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Bioglider: an integrated glider solution for enhancing environmental knowledge

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***Abstract*—This paper presents a technological solution for the observation and monitoring of the marine ecosystem. Three complementary devices, one optic imaging and one scientific acoustic instrument as well as one acoustic communication modem, have been integrated on glider platforms, providing qualitative and quantitative zooplankton and fish ecology observations, which are especially relevant in Nordic and Arctic polar regions. This 'Bioglider' solution has been tested on two available gliders.**

Another essential platform component for ocean observing are subsurface mooring lines which can complement glider observations in terms of temporal scales. Most of the time, they cannot have surface expressions in these regions because of sea-ice cover or harsh sea conditions, prohibiting real time data delivery. Underwater acoustic communication can allow the glider to serve as a data messenger, retrieving data from the moorings, complementing its measuring capacities. The Bioglider data transmission protocol and the Hydro-Acoustic Link Simulator were successfully tested in different test scenarios. We also developed a MIMO (Multi-input Multi-output) acoustic platform and obtained theoretical results about equalizing structures to face the harsh multipath acoustic underwater propagation. These developments address the challenges posed by sea-ice cover, harsh sea conditions, and maritime traffic, ensuring near real -time data delivery and enabling comprehensive observations of the marine environment.

The Bioglider sensor solution and Bioglider data transmission solution have been implemented or designed for the existing and commercially available gliders and are validated by first promising results from an operational, technological and scientific point of view.

I. INTRODUCTION

Ocean warming is affecting marine biodiversity [1] via a large number of processes that are largely misunderstood or still unknown, which triggers the need for better and systematic observing of biological communities, from plankton to fish. In particular, in situ biomass and organic carbon information and the density of plankton give crucial indications of the evolving large-scale transformations and are key elements for global understanding of the evolution of marine ecosystems.

It is still very challenging to unveil the complex ecological and biological processes in the marine ecosystem but such information and knowledge are also essential to provide adequate marine environmental protection measures while maintaining a sustainable exploitation of biological marine resources. Thus, it is key to observe and monitor biology and ecosystem Essential Ocean Variables (EOVs) at a range of space and time scales with a multiplatform approach using research vessels, fixed points observatories and mobile autonomous platforms. In this context, underwater gliders equipped with novel optical and acoustic sensors have a significant potential to collect and deliver the necessary data to build these new biological EOVs. Underwater gliders equipped with optical and acoustic sensors are particularly valuable in extreme environments, like the Arctic Ocean, where other platforms can be difficult to operate [2].

We have developed an integrated 'Bioglider' sensor solution for underwater gliders. Complementing the standard sensors usually present in a glider, mainly delivering physical and biochemical data of the water mass (temperature, salinity, oxygen concentration, fluorescence), two miniaturized devices, an optical imagery system (UVP- 6), manufactured by Hydroptic [3] and a scientific echosounder (WBT mini) [4] have been added to provide a 'smart' service for zooplankton and fish ecology applications. To complement the Bioglider capacities and when operated in ice-covered environments, an acoustic modem with higher transmission rates than existing ones is being integrated in a glider to exchange data with sub-surface moorings which can provide a full annual cycle of high temporal scale observations serving as reference data in the region of interest and allow cross-calibration of the data from the Bioglider. This is a useful solution for retrieving the data from the moorings in arctic regions where ice cover and harsh sea conditions prevent access to the surface to deliver data by satellite telemetry. The proposed Bioglider open

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solution is built from technological building blocks which are already available at TRL9 while the acoustic modem is still at TRL4 : low power sensors, software for control and analyses, such as artificial intelligence (AI) algorithms integrated on gliders, which allow to propose robust and affordable solutions for more comprehensive observations of marine ecosystems in coastal and deep seas, including in Nordic and Arctic environments.

A comparable technology has been developed by the Scripps Institution of Oceanography on the Spray glider [5], equipped with a low-power camera (Zoocam) with telecentric lens and a custom dual frequency Zonar (200 and 1000 kHz). The Zooglider has not yet been developed as a freely-available solution.

