultaneous Location and Mapping
SNR: Signal-to-Noise Ratio
TCXO: Temperature Compensated Crystal Oscillator
TL: Transmission Loss
ToF: Time of Flight
UAS: Unmanned Aerial System
UAV: Unmanned Aerial Vehicle
UNFCC: UN Framework Convention on Climate Change
USBL: Ultra Short Baseline
UTC: Universal Time Coordinated
UUV: Unmanned Underwater Vehicle
WHOI: Woods Hole Oceanographic Institution
WMO: World Meteorological Organization

1. **Introduction**

In the last decades, global warming is affecting the Earth’s climate and this is generating perilous consequences in all the planet regions, including the polar areas. These phenomena are principally monitored by satellite-based Climate Change Monitoring (CCM) methodologies contributing to depicting the global climate evolution [RD-01] [RD-02]. This work aims at giving an overview on how capabilities provided by underwater Positioning, Navigation and Timing (PNT) technologies can support CCM. The paper is structured as reported below. In section 2 an overview of Climate Change is provided, introducing the objectives at international level to stabilize GreenHouse Gas (GHG) concentrations in the atmosphere. Section 2.1 deals with a focus on how Climate Change is currently monitored, moving to the techniques used for under-ice monitoring in Section 3. In the same section the needs and PNT Key Performance Indicators (KPIs) are reported, considering principally both position and time accuracy in different steps of a typical operative scenario. Section 3 ends with the expected improvements introduced by advanced PNT technologies in the under-ice environment. Section 4 provides a focus on the PNT technologies mentioned in the previous section, highlighting challenges (endurance, range, accuracy, etc), performance, and alternative solutions introduced by environmental friendly assets such as gliders and bioinspired robots. Finally, a description of CCM scenario with glider fleet and the exploitation of data and images from the ambitious Earth observation programme concludes this work.

2. **Climate Change Context overview**

The Climate Change refers to long-term shifts in temperatures and weather patterns [RD-03]. These shifts may be natural, such as through variations in the solar cycle.

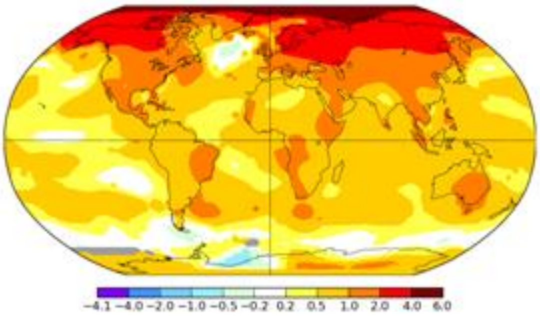

Fig. 1. Average surface air temperatures during winter from 2011 to 2020 compared to the 1951–1980 winter average [RD-04].

But since the 1800s, the impact of human activities gained a place among the main drivers of climate change, primarily due to burning fossil fuels like coal, oil and gas. Burning fossil fuels generates GHG emissions that act like a blanket wrapped around the Earth, trapping the sun’s heat and raising temperatures.

As a result, the Earth is now about 1.1°C warmer than it was in the late 1800s. The last decade (2011-2020) was the warmest on record. Fig. 1 confirms this pronouncement.

Many people think climate change mainly means warmer temperatures. But temperature rise is only the beginning of the story. Earth is a system, this means that everything is connected, so changes in one area can influence changes in all others.

The consequences of Climate Change now include, among others, intense droughts, water scarcity, severe fires, rising sea levels, flooding, melting polar ice, catastrophic storms and declining biodiversity.

With the polar ice caps melting, global sea levels rising and cataclysmic weather events increasing in ferocity, no country in the world is safe from the effects of climate change. That is the reason why European Commission, with the 2030 Climate Target Plan, proposed to cut GHG emissions by at least 55% below 1990 levels by 2030 in order to set European Union (EU) on a responsible path to become climate neutral by 2050 [RD-05]. Acknowledging that change in the Earth’s climate and its adverse effects are a common concern of humankind, the UN Framework Convention on Climate Change (UNFCCC) established an international agreement with the objective of stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system [RD-06]. In that framework, the UN Climate Change Conferences are yearly held.

According to the European Environment Agency [RD-07], GHG emissions in the EU decreased by 32% between 1990 and 2020, a notable overachievement of the EU’s 2020 reduction target of 20%. Preliminary estimates indicate that emissions rebounded in 2021 but remain below pre-COVID-19 levels. The 2021 emissions increase was driven by the recovery from the pandemic and a greater uptake of energy sources with higher emissions in the second half of 2021. To bring the 2030 target within reach, EU Member States will need to align their ambitions and efforts, in order to achieve the new net 55% reduction. Historical trends and future projections of EU emissions highlights the need for further efforts in cutting GHG releases.

2.1 Climate Change Monitoring (CCM): State of Art

A Climate Change Monitoring (CCM) System integrates satellite observations, ground-based data and forecast models to monitor and forecast changes in the weather and climate. A historical record of spot measurements is built up over time, which provides the data to enable statistical analysis and the identification of mean values, trends and variations. The better the information available, the more the climate can be understood, and the more accurately future conditions can be assessed, at the local, regional, national, and global level. This has become particularly important in the context of climate change, as climate variability increases, and historical patterns shift [RD-08].

The World Meteorological Organization (WMO) stimulates and coordinates climate-monitoring activities around the world and helps build climate-monitoring capacities in many countries. Despite the enormous strides made, significant gaps persist between the scientific and political understanding of how climate change risks cascade through environmental, social and economic systems. In order to monitor the state of the global climate, WMO uses seven state-of-the-climate indicators. Each climate indicator was chosen for its clarity, relevance to a range of audiences and ability to be calculated regularly using internationally accepted and published methods and accessible and verifiable data [RD-09].

The Global Climate Observing System (GCOS) is a co-sponsored programme that regularly assesses the status of global climate observations and produces guidance for its improvement. GCOS has identified a set of geophysical variables, called Essential Climate Variables (ECVs), which need to be observed to obtain evidence of climate change and to support climate research and emerging climate information services. Current 54 ECVs, listed in Table 1, are grouped into three categories: Atmospheric, Terrestrial and Oceanic. Among them, the Copernicus Climate Change Service routinely monitors and analyses more than 20 ECVs, by means of its space components, namely the Sentinel satellites [RD-10].

3 Climate Change under-ice monitoring

Ice environment is one of the most inaccessible and poorly known on Earth.

