An ice-tethered buoy for fish and plankton research

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I. ABSTRACT

In this paper the authors present bio-acoustical ice-tethered platform for optical, physical and ecological sensors (POPE), i.e. an ice-tethered buoy, equipped with an AZFP scientific echosounder for fish and plankton research under the ice in the Arctic. The POPE enables remote transfer of large volume of environmental information using flying vehicles as data-mules. The presented prototype has been tested in a salt-water, open-air pool through the winter of 2017-2018, and the first Arctic deployment is planned for November 2018. This paper covers the design of the instrument, including details on its operation, and data-collection mechanism.

II. INTRODUCTION

Climate change trends in the Arctic indicate increasing average water temperatures. The area covered by ice is reducing progressively, and there is evidence of boreal species spreading up north [1]. These conditions have already shown effects in the local and surrounding ecosystems, for example, plankton community shifts in timing, quantity, and composition in high Arctic fjords [2].

Long-term data series of under-ice fauna are crucial to better understand the natural and dynamic processes in Arctic regions. One of the limiting factors for such activities is lack of infrastructure, which makes long-term research in these regions a very challenging task. Manned expeditions to the Arctic ice layer are limited to remote research stations, a few year-round observatories, and research cruises lacking spatial resolution. Alternatively, automatic and autonomous sensors can be used. However, they are limited by the power and telecommunications infrastructure. This means that if large amounts of data are gathered, they need to be manually collected from the instrument itself.

"The Arctic Ocean ecosystems - Applied technology, Biological interactions and Consequences in an era of abrupt climate change" – Arctic ABC[1] – is a project aiming to document the under-ice Arctic ecosystem and to develop the necessary instrumentation. The project is lead by the University of Tromsø – the Arctic University of Norway (UiT), and includes cooperation with the Norwegian University of Science and Technology (NTNU), the University Centre in Svalbard (UNIS) and the Scottish Association of Marine Sciences (SAMS, UK).

One of the milestones of Arctic ABC is to create a set of ice-tethered platforms for optical, physical and ecological sensors (POPEs). They are designed to perform modern research in the Arctic [3]. The POPEs that are being developed include: an environmental platform to measure light and temperature in the water column, suitable for example for ice ridge research, the Sea Ice Mass Balance (SIMBA) [4], a platform for bio-acoustical research, and an autonomous weather station. This paper discusses the design and evaluation of the prototype of the bio-acoustical node, that is equipped with a scientific echosounder (Fig. 1).

Ice drifters and buoys equipped with diverse scientific devices have been successfully used to observe the Arctic ecosystem [5], [6], [7]. On top of the regular considerations needed for a marine buoy design, ice-tethered buoys face additional challenges. These include very low temperatures of operation, significant variations in light regime at the sampling site, risks of mechanical damages due to drifting among ice structures, and the likelihood of attacks by local fauna (e.g. polar bears). In addition, the environmental factors also influence the deploying-crew effectiveness, and safety.

The major contribution and novelty of the buoy presented in this paper is its data-retrieval mechanism. In order to provide a relevant set of measurements, the buoy's echosounder is configured to generate amounts of data that make it either very expensive, or almost unfeasible to be transmitted through the satellite links publicly available in the Arctic. Moreover, the area of deployment makes manual data retrieval logistically demanding and expensive if compared to buoys in waters free of ice.

The presented system uses either a manned aircraft or an unmanned aerial vehicle (UAV) as a data-mule to collect the observations from the buoy, as shown in [8]. The data-mule technique involves a vehicle that flies in the proximity of to the buoy, establishes contact with it, e.g. via radio, and transfers data from the buoy to its on-board memory. When the transfer is complete the aircraft travels back to a base where the data can be collected from it. Data-muling nodes are not limited to flying vehicles. If applicable other platforms can be used, e.g., ships or unmanned surface vehicles (USV), as long as they are able to come within the radio range of the buoy.

