

Space and Underwater precise PNT for the Society



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PULSAR

PNT Unknown trends: a Long-term key Sectors Assessment & Roadmap study

ESA Frame Contract N° 4000132185/20/NL/GLC

PULSAR: Assessment of Technology Trend in Key PNT – Call for Order 2

SUMMARY

- Introduction
- ESA NAVISP EL.1: PULSAR Project (CoO-2)
- State-of-the-Art of Underwater sensors and instrumentations
- Underwater PNT Scenarios overview
- PNT for Climate Change oceanographic exploration under-ice
- PNT for Underwater Critical Infrastructure monitoring, deployment and operations
- Conclusions

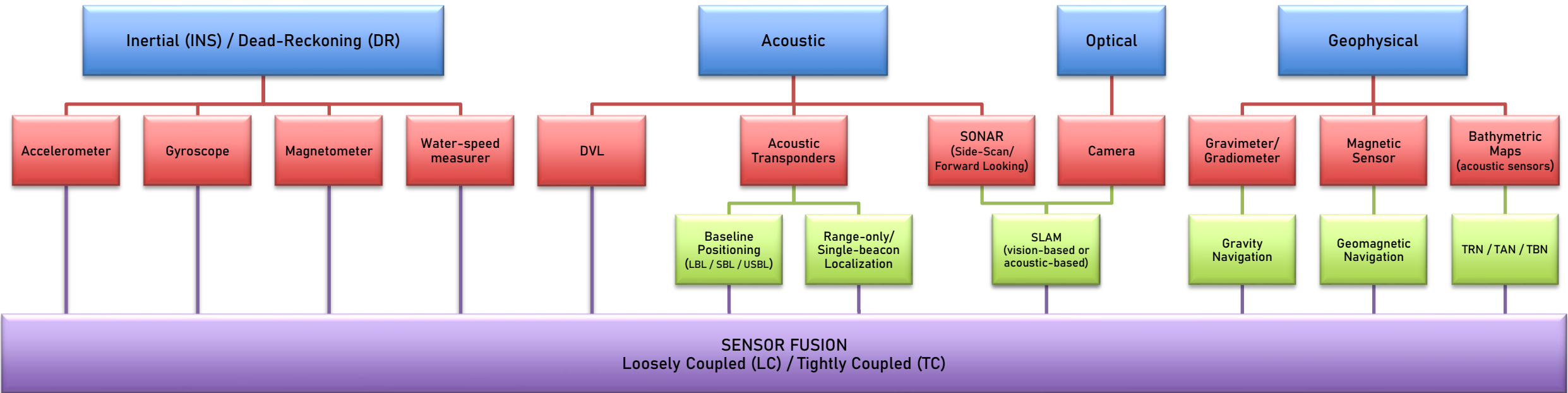
State-of-the-Art of Underwater sensors and instrumentations

• Primary Challenge of the Underwater Environment: **GNSS Unavailability**



Underwater positioning is comparable to indoor localization

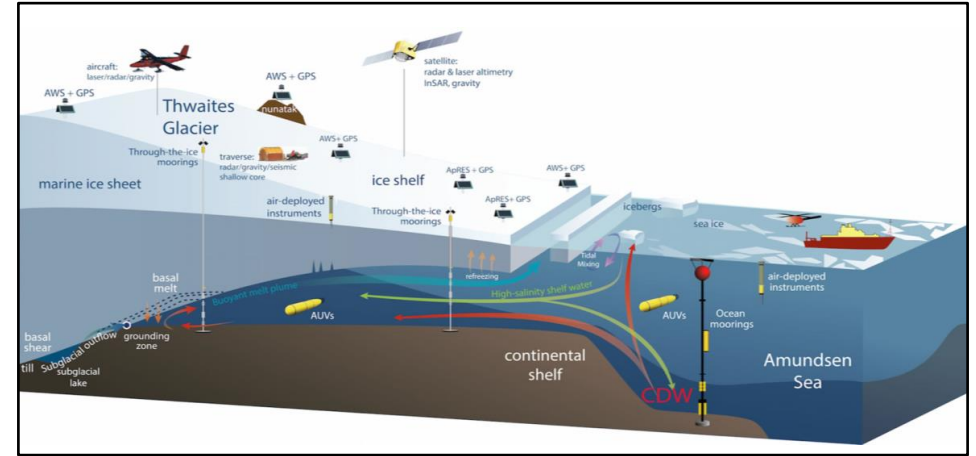
- Inertial sensors: precise DR for short periods, then position error grows.
- Acoustic sensors: good IMU-aid, but resolution decreases with range.
- Optical sensors: good resolution, but range is extremely short and drastically reduces with depth (light availability issue).
- Magnetic sensors: performance not affected by depth, but an accurate map of the local magnetic field is needed to navigate.