These Bioglider capacities are complemented with an acoustic modem that has been integrated to exchange data with subsurface moorings to allow the mooring information being regularly transmitted by glider and satellite joint telemetry. So far, no sustained activity or expertise in using gliders as data messengers has been developed by European research organizations, nor widely marketed to be uptaken by the research community. Based on advanced data transmission theory and platform concepts, we have developed a data transmission method and the corresponding protocols in order to maximize the data transfer rate between a moving glider and a fixed line both equipped with an acoustic modem. Complementary tests to analyze the benefit of this acoustic platform for the Arctic environment with its specific acoustic near-surface transmission channels are still under study.

The Bioglider solution has been tested during the Polar Front [6] and the Go North [7] cruises in 2022, where it successfully performed multiple dives. For example, Fig.2 displays plankton density as a function of depth as recorded by the echosounder along a glider dive track during the Polar Front cruise, together with images from the optical imagery device. An in depth cross-validation of the glider datasets with the data collected by the research vessels and surface autonomous vehicles is ongoing with promising first results.

II. COMBINED ACOUSTIC AND IMAGING SENSORS

The optical and the acoustic instruments provide complementary information, and when correlated can enhance the comprehension of the ecosystem. The imagery system provides pictures from a small water portion in front of the glider, recognizing particles > 100 μm at max 1.3 frames/second. It gives access to particle density by size class as well as taxonomic classes of Zooplankton. Acoustic measurements, on the other side, have a resolution depending on the frequency and the type of instrument. Differently from the Zooglider, our solution uses a broadband echosounder providing more precise results. It is capable of detecting and quantifying individual targets of a few centimeters (large zooplankton and micronekton) and when smaller particles are present, their concentration can be recovered from the data as well. The echosounder is configured to measure up to a range of 40 m under the glider, expanding the measuring range of the vehicle beyond the optical imagery measurement point at the front of the glider.

A. The imaging sensor : UVP-6 LP

The optical sensor, the UVP-6, was developed specifically to be used on autonomous or cabled platforms[8]. The UVP-6 LP (Low Power) is specifically designed for profiling floats and gliders. It is a miniaturized version of the UVP-5, and weighs 3,5 kg in air and consumes down to 0.8 W. Specific adaptation kits and developments allowed the UVP-6 LP to be mounted on the Seaglider, the Slocum and the SeaExplorer gliders. The data processing for classification and size class of the particles is done on-board which allows near real time (NRT) transmission of a small subset of the collected information [9].

As a result of the former European project BRIDGES [10], the UVP-6 LP was already available on the SeaExplorer gliders, and specific adaptation kits and hardware and software developments allowed the UVP-6 LP to be mounted on the Seaglider and the Slocum. In its last evolution, the Slocum adaptation kit fits both the G2 and G3 versions of this vehicle.

B. The EK80 echosounder

The miniaturized version of the scientific echosounder EK80 from Kongsberg Discovery, the WBT mini [4, 11], has been integrated (both hardware and software) into a Seaglider with a down-facing 333 kHz transducer using the DeepEcho module of this echosounder linked to the science bay of the vehicle with a SIRMA smart cable [12], developed during the BRIDGES project by CSCS. The hardware and software integrations have been done on the Seaglider and are ongoing for the Slocum G2 and the Slocum G3 glider.

In order to obtain data with minimum noise, the EK80 is physically disconnected from the Seaglider's electronic system while pinging. This is achieved by running the EK80 only on the way down on a separate rechargeable battery, which is recharged during the climb phase of the dive profiles. Due to the profiling nature of the datasets, a tailored echosounder data processing pipeline was developed to extract meaningful information from raw acoustic data. The next step and overall goal in this regard is to develop an open-source portable and scalable solution specific to glider platforms, which may be deployed on different processing layers, i.e. the glider platform, in the cloud or on-shore on a desktop computer.

III. UNDERWATER ACOUSTIC COMMUNICATION

Ocean observing relies on a range of essential components to gather data effectively. Among these, subsurface mooring lines play a crucial role, particularly when access is limited due to sea-ice cover, challenging sea conditions, which prevent NRT data delivery. Conversely, when it comes to under-ice navigation of gliders, NRT transmission will become imperative if remote control and NRT data delivery are required. To address these requirements, the use of

