Autonomous Under-Ice Surveying Using the MUNIN AUV and Single-Transponder Navigation

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***Abstract*— This paper reports what to our best knowledge is the first commercially delivered under-ice survey carried out by an autonomous underwater vehicle (AUV). The campaign was completed as a collaboration between Kongsberg Maritime (KM) and Ballard Marine Construction in January 2017. The surveys took place beneath a frozen lake in North America using a rental KM MUNIN AUV, with launch and recovery through a single hole on the ice not much larger than the vehicle itself. Localization was based on inertial navigation and acoustic positioning using single-transponders pole mounted through the ice. No dedicated homing devices were used during recovery.**

Unlike many previous reports on under-ice AUV missions, the mobilization and operations were low-logistics and truly commercial-off-the-shelf (COTS), that is, without any under-ice-adaptations being made to the AUV or supporting systems. Also, while reduced navigation performance traditionally has been non-consequential to any final data product, the data was in this case required to comply with the S-44 Special Order specification by the International Hydrographic Organization (IHO). This paper reports the operational experience, challenges, and lessons learned when doing commercial AUV operations under ice. Details are also given on the performance and setup of the single-transponder navigation.

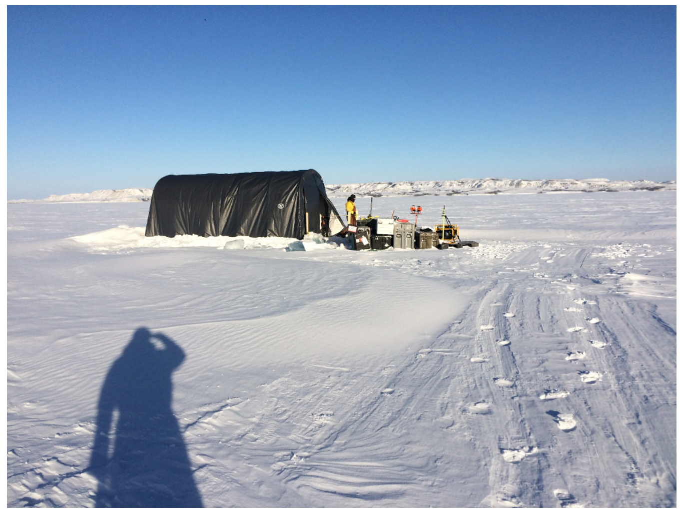

Fig. 1: The survey site was a frozen lake in North America, and the missions were done through a single hole on the ice, not much larger than the vehicle itself. The pictured shelter provided a base camp to plan, operate, and even deploy and recover the AUV. The air temperature at the work site was -35°C sustained, with a wind-chill of -57°C. Despite being first generation ice and only early January, the ice had reached nearly 70 cm in thickness.

I. Introduction

The Holy Grail for autonomous underwater vehicles (AUVs) has always been true stand-alone operations. Similarly, under-ice operations present perhaps the ultimate challenge, where besides the temperature (gradients) and environmental aspects; navigation, communication, mission control, and recovery are particularly demanding. At the same time, and as pointed out in [1]: ”once in the water, operating an AUV under-ice is not all that different than operating one in open water”. The obvious difference of course, is the presence of an ice-layer which increases risk, especially in unexpected circumstances, since the vehicle breaching the surface is not a failsafe. As also pointed out in [1], it is important to emphasize that an AUV which fails during a mission in open water has a very good chance of failing during the same mission under ice. With this in mind, it can be argued that successful under-ice missions can only be carried out if the platform is reliable to start with. The less adaptations required, means lower risk operations. The MUNIN AUV described in this paper builds upon several decades of continuous improvements through commercial and military operations with the Kongsberg Maritime (KM) HUGIN and REMUS AUVs. The campaign and surveys outlined herein were carried out with solely commercial-off-the-shelf (COTS) equipment, without any under-ice-adaptations being made to the AUV or supporting systems. Of course, ”no risk = no reward” [2], and under-ice missions will continue to push the limits of existing and new technologies. Utilizing a high degree of proven (COTS) technology at the same time means reduced risk, safeguarding the deliverable.