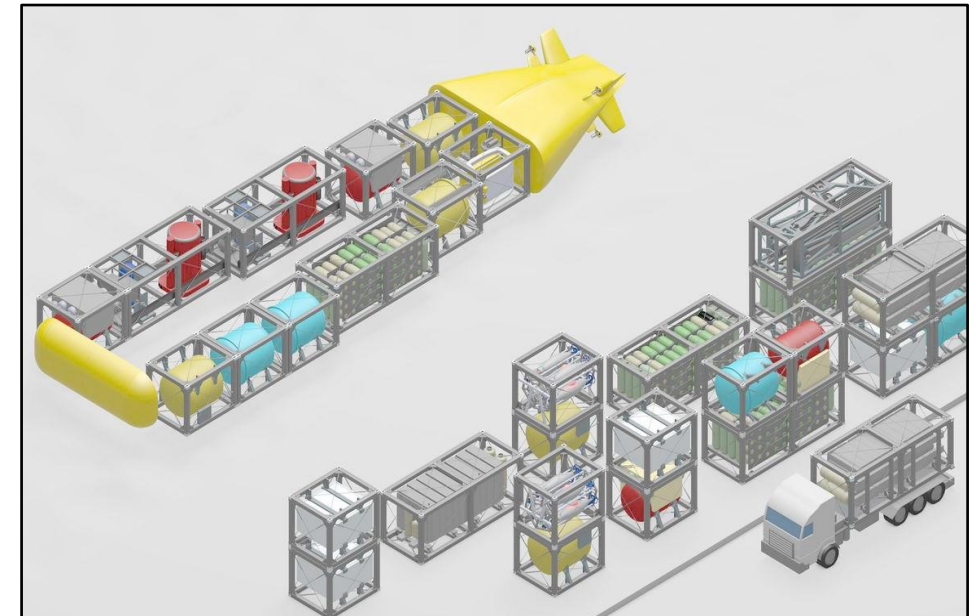
Underwater PNT Scenarios (1/2)

PNT for Climate Change oceanographic exploration under-ice Scenario: Exploration under an ice shelf

- Objective and purpose:
 - Establish PNT capabilities by mapping unknown environments in a complex huge unknown under-ice area with an underwater mobile network
 - Environmental-friendly solutions (e.g., electric-powered assets)
 - Geology Geophysics; Biology; Sea ice and climate; Ice shelves; Seafloor mapping.
- PNT Actual Capabilities:
 - GNSS-fix at surface
 - Inertial Navigation Systems (INS) + External acoustic beacons (LBL Acoustic Positioning)
 - Acoustic and Optical systems for collision avoidance
- Main Challenges:
 - INS error drift in absence of GNSS correction
 - LBL coverage and performances highly depends on water conditions
 - Power autonomy
 - Ice rapidly changes and moves, satellite observations cannot be real time (due to revisit time)
- Possible future developments:
 - *Bioinspired robots*: navigate in a more efficient way, causing less disturb to marine animals
 - *Mobile beacons*: extend the coverage of the LBL system
 - *XLUUV*, as a *docking station* (e.g., MUM), in place of expensive and pollutant mothership
 - *Unmanned Aerial Vehicles*: near-real time local assessment of ice conditions



- Climate Change Monitoring exploration of an ice shelf.



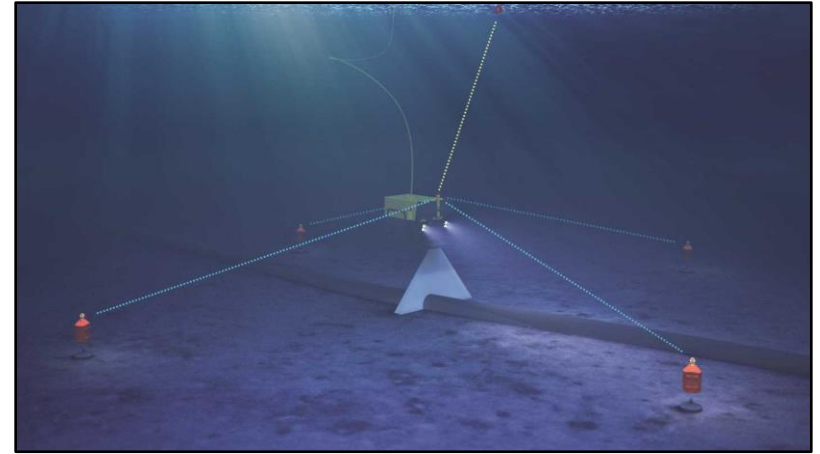
- MUM base and mission modules (©thyssenkrupp)

Underwater PNT Scenarios (2/2)

PNT for Underwater Critical Infrastructure monitoring, deployment and operations

Scenario: Fiber-optic cable (inspection post installation)

- Objective and purpose:
 - Inspect critical cable portions to detect and localize emerging anomalous conditions/damages
 - Reduce survey/repair time and environmental impact.
- PNT Actual Capabilities:
 - GNSS-fix
 - Inertial Navigation Systems (INS) + External acoustic beacons (LBL Acoustic Positioning)
 - Acoustic and Optical systems for collision avoidance
 - Magnetometers, Subsea cameras, Tone generator for accurate subsea cable location
- Main Challenges:
 - Lack of accurate cable database
 - Reliance on mother/auxiliary ships (high costs related to missions)
 - AUVs autonomy is not advanced enough to carry out autonomous high-precision and intervention operations
- Possible future developments:
 - *Mobile beacons*: extend coverage and accuracy of the LBL system
 - *XLUUV*, also able to work as a *docking station* (e.g., MUM), in place of expensive and pollutant mothership
 - *Underwater Intervention Drone (UID)* strategy, to have Survey&Repair missions
 - *Resident Systems* to have UUV or UID resident in docking stations



Underwater Intervention Drone – UID (Oceaneering®)