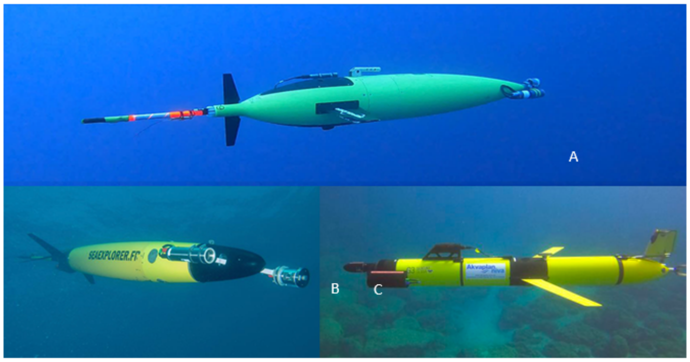

Fig. 1. UVP-6 integrated in the front of the gliders : Seaglider (A), SeaExplorer (B) and Slocum (C). Note the transducer of the EK80 facing downwards next to the wing on the Seaglider (A).

moorings with a surface expression above the ice cover can serve as a central hub for efficient two way data transmission to the land station via satellite communication. Efficient and robust acoustic communication between moorings and gliders is required to meet these two objectives. We have studied several acoustic modems and developed a universal digital interface with the glider sensors. Some heavy restrictions were imposed for the modem choice : energy consumption with low duty-cycles and dimensions. Based on advanced data transmission theory, we developed a data transmission method and corresponding protocols to maximize the data transfer rate between a moving glider and a fixed line carrying an acoustic modem. This allowed us to test the Bioglider Data transmission Protocol (BDP) and the Hydro-Acoustic Link Simulator (HALS), both of which have undergone successful testing in various scenarios. Software for delayed packet transmission and test scenarios have also been developed.

Moreover, these tests took into account energy-saving considerations, contributing to the overall sustainability and longevity of the observing systems. Also in practice, acoustic waves are strongly disturbed by several physical phenomena: significant attenuation, noise, multipath, Doppler effect, low propagation speed of acoustic waves (around 1500 m/s), triply selective channel (time, frequency, space). All these combined effects limit data rates to just a few tens of kbits/s per km [13-16]. We also have developed a MIMO (Multi-input Multi- output) acoustic platform and obtained theoretical results about equalizing structures to face the harsh multipath acoustic underwater propagation. Further tests to analyze the benefit of this acoustic platform for the Arctic environment with its specific acoustic transmission channels near the surface, including with ice cover, are foreseen.

Therefore, it is interesting for underwater acoustic systems to use new high spectral efficiency techniques such as high order constellations, faster-than-Nyquist (FTN) modulation, rotated constellations [17-20], and Multi-input Multi-output (MIMO) systems. All of these high spectral efficient techniques make synchronization and equalization at the receiver side, more complicated than with simple usual modulations.

In the project, we tested several turbo synchronization and equalization algorithms [21][22] leading to better system performance compared to the state-of-the-art solutions for several advanced modulation techniques. These algorithms inherently consider the characteristics of the modulation to enhance the system performance. They also take into account the characteristics of the underwater channel (time-varying, sparse...) to both reduce the receiver complexity and obtain lower bit error rates.

A solution allowing for remote data retrieval from moored sensors without the need to recover a mooring is of particular interest for observing systems in polar areas where sea ice cover prevents the surface access and hinders sea-to-shore satellite data transfer in NRT. Acoustic data retrieval from underwater sensors has been implemented in several ocean networks where data were harvested from a vessel or by a surface buoy equipped with an acoustic receiver. Data from the under-ice subsurface moorings can be acoustically recovered by a passing-by ice-capable vessel but ship traffic is very limited in ice-covered areas and weather and ice conditions can be often too harsh to allow stationary time needed for relatively slow data transfer via acoustic link. Autonomous underwater vehicles as gliders can provide a more flexible solution, serving as data messengers and offering more frequent access to subsurface moored sensors. The development of an underwater geopositioning system (UW-GPS) and acoustic navigation of gliders (and other autonomous platforms) operating under the sea ice is an emerging topic in polar ocean observing systems [23] is beyond the scope of this paper. Given the new possibilities coming up with gliders capable of under-ice homing and navigation, we have focused on developing a simple, cost-efficient yet robust, highly scalable system for acoustic data transfer between moored sensors and a glider. The system components for the mooring and glider nodes are based on off-the-shelf acoustic modems combined with a dedicated data integrator. The stand-alone solution can be integrated with any glider type. The design and development of mooring and glider nodes for acoustic data transfer is presented in Section 4 while field experiments to test the solution in the Baltic Sea and in the Arctic fjords are described in Section 5.