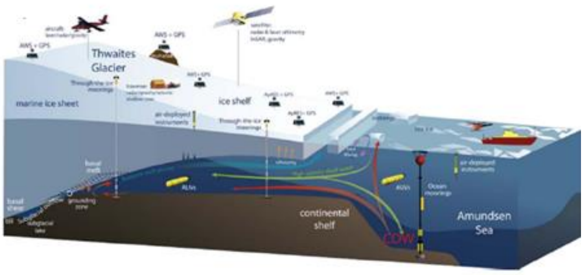

Fig. 1: Climate Change oceanographic exploration under an ice shelf [RD-11]

As also depicted in Fig. 2, proper knowledge of the underwater dynamics of such regions is crucial to a better understanding of issues such as glacier melting, or in general the role of the ocean in Climate Change.

Although remote sensing satellites are very accurate in monitoring the melting glaciers, they provide scarce or no information about under-ice water characteristics.

The latter ones represent a challenge for CCM, as currently only handful Ice Tethered Profilers (ITPs [RD-12]-[RD-13]) provide sustained monitoring of the upper Arctic Ocean water column. ITPs are deployed every year through the sea ice and they collect one profile per day (or more) of temperature and salinity from 5m depth down to 500m-800m. ITPs are a precious source of data, and allow discovering unknown aspects of the Arctic Ocean dynamics. Mobile platforms, in particular underwater robots, namely Unmanned Underwater Vehicles (UUVs), would represent a substantial integration of the ITPs, which move slowly with the sea ice without possibility to select the specific area where the data are collected.

The deployment of UUVs, Fig. 3, is far from being a standard operation. The number of activities carried out at very high latitudes during these years remained very low. Among them, it is worth to mention the activity of the National Oceanography Centre (NOC), or the Woods Hole Oceanographic Institution (WHOI). The reason is that there are a lot of challenges related to UUVs deployment and operations. They will be further addressed in following sections.

Now it is important to underline that the fundamental issue related to under-ice operations, and underwater operations in general, it is represented by the marine environment itself. Water medium is very conductive, which causes electro-magnetic (EM) waves to dissipate and attenuate very quickly [RD-15].

Table 1. Essential Climate Variables (ECV) [RD-14]

DOMAIN	**SUB-DOMAIN**	**ECV**
ATMOSPHERE	Surface	Wind speed and direction, pressure, temperature, …
	Upper-Air	Lightning, temperature, wind speed and direction, …
	Atmospheric composition	Aerosols, GHGs, clouds, ozone
LAND	Hydrosphere	Groundwater, lakes, river discharge, terrestrial water storage
	Cryosphere	Glaciers, ice sheets/shelves, permafrost, snow
	Biosphere	Albedo, fire, land surface temperature, soil moisture, …
	Anthroposphere	Anthropogenic water use, anthropogenic GHG fluxes
OCEAN	Physical	Sea level, sea ice, sea state, subsurface currents, …
	Biogeochemical	Oxygen, ocean colour, N_2O, inorganic carbon, nutrients, …

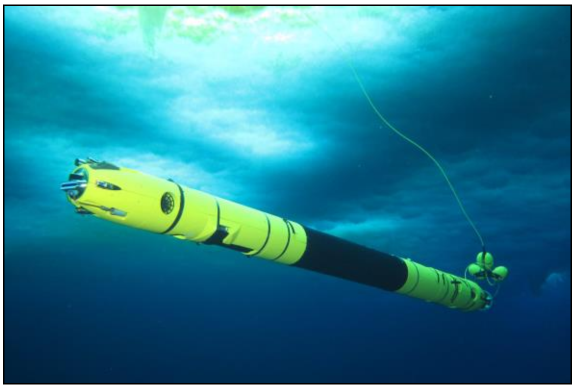

Fig. 3 Example of an Unmanned Underwater Vehicle (UUV): the Icefin under the McMurdo Ice Shelf [RD-16], Credit: Rob Robbins/NSF

The major impact of the extremely rapid EM attenuation is the unusability of Global Navigation Satellite Systems (GNSSs) underwater. This is particularly critical when considering underwater communication, as well as underwater positioning, navigation, and timing (PNT) aspects of UUVs operations. The category that is worsened the most by this drawback is the one to which semi- or fully autonomous vehicles belong, namely the Autonomous Underwater Vehicles (AUVs). The almost total inoperability of EM signals represents the key difference between underwater and above-water operations: any alternative system (acoustic, optical, magnetic) does not show coverage or accuracy that are comparable to the ones obtained through a GNSS.

3.1 Needs and PNT KPIs

In order to be effectively useful to CCM, a typical operational scenario is defined and analyzed. The aim is to determine technical requirements and understand the limits of current PNT technologies. Indeed, the scenario focuses on the exploration of the environment under an ice shelf, a large floating platform of ice that forms where a glacier, or ice sheet, flows down to a coastline and onto the ocean surface [RD-17]. An ice shelf is often very huge, it can reach a thickness of up to 900-1000 m and an extension of hundreds of kilometers. Thus, the navigation capabilities are challenging especially in terms of endurance.

The scenario consists in different phases that will be individually analyzed.

- *Deployment*: all the platforms and instruments, namely the assets, must be unfolded to reach the under-ice location to be explored.
- *Navigation and Data Acquisition*: once the assets reach the desired location, the exploration of the unknown area begin.
- *Homing*: when the exploration of the area is concluded, all the deployed vehicles have to go back to the recovery point.

The powerful capabilities required when performing PNT are as follows. Positioning is the ability to determine a generic target (person, object) position and orientation precisely with respect to a reference geodetic system (e.g., WGS84). Navigation is the ability to calculate a path from current position to a desired position anywhere in the world. Finally, timing corresponds to the ability to maintain accurate and precise time in accordance with time standards like the Universal Time Coordinated (UTC).

In above-water applications GNSS is the first choice to provide PNT services because of its advantages of wide coverage, high accuracy, and low cost [RD-18]. Under-ice PNT relies mainly on acoustic techniques and in some recent applications cameras are employed too. Magnetometers instead are likely to not being leveraged because an a priori map of the under-ice magnetic field is necessary to make them suitable for Underwater Positioning and Navigation. In reality, GNSS signals still have a role in every underwater mission to update UUV's position when they re-surface [RD-19]. With regard to the scenario being considered, the deployment point position (as well as the recovery point position) must be known with a high accuracy. Usually an icebreaking (or at least ice-capable) mothership is leveraged and its above-water location is periodically updated with a GNSS. The continuity of these data is critical especially in the Homing phase. In Polar Regions, large ice volumes are continuously melting. So, the position where UUVs are allowed to re-surface near the mothership and then recovered, is often different from the deployment point position. The accuracy of those measurements also becomes critical for the data acquisition phase. Under-ice properties and data, collected during the mission, need to be georeferenced in order to be effectively usable for a reliable CCM.