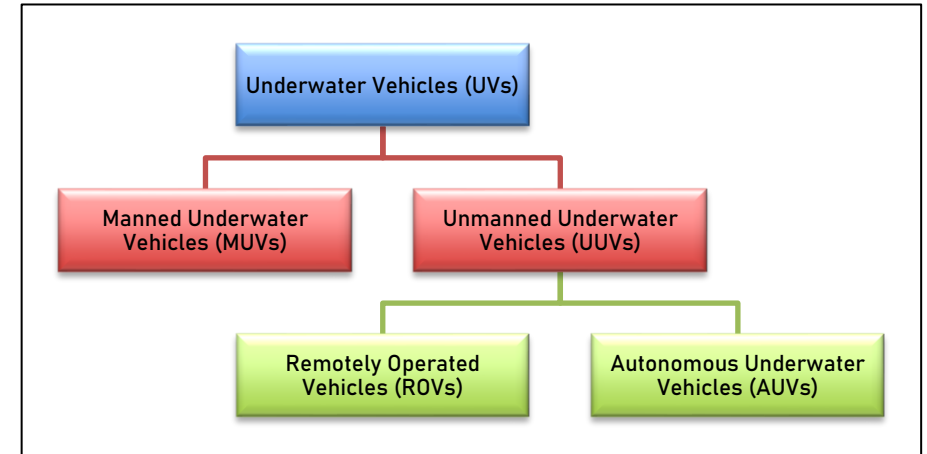
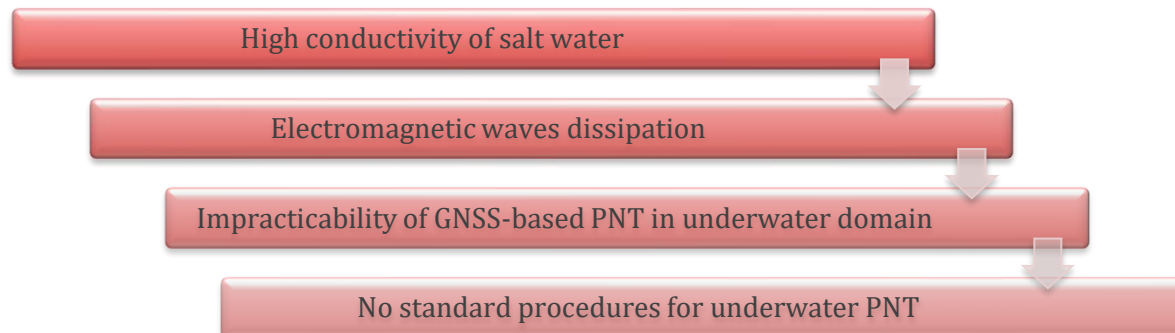
PNT for Climate Change oceanographic exploration under-ice



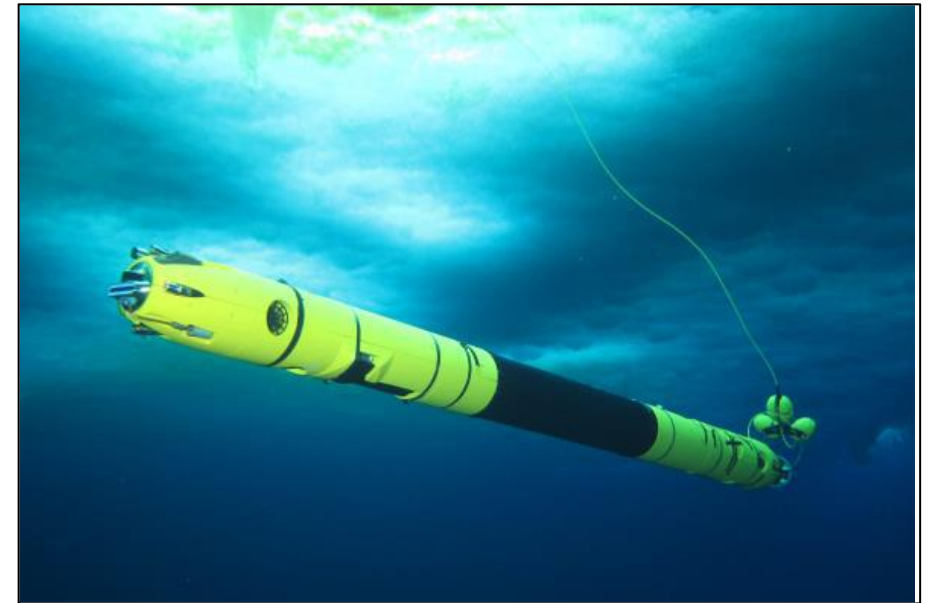
PNT for Climate Change under-ice monitoring

Monitoring the environment under Arctic ice

- **Remote sensing satellites** (e.g., *Copernicus Sentinel satellites*)
 - Advantage: accurate data on parameters like glacier mass balance.
 - Drawback: scarce information about under-ice water characteristics.
- **Ice Tethered Profilers (ITPs)**: monitoring upper Arctic Ocean water column
 - Advantage: sustained near-real-time under-ice monitoring.
 - Drawback: fixed to the ice floe, no possibility to move in a different area.
- **Unmanned Underwater Vehicles (UUVs)**, substantial integration of ITPs.
 - Advantage: possibility to move and reach different desired areas.
 - Drawback: underwater PNT is complicated by the water medium itself.