Section III of this paper presents the description of the physical layout of the bio-acoustical POPE together with its electronics and software. Section IV describes the

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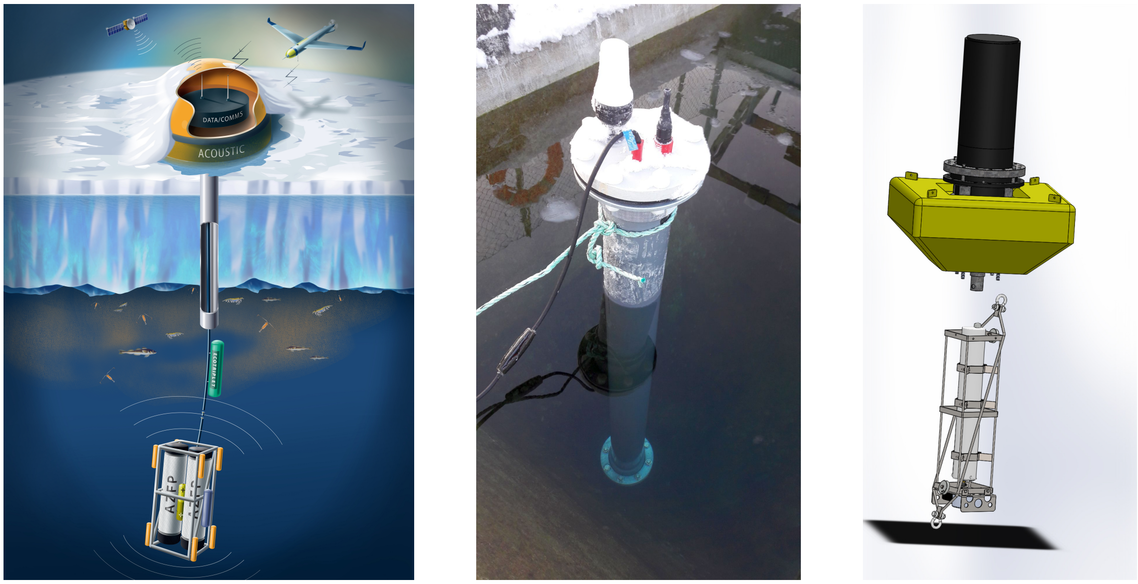
[1] http://www.mare-incognitum.no/index.php/arcticabc



(a) Visualization (b) Prototype (c) Final design drawing

Fig. 1: Arctic ABCs bio-acoustical ice-tethered platform for optical, physical and ecological sensors (POPE). (1a) The acoustic measurements are transferred using aerial data-mule, e.g. an UAV, while housekeeping information is sent via the satellite network. (1b)The first prototype of the bio-acoustical POPE was tested in controlled conditions, outdoors in a saltwater basin. (1c) the POPE units that will be deployed in the Arctic are being manufactured with challenges of Arctic environment and attacks from polar bears in mind.

unit's modes of operation, while section V discusses power consumption. Laboratory tests of the prototype are evaluated in section VI Data retrieval process and future developments are presented in section VII.

III. SYSTEM DESCRIPTION

A. Mechanics

The mechanical structure of the bio-acoustical POPE can be divided into three parts: a housing that sits on top of the ice, a float, and an underwater sensor hanging under the ice connected to the atmosphere through the instruments in the housing above the ice.

The prototype (Fig. 1b) used an acrylonitrile butadiene styrene (ABS) pipe that acts both as a housing and a floater. High density polyethylene (HDPE) is also being used for the purpose as both materials continue to be robust, yet resilient when operating at low temperatures. They are resistant to the ultra violet rays from the sun and provide a suitable alternative to metallic materials in this harsh environment.

The housing sits on a floater which is an APB Aqua 500 buoy (Polyform, Norway). It provides the required buoyancy to both the housing on top and the sensor underneath it. The sensor is attached to the buoy by means of an umbilical cable that transfers the weight of the submerged instrument to the top of the buoy, and includes communication and power lines that join the buoy's electronics with the sensor.

B. Underwater sensor

The POPE is designed to collect, store and transfer data from an Autonomous Zooplankton and Fish Profiler (AZFP, ASL Environmental, Canada). The unit sends an acoustic signal (ping) at four discrete frequencies, 38, 125, 200 and 455 kHz, and measures the returning echo. The reflected signal gives information about volume backscatter strength (Sv), which gives a notion of abundance and depth. The type of target, e.g. fish or zooplankton, is defined based on the differences between the different frequencies.

The sampling program of the AZFP is optimized to provide the highest quality of information from the habitat specific to the Arctic over a full-year period. The sensor pings once every 20 seconds (0.05 Hz). Data are averaged over 5-minute periods, in 1-m vertical bins. To optimize the signal to noise ratio (SNR), the pulse length is set to 1000 μs. The maximum range is set to 500 m because SNR decreases to unusable values (i.e. $< 10dB$) passed that limit.