While this paper reports the first commercially delivered under-ice AUV survey, there has been a number of papers published on scientific AUV operations under ice. Some examples include [2], [3], [4], [5], [6], [7], [8]. A further review on unmanned underwater vehicles in Arctic operations is provided in [9], [10]. Most earlier reports describe the design of new technologies and concepts, or specific research tasks to be investigated. Common to many is also the sheer scale of operations and mobilization, often involving a large number of assets, crew and operators. As mentioned in [2], the transportation of equipment and people was probably the most difficult logistical problem faced during the deployment. To the contrary, the campaign described in this paper was low-logistic; only involving five personnel in total, few assets, and only a couple of days for mobilization. The low-logistic base camp on the survey site is pictured in Fig. 1.

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At the end, the basis for successful under-ice AUV missions, with as low risk as possible, amount to proper planning and risk assessment [1], [9], [11], [12], as well as the level of vehicle reliability and autonomy. According to [13], [14] the level of autonomy achieved by an AUV is chiefly determined by its performance in energy autonomy, decision autonomy and navigation autonomy. Energy autonomy is measured by the power consumption of the AUV with subsystems, and the reliability and capacity of the onboard power sources. Decision autonomy is measured by the ability of the AUV to sense, interpret and act upon unforeseen changes in the environment and the vehicle itself. Navigation autonomy is the ability of the AUV to maintain an accurate and precise navigation solution with little or no position estimate error growth for extended periods of time, possibly with sparse external positioning available. For cases where regular Doppler velocity log (DVL) bottom track is not available, alternatives such as DVL water track, ice-relative navigation, or model aiding may be applied [14], [15], [16], [17], [18]. The most commonly used under-ice strategy for external positioning has been to apply low frequency long baseline (LBL) navigation for its range, and ultra-short baseline (USBL) navigation for its accuracy during homing and docking [5], [7], [10]. An ice-based single-beacon system providing mesoscale coverage for communication and navigation was suggested in [8] . An ice-based single-transponder approach is described subsequently.

While many of the earlier AUV under-ice reports rightfully based their actual missions on long range acoustics, it appears that the navigation performance often has been non-consequential to any final data product. For commercial hydrographic surveys however, the end-user requirements are the same whether the missions are done under ice or not. In many cases the end-users refer to, or require, absolute positioning according to set standards, e.g. the International Hydrographic Organization (IHO). This demands strict requirements for absolute navigational accuracy. While only considering medium range acoustics, this paper shows how this was achieved using a low-logistic solution. The success of this project has opened a new operational envelope for commercially deliverable datasets by surveying under-ice to hydrographic standards with no support vessel.

The remainder of this paper is organized as follows. The inertial and single-transponder navigation applied in the MUNIN AUV are discussed in Section II. The experimental setup is described in Section III including mission objectives, system and mobilization information, and lessons learned. Navigation performance and other experimental results follow in Section IV. Concluding remarks are given in Section V.

II. Single-Transponder Navigation

In the literature, the terms single-beacon, single-transponder, and range-only are used interchangeably. Pedantically, the difference between beacon and transponder is that the beacon does an active transmission, while the transponder replies to a request. Typically one-way-travel-time (OWTT) methodologies are applied with the beacon, while two-way-travel-time

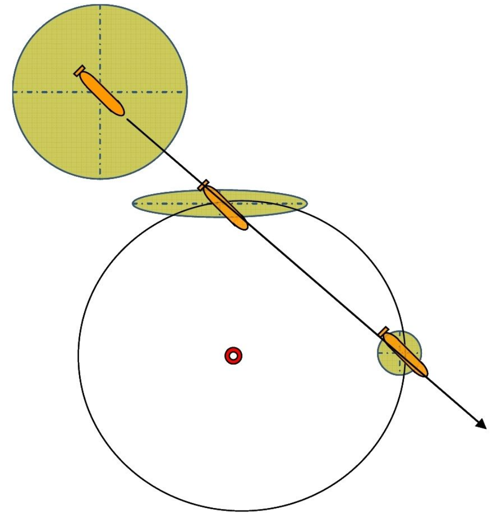


Fig. 2: Principle and effectiveness of UTP aided INS. The shaded areas are examples of horizontal covariance ellipses, initially compressed radially.

(TWTT) is common for transponders. Telemetry may be included in both cases, typically to distribute environmental data or location. In this paper the AUV interrogated transponders in order to do range-based navigation resolved through TWTT. The term single-transponder navigation is consequently used herein. For work related to single-beacon/transponder navigation refer to [8], [19], [20] and references therein.