As previously said, one critical requirement is related to the time synchronization. Indeed, sensors rely on precise timing to be effective. However, because time from GPS and Galileo is unavailable underwater, these sensors must leverage high precision clocks for internally stable and accurate time stamping. For current applications the short-term stability less than 10^{-11} at 1000s [RD-20] shown by a modern Chip Scale Atomic Clock (CSAC) can be considered adequate for underwater missions of even monthly duration, without requiring a high frequency of periodic resurface (an extremely tough task when navigating under an ice shelf) to perform GNSS resynchronization [RD-21].

One more demanding need is related to the operating conditions, instead. For instance, it is necessary that the navigation instruments can work at temperatures around the freezing point. Nameplate data of many different instruments indicate a minimum operating temperature even below 0ºC, but at a similar temperature, mechanical components that must move (e.g., the propeller of the AUVs), working in non-optimal conditions can increase energy consumption, thus reducing battery life, which is another critical challenge. The area to be explored under the ice is very huge: a coverage of 10 km is necessary. Considering underwater application this is a very tough requirement, especially considering the use of acoustic beacons as done in the most recent experiments (e.g., ICEX20 [RD-22]).

Requirements on horizontal and vertical (H/V) accuracy in positioning are not so stringent: it is sufficient to locate the vehicle with an accuracy of 50 m at the maximum range. To be more consistent, H/V accuracy requirements vary according to the different phases of the under-ice mission: during Navigation and Data Acquisition, the requirement on vertical accuracy is more stringent than the horizontal accuracy requirement. This is related also to the collision avoidance field: the vehicle should be capable of detecting and avoiding an obstacle which is in front of it. In the same way, it should be kept in mind that the environment to be explored is completely unknown, so it is the morphology of both the seabed and the underside of the ice shelf [RD-23]. Therefore, the vehicle has sensors on-board that will ensure to keep safe distances from both upper and lower physical obstacles. An accuracy of 2 m in vertical displacement (collision avoidance from ice and seabed) and half meter in horizontal displacement (collision avoidance from frontal obstacles) are necessary with a time to alarm of 10 s.

In Section 4, the overview of the nowadays available technology help to understand the limitations of underwater PNT with respect to the requirements that there have been discussed and resumed in Table 2.

3.2. Climate Change Monitoring methodologies supported by PNT technologies: expected improvements

In two recent missions of under-ice exploration at Pine Island Glacier (PIG), arguing that the environment beneath an ice shelf is almost totally inaccessible by other means than AUVs, a lot of data related to the investigation of the ice shelf's shape, the seabed bathymetry, the currents and the physical oceanography within the ice cavity has been collected first, where all operations has been carried out by an Autosub3 AUV [RD-24] by National Oceanography Centre (NOC). The second experiment, a one-year mission conducted by University of Washington and funded by Paul G. Allen Family Foundation, sought to demonstrate the technology and gather more data from the underside of ice shelves [RD-25]. In this case Seagliders were deployed and, together with them, the following assets were placed:

- Acoustic beacons moored at seafloor (in known locations), that played a fundamental role in the project.
- EM-APEX, floating instruments that drift with the currents at preselected depths to collect more data.

In particular the main difference between the two exploration strategies relied on the different kind of involved AUVs such as: the Autosub3, propeller-driven AUV, deployed by NOC, and the Seagliders, buoyancy-driven AUVs, deployed by University of Washington, see Fig. 4. The exploration experiences underlined the importance of time synchronization of the nodes of an underwater acoustic network, particularly when the nodes are AUVs operating in formation, is a prerequisite for the effective use of collected sensor measurements as well. One of the methods adopted to operate AUVs synchronously is to synchronize their clocks at the surface (typically by means of Global Position System - GPS) and then use a low-drift clock for maintaining the desired precision while submerged. Unfortunately, there are many situations in which the vehicle cannot easily surface. Under-ice exploration is a prime example of this restriction caused by the presence of the ice. So even if considering the navigation of a single AUV, its sensors rely on precise timing to be effective. These sensors have generally relied on Oven Controlled Crystal Oscillators (OCXOs), or Temperature Compensated Crystal Oscillator (TCXO), for stable and accurate time stamping within the sensor. A recent alternative is the Chip Scale Atomic Clock (CSAC): according to the manufacturer, Microsemi Corp., this has two orders of magnitude better accuracy than OCXOs or TCXOs oscillators. Precisely, CSAC maintains far higher accuracy for far longer periods, uses much less power and maintains a much more stable frequency despite the wide variations in temperature that sensors may encounter. Even if the measured clock drift is very low, in general UUVs need to periodically re-synchronize their clocks to that of a GPS emerging at the surface. Since in this under-ice scenario this is not feasible, in [RD-27] it is proposed to perform periodic acoustic clock synchronization. In particular, it is shown that the frequency of the periodic resynchronization can be extremely reduced using CSACs. For what concerns the under-ice scenario, the mission is focused on oceanographic measurement. Thus, for acoustic positioning at a maximum range of 10 km, an error of even 100 m can be accepted.

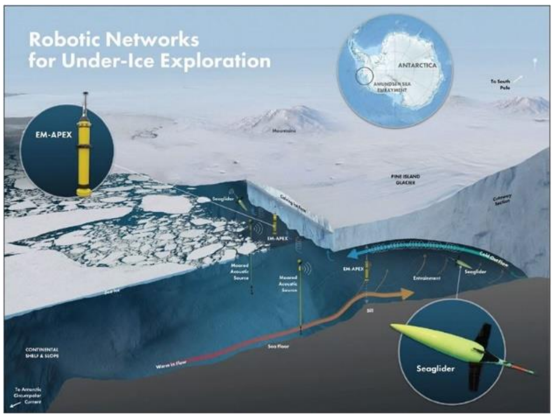

Fig. 4: Infographic of the mission under the PIG ice shelf [RD-26]

Considering a range measurement made by an AUV, the error of the clock on-board leads to an error in ranging equal to the product between it and the speed of sound *c*. It is possible to get an idea of the maximum acceptable error e_{max} that is possible to cumulate by the AUV's clock in the following way. Neglecting all the issues in acoustic transmission, considering a value of *c* equal to 1450 m/s, e_{max} around 10^{-3}s. By considering all the approximation, this is a very optimistic forecast. But even if this is a very rough approximation, e_{max} is likely to reach a value not lower than 10^{-5}s. An atomic clock will stay far from a similar error probably for a period longer than the mission duration.

This is also the reason why the Seagliders of University of Washington successfully navigated for one year under PIG ice shelf.

Collision avoidance is another important feature: AUVs that perform exploration under the ice shelf must have sensors on-board that will ensure to keep safe distances from both upper and lower physical obstacles, as well as to detect and avoid obstacles in front of them.