The instrument hangs 15 m under the surface. Its directional transducers point downwards, which means that there is a gap between the surface and the instrument that is not insonified. However, the biological activity right under the ice keel is of particular interest, so a second bio-acoustical POPE is going to be deployed in the vicinity, with the upward looking echosounder. Units will be deployed $> 500\ m$ from each other to minimize interference in the readings. The second AZFP will be configured with the same ping rate and pulse lengths, however, vertical bins of 20 mm and 25 m range.

The units are expected to collect 1 GB of data per year for downward looking echosounder, and 2.84 GB of data per year for the upward looking echosounder. The internal AZFP battery is capable of handling the proposed sampling scheme for over a year. To transfer data from the AZFP to the surface unit, power is supplied from a battery on the surface housing.

C. Electronics and software

The electronic system (ES) of the buoy supports long-term operations enabling data-collection using cutting-edge technologies in the Arctic regions (Fig. 2). It handles three main functions: (1) retrieves the data from underwater sensor and copies it into the hard disk above the ice-layer, (2) provides housekeeping information to the user, i.e. such as GPS position, battery level, system status information, and (3) provides access to the data using the high-speed radio-link.

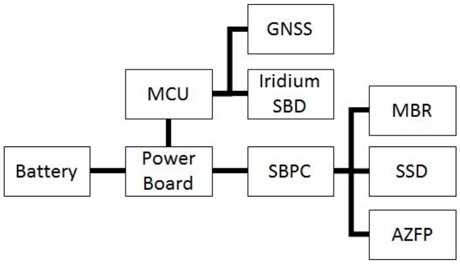


Fig. 2: Electronic System diagram. The MCU, together with a power board administrate the power to the individual components. These include location (GNSS), Iridium satellite communication (SBD), sensor data-backup (SBPC), radio (MBR), data storage (SSD), and scientific instrument (AZFP)

The ES uses two computation units: a main control unit (MCU), and a Single Board PC (SBPC). The MCU is a low-energy data-logger which controls the power distribution to all components in the buoy. It also communicates the housekeeping information to the user via Iridium Short Burst Data (SBD) messages, receives SBD messages send by the user, and uses them to configure power-cycles of ES components. To keep the system robust each component executes its program automatically after the power is supplied. Therefore the SBD power cycles define how often the underwater-sensor-data are being backed-up inside the ES memory. By default it happens once a day when the MCU supplies power to the SBPC. The SBPC boots into a Linux-based operating system, executes a custom made synchronization program that back-ups the data from the sensors, and stores it the allocated physical memory. The program collects the full lists of files and their sizes from the echosounder. When the list is retrieved, the program verifies that each file exists on the internal storage, and that the size of the backup matches the size of the original file in the echosounder. If the file does not exist or if their sizes are different, the backup file is downloaded again. For safety reasons no data is being deleted at any time. Frequent data backup prevents from complete data-loss in a situation when the sensor is damaged, or communication is not possible, e.g. tether cut by the ice motion.

In the presented system, the MCU role is held by a CR6 (Campbell Scientific Ltd., UK) measurement and control datalogger. The unit is designed to operate in temperature ranges between -40°C and +70°C (extended version is available). Current consumption depends on mode of operation and scan frequency. In an *idle* mode it is bellow 1 mA, while when *active* it takes 3 mA for 1 Hz scan, and 67 mA for 20 Hz scan.

The SBPC is TS-7250-V2 (Technologic Systems Inc., USA), equipped with 1 GHz ARM (Marvell PXA168) and 512 MB RAM. Its fanless operating temperature range is -40°C to 85°C. Power consumption ranges from 1.00 W to 2.58 W, typically reaching 1.21 W. Mean time between failures (MTBF) is 2 052 852 hours. The SBPC is equipped with an 1.92 TB SSD drive Extereme 900 (Sandisk, USA).

GPS data is acquired by the GPS16X-HVS (Garmin Ltd., USA) receiver. It is a 12 channels satellite receiver with the output frequency of 1 Hz, designed to operate in temperatures between -30°C and +80°C. Cold acquisition takes approximately 45 s.

Iridium communication is accessed using RockBLOCK+ (Rock Seven, UK) – based on Iridium 9602 modem, dedicated for M2M. It has build-in antennae, and operates in temperatures between -40°C and +85°C.

