Use of underwater gliders on marine surveillance and observations

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Abstract

Coastal gliders with Passive Acoustic Monitoring (PAM) systems play a pivotal role in studying underwater soundscapes and monitoring marine noise pollution. These silent, buoyancy-driven platforms enable long-term deployments, simultaneously collecting acoustic and environmental data. Additionally, gliders offer a cost-effective, non-invasive, and flexible solution to monitor large spatial and temporal scales, addressing the limitations of traditional moored PAM systems.

In this project, we evaluate the effectiveness of using a glider for underwater listening and acoustic monitoring. Descent and ascent phases of the glider cycle, comprising 72–80% of mission time, are ideal for acoustic recording. Optimizing settings, minimizing surface time, can enhance their suitability for PAM applications. This project also demonstrated their ability to detect specific signals even in stratified environments like the Baltic Sea, underscoring the need for refined acoustic models to address variability due to depth, orientation, and thermocline effects.

As underwater noise pollution remains a global challenge, advancing glider-based PAM systems represents a significant step forward. Beyond environmental monitoring, these systems also contribute to national security by improving the ability to track anthropogenic activities, such as ship traffic, in sensitive or strategic maritime areas.

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Keywords national defence, research, comprehensive defence approach, autonomous, ocean glider, oceanography, marine research, acoustics, soundscape, speed of sound, sound intensity, noise, maritime surveillance, monitoring, stratification, coastal waters

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Tekijät Ivia Closset, Kimmo Tikka, Tuomo Roine, Jaakko Seppänen, Simo-Matti Siiriä, Lauri Laakso
Yhteisötekijä Ilmatieteen laitos

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Tiivistelmä

Passiivisella, akustisella monitorointijärjestelmällä (Passive Acoustic Monitoring (PAM)) varustetut liitimet ovat keskeisessä asemassa vedenalaisen äänimaiseman tutkimisessa ja meren melusaasteen seurannassa. Hiljaiset, nosteen muutoksia käyttävät robotit mahdollistavat pitkäaikaiset mittauskampanjat, joilla ne keräävät samanaikaisesti akustista sekä olosuhde- että ympäristödataa. Toisin kuin perinteiset ankkuroidut PAM-järjestelmät, liitimet tarjoavat kustannustehokkaan, ei-invasiivisen ja joustavan ratkaisun suurten merialueiden alueiden pitempiaikaiseen tarkkailuun.

Projektissa arvioimme liitimen tehokkuutta vedenalaiseen kuunteluun ja akustiseen valvontaan. Liitimen sukellus- ja nousuvaiheet (72–80 % ajasta), ovat ihanteellisia akustiseen tallennukseen. Sukellus-asetusten optimointi ja pinta-ajan minimoiminen voivat edelleen parantaa liidinten soveltuvuutta. Projekti osoitti liidinten kyvyn havaita signaaleja kerrostuneessa ympäristössä, kuten Itämerellä. Tämä korostaa tarvetta kehittää akustisia malleja olosuhteiden aiheuttamalle vaihtelulle.

Vedenalainen melusaaste on maailmanlaajuinen haaste, joten liidinpohjaisten PAM-järjestelmien kehittäminen on merkittävä edistysaskel. Ympäristön seurannan lisäksi nämä järjestelmät edistävät myös kansallista turvallisuutta parantamalla kykyä jäljittää ihmisen toimintaa, kuten laivaliikennettä herkillä tai strategisilla merialueilla.

Klausuuli Tämä julkaisu on toteutettu osana Maanpuolustuksen tieteellisen neuvottelukunnan (MATINEn) tutkimusrahoituksen toimeenpanoa. (www.defmin.fi/matine) Julkaisun sisällöstä vastaavat tiedon tuottajat, eikä tekstisisältö välttämättä edusta puolustusministeriön näkemystä.

Asiasanat maanpuolustus, tutkimus, kokonaismaanpuolustus, autonominen, liidin, meritiede, merentutkimus, akustiikka, äänimaisema, äänennopeus, äänenvoimakkuus, melu, merivalvonta, monitorointi, kerrostuneisuus, rannikkovedet, maanpuolustustutkimus, kokonaismaanpuolustus

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Undervatten glidar för havsövervakning och i observation

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Referat

Glidarna med ett passivt, akustiskt övervakningssystem (Passive Acoustic Monitoring (PAM)) spelar en central roll i studier av undervattensljudlandskap och övervakningen av marina bullerföroreningar. Dessa tysta robotar med justerbart lyft möjliggör långsiktiga mätkampanjer där de samtidigt samlar in akustiska, förhållande och miljödata. Till skillnad från traditionella förankrade PAM-system erbjuder glidarna en kostnadseffektiv, icke-invasiv och flexibel lösning för långsiktig övervakning av stora havsområden.

I projektet utvärderade vi effektiviteten av att använda glidare för undervattens-avlyssning och akustisk övervakning. Dyk- och stigningsfaserna (72–80 % av tiden), är idealiska för akustisk inspelning. Att optimera dykinställningar och minimera yttiden kan ytterligare förbättra glidarnas lämplighet. Projektet påvisade också glidarnas förmåga att upptäcka vissa signaler även i en stratifierad omgivning, såsom Östersjön. Detta belyser behovet av att utveckla akustiska modeller för att hantera variationer förorsakade av djup, riktning och termokliniska effekter.

Undervattensbuller är en global utmaning, så utvecklingen av gliderbaserade PAM-system är ett viktigt steg framåt. Förutom att övervaka miljön bidrar dessa system även till nationell säkerhet genom förbättrad förmågan att spåra mänsklig aktivitet, såsom sjöfartstrafik i känsliga eller strategiska havsområden.

Klausul

Den här publikation är en del i genomförandet av forskningsfinansiering av Försvarets vetenskapliga delegation. (www.defmin.fi/matine) De som producerar informationen ansvarar för innehållet i publikationen. Textinnehållet återspeglar inte nödvändigtvis statsrådets ståndpunkt.

Nyckelord

försvaret, forskning, totalförsvaret, autonom, ocean glider, oceanografi, havsforskning, akustik, ljudlandskap, ljudets hastighet, ljudstyrka, buller, havsövervakning, monitorering, skiktning, kustvatten

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Contents

1 Introduction

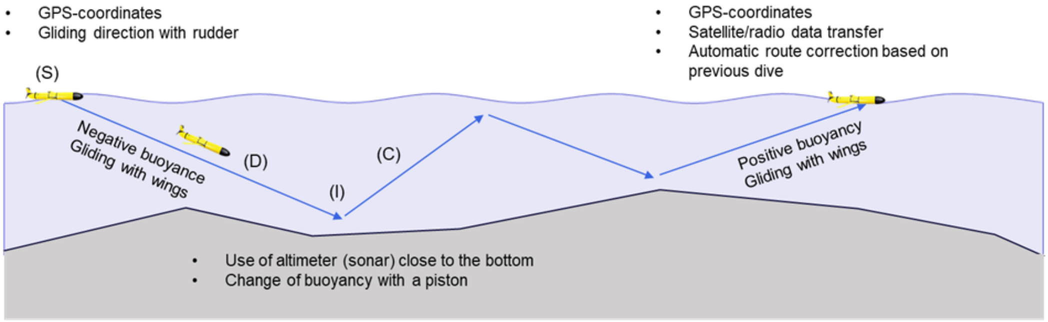
There is an increasing need to measure and report levels of underwater sound in the ocean, partly driven by the need to conform to regulatory requirements regarding assessment of the environmental impact of anthropogenic activities but also related to national security.