A system for acoustic data transfer was designed to solve the problem of retrieving data recorded on long-term underwater installations (e.g. subsurface moorings) with an autonomous underwater vehicle (glider). The system is physically split into two parts. The mooring acoustic node (MAN) is responsible for recording data from moored sensors (e.g. CTD, ADCP, O2 sensor, etc.) and transmitting data to its glider counterpart using a acoustic modem. The glider acoustic node (GAN) is responsible for downloading data stream from its mooring counterpart using acoustic modem and storing data for later retrieval and/or their transmission to shore via satellite link. A dedicated communication layer is built on top of commercially available 'off-the-shelf' acoustic modems. Short range acoustic communication (up to about 500 m) was assumed as glider pilots can maneuver gliders relatively close to underwater installation to achieve better propagation conditions with lower attenuation of acoustic signal. Acoustic modems tend to deliver higher baud rates, more reliable communication with lower power consumption and smaller factor for short range communication. Different requirements were defined for the mooring and glider acoustic nodes. For MAN, the minimum lifetime of one year was required with capability of data retrieval by a glider at any time. The battery pack integrated in MAN should power both its data integrator and the acoustic modem. The mooring node should be capable of retrieving data from commonly used oceanographic sensors from different manufactures to ensure compatibility with existing equipment. The glider node GAN should have operation time up to the length of a glider mission and, if fully integrated on a glider, a capability to be switched on/off on demand. In the self-contained version, GAN includes its own built-in power source while after full integration it can run on the internal glider battery pack. Data transmission protocol on GAN should be able to resume data download from the last received record to assure the power and time efficiency of acoustic communication. Different acoustic modems were evaluated based on openly available specification datasheets with main criteria including power consumption, body factor (size and weight) as well as market availability and responsiveness of manufacturer support. For the Bioglider test phases, 'Modem 6 Nano' from Sonardyne was selected from the range of available off the shelf modems. Power consumption in listening mode was especially crucial for the mooring node since the minimum year-long operation was expected and unknown irregular data retrieval scheme was foreseen. Modem 6 Nano in listening mode has less than 5 mW power draw. Modem 6 Nano offers 100-3500 bps rates for data transition between modems. Energy use of the whole system depends on the total data volume transmitted by the modem link and is mostly independent of data retrieval frequency, except for protocol overhead. Thus, power requirements for GAN can be considered linear in time and calculated from deployment time and total data volume to be transferred by modems. Based on the example of a widely used CTD sensor RBR Concerto3, the total data volume was estimated. In standard configuration, the RBR sensor generates about 120 bytes ASCII string per each sample (time, conductivity, temperature, pressure, sea pressure, depth, salinity, speed of sound, specific conductivity) stored in the internal memory for backup. When set with the sampling interval of 1 hour, the CTD sensor generates about 1 MB file per year.

To obtain maximum efficiency, the mooring and glider acoustic nodes were designed based on the same electronics and software with configuration options that switch functionality. As a design choice for software development NUTTX open-source POSIX compatible operating system was used with C/C++ programming language. The ability to compile as a x86 application for GNU/Linux was useful to speed up the system development. Since all devices (modems, CTD sensor) use serial interfaces (RS232), they are working in the same way on a POSIX layer as are the files and filesystem. In that way the developed software runs in the same way on the bare STM32H743 microcontroller and on a PC with GNU/Linux. Using NUTTX operating system also allows embracing modularity of the whole logic with e.g. CTD data logger functionality separated from data transfer functionality. That gives an advantage to easily extend the system for new sensors. Using the embedded operating system also gives access to its standard tools like system shell, files management, time management, and many others.