It must be clarified that not all the currently used AUVs are equipped with obstacle avoidance systems, mainly because the mission area is well known and mapped. One of the major challenges in under-ice exploration is the very little knowledge of the environment [RD-28]. Therefore, it is necessary to identify some exteroceptive sensors that may help to provide information about the environment and help in detection and then avoidance. Again, some acoustic sensors, more specifically sonar sensors, belong to this category. Two types of technology share the name “sonar” (from “sound navigation and ranging”): active sonar involves the emission of pulses of sounds and then the returning echoes are listened, while passive sonar essentially listens and detects signals against a background of ambient noise. The information required to a safe navigation can be so provided by a so-called Forward-Looking Sonar (FLS). It produces a beam of a certain swath to detect objects in the illuminated area (so forward, but also upward or downward).

Optical technologies are a relevant option to provide similar information. Despite the poor transmission of light through water, which results in a limited range for imaging systems, they have been also recently used to perform vision-based underwater Simultaneous Location and Mapping (SLAM) [RD-29], as described in following sections.

4. Underwater PNT technologies

In the previous section some high level underwater PNT
In the previous section some high level underwater PNT KPIs related to CCM application have been identified.

The next step is to understand the limits of current PNT technologies. It is therefore necessary to focus on what kind of platforms are nowadays deployed and what sensors they are equipped with.

In general, Underwater Vehicles (UVs) fall into two basic categories, which are UVs with a crew, so the Manned Underwater Vehicles (MUVs) and UVs without a crew, namely the UUVs. Over the years, the development of UUVs differed not only in terms of size or operations to carry out, but also in terms of degree of autonomy. The lowest level of autonomy is gained with Remotely Operated Underwater Vehicles (ROUVs or simply ROVs): An umbilical cable, or tether, physically links the ROV (therefore, it is termed tethered), to both its power supply and to a control station, where a specifically trained operator guides it, based on sensor’s measurement [RD-30].

Most ROVs have on board high-definition cameras and robotic arm manipulators; these human interface systems augment operator’s working abilities providing increased intervention performance. Actually, this is not always necessarily true, because when intervention capabilities are taking into account, the topic probably concerns a particular type of ROVs: working-class ROVs. Those are distinct from the observation-class ones.

However, the main drawback of ROVs comes from the above-mentioned tether, which results in constrained vehicle maneuverability and short mission range. Hence, the first advantages of AUVs: unmanned, untethered, self-propelled vehicles. An AUV navigates without real-time control by human operator for a range of time that can last from few hours to several days. Moreover, it can also intelligently make decisions and change their mission profiles based, for instance, on changes in environmental data. Thus, resulting in not abandoning the operational area, and so resuming and carrying out its mission, even in the worst conditions.

4.1 Remotely operated and autonomous platforms: sensors and instrumentations for state-of-the-art underwater navigation and data collection

The simplest method to locate a vehicle is through Dead Reckoning (DR). It is typically done using an Inertial Navigation System (INS). Then to correct the unavoidable localization error, the most reliable choice is coupling inertial measurement with GNSS measurement.

In underwater applications the unavailability of GNSS

Table 2. Needs and PNT KPIs

STEP	NEED	PNT KPI
1 – Deployment 3 – Homing	Deployment/Recovery point positioning	Lat/Lon accuracy: 1.5 m
		Continuity: 99.9% over 3 hours
	Mothership-UUVs communication link	Range/Coverage: 1000 m
		H/V accuracy: 50 m at max range
2 – Navigation and Data Acquisition	UUVs positioning	Range/Coverage: 10-50 km
		H accuracy: 50 m at max range
		V accuracy: 1 m at max range
	Time synchronization	Maximum clock error before re-synchronization > 10^{-5} s
	Collision avoidance	V accuracy: 2 m
		H accuracy: 50 cm
		Integrity Alert Limit: 25 m
		Time to alarm: 10 s

makes necessary for UUVs to re-surface and acquire a new position-fix. Then they will have to reach again the location of interest. This latter task is not easy if adequate navigation capabilities are not available. However, this process can result in potential inefficiencies, being resource-intensive and time-consuming.

In underwater domain, one first classic approach is to couple INS with a Doppler Velocity Log (DVL) [RD-31], which measures the velocity by transmitting acoustic pulses and measuring the Doppler shifted returns from these pulses.

However, DVL is subject to drift and biases as well as the INS, leading to growing position uncertainty. Another way of leverage acoustic signals is to employ acoustic transponders, electronic devices used to receive and transmit signals. The basic idea is to leverage external beacons deployed in known positions that returns the signal coming from the vehicle. Then the position is determined by measuring the Time of Flight (ToF) of the signal to calculate the distances between the vehicle and each beacon. This technique is called Baseline (BL) Acoustic Positioning System and depending on the distance between the beacons it is possible to distinguish the following three categories [RD-31]. With Long Baseline (LBL) Positioning, the beacons are typically anchored (either above water or to the seabed) in the corners of the work site within which the vehicle operates. The BL is of hundreds or thousands of meters. The BL is in the order of the meters and the accuracy improves with spacing, when using Short Baseline (SBL): the transponders are deployed from boats or ships that are either anchored or under way. Finally, Ultra-Short Baseline (USBL) provides the use of three or more transducers separated by a BL of 10 cm or less. Then positioning is performed through phase difference measurement. In Fig. 5 there are the pictorial representations of the different methods.

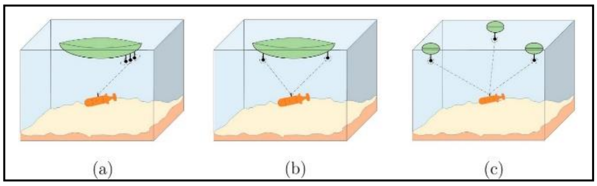

Fig. 5. Baseline Positioning: (a) USBL, (b) SBL, (c) LBL [RD-32]

As an alternative to the use of external assets it is possible to leverage the characteristics of the environment: if an AUV collects information about the surroundings, it is possible to match it with the already available one. This technique is referred to as Geophysical Navigation. The main drawback is that the a priori knowledge of the environment, is essential. This information can be not available, so the alternative technique is Simultaneous Localization and Mapping (SLAM). The AUV builds a consistent map of the environment, and it determines its unknown location within this map. To acquire the necessary information and build the map of the environment, it is possible to leverage again acoustic signals using sonar sensors, and so performing the so-called acoustic SLAM. Two types of technology share the name "sonar" (from "sound navigation and ranging"): active sonar involves the emission of pulses of sounds and then the returning echoes are listened, while passive sonar essentially listens and detects signals against a background of ambient noise [RD-33]. It is possible to use different kind of instruments like cameras or magnetometers: all are valuable alternatives if they can provide reliable information about the surrounding environment.

4.2 Under-ice exploration challenges

Under-ice exploration presents even more difficulties in navigation and communication than in an underwater environment. In addition to the GNSS underwater unavailability, there is a much more significant multipath brought on by the sea ice floating. Drifting sea ice results in very limited maneuverability (especially in ice breaking operations) and it is also a threat to the cables used to deploy instrumentation. Furthermore, it must be considered that large part of polar seafloor remains uncharted at present [RD-34]. So, acoustic sensors are widely used in different underwater vehicles both for data collection and for navigation and communication. Unluckily the behavior of sound waves is anything but linear and strongly dependent to the local speed of sound [RD-35].