Passive acoustic monitoring (PAM) is a field of research aiming at capturing underwater sounds to infer information about their sources in a non-invasive way. It is used to study various types of sounds and in particular those produced by human activities which can cause significant threats to marine ecosystems (i.e. shipping, seismic surveys, wind farms). Ship noise, driven by propeller cavitation, engines, and hull flow, is a major contributor to the noise pollution in the Baltic Sea, with rising maritime traffic expecting to significantly amplify ambient noise levels for the next decade (Hildebrand 2009; Erbe et al., 2012). Ships generate noise across a wide frequency range, with source levels varying depending on vessel type and speed, making every ship's acoustic signature unique.

Nowadays, there is a consensus that the monitoring of Baltic Sea soundscape and sound pollution is insufficient with respect to the regulatory requirements (HELCOM, 2023). Attempts to report measured noise levels are sometimes difficult to obtain and they can be scarce in some area of the Baltic Sea. Autonomous Underwater Vehicles (AUV) such as drones and gliders represent an emerging technology providing a reliable and relatively inexpensive method to collect acoustic and environmental marine data over large spatial scales.

Gliders are AUVs that patrol an area by navigating between preprogrammed waypoints and depths in a saw tooth path by changing their buoyancy to generate motion (figure 1 – Webb et al., 2001). They reach the ocean surface at selected times, which can be used to communicate with the instrument to change the mission, adjust the configuration, or transfer data via an Iridium satellite connection. The lack of a propulsion motor and propellers significantly reduces mechanical noise generated by the glider.

Figure 1. Schematic picture of an underwater glider cycle. One cycle (from surface to surface) contains a few yos (ups and downs) that can be divided into four phases: Surface (S), Diving (D), Inflection (I) and Climbing (C).



Therefore, coastal gliders present a promising option for PAM, offering silent operation and the capability to collect hydrographic data, including sound velocity which is a key parameter for modeling sound propagation. By collecting both acoustic and environmental data, gliders give the opportunity to connect the gap between sound signals and the surrounding environment, providing a comprehensive 3D view of physical and biological processes over time and space (Cauchy et al., 2023). Moreover, their versatility and autonomous operation make them valuable tools for continuous and remote monitoring in challenging marine environments. From our records, they have however never been used for PAM application in the Baltic Sea.

2 Research objectives

The aim of this project was to explore the opportunities and challenges associated with the use of a PAM-equipped glider for monitoring anthropogenic activities, particularly ship traffic, and addressing national security concerns within the unique context of the Baltic Sea environment.

In this report, we address the following specific objectives:

- **Evaluate the effectiveness of using a glider for underwater listening and acoustic monitoring** by investigating the impact of the glider's self-generated noise on its detection performance and propose strategies to optimize its operation
- **Integrate and analyze simultaneously collected environmental and acoustic data** and assess the glider's ability to detect and monitor specific acoustic signals in different environments.

Additionally, this project was built to strongly contribute to the advancement of global practices in underwater acoustic monitoring through international exchanges and collaborations by actively participating in international initiatives and exercises, such as *NATO Centre for Maritime Research and Experimentation* (CMRE) and *NATO Robotic Experimentation and Prototyping using Maritime Uncrewed Systems* (REPMUS). Through these collaborations, it facilitated knowledge exchange, tested innovative approaches, and fostered the establishment of strategic partnerships.

3 Material and Methods

3.1 Instrumentation

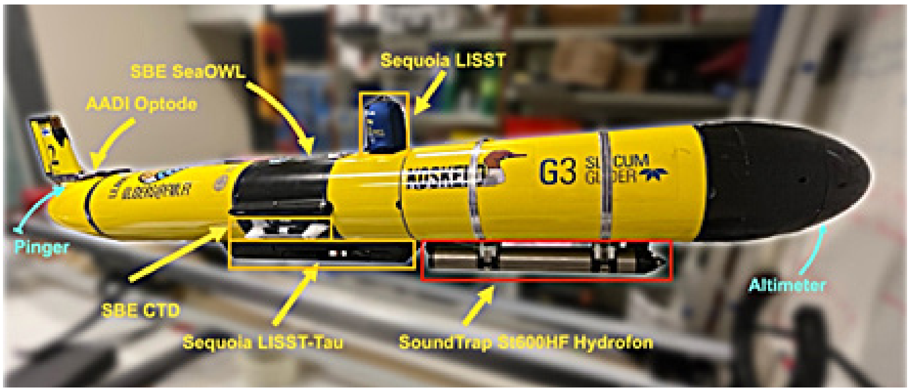
3.1.1 Glider configuration

For this project, a Teledyne Instrument Slocum G3 (called "Koskelo") mounted with a 200m piston engine, was equipped with a pumped SBE GLDCTD, an Aanderaa Oxygen optode with a fast foil (8s), and a SBE SeaOWL fluorometer as a basic configuration setting. In addition, a Sequoia LISST-Tau transmissometer, a Sequoia LISST particle analyzer and an Ocean Science SoundTrap ST600-HF hydrophone have been included in the instrumentation pack of the glider (figure 2). This configuration of the instrument enables a high spatial and temporal resolution collection of parameters such as temperature, salinity, oxygen concentration, chlorophyll a fluorescence, underwater turbidity and visibility, and underwater noise.

The SoundTrap ST600-HF hydrophone is a compact self-contained sound recorder for underwater acoustic research. This specific model is intended for high frequency recording with 150 kHz of bandwidth (20 Hz - 150 kHz ± 3dB) and 32 kHz sample rate. For the purpose of the project, and to ease the management of large amounts of data, The SoundTrap was configured in a semi-continuous recording mode, generating uninterrupted 5-minute files recorded back-to back.

Note that during the project, the glider was equipped with a Sonotronics' Equipment Marking Transmitters (ETM). This device is primarily used as a safety backup to manually locate the glider in case of an emergency recovery when its position is unknown and communication unavailable. Here, it was also used as a moving sound-source (or fixed sound source from the glider's perspective) emitting at 76 kHz.

Figure 2. Glider "Koskelo" equipped with the sensors used during MATINE project (wings not attached to the glider).



3.1.2 Mooring configuration

Bottom-moored acoustic systems are autonomous recorders equipped with hydrophones and anchored to the seafloor at specific depths above the seabed. They are deployed from ships at a predetermined location and can collect acoustic data over relatively long time periods. Acoustic data cannot be transferred remotely and therefore can only be obtained upon recovery of the system. The systems are generally recovered by acoustically activating a release mechanism that allows the system to disconnect from the anchor.