On MAN the communication with RBR Concerto3 is done via RS232 serial port with a 115200 baudrate. CTD is set up to stream data to serial while logging data internally for later comparison. ASCII logging format has been adopted and data are written to a log file, with flushing buffers and sync after a write, to ensure data availability for other processes. To ensure consistent data transfer logic, a dedicated Bioglider Protocol (BGlP) was developed. MAN logic is passive in terms of communication and works as a service provider to reply for commands queried by GAN. To utilize the full potential of the Modem 6 Nano, both command and data modes are used. MR command is used to remotely interrogate another Modem 6 in range to estimate the range between GAN and MAN. MR command combined with DIAG command returns signal quality estimation. MR query is highly optimized as a very short pulse as it is used to report round trip time in microseconds. It also works internally between modems alone even if MAN fails to respond. Although Modem 6 Nano offers more sophisticated modes, a simple "Fire and Forget" mode of communication was implemented in our system where communication protocol was built on top of the simple mode, similarly to the simple UDP over IP. The 'Fire and Forget' mode includes data integrity checks and assures that only error free packets are received therefore no erroneous data transfer was observed through the tests. After checking that MAN is in range and switching to data mode, a set of queries and replays is executed by GAN. A data ping command is used to interrogate that data link is available, but also to synchronize both nodes. It is also used to estimate the roundtrip time when Modem 6 Nano devices are used, as they do not provide MR commands with roundtrip time. After successful ping query, a pull command of BGlP protocol is queried by the glider and used to pull one or more chunks of data from MAN. As each query takes about 2-4 seconds, it increases efficiency when more than one data chunk is queried at a time. GAN using chunks can download the whole data log file. For performing real time tests, a query for the most recent data was implemented. BGlP protocol is also designed and implemented as a binary protocol with the same principles but being more space efficient and can be used for ASCII and binary data log files as well.

In terms of the external hardware design, the main body of the mooring acoustic node is a 316 Stainless Steel custom-machined pressure resistant cylinder container with end caps sealed by double O-rings. It contains a data integrator and a dedicated battery pack. Modem 6 Nano and underwater sensors (in our test case the RBR Concerto3 CTD) are connected to MAN by external underwater cables with MacArtney SubConn Micro Circular 6 and 8 pin connectors. For sea tests described in Section 5, the MAN main unit and CTD were mounted on a dedicated in-line stainless steel bar with the acoustic modem attached to the mooring cable above the bar. In the self-contained version, the glider acoustic node fits into a pressure aluminum housing with acrylic end caps. Due to its small dimensions (the diameter of 2" and the length of 30 cm) it can be easily attached to a glider as an external extension with the Modem 6 Nano directly connected to an 8 pin female bulkhead connector. Pressure rating of the MAN and GAN setup is limited by the acoustic modem rating of 500 m. The mooring node is powered by the alkaline battery 12s3p pack with 12-20 V or the Li-ION rechargeable battery pack, both easily replaceable in field. The glider node power source is Li-ION battery pack 4s2p with the nominal voltage of 14.8 V made of 18650 cells.

IV. TESTING AND SCIENTIFIC RESULTS

The Bioglider sensor solution, i.e. a glider mounted with the UVP-6 LP optical imaging sensor and the EK80 echosounder, was tested during two recent measurement campaigns, namely the Polar Front and the Go North cruises, where it successfully performed multiple dives.

A. Polar Front and GoNorth cruises

1) Polar Front 2021 : During this mission, the Seaglider had a UVP-6 installed on the nose which was the first completely autonomous launch with this mounting configuration. The UVP-6 was configured to operate in the upper 100 m only. The UVP-6 collected images during 28 dives and collected thousands of images during each dive. It was part of a fleet of autonomous vehicles, with a second Seaglider and two Sailbuoys, one equipped with the EK80. This helps understand the correlation between acoustic and optical data. Even if the Bioglider solution can be used as a solitary platform, it could be used in conjunction with other relevant platforms as part of a glider swarm [24] or part of the multiplatform approach.

2) Polar Front 2022: The Seaglider 'SG644' equipped with active acoustics (EK80 WBT mini) and underwater vision profiler (UVP-6) was deployed during the Polar Front 2022 cruise. The WBT mini and 333 kHz single beam transducer were post-calibrated using a 25 mm sphere for a target strength broadband frequency response analysis, no on/off-axis calibration was possible with single-beam.

The glider successfully recorded 86 dives, providing 86 profiles of EK80 measures (during descent) while the UVP-6 captured data at the descent and ascent, providing thousands of vignettes (Table 1), which are samples of the image capturing individual objects. The EK80 on the glider data showed consistent patterns of shallow strong schools (likely capelin) and midwater aggregations (krill) throughout the dives comparable to what was seen from the EK60 of the vessel.