- Underwater Vehicles Classification



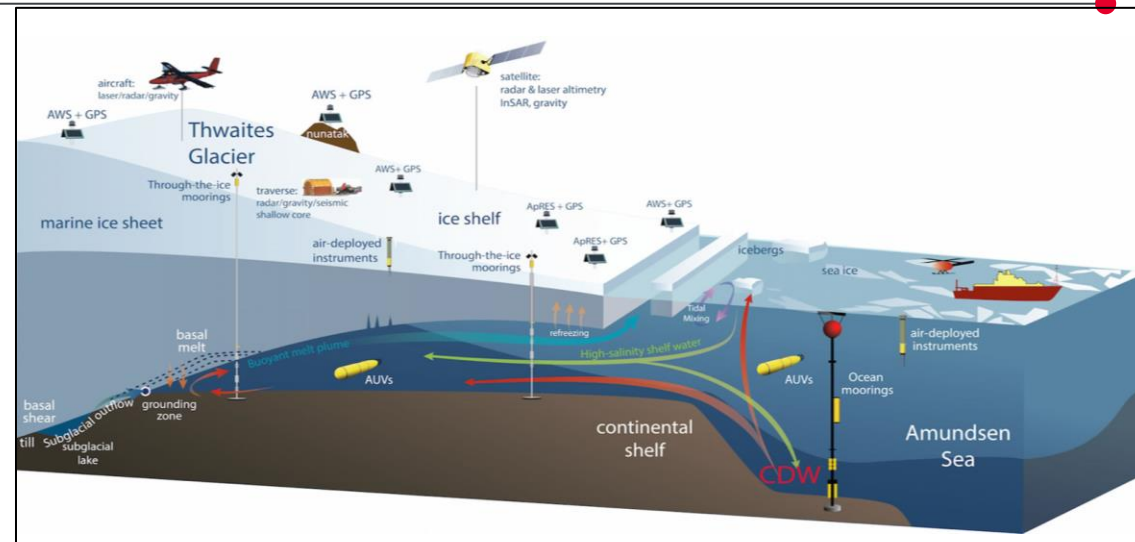
- Example of an Unmanned Underwater Vehicle (UUV): the Icefin under the McMurdo Ice Shelf (Credit: Rob Robbins/NSF)

PNT for Climate Change under-ice monitoring

Needs and PNT KPIs

Different phases of an under-ice operational scenario

- 1. Deployment:**
all the assets are unfolded to reach the under-ice location.
- 2. Navigation and Data Acquisition:**
the assets reach the unknown area and the exploration begin.
- 3. Homing:**
the exploration of the area is concluded, the vehicles go back to the recovery point.



- Climate Change Monitoring exploration of an ice shelf.
(Credit: The International Thwaites Glacier Collaboration, T. A. Scambos et al. 2017)

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 V accuracy: 2 m
	Collision avoidance	H accuracy: 50 cm Integrity Alert Limit: 25 m
		Time to alarm: 10 s

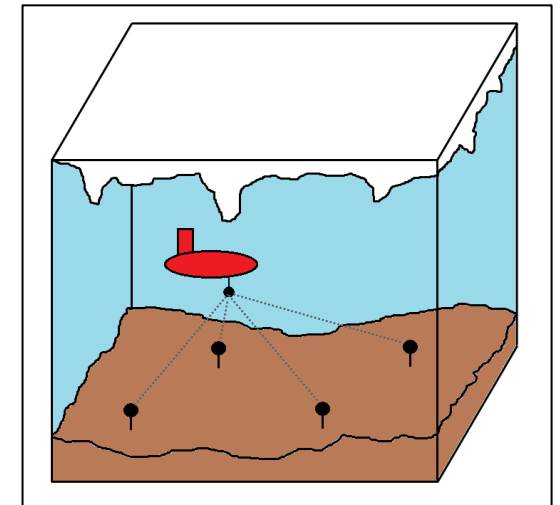


PNT for Climate Change under-ice monitoring

CHALLENGES

The analysis of the State-of-the-Art pointed out the following limitations to overcome for potential future improvements:

- Ultra Short Base Line (USBL) systems do not fill H/V accuracy required in far range positioning.
- The maximum range R_{\max} of Long Base Line (LBL) systems is significantly less than the desired one and a limited accuracy is attained at R_{\max}
- The accuracy of LBL positioning is limited at far range, but in case of an oceanographic data acquisition mission, even a 15-20 m error in positioning can be accepted.
- Optical camera may not have sufficient features to make useful measurements.
- Still reliance on expensive and polluting mother/auxiliary ships.
- Ice rapidly changes and moves at an average speed of 1 km/h and satellite earth observations might be not sufficiently responsive for real time assessment due to long daily revisit time.
- Precision in Time synchronization issues
- Limited AUV's battery life
- Disturbance to marine fauna



- LBL positioning system under ice

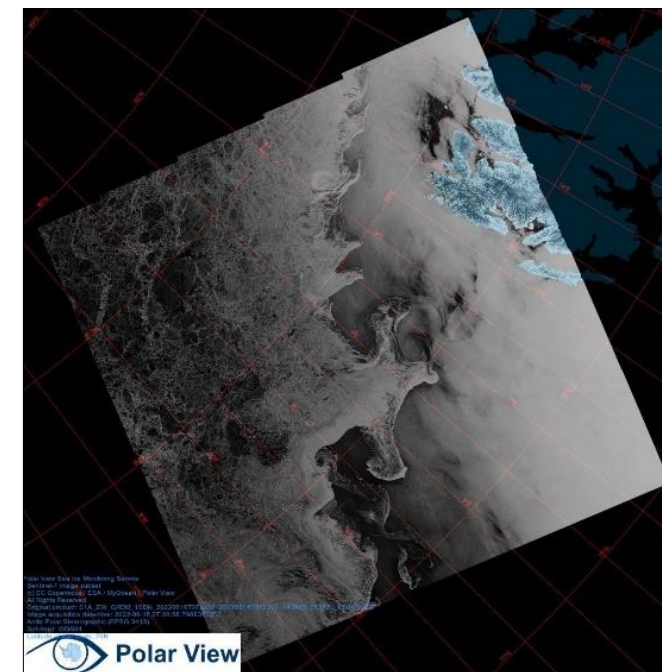
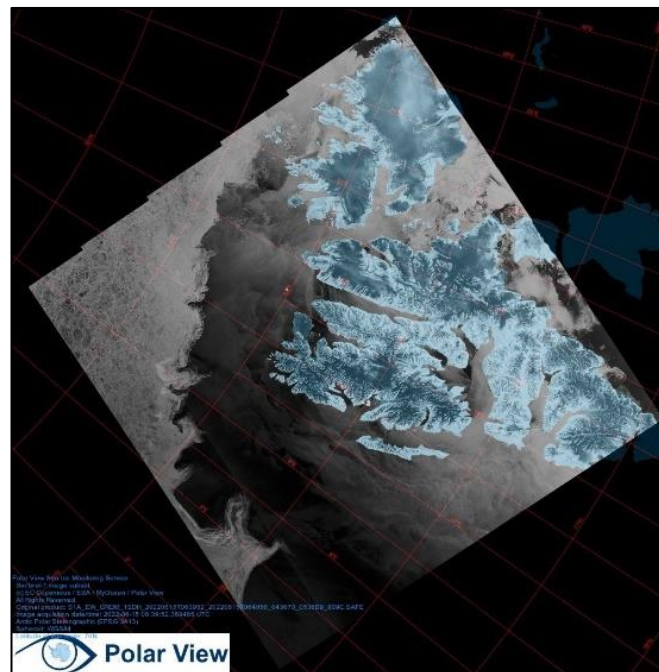
Under-ice exploration challenges and solutions