The single-transponder navigation option available on all the KM AUVs is denoted UTP (underwater transponder positioning), and has earlier been described in [20] for seafloor deployment. The algorithm is based on a synthetic baseline principle, where the AUV position uncertainty ellipse is compressed radially as seen in Fig. 2 when moving through the area coverage of the transponder. When combining the range measurement from the transponder to the AUV with the known position of the transponder, the UTP algorithm is able to derive a georeferenced position fix which can be used for aiding the inertial navigation system (INS) found in the AUV. The INS consists of navigation equations and an inertial measurement unit (IMU), an it is autonomous by itself. However, due to inherent errors of the IMU, the INS solution will drift over time. The UTP measurements are used for aiding the INS in order to limit or counter the drift. A large toolbox of aiding sensors and techniques are available to the KM AUVs. In addition to UTP, the IMU and complete set of aiding sensors applied in this paper are described in Section III-B.

Since the position uncertainty ellipse is compressed radially, some concern must be given to the deployment of the transponders, and sought that the uncertainty ellipse ideally becomes circular. This means that both geometry and distance must be considered. Also, the larger the vertical offset between transponder and AUV, the less horizontal the range becomes. This again means that is provides less information about the horizontal movement of the AUV. It is therefore beneficial to have the AUV and transponder in the same water layer when considering sound speed scaling.

Fig. 3: The MUNIN AUV at the launch and recovery hole.The black clamps show how the vehicle is made up in modular sections; easily transportable.

III. Field Experimental Setup

A. Mission objective

A pipeline leak can be devastating to the wildlife and community, and as such all pipelines need to be monitored on a regular basis to establish depth of burial and any changes from previous inspections. A common approach is to apply a "Smart Pig", which is a cylindrical device placed inside a pipeline to gather information on the condition and location of the pipe. Data from the Pig is georeferenced using inertial navigation and aiding from e.g. speed wheels, and as a result it is limited to moderate distances.

The primary purpose of the operation was to measure multiple pipeline depths of burial and to co-register with data previously obtained with a Pig. The deliverable payload data from the AUV would be georeferenced data from a multi-beam echo sounder (MBE) and sub bottom profiler (SBP). In terms of absolute navigation accuracy, all the positions had to comply with the IHO S-44 Special Order specification, namely 2 m horizontally with a 95% confidence level. A tough requirement, which for fully autonomous AUV missions is challenging in open water, and compounded further under ice.

The survey area was multiple pipeline crossings on a fresh water lake in North America. The maximum depths were only 16 m, spanning 6 km across. Given the time constraints within the contract, any work had to be completed prior to end of January 2017. With an ice thickness of 70 cm and difficult lake access, this ruled out any vessel activities. Similarly, the sheer range ruled out ROV use, leaving AUV as the only viable solution. Access to the water was done through an ice hole and mobilized by hand. Given the depth of surface snow, vehicle access was challenging, hence only a low-logistic, man-portable vehicle could be used. Using single-transponder navigation, the MUNIN AUV would provide fast data acquisition, whilst complying with the strict navigational and operational requirements.

B. Vehicle description

The MUNIN is a low-logistic commercially developed AUV from KM; partly based on the hull structure from the KM REMUS 600, and with software, firmware and topside from the HUGIN. The acoustic navigation and data links (cNode) are also the same as on HUGIN. Special for MUNIN is the new integrated navigation and payload section, which contains the IMU, DVL, MBE and side scan sonar (SSS). It is also possible to replace the SSS with a synthetic aperture sonar (SAS). The benefit of having all these important navigation and payload sensors in a single rigid unit is that it can be factory calibrated. This again allows quick, repeatable, and accurate mobilization, without the need for cumbersome in-water calibration; ideal for low-logistic mobilization, assembly on the ice or elsewhere, and when time to product is critical.

MUNIN, pictured in Fig. 3, is modular and can be shipped in man-portable containers requiring no mechanical assistance to assemble. Comprising of four primary modules the vehicle can be adapted easily by simply adding new sensor sections. For the campaign discussed herein, it utilized the navigation sensors outlined in Table I and Table II. A conservative specification of the in-situ KM INS with DVL aiding alone is 0.08% of traveled distance (CEP50), straight line, at 60° latitude. As indicated in Fig. 4, the number could probably be lowered to about 0.04% (CEP50). Uncertainty in dynamic roll and pitch is 0.005°, and 0.02°· sec(lat) for heading, all 1σ.