IV. MODES OF OPERATION

The prototype of the buoy is fully configurable using SBD messages. In the POPE to be deployed in the Arctic these message are going to be extended with few more functions. Command-masks for 5 modes of operations will be defined in order to simplify use of the unit, see Fig. 5. The new message format contains 8 fields:

- MODE – a mode name that activates certain command-mask. Available options: *standard*, *predownload*, *download*, *debug*, *service*
- TIME(UTC) – full hour (0-23) at which the selected mode should start.
- MAIN_INTERVAL – interval (hours) between GPS position update, and SBD inbox check. Mode of operation can change only at that moment.
- SBPC_ON – defines what should be the power setting of SBPC (ON/OFF) when next MAIN_INTERVAL event occurs.
- IRIDIUM(DIALUP)_ON – defines what should be the power setting of Iridium dial-up (ON/OFF) when next MAIN_INTERVAL event occurs.
- RADIO_ON – defines what should be the power setting of radio (ON/OFF) when next MAIN_INTERVAL event occurs.
- AZFP_ON – defines what should be the power setting of AZFP communication power line (ON/OFF) when next MAIN_INTERVAL event occurs.
- TIMEOUT – timeout after which the power to all components will be cut-off, regardless of progress of

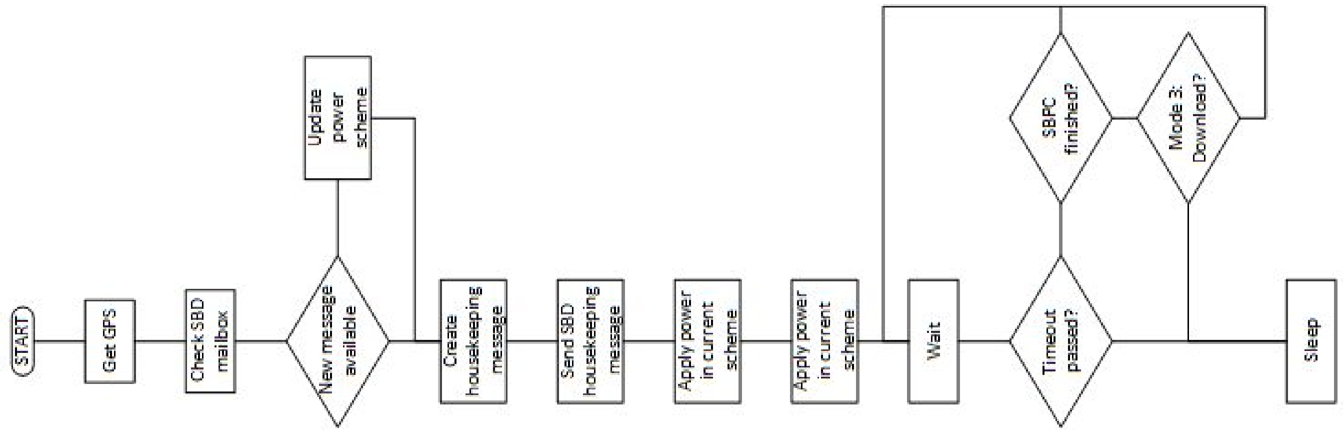


Fig. 3: The MCU controls the operation of the components of the POPE. This software diagram illustrates the flow of the main control program.

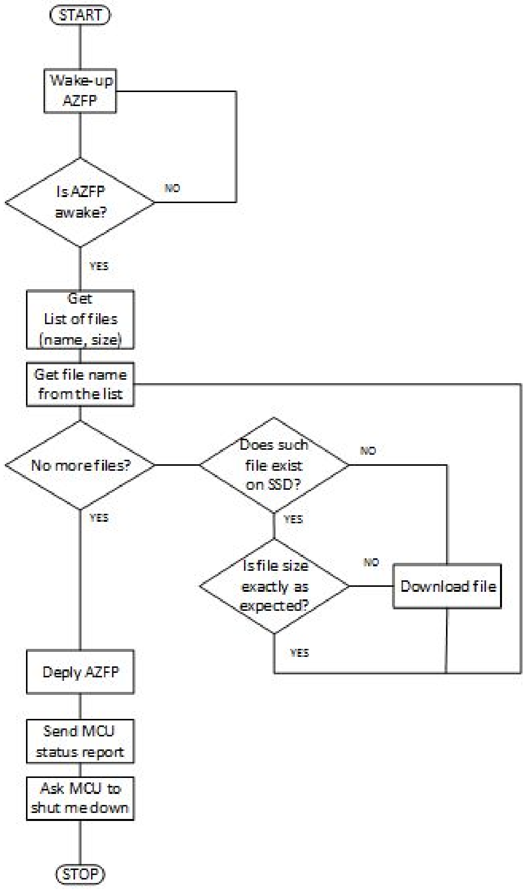


Fig. 4: The POPE's SBPC software diagram illustrates how device backs up the environmental observations from the AZFP.