Two moorings have been set up 1km apart from each other *(see "Field experiments" section)*. One fixed mooring has been equipped with an Ocean Science SoundTrap ST500-STD hydrophone. The other mooring carried two Sonotronic pingers emitting at 34 kHz and 70 kHz and used as sound-source for the experimentation. Both pingers used their typical emitting patterns so that their sound can be easily recognized and distinguished from the glider's own pinger.

The SoundTrap ST500-STD hydrophone is a sound recorder similar to the one used on the glider. This specific model is optimized for long term deployments with 60 kHz of bandwidth (20 Hz - 60 kHz ± 3dB) and 24 kHz sample rate. This SoundTrap was configured similarly to the one installed on the glider.

3.2 Supporting data

Accurate bathymetric data is crucial when operating the glider in shallow areas. To support this, two complementary data strategies were employed during the project: satellite observations from ICESat-2 and data from EMODNET.

ICESat-2 is an Earth observation satellite carrying the Advanced Topographic Laser Altimeter System (ATLAS), a space-based 532 nm lidar producing six adjacent surface profiles. ATLAS is capable of shallow-water bathymetry, in profiling the seafloor down to 40 m depth in good conditions. ICESat-2 repeats the same ground track every 91 days, with 10 km ground track separation at equator. The wavelength of the ICE-Sat2 lidar is the same as used in the underwater visibility observations with the glider.

EMODnet (European Marine Observation and Data Network) offers common map and Application Programing Interfaces (API) to the EMODnet Digital Terrain Model (DTM) as EMODnet Bathymetry service. In the Finnish territorial waters, the original data is an extraction from the Finnish Maritime Administrations official sea charts with pixel size of 300m. The EMODnet Bathymetry has an API service for pointwise or along a line segment depth values from the bathymetric DTM data. In this study we used API services (see examples in Appendices) and General MappingTools (GMT) routines to estimate a bathymetric grid for Utö mission area.

3.3 Field experiments

A total of four successful deployments were carried out in the Baltic Sea with the hydrophone mounted on the glider. The first two deployments focused primarily on setting up the glider and hydrophone, as well as optimizing the glider’s attitude and performance. The subsequent two deployments were dedicated to designing an experiment to evaluate the glider’s ability to monitor the marine soundscape. Two additional deployments were carried out within the frame of this MATINE project without the hydrophone (Table 1).

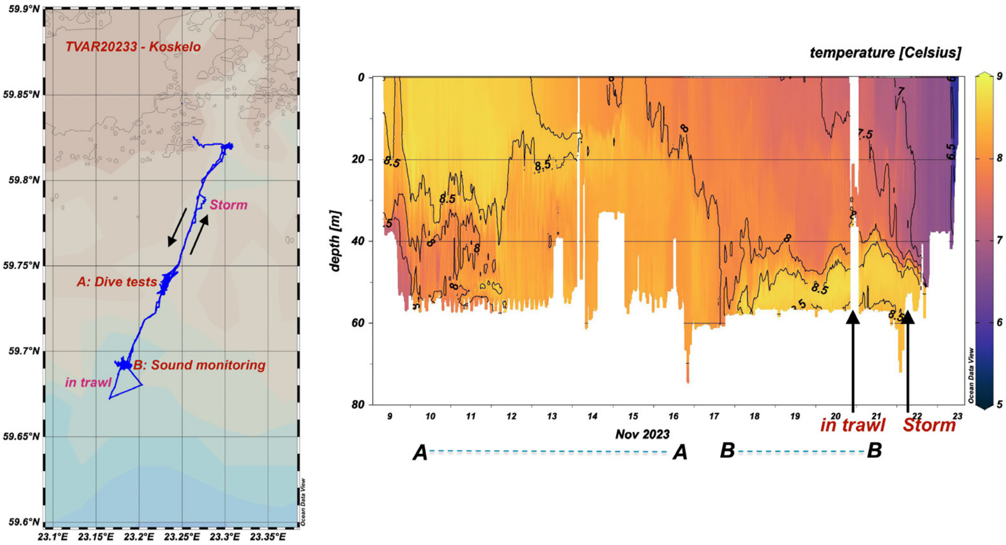
Table 1. MATINE glider missions

Name *(mission folder)*	**Area**	**Season**	**Duration** *[days]*	**Description**
Tvärminne I *(TVAR20232)*	Storfjärden	Sept 2023	1	Test setup
Tvärminne II *(TVAR20233)*	South of Tvärminne	Nov 2023	15	Piloting tests
Tvärminne III *(TVAR20242)*	South of Tvärminne	May 2024	8	Controlled experiment in shallow area
Utö *(UTO2024)*	South of Utö	Jun 2024	17	Controlled experiment in deep area
REPMUS *(REPMUS24)*	Troia, Portugal	Sept 2024	15	International Co-operation
Upinniemi *(UPI2024)*	Upinniemi	Oct 2024	1	Operation with Navy

3.3.1 Trial deployments (Tvärminne I & II)

Two missions were conducted in Tvärminne during fall 2023 to evaluate the glider configuration with the hydrophone. Initial short tests (Tvärminne I) demonstrated the functionality of the setup, although the balancing required further adjustment. Due to the shallow test area, the glider generated significant noise during normal operations. Then, a two-week campaign (Tvärminne II) focused on improving the balancing and testing of various diving modes in deeper waters (50–70 meters) to identify the quietest operation possible. For example, the altimeter was deactivated in a well-known, sufficiently deep, and flat area (period B in figure 3); and adjustments were made to the diving angles to optimize quiet movements (period A in figure 3). Towards the end of the campaign, the glider was briefly entangled in a fishing vessel's trawl net but endured the approximately 7.5-hour torment without damage. Once the trawler stopped, the glider freed itself and resumed the mission as planned.

Figure 3. The path of the glider (a) and temperature profile recorded by the glider (b) during Tvärminne II mission (Nov 2023) showing the different tests performed (A: piloting tests; B: No altimeter) as well as the period when the glider was caught in a trawl.