In Fig. 6 two typical sound-speed profiles are represented: the underwater one is a typical profile resulting from the data tabulated in [RD-36], whilst the under-ice sound speed profile is computed from Conductivity, Temperature, Depth (CTD) data acquired during the ICEX11 mission in Alaska by Naval Postgraduate School officers in 2011 [RD-37]. The speed of sound strongly depends on temperature, salinity, and pressure, but those parameters are affected by seasonal and diurnal changes as well as by geography. This means that the value of the speed of sound at different depths is hardly predictable and many measurements must be done to estimate it. The different propagation paths as function of copious factors result in a remarkable change in signal strength, which is standardly measured by the Transmission Loss (TL). These losses increase with both increased frequency and increased range, and one might think to use low frequencies to reduce the effect, but at very low frequencies the interaction with the sea bottom can cause even high losses [RD-38].

Thus, typical values of sound frequencies used in under-

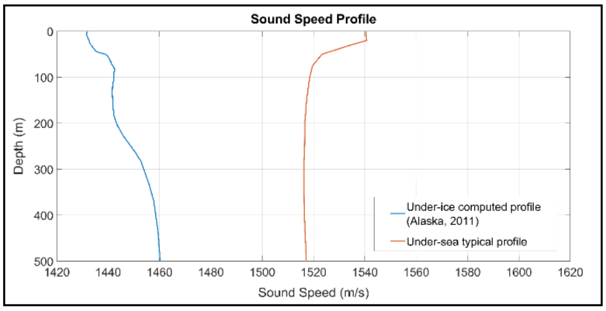

Fig. 6. Comparison between underwater and under-ice sound speed profiles.

ice environments are between 500 Hz and 1 kHz. In reality the signal is not marked by a given frequency (also called carrier) only, but it is characterized by a specific bandwidth (BW) centered on the carrier. The width of the band is the maximum data quantity that is possible to send. But this does not mean that the larger is the BW, the better will be the quality of the communication. There is a noise that is caused by the agitation of electrons that cannot be eliminated since electrons exist in all materials. This so-called thermal noise is function of temperature, but also of BW. The parameter that is usually used to evaluate the quality of the communication is the Signal-to-Noise ratio (SNR), the ratio between signal power and the power of the total noise present in the considered system. The behavior of the acoustic signal thus greatly impacts the performances of Acoustic Navigation, with a strong reduction of range and accuracy.

Focusing on the vehicles, one of the major drawbacks of propeller-driven AUVs is related to their endurance, which hardly is more than few dozens of hours, depending on the application. Completely different endurances are the buoyancy-driven gliders capable of. This kind of vehicles is not equipped by traditional propellers or thrusters, but it is just fitted with hydrofoils: the motion of a not fixed internal mass (typical its own battery) leads an imbalance that allows the glider to pitch up and down, as well as rolling left or right . The combination of upward/downward force with the change in attitude allow the wings and body to generate the hydrodynamic lift and drag forces which propel the gliders horizontally and vertically through the water [RD-39]. The vehicle continuously dives and climbs in the water column at very low speed, usually at about 1-2 km/h, but can maintain this speed for months on end [RD-40]. A drawback to this very long endurance is a limited maneuvering capability, but it is rarely a tight requirement in typical applications where gliders are deployed (oceanographic measurement foremost).

Another critical challenge of sea ice environments is represented by the fact that ice is not fixed, but continuously moves and changes [RD-41]. The two Copernicus Sentinel-1 satellite images reported in Fig. 7 clarify the previous statement: the Greenland Sea between Greenland (not visible) and Svalbard Islands is captured. The picture on the right have been acquired almost 25 hours after the picture on the left. The morphological variation of the ice (in grey) is evident. Then, the analysis of some extreme points of the ice front also shows displacements of about 26 km. It corresponds to a movement of about 1 km/h which is fast enough to be an issue for most of AUVs, especially in the Homing phase of the mission that includes the re-surface of the assets. Moreover, in the Navigation phase ice change is particularly dangerous for a glider, whose speed (often less than 2 km/h) strongly depends on the local ocean current, and eventually the glider.

Ice movement is an issue not only for UUVs, but for any asset deployed, either underwater like ITPs, or above-water, like the mothership. In considering the latter, especially if it is not an ice-breaking ship but simply an ice-capable vessel, crew members must be constantly aware of ice conditions. Following safety rules is also critical since in case of problems, e.g., stuck in ice, several weeks, icebreakers and rescue ships may then be needed to escort the mothership to safety [RD-42]. Such a situation therefore carries a significant monetary burden. In general, the use of mothership involves no small expense even under nominal operating conditions. But above all, the aspect that is most concerned during this analysis is the environmental one. According to [RD-43] marine shipping is responsible for 18-30% of nitrogen oxides and 9% of sulfur oxides of total air emissions. This explains why in the next section, among the possible solutions an alternative that could result in a replacement for the over-polluting ship is included.