TABLE I: IMU specifications

	Bias		Scale Factor		
Model	Gyro	Acc	Gyro	Acc	**Rate**
Honeywell HG9900	0.003 deg/h	25 μg	5 PPM	100 PPM	300 Hz

TABLE II: Main navigation aiding sensors

Variable	**Sensor**	**Precision**	**Rate**
Position	KM UTP (single-transponder) NovAtel GPS (onboard AUV)	<10 cm 1.5 m RMS	Varying‡ 1 Hz
Velocity	RDI DVL 300kHz	±0.4 %±0.2 cm/s	>1 Hz
Pressure	Paroscientific	0.01 % full scale	1 Hz

‡ Depends on the range from the AUV to the transponder. Usually >1/2 Hz.

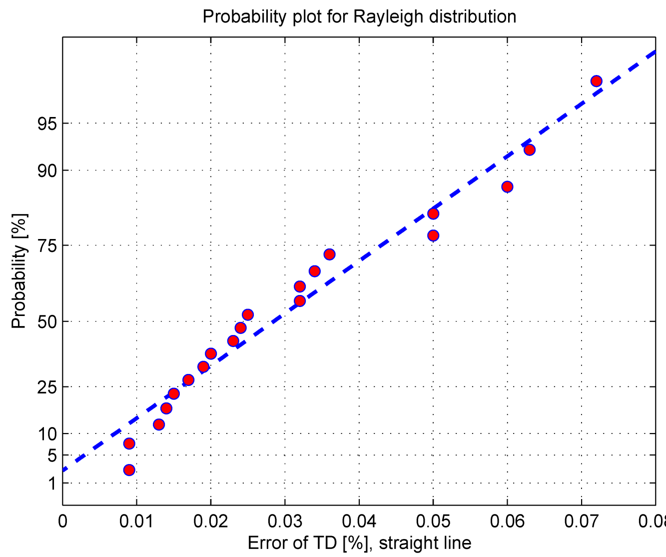


Fig. 4: Result of the last 20 in-situ navigation verification runs carried out with HUGIN and MUNIN in Horten, Norway, during the time period October 2016 to June 2017. The test is standardized and is always carried out during e.g. a factory acceptance test (FAT). The test consists of running the AUV at about 170 m depth along a 7 km straight line with DVL-aided INS (no external positioning). The in-situ navigation is then compared to a reference solution generated in NavLab [21], having continuous GNSS-USBL measurements.

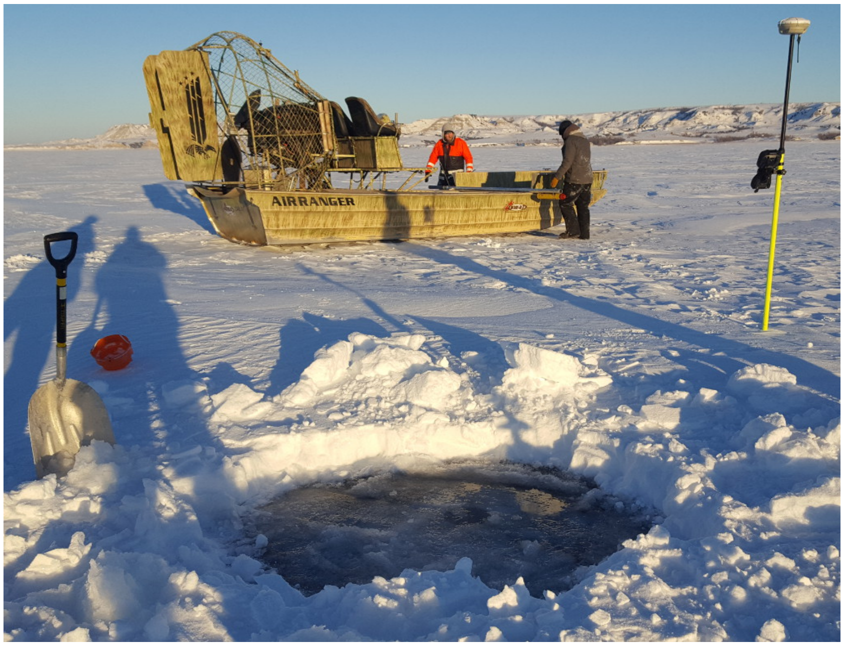


Fig. 5: An airboat turned out to be the best option for getting personnel and all equipment to and around the site. Also seen in the picture is the RTK GNSS equipment used for doing the single-transponder absolute localization.