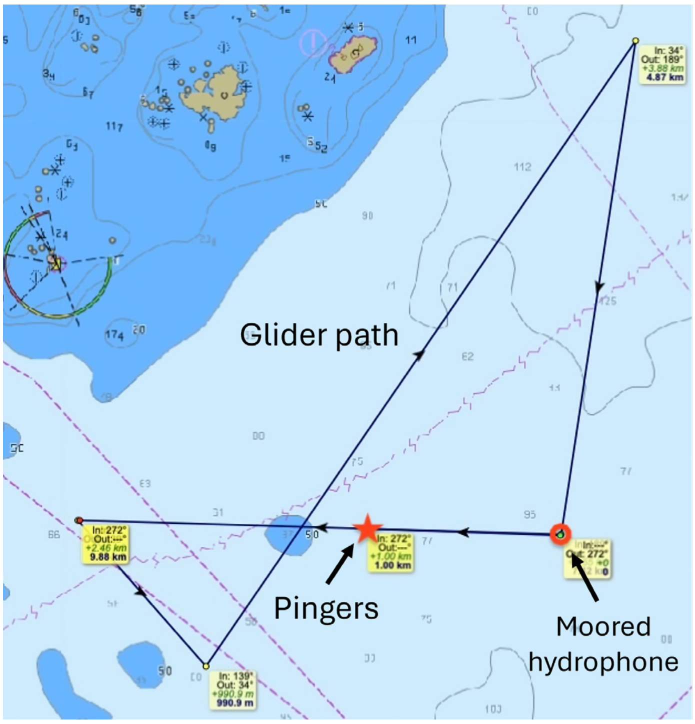


3.3.2 Experiments (Tvärminne III & Utö)

The main purpose of the two deployments conducted in spring and summer 2024 was to compare recordings collected along the same experimental setup in a shallow coastal area (Tvärminne, May 2024) vs. a deep open water region (Utö, June 2024). The experiment was designed to study the propagation properties and transmission in different environments and target area with different bathymetry were selected as sound propagation is expected to be mostly affected by the local bathymetry. The summertime field campaign at Utö allowed us also to investigate the impacts of thermocline on glider-based hydrophone observations.

The experimental design consisted of a moored ST500 hydrophone and two sound sources (pingers) anchored 1 km westward from the mooring to give a constant distance reference for the experimentation (Figure 4). The hope was that fluctuations in sound intensity in this dataset can be interpreted as due to environmental variations (e.g. water temperature, density) and give a reference for the dataset recorded by the glider. The glider was following a butterfly pattern centered around the anchored sound sources and flying over the fixed hydrophone, allowing collection of observations along two axes (Figure 4).

Figure 4. Design of the experiment and pre-programmed glider route for Utö mission (June 2024). The black lines represent the glider's track, the red dot indicates the mooring with the fixed hydrophone, and the red star marks the mooring with the pingers.



3.3.3 Additional deployments (REPMUS & Upinniemi)

During the Matine project, two additional missions were performed in summer and fall 2024:

The **REPMUS24** exercise (Portugal, September 2024) was designed to test the ability of autonomous systems to operate together and increase the understanding of new threats in the maritime environment. FMI's glider team was a part of the Finnish delegation with one Slocum G2 glider ("Uivelo") successfully ran a two-week mission for the Rapid Environmental Assessment (REA) workgroup. The objectives of this exercise, co-operation and piloting experience, were fully reached.

UPI2024 was a short, few hours mission close to the shore South-West of Upinniemi (South Finland) in October 2024. One of the goals was to practice deployment and recovery in collaboration with a navy vessel and inside a relatively enclosed area.

3.4 Data processing

3.4.1 Audio data

Soundtrap rawdata were recorded in .WAV files representing 5 minutes of continuous recording and were then processed to determine variation in ambient-noise level via a combination of semi-automated and manual methods using scripts that were executed with Python. The raw files were first combined to form continuous recordings corresponding to the different phases of the glider cycle and a spectrogram was generated for each of the climbing phases. Pressure spectral densities (PSD) were computed for each file and subsequently converted to decibels to enhance the resolution of small variations. Noise levels over the frequencies of interest (i.e. 34kHz, 70kHz and 76kHz for the low, high and glider pingers respectively) were then filtered and extracted using standard signal processing methods (e.g. noise filtration, baseline and peak definition). From the glider's perspective, the 76 kHz pinger served as a fixed sound source and was used to normalize the other two datasets, reducing biases introduced by data analysis and file segmentation, and ensuring data comparability. A simplified version of this analysis was performed on the audio dataset from the moored hydrophone.

3.4.2 Glider data

Slocum gliders store measurement data in multiple binary files. While smaller sample files are typically transmitted via satellite during the mission, the full dataset is recorded on memory cards and accessed after the mission's completion. Data from each deployment was transferred to an external hard drive, used for data processing and analysis.

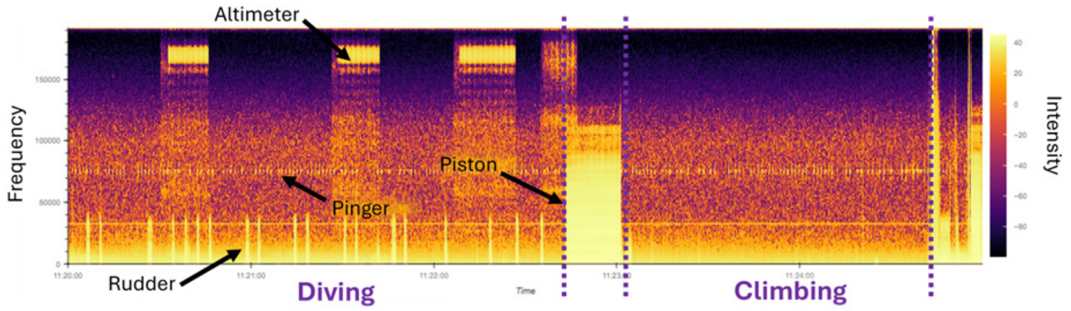
Glider's binary rawdata were combined and converted to .NC files corresponding to one deployment. Data analysis was performed using several pre-existing software tools, including Python packages available on GitHub, such as dbdreader (developed by Lucas Merckelbach) and pyglider (by the PyGlider team), alongside custom-developed scripts.

The glider records sensor data along with various technical parameters used for navigation (e.g. pitch angle, roll, piston motion), which provide valuable insights into its operation and can be used for performance evaluation and operational control. A selection of the different parameters measured by the glider during a single day of Utö mission is provided in the *Appendices* (figures A4 and A5).

4 Results

4.1 Acoustic signature of a glider cycle

Figure 5. Spectrogram illustrating the main sounds produced by a glider recorded with a glider-mounted hydrophone.



The soundscape observed during a complete glider yo (i.e. consisting in one dive, inflection, ascent and surfacing) is illustrated in figure 5. It primarily consists of constant background noise, likely originating from distant events such as waves or wind, as well as water flow around the glider, predominantly confined to frequencies below 5000 Hz. Electrical noise pollution from the science payload (CTD, oxygen optode, fluorometer and transmissiometer) is characterized by a continuous spectral peak around 33kHz.

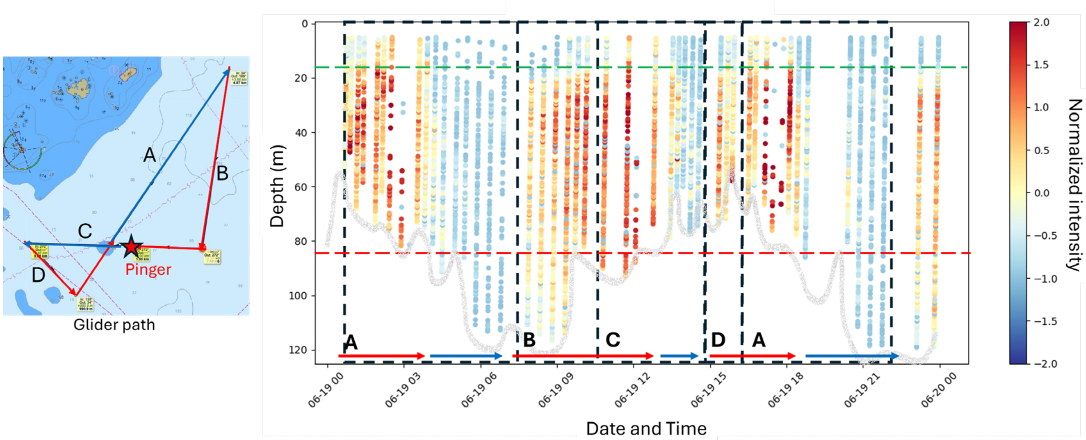
Several more isolated features can also be identified from the spectrogram:

- During the surfacing phase, noise is predominantly generated by the interaction of the glider with the sea surface (highly positive buoyancy, downward pitch). Splash sounds from waves hitting the hull and the hydrophone oscillating between in-air and underwater positions generate a mix of multiple broadband, impulsive sounds.