Underwater PNT technologies

The role of satellite observations in under-ice missions

- **Daily large-scale ice morphology assessment**
 - even with a large revisit time of no less than 24 hours, satellite-based assessment of ice condition is the main solution for mission planning.
- **GNSS position-fix**
 - GNSS surface references are still crucial for any UUV involved when surfacing, as well as for the mothership if it is used.
- **Data georeferencing**
 - the data, collected during underwater missions, need to be georeferenced and integrated with satellite information to improve the Climate Change Monitoring (CCM) capabilities.

Sentinel-1 satellite images used by NATO STO CMRE for mission planning of the Nordic Recognized Environmental Picture 2022 (NREP22)

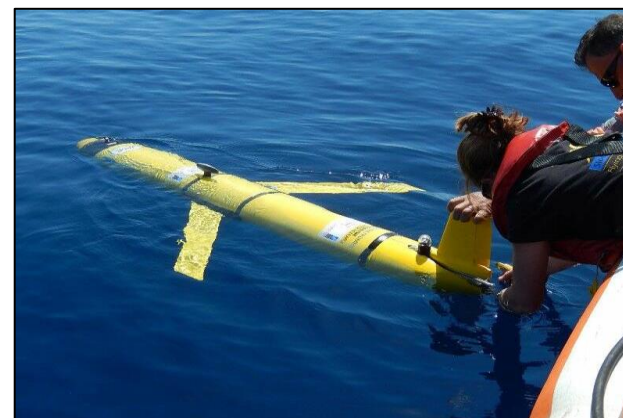
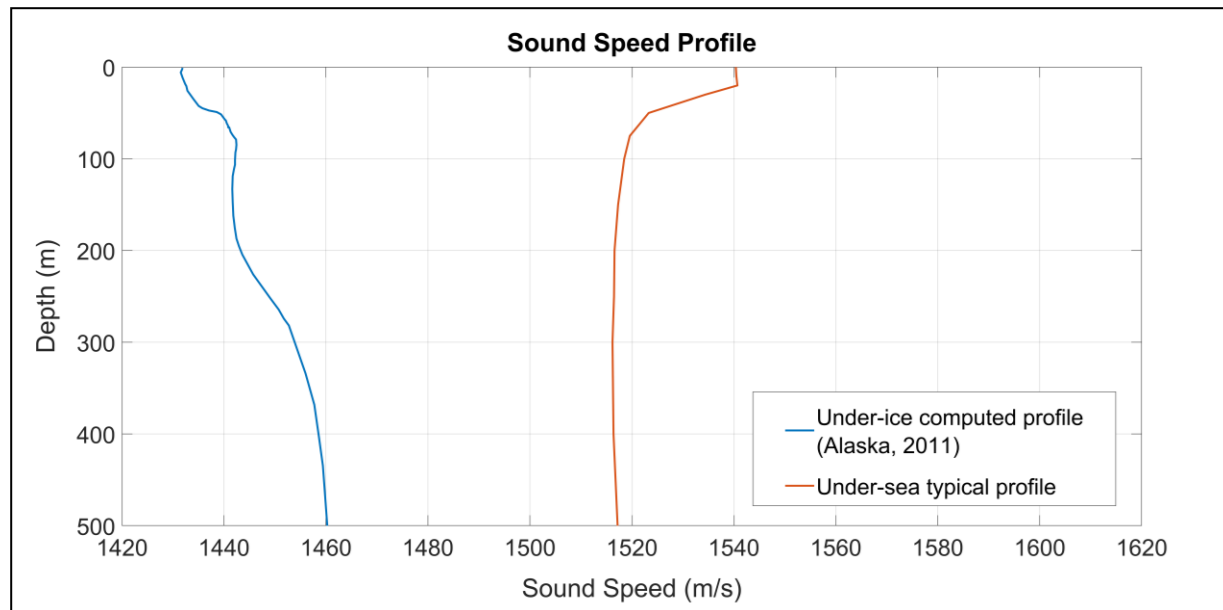
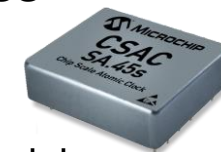


- Ice change and movement in Greenland Sea off the Svalbard Islands (Credits ESA @ Sentinel-1)