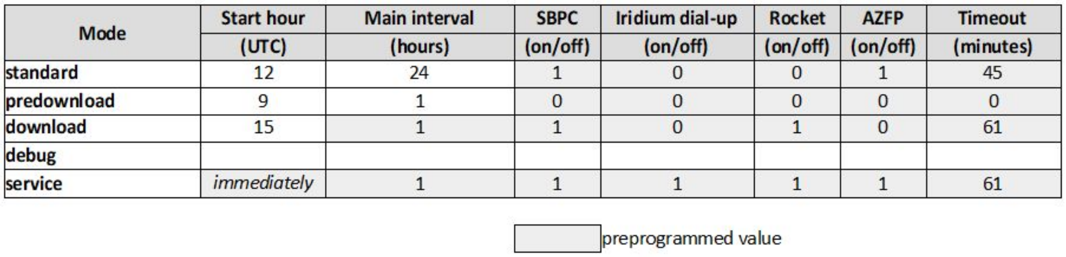
operation. If larger then MAIN_INTERVAL the power will not be cut-off.

The 5 predefined modes can be activated by messages that are received when SBD modem is on. The MCU always follows the routine presented on Fig. 3. The software on the SBPC is always following the same schedule, and is not aware of current mode of operation. The SBPC routine is presented on Fig. 4. Thanks to such approach, each power cycle tests full functionality of the SBPC software, and system debugging is more complete. Initial state of the MCU (after connecting main power source) is *Mode 5: Service*.

1) Mode 1: ***Standard*** The AZFP is pinging using its own battery and the sampling program described in section III-B). The MCU is idle and the power for the rest of the components is cut-off. The MCU wakes-up at a predefined time (first start at *TIME(UTC)*, repeat every *MAIN_INTERVAL*, see section IV). It turns on the GPS and SBD modem in order to check for incoming messages and send housekeeping data. The SBPC and AZFP are then powered from the buoy battery and data are backed up from the sensor to the hard disk in the housing. After the download is finished, the AZFP goes back to sampling, and power to SBPC, AZFP, GPS, SBD is cut-off. The AZFP continues operation on its internal battery. The MCU goes back into idle state. The entire process needs to be finished within 45 minutes, otherwise a timeout will cut the power regardless of the operation progress.

2) Mode 2: ***Pre-download*** The POPE expects a data-mule to establish contact within the next 24 hours, however, the precise time-of-arrival is unknown, as it depends on weather conditions, and the data-muling vehicle status. The AZFP is collecting data using its own battery at the prescheduled rate. The SBPC stays off, and no data are being transferred from AZFP to the SBPC. The MCU wakes-up GPS and Iridium every hour in order to check for incoming messages and send housekeeping data.

3) Mode 3: ***Download*** The arrival time of the data-mule is known. The MCU wakes up the SBPC and the radio indefinitely, or until the mode is changed by an arriving SBD message. The MCU wakes up the GPS and Iridium every hour to check for incoming messages and send housekeeping data. The AZFP is pinging using its own



Mode	Start hour	Main interval	SBPC	Iridium dial-up	Rocket	AZFP	Timeout
	(UTC)	(hours)	(on/off)	(on/off)	(on/off)	(on/off)	(minutes)
standard	12	24	1	0	0	1	45
predownload	9	1	0	0	0	0	0
download	15	1	1	0	1	0	61
debug							
service	*immediately*	1	1	1	1	1	61

▭ preprogrammed value

Fig. 5: The 5 modes of operation of the bio-acoustical POPE allow environmental information to be gathered, backed up, and transmitted wirelessly while optimizing the use of the battery. They also allow the POPE to be remotely configured by a user and the system to be diagnosed if necessary.

battery at prescheduled rate. No data is being transferred from AZFP to the SBPC. Due to lack of power on the AZFP communication line, the SBPC cannot connect to the AZFP and the data-backup software is stopped after 5 trials. SBPC requests to the MCU to turn off its power and goes to idle, however the request is ignored. When data-mule is in the radio-range, the radio establishes connection between SBPC and the data-mule automatically. The data-mule runs the program that detects the presence of the POPE, and starts retrieving data using a standard mechanism, e.g. *rsync*.