- The main maneuver of the glider consists of moving its piston and battery set in order to modify its attitude and transition from the ascent (slightly positive buoyancy, upward pitch) to the surfacing phases or from the surfacing to the diving phase (slightly negative buoyancy, downward pitch), or when proceeding to an inflection (i.e. changing the buoyancy and pitch at the bottom or at the top of the yo). Noise production during this maneuver is dominated by approximately 20 seconds of loud noise from the buoyancy pump, covering most of the spectrum (from 20Hz to around 120kHz) and completely masking the underwater soundscape.
- The glider's altimeter is generally used during the diving phase to detect and avoid the seabed by triggering the bottom inflection. The maximum intensity of the altimeter pings is centered around 180 kHz, however, echoes from these pings cover the full spectrum interfering with the recorded information.
- During the diving and climbing phases, the glider is passively gliding through the water column, however, mid-profile adjustments of the rudder may occur for repositioning and steering the glider against currents. Such adjustments generate sharp noise of short duration (1-2 seconds) that do not exceed 50 kHz.
- As described in the *Material and Methods* section, the glider is carrying a pinger emitting at 76 kHz. This signature is clearly identifiable on the spectrogram.

4.2 Glider-based observations of high frequency sound sources

Figure 6. Normalized intensity of a moored sound source (colored dots) recorded with a hydrophone mounted on the glider. The glider path is shown on the map, red and blue arrows correspond to the periods when the hydrophone is facing or not facing the sound source, respectively. Grey line represents the ocean floor, red and green dashed lines represent the depths of the sound source and thermocline, respectively.



As detailed in the *Materials and Methods* section, the signal intensities at the frequencies of interest (i.e. 34kHz and 70kHz) were extracted, filtered and normalized using the signal from the glider's pinger (76 kHz) as a reference. It is important to note that many assumptions have been made to produce these figures, the interpretation of the signal must be approached with caution, particularly for quantitative analyses. At this stage only qualitative interpretations are provided, as more detailed and complex analyses are required, which was beyond the scope of this project.

For this analysis, we used data collected exclusively during all climbing phases for Utö's deployment, as these recordings required less pre-cleaning treatment and allowed for clearer interpretation. Figure 6 displays the glider recording at 34 kHz (low frequency moored pinger), captured on June 19th 2024 when the glider performed a full loop of the "butterfly" shape pattern. Two major trends can be observed in this figure. These trends are consistent throughout the entire Utö deployment and within all datasets (i.e. associated with both low and high frequency pingers).

- The signal intensity is higher when the hydrophone is pointing toward the sound (warm color in the figure) and drops abruptly once the glider passes the mooring equipped with the pingers, at which point the hydrophone is oriented away from the sound source.
- The signal intensity decreases as the glider approaches the surface, a trend that is particularly evident when the hydrophone is oriented toward the sound source. Under these conditions, the intensity of the 34kHz moored pinger can vary significantly, ranging from more than twice the intensity of the reference at depth to on average 50% lower compared to the reference above 20m.

5 Discussion

5.1 Defining the optimum glider operations for passive acoustic monitoring

While they glide quietly through the water column, without any propulsion noise, gliders generate noise when performing maneuvers or interacting with their environment. For Passive Acoustic Monitoring purposes, the main objective of the glider pilot will be to reduce these maneuver periods to their minimum. Most of a glider's maneuvers – and therefore its self-noise – occur during the transition between two successive steady phases or when the glider is afloat at the surface of the ocean (figure 5). During Tvärminne and Utö's deployment, time spent at surface, diving, operating a bottom inflection and ascending were extracted from glider's navigation data files to provide quantitative observations of the relative importance of each of these phases and transitions, and the implications for passive acoustic monitoring applications (table 2).

Table 2. Duration and percentages of different glider operating phases (refer to the text for more details)

Phase name	**Duration** *Tvärminne*	**Duration** *Utö*	**Percent of time** *Tvärminne*	**Percent of time** *Utö*
Surface	1 days 17:43:30	1 days 14:18:08	22%	11%
Inflection	0 days 06:38:18	0 days 05:30:42	3.5%	1.6%
Diving	2 days 22:05:20	4 days 22:41:01	37%	35%
Climbing	2 days 16:10:52	6 days 17:29:30	33%	47%

Because of the noise generated when activating the buoyancy pump upon reaching or leaving the surface of the ocean, as well as the loud splash sounds of waves hitting the hull, the surfacing phase is considered unsuitable for audio-recording purposes. Throughout the glider's cycle, this phase represents the primary cause of acoustic monitoring time loss. Interestingly, this time is doubled when the glider operated in shallow waters (22% of the total time spent at sea in Tvärminne) compared to deeper waters (11% of the total time spent at sea in Utö).

Glider pilots typically aim to minimize surface time by reducing the volume of data transmitted. This can be primarily achieved by limiting the data exchanged with the glider, such as down-sampling scientific data files prior to transmission, with the complete dataset being retrieved after the glider's recovery. Surface time can also be reduced by increasing the number of yos during a cycle. However, this option can impact the precision of the glider's positioning and subsequently hinder its navigation.

The bottom inflexion transition is another obvious period that is considered unsuitable for recording purposes. It can be easily excluded from the audio-recordings as its occurrences are logged in the glider's navigation files. Acoustic monitoring time loss associated with the bottom inflection transition is however marginal, with this phase accounting for less than 5% of the total duration of the glider mission. Similarly to the surfacing phase, this time is doubled when the glider operated in shallow waters (3.5% of the total time spent at sea in Tvärminne) compared to deeper waters (1.6% of the total time spent at sea in Utö).

The diving and climbing phases are more or less similar, as the glider passively moves through the water column, relying solely on the buoyancy settings made during the previous surface or bottom inflection transition phase. Mid-profile adjustments, such as slight changes to the piston position, rudder movements, or altimeter activation, occasionally occur for steering, controlling vertical speed, or sensing the ocean floor. These adjustments are typically brief (<10 seconds) and are systematically logged in the glider's data files. The frequency of these events can be adjusted by the glider pilot or even completely disabled, although this might come at the cost of reduced navigation performance. It has been successfully tested during the pre-experimental deployments (Tvärminne November 2023) when the altimeter was turned off in a deep and flat area and the steering strategy adapted to maximize the proportion of quiet navigation. Alternatively, these events can be identified and excluded from the acoustic dataset during post-processing analysis.