Sensor	***Parameter***	***Sampling freq.***	***Data recorded***
CT	*CT*	*Every 5 secs*	*172 profiles (86 up, 86 down)*
Optode	O_2	*Every 5 secs*	*172 profiles (86 up, 86 down)*
WBT mini + 333 kHz single beam transducer	*Acoustic backscatter*	*Continuous during descent*	*86 profiles (down only) (14.5 GB)*
UVP-6	*Images*	*Above 100 m: 2 Hz Below 100 m: 0.5 Hz*	*172 profiles of images (1.8 GB)*
Depth	*Depth*	*Dive to seafloor (within 30 m)*	*30m, 90m, 210m, then 360 m*

Table.1 Sensors and configuration of the 'Bioglider' Seaglider during the Polar Front 2022 deployment

B. GoNorth Cruise 2022

GoNorth is a Norwegian Arctic program that aims at better understanding the not well understood ecosystem between Nordaustlandet and Kvitøya, north of Svalbard. The need for knowledge in this area is essential, because since 2009, UN's Continental Shelf Commission agreed to Norway's demand and this area is now part of the Norwegian seas. The project answers to the government's Ocean Strategy addressing knowledge building and sustainable development and adds a new dimension to the policy. Hence, the GoNorth team pursued a wide-ranging and cross-disciplinary scientific program to acquire new and essential knowledge about the oceanic areas, from the sea-floor and subsea geology through the water column and up to the surface sea ice. The Seaglider mounted with both, the acoustic and the imaging device, was deployed during two weeks from the 17th to the 31st of October 2022, with technical improvements of the glider and UVP-6 pressure sensor and an improved calibration of the EK80 and new settings of the acoustic sensor, i.e., 2.048 ms, 38 W, 50 m max range and a 0.75 sec ping interval for a target resolution of 7-8 mm.

C. Scientific results

An in depth cross-validation of the acoustic and optical Bioglider datasets with the data collected by the research vessels and surface autonomous vessel is ongoing to determine the exact scientific benefit of the combination of both sensors, and first results look very promising. While the UVP-6 gives an image of the size and taxonomy at the front of the glider, the EK80 gets data for the 40 m of water column under the glider, which can extrapolate the UVP-6 LP data (see Fig.2).

Sorting UVP-6 vignettes is time consuming and the methodology set up was to select first potential dives regarding the EK80 data and extract corresponding imagery vignettes from the UVP-6 data. First objective is to compare particle density measured by both sensors. First results are encouraging and deliver very preliminary hints with regards to the scientific potential of this Bioglider solution.

D. Sea tests of the acoustic data transfer

The first sea tests of the stand-alone acoustic node integrated on a glider as the external extension took place on 9-11

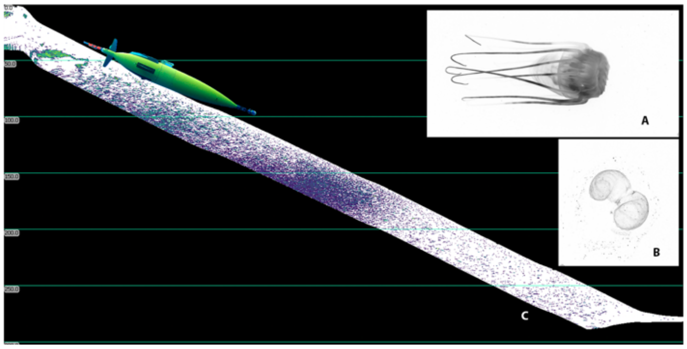

Fig. 2. A/ and B/ Plankton images are captured with the UVP-6 and – C/ shows the EK80 echogram of the organism density as function of depth along an exemplary dive track of the Seaglider during the Polar Front cruise.