4) Mode 4: ***Debug*** Enables to apply custom power settings to every component, as well as interval for SBD messages updates and checks.

5) Mode 5: ***Service*** SBPC, radio, and AZFP are powered indefinitely, or until the mode is changed by an arriving SBD message. The MCU wakes-up GPS and Iridium every hour to check for incoming messages and send housekeeping data.

V. POWER CONSUMPTION

The POPE is designed to be powered from a battery pack with a nominal voltage of 15V. Power consumption varies between modes of operation. There are 4 major tasks that are analyzed to estimate long-term power consumption of the buoy (Fig. 6).

Task 1 is an idle state. In this mode constant power consumption is approximately 2 mA.

Task 2 is SBPC boot, GPS data acquisition, and SBD messages operations. During this task average power consumption increases in few steps to 202 mA, and the process takes around 1 minute.

After SBPC is booted, the AZFP data are backed-up in Task 3. The process takes in average 36 minutes (over a one-year period). During that time, power consumption oscillates around 500 mA, with peaks reaching 2 A.

Task 4 is data retrieval using data-mule. During this task the SBPC and radio are on, and the average power consumption is approximately 650 mA.

Direct power measurements together with the estimated time of operation indicate that a 198 Ah @ 15 V battery could provide enough power for 12 months of operation with 4 data-retrieval flights.

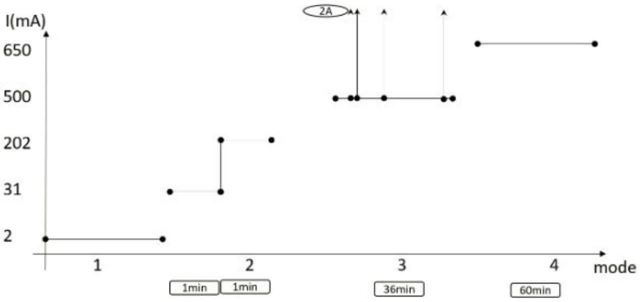
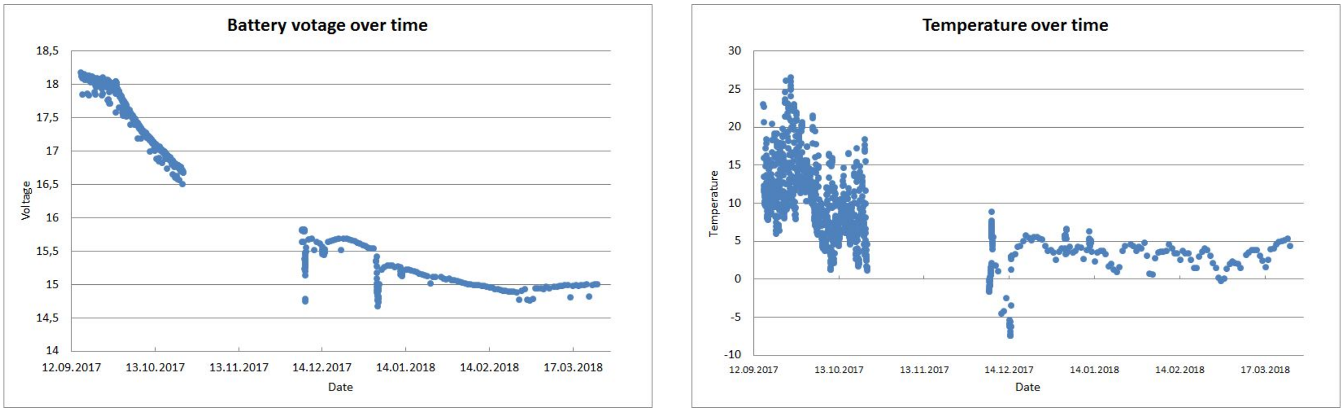


Fig. 6: Power consumption. Four different tasks, 1) idle, 2) booting, 3) data backup from the echosounder, and 4) wireless transmission to a data mule, account for the power budget of the POPE during its year-round operation.