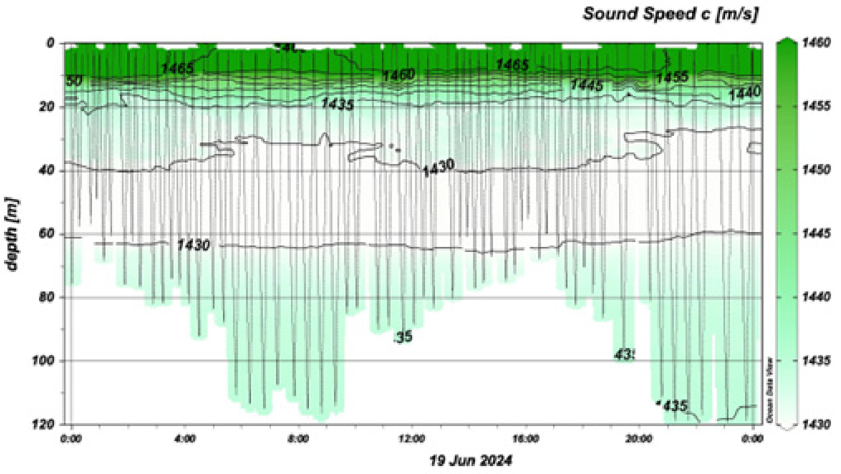
The descent and ascent phases represent ideal conditions for Passive Acoustic Monitoring applications. Together, these phases make up the majority of the glider's operational time, each accounting for roughly one-third of the total mission duration. At Tvärminne, the distribution between descent and ascent was nearly equal, whereas at Utö, the ascent phase was significantly prolonged, comprising up to 47% of the total time. This difference is likely influenced by the glider's ballasting setup and the greater depth of the waters. In total, between 72% and 80% of the glider's time at sea is well-suited for audio recording operations.

5.2 Monitoring spatial and depth-dependent variations in underwater noise

The glider successfully detected the low-frequency pinger (34 kHz) throughout the entire experiment (i.e. at any point of the butterfly-shape pattern), despite significant variations in noise levels over the duration of the deployment depending on whether the glider was oriented toward the sound source or moving away from it.

Underwater signal intensity also varied with depth, likely due to complex acoustic propagation processes such as reflection from the seabed and the surface, as well as refraction between water masses of different densities. This is indeed particularly prominent in the shallow, highly stratified waters of the Baltic Sea. During Utö's experiment, two hypotheses can be proposed to partially account for the vertical variations in the noise levels observed in figure 6. One key factor is the change in the glider's inclination which alters the hydrophone's orientation relative to the sound source during the transition phases. While this effect is expected to occur in a similar way during glider turns at the beginning and at the end of the climbing phase, it appears less pronounced at depth compared to when the glider is approaching the surface. This points out another significant factor: the presence of strong water density gradients, such as thermocline, which can influence sound speed propagation. Indeed, sound velocities estimated from glider's data show drastic change centered around ~15m while being invariant below this depth (figure 7).

Figure 7. Variations of sound speed (in m/s) with time and depth calculated from glider data on June 19 during Utö mission. Light grey straight lines correspond to glider yos and color to the speed of sound.



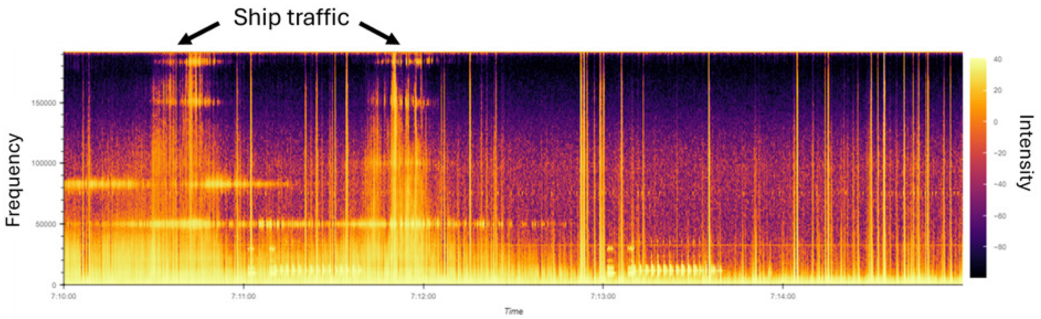
Further analysis is however required to draw conclusive results about the link between the presence of thermocline and the variations of noise levels with depth, including examining additional frequencies, comparing the soundscapes between deep and shallow areas (i.e between Utö and Tvärminne) and more importantly, ensuring the capability to use absolute sound level measurements. For example, different sound frequencies propagate in distinct ways, requiring careful consideration of sound propagation modeling to accurately interpret variations in measured intensity. The position and depth of both the glider (as the receiver) and the pingers (as emitters) are also essential parameters to consider when extrapolating information relative to the trajectory of the sound from the raw signal. Monitoring sounds emitted within the surface layer (above the thermocline) versus those originating from greater depths will likely require the development of distinct analytical approaches.

5.3 Challenges faced during glider operations

Using autonomous vehicles in coastal seas presents significant challenges compared to the open ocean. Coastal areas face hazards like shipping congestion, shallow and rapidly shoaling bathymetry, strong tides, currents, and waves. During the Matine project, several noteworthy observations have raised our attention and should be considered for future glider-based PAM activities in the Baltic Sea.

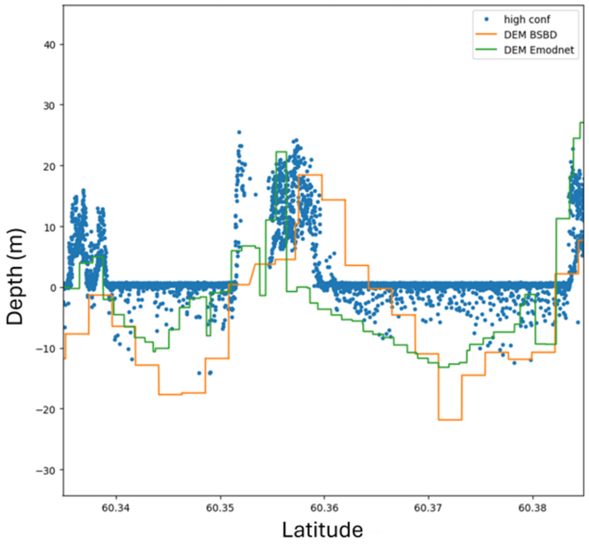
Towards the end of the Tvärminne II mission, the glider was briefly entangled in a fishing vessel’s trawl net (the tragic experience of fish getting caught in fisherman nets is therefore documented in the files associated with this deployment).
This incident, although rare for glider operations, highlights the potential risks associated with vessel encounters, particularly in busy marine areas like the Baltic Sea. Ship noises have been successfully recorded during our Matine deployments. Figure 8 displays the spectrogram for September 12th 2023 showing broadband increases in spectral intensities associated with shipping traffic near the glider path. This result highlights the significant presence of maritime activity in the region and its potential impact on the acoustic environment, which could influence both glider performance and the overall soundscape of the area.