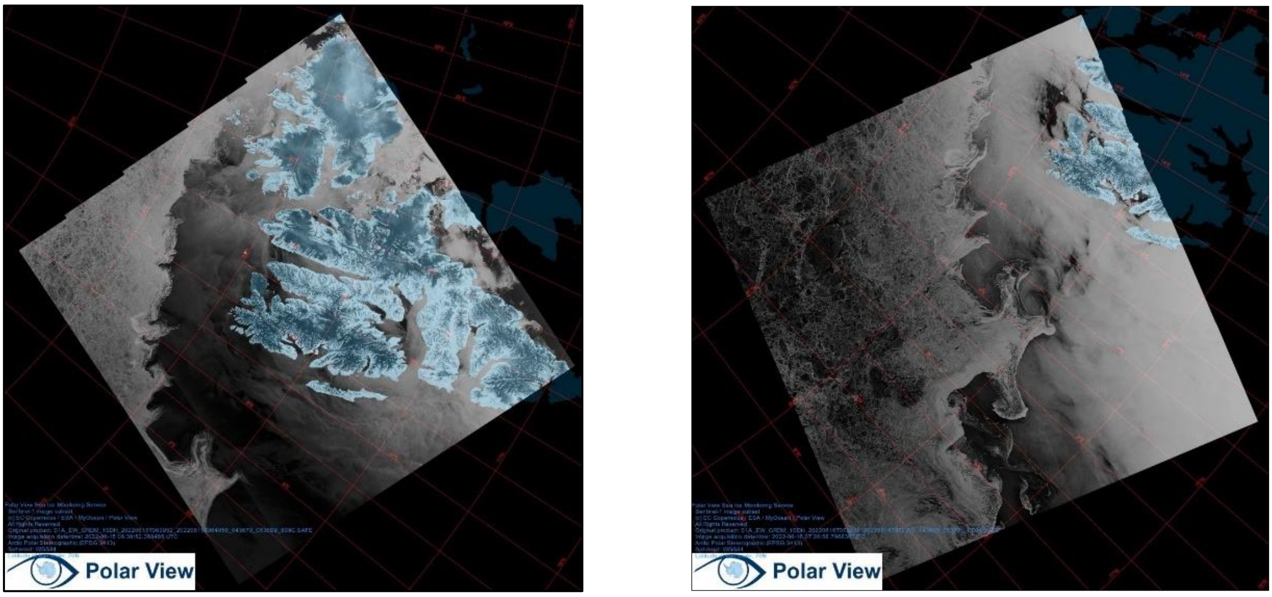

Fig. 7 Ice change and movement in Greenland Sea off the Svalbard Islands (in blue) in 25 hours (ESA @ Sentinel-1).

4.3 Possible solutions

When operating under-ice, there are several challenges affecting the overall PNT performances.

- The range and accuracy of BL systems can be limited by reflectivity issues and intense multipath.
- Optical cameras may not have sufficient features to make useful measurements.
- Ice rapidly changes and moves [RD-44], this adds complexity especially to the surface phase.

To face those issues, some possible technological solutions are selected as the most promising ones.

Starting from the last problem of diurnal ice movement, the solution that first can be taught is to leverage satellites observations in order to monitor that movement. Unluckily the long revisit time of a satellite over the same small portion of Earth surface is too high to be considered for a real time application. In order to cope to this responsiveness issue, new Geo-information techniques are able to exploit different Earth observation Satellites and fuse different remote sensing imaging sources including also the ones collected by manned aircrafts and Unmanned Aerial Vehicles, which represents an interesting alternative technology simple to use, not expensive, and timely in producing aerial photographs of the surveyed area. In recent years, UAV remote sensing technology has developed rapidly and has been widely used in different applications from land use mapping and topography to emergency response, and aftermath assessment [RD-45]. With continuing advancements in functionality, flight time, and payload capabilities, commercial UAS are becoming increasingly capable as aerial survey tools and by using mid-range digital cameras, it is possible to produce very high spatial resolution data. From few years UAS are used for the identification, classification, and monitoring the movement of the ice shelf, as well as in general also floating ice movement [RD-46]. This can be very helpful for different under-ice application.

The limited range of the LBL positioning system, as well as its limited accuracy at the farthest range, are open issues. An interesting possibility is to use environmental data collected in situ and leverage modern algorithms of artificial intelligence (AI). Acoustic propagation highly depends on local environmental conditions, salinity and temperature above all. The accurate knowledge of these parameters, together with an AI trained on historical environmental data, may improve the estimation of the underwater location where the acoustic propagation is the best possible in the explored area. Another criticality is related to the battery life of all the platforms deployed under the ice. An interesting solution is a double-sided answer to also another concern, an environmental one. Thyssenkrupp Marine Systems together with partners from industry and science are developing the Modifiable Underwater Mothership (MUM) [RD-47], a modular extra-large unmanned underwater vehicle (XLUUV). It will be composed of almost freely configurable base and mission modules, enclosed by a hydrodynamic casing. Being also able to work as a rechargeable docking station, MUM can allow the employment of resident systems [RD-48].

It should be pointed that the deployment of such a huge submersible, will valuably lead to not make use of an expensive and pollutant mothership. This green aspect is the key driver for the future technological solutions that must be pursued, according to the main objective of performing CCM.

Following this line of thought, it is worth to mention a particular category of AUVs, namely bioinspired robots. Based on the motion of marine animals, different UUVs have been manufactured in the last decades. Animals have evolved due to their habitat after natural selection to the point of having physical characteristics and excellent morphology [RD-49]. Through a bioinspired optimization approach, it is possible to improve navigation performance. The power consumption can be reduced as well as the disturbance to marine fauna. Interesting designs that should be taken into account emulates the gliding motion of a manta ray. Among them there is the BOSS Manta Ray AUV, developed within B.O.S.S. (Bionic Observation and Survey System) project [RD-50].

5. CCM Mission planning and operative challenges

The role of satellites observation is crucial in the discussed operative scenario. Satellites provide long-term pan-Arctic measurements. These are essential from the initial stages of under-ice exploration mission planning.

Indeed, the accurate knowledge of ice morphology is indispensable to perform safe operation, especially when a mothership is involved.

However, in this research a fundamental focus was placed on the future possibilities of not using a ship as overly polluting.

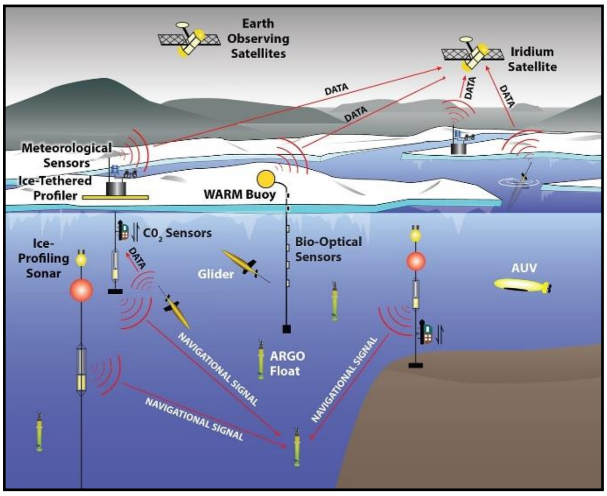

Fig. 8 Technologies for autonomous Arctic Ocean observing. Red lines mark examples of underwater acoustic navigation and communication paths and satellite telemetry for instruments on the surface [RD-51].

So, it is necessary to consider a scenario of a network of autonomous platforms deployed to explore Arctic environment, such as the one described in [RD-51] and reported in Fig. 8.

Here the second fundamental role of satellite observations, namely ranging observations, is highlighted. Underwater assets exchange signals with each other. Some among them are characterized by a surface part, out of the water (e.g., the WARM buoy). There it is possible to get a data link with a satellite. In the case of AUVs, in particular the glider on the right side of the picture, the vehicle is fixing its position with high precision before re-surface.

In summary, the use of satellite EO is fundamental for the success of the exploration mission in the under-ice environment of the Arctic. Besides enabling safe and efficient exploration of the under-ice environment in the Arctic, space EO, e.g. performed by Copernicus satellites, provides long-term measurements of the ice morphology, which is essential in the planning phase of the exploration mission. For instance, the two Sentinel-1 satellite images reported in Fig. 7 are actually part of the dataset used by the NATO Centre for Maritime Research and Experimentation (CMRE) to plan the Nordic Recognized Environmental Picture 2022 (NREP22) mission.