VI. LABORATORY TESTS

In the initial phase the selected SBPC, a radio and hard-drive were stored in the freezer set to -25° C for 10 days. The system executed cycles that consisted of two phases. In the first phase, the power was OFF for 2 hours to let the system cool down. In the second phase it ran for 1 hour on high-load. During these 10 days, the system went through approximately 80 cycles. When ON, the system was heavy loaded, generating a 1 GB set of a random data using Linux /dev/urandom stream, which was saved on the hard-drive. This test revealed no issues with the system, apart from system logs filling internal memory, which was quickly fixed. A detailed check revealed no issues with the performance of the hard drive.

The next step was a long-term outdoor test in a controlled environment of the POPE prototype. The test started on September 15th, 2017 and lasted until March 26th, 2017, completing 6 months-long outdoor deployment through the winter. The surface part stayed first 3 months on the ground (15.09.2017 - 14.12.2017), to experience significant diurnal temperature changes, followed by an equivalent period in the water (14.12.2017 – 26.03.2018) experiencing lower temperature variations, but in salty water environment. During the test 1152 Iridium SBD housekeeping messages were received, however between 23.10.2017 and 7.12.2017 the Iridium modem was temporarily deactivated. When the Iridium modem was active the temperature and battery status



(a) Battery voltage over time

(b) Temperature of CR6 over time

Fig. 7: Example of housekeeping data. The POPE housekeeping information are useful for the user to diagnose the system health and status.

were monitored and the curves are shown in fig. 7. The echosounder was submerged for the entire test.

VII. DATA RETRIEVAL AND FUTURE DEVELOPMENT

The amount of data generated by a single buoy in the Arctic ice layer is reaching the point where an alternative to satellite communication is necessary. That is caused by a set of factors such as energy consumption, available transfer speed, and costs of satellite use.

In the presented approach, the authors plan to utilize flying vehicles to retrieve the data from the POPE, based on their previous experience from [9], [8]. A set of milestones have been set. In the early phase a Dornier Do-228 (Lufttransport AS, Norway) equipped with a special pod[2] that includes an advanced maritime radio system will reach the buoy and collect its data. At the same time, research is being conducted with the goal to reach the POPE using an Unmanned Aerial Vehicle (UAV) equipped with similar type of radio-payload.

The data retrieval process is similar for both manned airplane and UAV. When the data-retrieval mission start, the buoy will be set to *predownload* mode of operation, waiting for information about exact plane arrival time. When the time is determined the buoy will be commanded to enter the *download* mode. As the plane approaches the node, the radio will establish communication, and a computer on-board the aircraft will start data collection process using, e.g. *rsync* software. When the full data set is received the buoy will be set to *standard* mode of operation using SBD message, and the plane will return to base with the scientific observations gathered by the underwater instrument.

The expected transfer rate depends on the radio technology used. For the first iteration, the Maritime Broadband Radio (MBR, Kongsberg, Norway) was selected. At the current stage of development, an asymmetric link is expected to provide an average transfer speed of approximately 13-14.5 Mbps from the buoys to the plane. That should allow to download 4 GB (full set of yearly data, 1 + 3 GB) from 2 buoys in roughly 35 minutes.

The buoy will start its Arctic operation in November 2018, and its data-retrieval process using a flying data-mule is expected to be tested in early 2019. Further development of the radio technology, as well as improvements to the data-muling process, should allow multi-gigabytes, unmanned data-retrieval campaigns in the Arctic regions within the next years.

The development of the bio-acoustical POPE will continue after the first deployment. The next generation of the bio-acoustical POPE is intended to collect data using a wideband echosounder. Preliminary analysis of data from this instrument shows that a yearly data set is likely to exceed 100 GB, which is a major consideration when evaluating data transport methods. That is also one of the main motivation factors for further development of data-muling UAVs.

VIII. CONCLUSIONS

In this paper the design of the Arctic ABC bio-acoustical POPE was presented. This ice-tethered buoy with a scientific echosounder is going to collect ecological information on the distribution of fish and plankton in the water column under the Arctic ice layer for a period of at least one year.

The POPE is physically divided into a housing that contains the electronic systems, a float and an AZFP as its scientific instrument. It operates in five different modes that optimize the use of the embedded battery power and provide remote and wireless communication with its user.

The amount of data generated by the AZFP through its deployment justifies the use of flying data-mules instead of satellite links available in the Arctic. The first deployment of the buoy is planned for November 2018.

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[2] http://norut.no/en/news/verdens-forste-passasjerfly-miljoovervaking-er-norsk

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