Figure 8. Example of a spectrogram measured at Tvärminne when four boats passed by.



Glider operations in the Baltic Sea face significant challenges associated to the shallow bathymetry. While gliders have the ability to sense the ocean floor and adjust their trajectories accordingly, we complemented this capability with predictive bathymetric data from EMODnet analyses and satellite observations. These supplementary data sources were used to forecast the seafloor depth in deployment areas, enabling us to identify zones most suited to our objectives. Preliminary results from this analysis indicate that satellite-based mapping of the Baltic Sea bathymetry is possible at least on shallow areas, between sea surface and approximately 10 meters depth (figure 9). This approach allowed us to assess the accuracy of satellite-based bathymetry predictions in guiding glider navigation and optimizing mission planning in complex coastal environments.

Figure 9. An example of a height profile from ICESat-2 data in Archipelago Sea (blue dots) against the calculation from the Baltic Sea Bathymetric Database (orange line) and EMODnet database (green line).



Finally, Slocum gliders rely on GPS satellites to accurately determine their position. Upon surfacing, the glider establishes a GPS connection twice: first to acquire its position and estimate surface currents, and again just before diving to confirm the position. On the morning of May 11 (Tvärminne III), the GPS signal was disrupted, and the glider received an erroneous position 25 km SSW of the correct location. This inaccurate position led to a faulty current correction estimate, causing the glider to travel 0.5 km north instead of east on its subsequent dive. Fortunately, the glider corrected this error during the following dives, once it obtained the correct position on the next resurfacing. This incident underscores the importance of monitoring factors which can affect GPS signal reliability (such as solar storms, space weather or anthropogenic activities).

5.4 Guidelines for future applications

Passive Acoustic Monitoring systems associated with gliders can provide sustained acoustic monitoring of key areas that are potentially hard to reach with the usual moored PAM systems. Their profiling ability and slow speed allows for an exceptional increase of the spatial resolution of measurements compared to moorings.

Several key advantages orientated our choice toward an add-on Soundtrap attached externally to the glider. Indeed, Self-contained PAM systems, such as Soundtraps, are autonomous recorders that do not rely on the glider’s computer or power supply. Low power consumption is an essential requirement for any sensor intended for routine glider missions (Kowarski et al., 2020). While efficient and versatile, their integration requires proper ballasting adjustments to preserve the glider’s buoyancy, and careful positioning to reduce drag during navigation. They are used for pre-programmed sampling missions, with data being processed only after recovery, making real-time decision-making and mission adjustments based on observations impossible.

Integrated PAM systems are more expensive but offer advanced functionalities, such as real-time data processing, remote control of the instrument allowing the pilot to adjust the acoustic sampling based on observations (Kowarki et al., 2020). They have the ability to enhance data quality by recording only when platform noise is absent as they can be turned off and on by the glider’s operating system. However, they draw power from the glider’s batteries and therefore require wise supervision to maintain glider endurance. Additionally, thanks to their smaller size compared to self-contained PAM systems, a glider can accommodate an array of several hydrophones, enabling the localization of the sound emitter, which cannot be done with only one device (Küsel et al., 2017).

6 Conclusions

This project highlights the potential of coastal gliders equipped with PAM systems to advance our understanding of underwater soundscapes and support the monitoring of underwater noise pollution. Gliders offer unique advantages as silent, buoyancy-driven platforms capable of long-term deployment. They enable the simultaneous collection of acoustic and environmental data, connecting underwater noises and the surrounding oceanic conditions. This integration is essential for developing accurate sound propagation models, which are key to assessing noise pollution and understanding its impact on marine ecosystems. Furthermore, gliders provide a cost-effective, non-invasive, and flexible solution for monitoring large spatial and temporal scales, addressing some of the limitations of traditional moored PAM systems.

Coastal gliders operate quietly while gliding but generate self-noise during maneuvers and surface interactions, limiting their effectiveness for PAM activities. The surfacing phase, particularly in shallow waters, is the main source of time loss for PAM, while descent and ascent phases, making up 72–80% of mission time, are ideal for acoustic recording. Optimizing glider settings, minimizing surface time, and excluding noisy events from datasets can enhance their suitability for PAM applications. Additionally, this work demonstrated the ability of gliders to detect specific signals, such as a 34 kHz pinger, even in stratified environments like the Baltic Sea. Signal variability due to depth, orientation, and thermocline effects emphasizes the need for further refinement of acoustic propagation models and analytical approaches to account for such complexities.

As underwater noise pollution continues to pose a global challenge, the advancement and integration of glider-based PAM systems represent a critical step forward. Beyond their role in addressing environmental concerns, these systems also contribute to national safety by enhancing our ability to monitor and assess underwater activities, such as ship traffic and other anthropogenic sources, and identify new threats, like gliders and other autonomous platforms in sensitive or strategic maritime areas.

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Appendices

Field work

Figure A1. The first glider is deployed, the second is waiting for the deployment during one of the Tvärminne trial deployments.

Supporting data from EMODnet

Figure A2. Bathymetry according to EMODnet map service South of Tvärminne (A) and South of Utö (B) https://emodnet.ec.europa.eu/geoviewer/

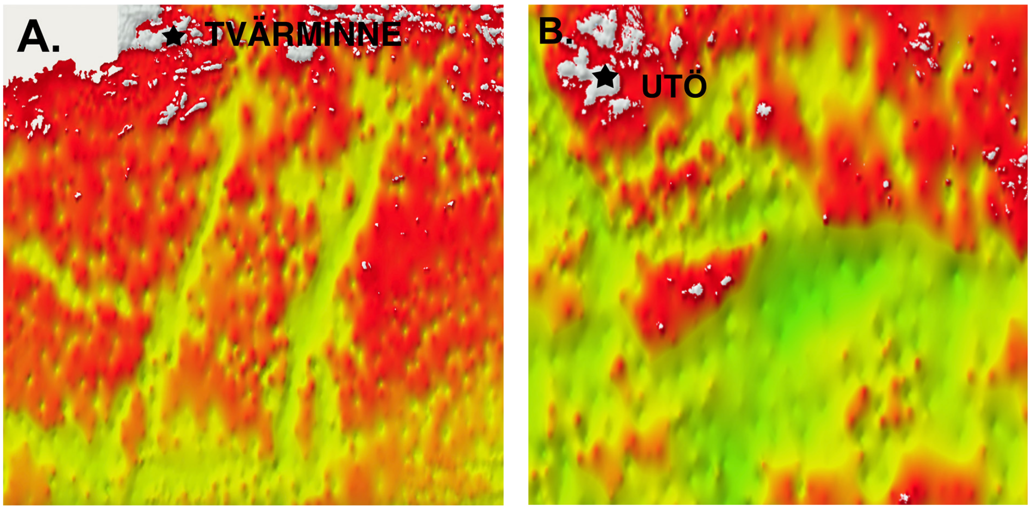
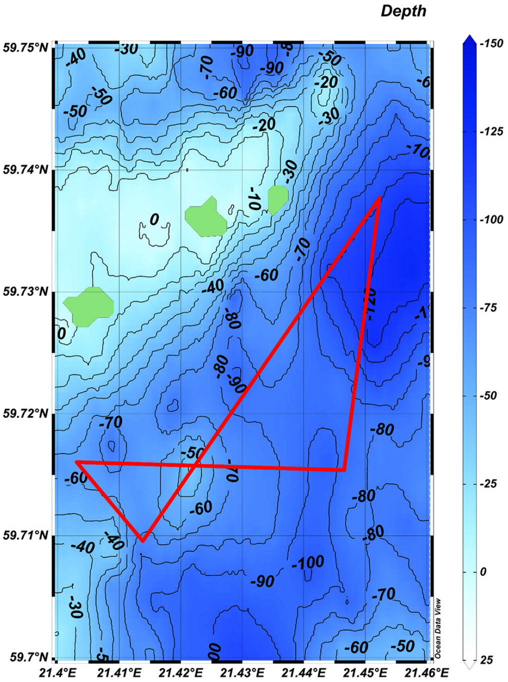