In the CCM scenario a fleet of AUVs is deployed in conjunction with other moored assets. The effective deployment and management of this fleet is heavily reliant on EO data. This is achieved through a geoinformation analysis of optimal routes, which is determined by merging imaging data from multiple remote sensing sources. The accurate knowledge of the ice morphology helps to ensure the safety of the operation, especially when a mothership is involved.

In the previous section, it has already been noted how UAVs have the advantage of being able to collect data from a variety of altitudes and angles, allowing for a more comprehensive view of the environment. Their use, however, is not intended as substitutes for satellites, but rather as a complementary tool: being equipped with various sensors and instruments, such as cameras and lidar, UAVs gather a wide range of data types. Overall, while satellites remain a crucial component of under-ice exploration missions, the use of UAVs alongside them can enhance the quality and timeliness of the data collected.

6. Conclusion

In this work it was investigated how CCM can be supported by underwater PNT technologies and how Underwater PNT is intended to be integrated with GNSSs and CCM. Consequently, under-ice PNT technologies/solutions and their limitations were analysed in this paper.

Currently, CCM System integrates satellite observations, ground-based data and forecast models to monitor and forecast changes in the weather and climate. Unfortunately, they provide scarce or no information about under-ice water characteristics. Moreover, the under-ice environment is characterized by EM attenuation that causes an unusability of GNSS technology. This is particularly critical when considering underwater communication, as well as underwater PNT aspects of UUVs operations.

After the definition of a practical operative scenario, the technical requirements and limits of current PNT technologies was investigated, strengthening the importance of Clocks and Time Synchronization solutions. CSACs resulted to be a valid solution for under-water applications, since they have a stability of 10^{-11} at 1000s. They have higher accuracy for far longer periods, uses much less power and maintains a much more stable frequency despite the wide variations in temperature that sensors may encounter.

Currently, under-ice PNT relies mainly on acoustic techniques (active and passive sonars) and in some recent applications cameras (optical navigation) are employed too. Forward-Looking Sonar (FLS) are usually used to provide information required to a safe navigation. Another technique recently introduced for the underwater navigation is visual-based, called SLAM. Concerning under-ice platforms, which typically require 2 m V accuracy and 0.5 m H accuracy, manned and unmanned ones can be employed; ROVs are a particular class of platforms, that are characterized by constrained vehicle maneuverability and short mission range. On the other hand, AUVs navigate without real-time control by human operator for a range of time that can last from few hours to several days. Among them, gliders are currently used since they have not traditional propellers or thrusters, so they are characterized by long endurance but low maneuverability. INS, coupled with DVL, are typically exploited to locate these platforms, in combination with GNSS measurements only when they return above-surface.

So, for the under-water navigation, external beacons can be introduced. This technique is called Baseline (BL) Acoustic Positioning System and, according to beacon relative distance, SBL, LBL and USBL can be installed.

Then, to face all the challenges presented in the paper, e.g., GNSS under-ice unavailability and ice-movement and multipath, different solutions have been proposed as the usage of UAV to collect data rather than satellites that have larger revisit time. Moreover, AI can be used to process large amount of historical data of the environment. Finally, a particular case of AUVs, called bioinspired robots, was introduced, highlighting the necessity to be more sustainable. The last section introduced the way to combine CCM satellites with SAR/EO sensors and previous PNT technologies for under-ice exploration missions.

References

[RD-01] S. J. Purkis and V. V. Klemas, "Remote sensing and global environmental change," John Wiley & Sons, 2011

[RD-02] J. M. Piwowar et al., "Hypertemporal analysis of remotely sensed sea-ice data for climate change studies," *Progress in physical geography*, vol. 19, no. 2, 1995

[RD-03] United Nation, "What Is Climate Change?" [Online]. Available: https://www.un.org/en/climatechange/what-is-climate-change

[RD-04] NASA Goddard Institute for Space Studies (GISS), "GISS Surface Temperature Analysis (v4)," [Online]. Available: https://data.giss.nasa.gov/gistemp/maps/index_v4.html

[RD-05]: European Commission, Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people, Brussels, 2020

[RD-06] United Nations, "United Nations Framework Convention on Climate Change" (1992)

[RD-07] European Environment Agency, "Total greenhouse gas emission trends and projections in Europe" October 2022. [Online]. Available: https://www.eea.europa.eu/ims/total-greenhouse-gas-emission-trends

[RD-08] UN Climate Technology Centre and Network, "Climate change monitoring," [Online]. Available: https://www.ctc-n.org/technologies/climate-change-monitoring

[RD-09] World Meteorological Organization, "Climate Indicators and Sustainable Development," [Online]. Available: https://library.wmo.int/doc_num.php?explnum_id=10804

[RD-10] Thépaut et al. "The Copernicus Programme and its Climate Change Service," IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium, 2018

[RD-11] T.A. Scambos, et al. "How much, how fast?: A science review and outlook for research on the instability of Antarctica's Thwaites Glacier in the 21st century," Global and Planetary Change, Volume 153, 2017, Pages 16-34, ISSN 0921-8181, https://doi.org/10.1016/j.gloplacha.2017.04.008

[RD-12] J. M. Toole et al., "The ice-tethered profiler: Argo of the Arctic," Oceanography, vol. 24, no. 3, 2011.

[RD-13] R. Krishfield et al., "Automated ice-tethered profilers for seawater observations under pack ice in all seasons," Journal of Atmospheric and Oceanic Technology, vol. 25, no. 11, 2008.

[RD-14] Global Climate Observing System, "Essential Climate Variables," [Online]. Available: https://gcos.wmo.int/en/essential-climate-variable

[RD-15] A. Waite, SONAR for practising engineers, 3rd ed., Wiley, 2002, pp. 47-49.

[RD-16] M. Meister et al., "Antarctic Deep Field Deployments and Design of the Icefin ROV," Global Oceans 2020: Singapore – U.S. Gulf Coast, Biloxi, MS, USA, 2020, pp. 1-5, doi: 10.1109/IEEECONF38699.2020.9389361.

[RD-17] R. Greve, H. Blatter, Dynamics of Ice Sheets and Glaciers, 2009, Springer

[RD-18] S. Han, Z. Gong, W. Meng, C. Li and X. Gu, "Future Alternative Positioning, Navigation, and Timing Techniques: A Survey," IEEE Wireless Communications, vol. 23, no. 6, pp. 154-160, December 2016.