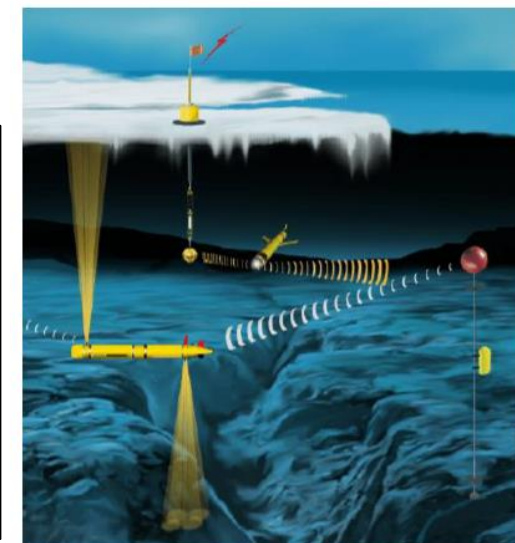
Under-ice exploration solutions and improvements

Underwater PNT technologies

- Underwater **recharging stations** and **gliders** employment
- **XLUUV** (extra-large unmanned underwater vehicle) as underwater mothership (also for recharging)
- **Bio-inspired robots** emulating motion of marine animals
- Remotely Operated Underwater Vehicles (**ROUV**) employment
- **AI techniques** to improve acoustic propagation
- Daily **satellite observations** and swarm of **UAVs** for more frequent local observations
- High precision clocks for internally stable and accurate time stamping. Short-term stability less than 10^{-11} at 1000s with **Chip Scale Atomic Clock (CSAC)**, without high frequency periodic resurface (under an ice shelf) to perform **GNSS resynchronization**.
- Improvements in **Dead Reckoning (DR)** with multi-modal measurements (inertial, local multi-beacon acoustic position systems, etc..)

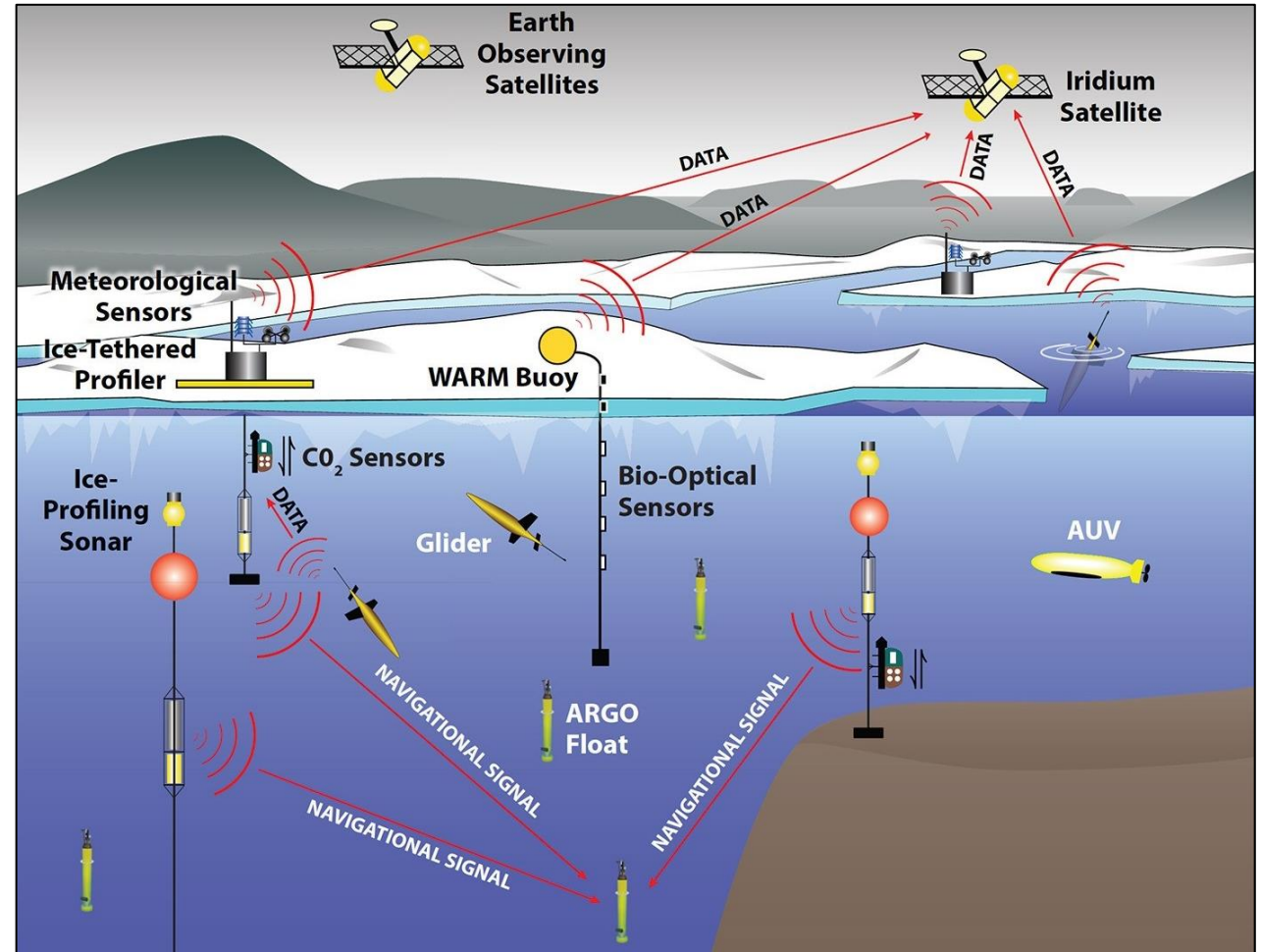


- Deployment of an Autonomous Underwater Glider



Climate Change Monitoring (CCM) mission planning and operative challenges

- The accurate knowledge of **ice morphology** is indispensable to perform safe operation, especially when a mothership is involved → usage of **EO satellites** (e.g., *Copernicus*).
- In order to cope with the EO revisit time & responsiveness, **Geo-information techniques** are able to exploit different EO Satellites and fuse different remote sensing imaging sources including also the ones collected by manned aircrafts and Unmanned Aerial Vehicles (UAVs) equipped with cameras, lidars, etc.
- The second fundamental role of satellite observations is namely **ranging observations**. 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.