Figure A3. Utö bathymetric grid estimated with 5000 random points in the study area used to plan the glider path (red line).



Environmental parameters measured by the glider

Figure A4. Underwater visibility measured by the glider on June 19 during Utö mission. The transmissometer TAU has an optical path length 15 cm and nominal source wavelength 532nm (green). Tau-value varies from 1 to 0, where 1 is completely transparent (no signal loss) and 0 opaque (full signal is lost).

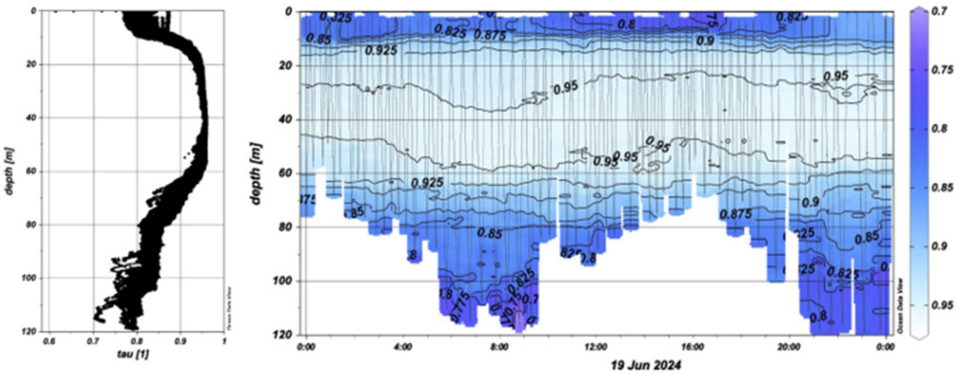
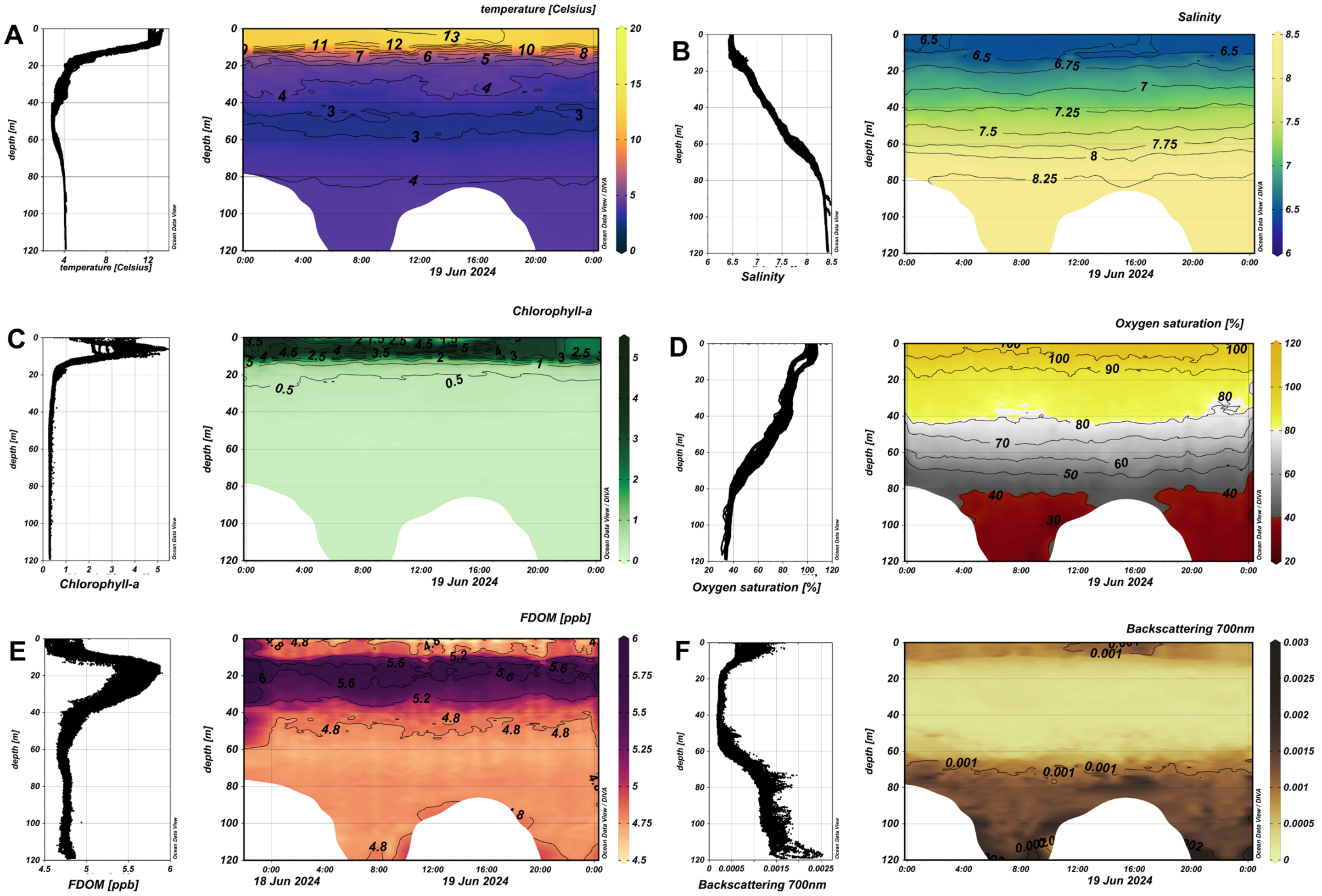


Figure A5. Other parameters measured by the glider on June 19 during Utö mission: Temperature (A), Salinity (B), Chlorophyll a (C), Oxygen concentration (D), fDOM (E) and 700nm backscattering (F).



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