[RD-19] P. J. B. Sánchez, M. Papaelias and F. P. G. Márquez, "Autonomous underwater vehicles: Instrumentation and measurements," in IEEE Instrumentation & Measurement Magazine, vol. 23, no. 2, pp. 105-114, April 2020, doi: 10.1109/MIM.2020.9062680

[RD-20] Microchip, "Better Undersea Sensing With the Chip Scale Atomic Clock (CSAC)," [Online]. Available: https://ww1.microchip.com/downloads/en/DeviceDoc/00003876.pdf

[RD-21] Kebkal, K., et al. "Underwater acoustic modems with integrated atomic clocks for one-way travel-time underwater vehicle positioning." Proceefings of the Underwater Acoustics Conference and Exhibition (UACE). 2017.

[RD-22] T. Schneider, H. Schmidt and S. Randeni, "Self-Adapting Under-Ice Integrated Communications and Navigation Network," 2021 Fifth Underwater Communications and Networking Conference (UComms), Lerici, Italy, 2021, pp. 1-5, doi: 10.1109/UComms50339.2021.9598012.

[RD-23] K. W. Nicholls et al., "Measurements beneath an Antarctic ice shelf using an autonomous underwater vehicle," Geophysical Research Letters, vol. 33, no. 8, 2006

[RD-24] S. D. McPhail et al., "Exploring beneath the PIG Ice Shelf with the Autosub3 AUV," OCEANS 2009-EUROPE (2009)

[RD-25] H.Hickey , "One year into the mission, autonomous ocean robots set a record in survey of Antarctic ice shelf," University of Washington, January 2019. [Online]. Available: https://www.washington.edu/news/2019/01/23/one-year-into-their-mission-autonomous-ocean-robots-set-record-in-survey-of-antarctic-ice-shelf/

[RD-26] G. Cario et al., "Clock synchronization and ranging estimation for control and cooperation of multiple UUVs," OCEANS 2016 - Shanghai (2016)

[RD-27] C. Kunz et al., "Deep sea underwater robotic exploration in the ice-covered Arctic ocean with AUVs," in 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2008

[RD-28] J. González-García and al., "Autonomous Underwater Vehicles: Localization, Navigation, and Communication for Collaborative Missions," Applied Science, vol. 10, no. 4, (2020).

[RD-29] R. Christ and R. W. Sr, The ROV Manual - A User Guide for Observation-Class Remotely Operated Vehicles, Butterworth-Heinemann, 2007

[RD-30] C.M. Lee, S.W. Hong, and W.J. Seong, "An integrated DVL/IMU system for precise navigation of an autonomous underwater vehicle," in Oceans 2003. Celebrating the Past... Teaming Toward the Future (IEEE Cat. No. 03CH37492), vol. 5. IEEE, 2003.

[RD-31] G. Cario and al., "Analysis of error sources in underwater localization systems," in OCEANS 2019 - Marseille, Marseille (FR), 2019.

[RD-32] A. Sahoo and al., "Advancements in the field of autonomous underwater vehicle," Ocean Engineering, vol. 181, 2019.

[RD-33] R. Gomez-Ojeda and al., "PL-SLAM: A Stereo SLAM System Through the Combination of Points and

Line Segments," IEEE Transactions on Robotics, vol. 35, no. 3, (2019).
[RD-34] S. D. McPhail et al., "Exploring beneath the PIG Ice Shelf with the Autosub3 AUV," OCEANS 2009-EUROPE (2009)
[RD-35] F. B. Jensen et al., Computational Ocean Acoustics, New York: Springer, 2011.
[RD-36] Audet Jr, John J., and Gregory G. Vega. AESD Sound-Speed Profile Retrieval System (RSVP). OFFICE OF NAVAL RESEARCH ARLINGTON VA ACOUSTIC ENVIRONMENTAL SUPPORT DETACHMENT, 1974.
[RD-37] Freitag, L., Koski, P., Morozov, A., Singh, S., Partan, J., "Acoustic communications and navigation under Arctic ice." 2012 *Oceans*. IEEE, 2012.
[RD-38] P. Norgren, and S. Roger. "Using autonomous underwater vehicles as sensor platforms for ice-monitoring." (2014)
[RD-39] R. Bachmayer and al., "Underwater gliders: recent developments and future applications," in Proceedings of the 2004 International Symposium on Underwater Technology, 2004
[RD-40] National Oceanography Centre, "Gliders," [Online]. Available: https://noc.ac.uk/facilities/marine-autonomous-robotic-systems/gliders
[RD-41] L. Barker et al., "Scientific Challenges and Present Capabilities in Underwater Robotic Vehicle Design and Navigation for Oceanographic Exploration Under-Ice," Remote Sensing, vol. 12, no. 16, 2020
[RD-42] M. Humpert, "A new study calculates the likelihood of ships of becoming stuck in Arctic sea ice," High North News (2021, March) [Online]. Available: https://www.arctictoday.com/a-new-study-calculates-the-likelihood-of-ships-of-becoming-stuck-in-arctic-sea-ice/
[RD-43] Schrooten L, De Vlieger I, Panis LI, Chiffi C, Pastori E (December 2009). "Emissions of maritime transport: a European reference system". The Science of the Total Environment. 408 (2): 318–23.
[RD-44] Makinson, Keith, et al. "Diurnal and semidiurnal tide-induced lateral movement of Ronne Ice Shelf, Antarctica." Geophysical Research Letters 39.10 (2012)
[RD-45] Z. Yang, et al., "UAV remote sensing applications in marine monitoring: Knowledge visualization and review," Science of The Total Environment, Vol. 838 (2022)
[RD-46] F.S.Leira, et al. "A UAV ice tracking framework for autonomous sea ice management." 2017 International Conference on Unmanned Aircraft Systems (2017)
[RD-47] A. Kaschube, N. Richter, M. Schiemann, H. Wehner, P.-M. Haselberger and C. Frühling, "MUM - Large Modifiable Underwater Mother Ship," in Underwater Technology Conference, Berlin, 2017.
[RD-48] M. Golz, S. Ritz, F. Boeck, N. Richter, P.-M. Haselberger, H. Wehner, M. Schiemann, E. Rentzow, T. Jeinsch and G. Holbach, "MUM – Large Modifiable Underwater Mother Ship: Requirements and application scenarios," in OCEANS 2017 MTS/IEEE Kobe, Kobe, Japan -
[RD-49] J. Neira et al., "Review on unmanned underwater robotics, structure designs, materials, sensors, actuators, and navigation control," Journal of Robotics, 2021
[RD-50] I. Glushko et al., "Software Control Architecture for the BOSS Manta Ray AUV Actuation System," 2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV), 2018
[RD-51] C.M. Lee , M. DeGrandpre, J. Guthrie, V. Hill, R. Kwok, J. Morison, C.J. Cox, H. Singh, T.P. Stanton, and J. Wilkinson. 2022. Emerging technologies and approaches for in situ, autonomous observing in the Arctic. *Oceanography* 35(3–4): 210–221, https://doi.org/10.5670/oceanog.2022.127.