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. (Credit: C.M. Lee, et al. "Emerging technologies and approaches for in situ, autonomous observing in the Arctic", 2022)

PNT for Underwater Critical Infrastructure monitoring, deployment and operations



Underwater Critical Infrastructures (UCIs) – Overview (1/2)

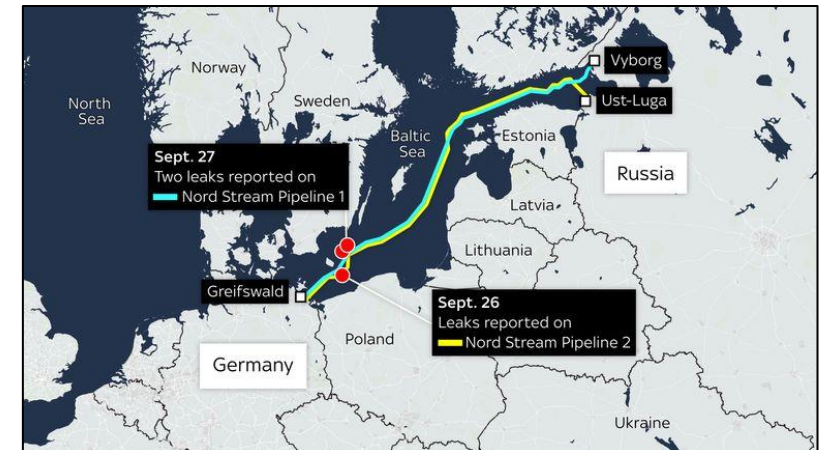
Underwater Critical Infrastructures (UCIs), such as offshore platforms and windfarms, underwater oil/gas pipelines and fiber optic cables networks, represent undersea assets or systems which are essential for the maintenance of vital social functions.

The activities related to their **installation**, **operation** and **inspection** require instruments and vehicles that operate with a very high level of **Position Navigation and Timing (PNT) accuracy**, **below cm**.

The recent Nord Stream 2 accident, occurred on September 2022, strengthened the need for a rapid and accurate UCI monitoring and control processes, and the usage of Autonomous Underwater Vehicles (AUVs) became a key point.



Purpose: to give a detailed overview on how capabilities provided by **underwater PNT technologies** can evolve to improve the support in UCI Installation, Operation & Maintenance



Nord Stream 2 accident

Underwater Critical Infrastructures (UCIs) – Overview (2/2)

Most of the procedures followed by operators to install and maintain UCIs can be summarized in the following steps:

- Pre-lay survey
- Beacons positioning
- Navigation and close Inspection
- Intervention

1. Survey step: performed almost **6 months** before the installation to verify and validate the geographical area of the seabed where the UCI will be deployed.

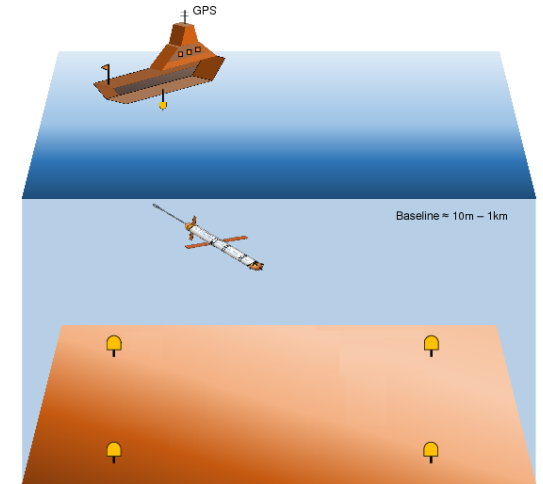
2. Beacons positioning step: **AUVs** autonomously reach the desired position, **Beacons** (i.e. Long Base Line – LBL) are continuously linked to a GNSS reference and their position on the seabed is geo-referenced.

3. Navigation and close inspection step: the **AUVs** autonomously reach the area delimited by the beacons, perform **autonomous navigation**, accurate **seafloor mapping** and **data acquisition**.

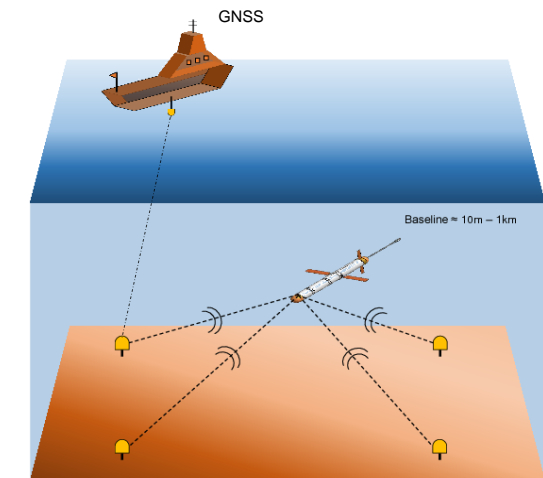
4. Intervention step: a vehicle repairs the identified damage through **manipulators**, remaining extremely stable during the operation.

Assets & instruments

- AUV
- Sensors
- Actuators




2. Beacons positioning step



3. Navigation and close inspection step

UCI PNT stakeholder needs and Key Performance Indicators (KPIs) (1/3)

In the context of PULSAR Project, funded by European Space Agency, has been performed a detailed assessment from June 2022 to May 2023 about Underwater PNT technologies.