May 2023 during RV Oceania cruise in the Baltic Sea. A short mooring equipped with the mooring acoustic node, RBR Concerto 3 CTD, subsurface buoyancy and a single acoustic release was deployed at the water depth of 50 m at the position 54°50.6'N and 018°40.55'E south-west of the Gdansk Deep. The mooring acoustic node was located approximately 10 m above the bottom. Access to the Slocum G1 glider 'Mia', owned and operated by Tallin Technical University was obtained from the LISTEN project under the JERICO-S3 Transnational Access call. The glider acoustic node consisting of the Modem 6 Nano acoustic modem and data integrator in the separate pressure case was attached to the bottom of the Slocum glider with an external harness. To obtain the neutral buoyancy of the external setup, four blocks of Subsea Buoyancy Foam were integrated in the harness on the top of the vehicle. The main aim of the Baltic Sea experiment was to test the efficiency of mechanical integration of the acoustic node on the Slocum glider, including glider behavior during the flight with the increased form drag. The communication between the glider and mooring acoustic nodes was also tested. The originally planned glider trajectory in the form of a star centered at the mooring location could not be achieved due to the harsh weather conditions and very strong currents (occasionally exceeding 1 m/s) in the test area. However, a few flights along the irregular paths and with varying distance to the mooring location were performed over two days, showing a low impact of the external extension on the glider performance and in general, proving feasibility of using a simple self-contained acoustic node. Service acoustic communication in the command mode was established between acoustic modems on the mooring and glider. However, due to the unusual and difficult environmental conditions in the Baltic (strong currents preventing a good control of glider trajectory) and suboptimal modem performance, no data transfer between acoustic nodes was achieved during the sea trial. The results from the Baltic Seas tests were also used to tune the setup of acoustic modems for future tests. The following sea tests of the glider and mooring acoustic nodes were carried out in the polar environment during the Arctic expedition AREX2023 of RV Oceania in summer 2023. Since we had no glider available for the polar experiment the glider acoustic node was tested from a slowly moving small boat or drifting research vessel. To simulate ascending and ascending dives of a glider, the glider self-contained node connected to the RBR Concerto 3 CTD was slowly lowered and hoisted to the desired depth on a winch cable during the boat drift. The sea tests were performed in three steps, including (i) short-range data transfer between acoustic modems separated between the ships aft and bow (approx. 40 m), (ii) medium-range acoustic transfer when the acoustic mooring node was lowered from the vessel and data were received with the glider node lowered from a small boat within the distance of 50-500 m from the vessel, and (iii) medium to long range data transfer between the subsurface mooring and the glider node lowered from the vessel drifting across the mooring position within the distance up to 1 km. Two first tests were carried out in the deep basin of Magdalena fjorden, the Arctic fjord with tidal glaciers in the northern Svalbard. The long range test took place in the deep waters in the front of Krossfjorden, another Arctic fjord in the north-western Svalbard. Both locations were characterized by a strong stratification of the water column with cold and fresh Arctic water overlying the warm and salty Atlantic-origin water masses. During the short-range experiment the mooring acoustic node, transmitting data collected with the connected RBR CTD, was subsequently lowered to the depth of 10 m (above the thermocline), 20 m (within the thermocline) and 90 m (below the thermocline and approx. 10 mab). The transducer of the glider acoustic node was lowered on a cable to the depth of 5 m below the surface (above thermocline). The glider acoustic node was running on a PC to debug protocol in real time. The tests were conducted to check the internal working scheme of the BGlP protocol in a real environment. In particular, the timeouts in protocol due to the changing distance between transducers have significant impact on delays between transmission and reception of each command and then on query and reply of BGlP protocol. Based on the short-range

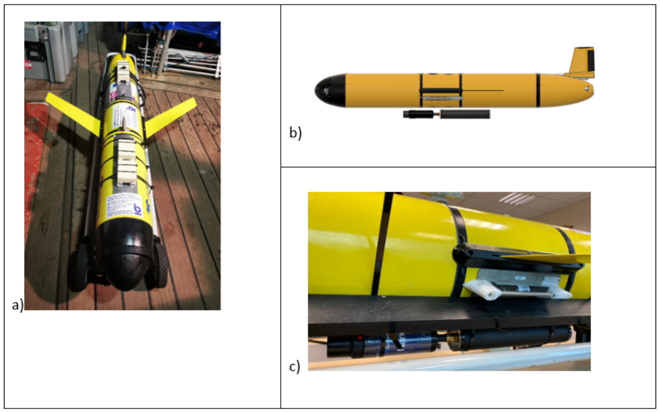

Fig. 3. (a) The Slocum glider Mia before deployment in the Baltic Sea (the buoyancy blocks visible on the top and the acoustic node mounted but not visible at the bottom), (b) a conceptual design of the self-contained glider acoustic node on Slocum, and (c) the glider acoustic node attached to the Slocum bottom.