The main payload sensors were the KM EM 2040 and the Edgetech 2005 SSS/SBP, with the SBP being in a separate modular section. In addition, the different sections contained integrated Wi-Fi and Iridium, strobe, and a single 5.5 kW battery, enabling up to 12 hours sub-sea (with the potential to run an extra battery section doubling endurance). The foremost section consisted of a conductivity and temperature (CT) sensor, along with the nose weight release containing a painter line for recovery, whilst the very forward face had a forward looking sonar (FLS) integrated. The FLS is used for obstacle avoidance, and for providing input to the vertical part of the guidance system, resulting in a smooth height trajectory also over rough terrain.

C. Mobilization

1) Base camp: The location of the base camp was governed primarily by required depth of water to launch. Given the vehicle length of approximately 4.5 m, the estimated rate of rotation, and 20-30° initial pitch descent angle, it was decided that a minimum of 8 m water depth would be required for deployment. The flat topography meant that the base camp was mobilized some 800 m from shore before achieving this depth. With up to 2 m snow drifts all standard surface vehicle access to the base camp location proved impossible. Neither a 4x4 ATV or an 8 wheel Argo could navigate the conditions, therefore the next solution was an airboat as seen in Fig. 5. It provided access to and from shore for all equipment and personnel, proving invaluable when deploying transponders several km away from shore. Once on site, the 7x3 m tent shown in Fig. 1 was erected to house all vehicle operational equipment and to conduct operations. With 55 km/h winds, the tent was secured by simply drilling holes in the ice and letting storm anchors freeze in place.

The AUV itself requires surprisingly little to function with respect to topside equipment; programming can be done on any laptop via Wi-Fi or hard connection whilst vehicle power requirements are met via the charge station. Charging required 220 volts AC, demanding larger generators to be brought onto the ice. These were initially housed outside the tents in the open but extreme temperatures meant they would stall in the nights. High winds meant an estimated -57°C wind-chill, and with the blizzard snow conditions the generators simply failed; indeed through the course of one evening two generators were written off. Protection using an ice fishing hut was erected for the generators, with no subsequent failures.

The last tool to be housed within the base camp was a small 30 cm long remotely operated vehicle (ROV) with 50 m of umbilical. Given the likelihood of the AUV returning exactly to the hole being somewhat daunting, the ROV was equipped with a gripping manipulator for pulling the AUV back to the ice hole should it be required. However, as discussed in Section IV this turned out not to be always needed as the AUV performed and navigated very well, and repeatedly returned to the hole as planned.

As for the vehicle assembly it was completed within the base camp tent; by hand using standard cradles to house each module and sliding each together before clamping. Positioned to one side of the tent the ice hole was then cut using a sled mounted chainsaw. Given the vehicle length and the intended recovery through the same hole it was cut to be 6x1 m.

2) Launch: The vehicle was lifted and released into the water with a gantry crane and chain block assembled within the tent. Once floating on the surface a mission can be started with a configurable delay. While in wait-state the ranges and communication between the AUV to the deployed single-transponders were verified, giving some confidence before mission launch. The vehicle was then pressed down into the water using makeshift poles with U shape brackets to prevent slipping. At the same time the operator would monitor the pitch angle over Wi-Fi in order to level the AUV at the desired 20° descent angle. Once pitch had been established the tail would then be pressed in unison with the nose a further 1 m below the surface to await propeller spin up.

It became apparent after the second mission that the initial pitch descent angle was critical when working in a shallow 8 m void. Given the vehicle length should it come into contact with the ice, the speed and size of the fins would be insufficient to generate downward drive, essentially stranding the vehicle under the ice. Careful programming meant that the vehicle would fault if the targeted depth could not be attained within a set period or if the heading according to the mission plan is not possible. If the above scenarios eventualized the vehicle would fault within reach of the ROV. To be clear, with 1 m depth on the rear tail section a 10° pitch angle would result in the vehicle being trapped against the ice whilst 35° would result in seafloor contact. For the subsequent six missions launches, and decent angle with between 15-25° all resulted in successful entry to mission and completed without issues.