Step	Needs and PNT KPI	Available PNT Technologies
<u>1. Preliminary survey</u>	<ul style="list-style-type: none"> IMO Requirements Absolute Horiz. Accuracy: 10 m Alert limit: 25 m Time to alarm: 10 s Availability: 99.8% per 30 days Long Base Lines – distance precision (cm) up to 10000m range 	<ul style="list-style-type: none"> Mother-ship (DP 2 or 3) plus UUV GNSS/DGNSS Pipetracker Magnetometer (Shallow water) Subsea camera for unburied cable (deep water) LBL 0.02m accuracy (@Kongsberg)
<u>2. Beacons Positioning</u>	<ul style="list-style-type: none"> Beacon-GNSS ref. connection Coverage: max distance from GNSS reference depends on depth (shallow/deep) H/V accuracy: 5 m at max range from mothership 	<ul style="list-style-type: none"> USBL acoustic positioning (@iXblue) Op. Range: 1000 m or 4000 m H/V accuracy: 0.5% range (5 m) or 0.1% range (4 m) Min. operating temperature: -5°C
	<p>High precision time synchronization</p>  <p>* Chip Scale Atomic Clock</p>	<ul style="list-style-type: none"> Chip Scale Atomic Clock* (CSAC, @Microchip) at $T=25^{\circ}\text{C}$ at shipment <ul style="list-style-type: none"> $\pm 5.0E-11$ maximum frequency offset Short-term stability <10-11 @1000s Minimum operating temperature: -10°C (over extended time period may yield unpredictable aging performance)

UCI PNT stakeholder needs and Key Performance Indicators (KPIs) (2/3)

Step	Needs and PNT KPI	Available PNT Technologies
<u>3. Navigation and close inspection</u>	<ul style="list-style-type: none"> AUVs LBL positioning H/V position accuracy: 30 cm at max range H/V velocity accuracy: Range/Coverage: 100 m – 1 km 	<ul style="list-style-type: none"> LBL acoustic positioning (@EvoLogics) Typical static accuracy: 0.05% of R_{max} 50 cm at 1 km Frequency Range: 8 kHz – 16 kHz Range: max 8 km (hemispherical, 40W, 7-17 kHz) max 6 km (120° pattern, 65W, 15-27 kHz) Minimum operating temperature: 0°C
	High precision time synchronization	<ul style="list-style-type: none"> Chip Scale Atomic Clock as in beacon Positioning step
	<ul style="list-style-type: none"> Cable area mapping Accuracy: tens of cm Continuity: 99.5% over 3 hours 	<ul style="list-style-type: none"> Magnetometer (Shallow water) Subsea camera for unburied cable (deep water) Downward-looking Multibeam Echosounder (MBES, @Kongsberg) Swath coverage sector: 140 deg Range resolution: 1 cm Min. operating temperature: - 2° Continuity: % over 3 hours
	<ul style="list-style-type: none"> Collision avoidance from obstacles Horizontal Accuracy: 1 m Integrity Alert Limit: 25 m Time to alarm: 10 s Continuity: 99.9% over 3 hours 	<ul style="list-style-type: none"> Forward-Looking Sonar (FLS, @Kongsberg) Depth rating: 4000 m Range: 0.2 m to 200 m Coverage: 200 deg Range Resolution: 1 cm Angular Resolution: 2 deg Min. operating temperature: -2°C
<u>4. Intervention</u>	<ul style="list-style-type: none"> High precision intervention capabilities (IMO): H/V accuracy in vehicle's position w.r.t. the cable damage's position: 10 cm Alert limit: 25 cm Time to alarm: 5 s Continuity: 99.9% over 3 hours 	<ul style="list-style-type: none"> LBL acoustic positioning of the vehicle (@iXblue) Op. Range: 1000 m or 4000 m H/V accuracy: 0.5% range (5 m) or 0.1% range (4 m) Min. operating temperature: -5°C Industries are starting using resident ROVs with docking station

UCI Current challenges in the underwater environment

The analysis of the UCI State-of-the-Art pointed out the following limitations to overcome for potential future improvements:

- In addition to GNSS unavailability under-water, a challenging aspect is related to the **strong dependence from expensive and polluting vessels**, both in terms of navigation and AUV battery life.
- Usage of platforms avoiding **impact on the maritime ecosystem**.
- **Range of Long BaseLine (LBL)** systems is significantly less than the desired one;
- **Accuracy of LBL systems**: significantly less than the desired one, especially in case of close interventions. So, the intervention of a support vessel is still required and necessary;
- **Magnetometers** are not good for depth of burial;
- **Underwater PNT resilience** → Often AUV/UUV get lost.

Conclusions

- Underwater PNT Scenarios studied during NAVISP EL1 PULSAR project on *Underwater PNT for a greener Earth* have been presented.
- Stakeholder needs, State of the Art, Technology GAP analysis and solutions for subsea precise PNT have been investigated for:
 - ✓ *PNT for Climate Change oceanographic exploration under-ice*
 - ✓ *PNT for Underwater Critical Infrastructure monitoring, deployment and operations*
- **High operation costs** for expensive and polluting support Vessels and LBL network of beacons deployment.
- Improvement of continuous and raising **adoption of AUVs** in many (not yet all) operational scenarios (AUV/ROVs and UIDs, Docking Stations) along with increasing **battery lifetime** performance and sub-marine recharging stations for **higher endurance**.
- Main aspects to tackle are the **PNT accuracy** in relative navigation provided **by on-board sensor fusion**, to achieve **submeters performances** of a **few cm**, and **undersea assets absolute navigation**.
- Telespazio is working on forthcoming solutions with space assets for Underwater precise and resilient PNT applications.



THANK YOU
FOR YOUR ATTENTION

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