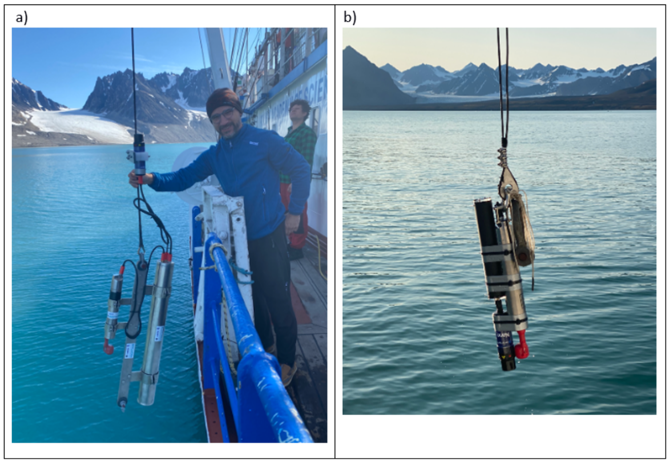

Fig. 4. (a) MAN lowered from the ship crane for short range tests in Magdalena fjorden, and (b) GAN lowered from the ship's crane to simulate glider dives during the test in Krossfjorden.

test, the optimal modem parameters with a bit rate of 900 bps, command output gain of 184 dB, data output gain of 175 dB, and input gain of 30 dB were established as providing the most robust communication in the tested environment.

During the small boat experiment, the mooring acoustic node connected to the RBR CTD was set up from the vessel at the depth of 90 m in a similar way as during the previous test while the glider node was deployed from the boat moving away from the ship and stopping at the distance of 100, 200, 300 and 500 m. The self-contained glider acoustic node was lowered by hand from the boat between the sea surface and the bottom to obtain the full depth profile of acoustic transmissions. The preliminary results indicate that the communication range of the developed system exceeded expected values. Tests were also conducted to check whether the self-contained version of GAN is capable of communicating on longer ranges and to record delays between queries and replies.

During the long-range test in deep water next to Krossfjorden, the short subsurface mooring was placed at the water depth of 220 m with the top buoyancy reaching to approx. 100 m below the sea surface. The mooring acoustic node with the connected RBR CTD was located at the approx. depth of 200 m and 22 m above the bottom. The pressure case which contained the mooring data integrator and battery pack and the RBR Concerto 3 CTD were mounted on a dedicated stainless-steel frame deployed inline while the acoustic modem was clamped to the mooring rope about 0.5 m above the frame, looking upward. The first buoyancy element on the mooring (two Vitrovex glass balls) were attached inline approx. 40 m above the modem. The setup was fully recovered after concluding the test.., The vessel was positioned about 1 km upstream of the mooring position and slowly drifted towards, over, and beyond the mooring with the average speed of 0.5-1 knots. The glider acoustic node was slowly lowered and hoisted from the ship crane between the surface and about 200 m depth in 20 m intervals to simulate descent and ascent of a glider. The preliminary results allow for the efficiency of data transfer (error-free transmissions) in the function of the distance between GAN and MAN. Since the BGlP is a bidirectional protocol, delays added to communication (time lags between queries and replies) have a significant impact on the overall throughput of the data stream. That said it is crucial for a glider to navigate as close as possible to the mooring to achieve faster data download data. Further analysis of data collected during the Arctic tests will provide more detailed statistics of the quality of received transmission for different geometries (depth-distance) of the glider and mooring acoustic nodes.

V. CONCLUSION

The Bioglider sensor solution addresses the need for increased monitoring of biological communities, in line with most recent technology developments. Miniaturized sensors with great observing capabilities integrated on autonomous platforms open new possibilities for biological observations, coupled with physical data already measured by the gliders, especially in harsh difficult-to-access environments like the Arctic. Technological developments based on sensor mechanical and electrical integration in gliders have been tested at sea and proved successful, while showing new opportunities for future improvements. Data analysis is ongoing and should provide detailed scientific evidence of the complementarity of both acoustic and imaging sensors. Underwater acoustic communication with gliders is a new domain with great potential for improving near real time data transmission for environmental monitoring. They range from modem and communication design to the new Bioglider data transmission protocol and the Hydro-Acoustic Link Simulator, both of which have undergone successful testing in various scenarios and have paved the way for the future communication capacity. Going forward the latter will enable gliders to act as a data messenger, retrieving the data of moorings with no surface expression as well as for potential underice remote controlled navigation. These two Bioglider solutions can be implemented on separate gliders and possibly on one glider in the future. They open new possibilities to study coupled physical and biological processes undergoing in Nordic and Arctic ecosystems and to better support the multiplatform monitoring of these regions.

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