3) Recovery: The initial intention was to do conduct recovery via net-capture, and to do this perpendicular to the hole in order to present a larger target. With the ROV availability however, and with the potential for damage, it was decided to stop the vehicle 10 m back from the hole and let it coast in with any final recovery being done by ROV. Based on the first mission it was quickly established that the ascent from 2 m of depth would require approximately 4 m of drift before coming to rest under the ice. Interestingly, stopping the vehicle 4 m short of the ice hole was not the only mission edit required since the propeller created a counter torque which resulted in a constant trim about the roll axis. At mission-end when the propeller stopped the vehicle rotated and a drift of about 2 m in the starboard direction was observed. Hence by shifting the end point a of mission 4 m before and 2 m to port, the recovery should be at the ice hole. Whilst not 100% successful initially, after four missions the recovery point had been tuned enough that the vehicle could be recovered directly at the ice hole with nothing but a boat hook. Since no dedicated homing devices such as USBL were utilized, the AUV had to rely on absolute navigation from its INS and single-transponder navigation.

4) Risk assessment: Some thought also has to be given to vehicle safety, e.g. how would it be located should the vehicle not come back. It was decided to use the KM cPAP 30 pictured in Fig. 6. It is an internally housed battery operated acoustic ranging tool with a dunking transducer. Using an auger and battery drill, the water could be accessed and a range to the vehicle given. By ranging from three locations the vehicle position could be pin pointed through simple triangulation fairly easily. Some discussion has been raised from previous researchers about sound propagation through the ice medium and whether reliable interrogations could be established [22]. Prior to first mission deployment considerable testing was done to determine interrogation integrity at various ranges and through several tests up to 2.2 km could be achieved with relative ease. The cPAP 30 was left on charge within the base camp and served a secondary purpose in that the dunker could be utilized during mission to give confidence that the vehicle was operating, i.e. moving as expected.

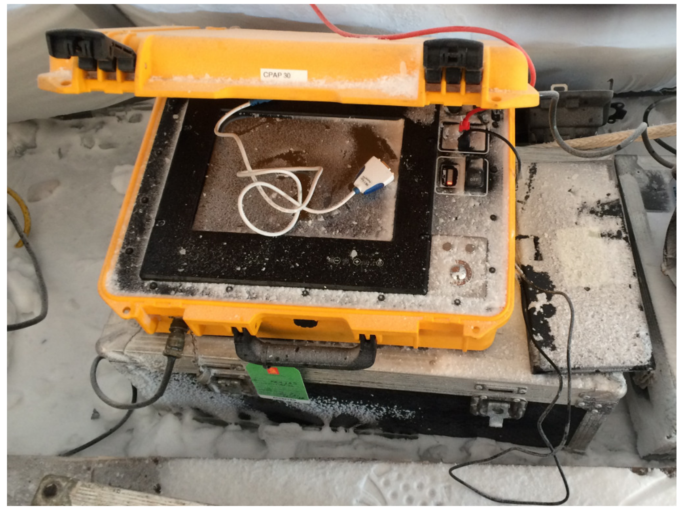


Fig. 6: The portable KM cPAP30 acoustic tester following a generator blackout.

D. Single-transponder deployment

The transponders used for doing the single-transponder UTP navigation were the KM cNode Mini [23] with 180° transducer (3dB cut off beam pattern), hence directivity was of a lesser concern. Although traditionally installed on the seafloor via a clump weight with line and float, navigation and communication transponders can also be anchored through and from the ice. Based on the ice conditions and shallow water depth, it was decided to attach the transponders to the base of 3 m poles through the ice. The deployment of the transponders is pictured in Fig. 5 and Fig. 7. After a short time holding in place, the poles froze in and the transponder locations remained fixed thereafter. Given the length of the crossing at 6 km and the expected working range of the transponders, typically about 1500 m, it was intended to utilize three units, equally spaced along the baseline 100 m to the side and parallel to the pipelines. The pipelines were aligned virtually north to south. The use of three transponders would ensure that the AUV would almost be constantly within range of a transponder for interrogation, with the aim to reduce any positioning error drift. Unfortunately, the northern transponder (M28) failed during the initial mission, hence the remaining missions were continued with two (M40 and M47). As a result the northernmost part of the survey would have less coverage.

Once deployed, communication was verified from the base camp. Since the range to M28 was more than 3 km, direct interrogation was not possible. However, the cNode technology allows for an acoustic backbone to be created. This meant that it was possible to interrogate M40 from base station and

Fig. 7: The single-transponder deployment on the fixed ice was done with simple equipment, and using 3 m long poles. After a short time holding in place, the poles froze in and remained fixed thereafter.

request it to interrogate M47 which in turn interrogated M28, replying back down the line. This acoustic backbone also allows the transfer of log data down the line. The main purpose was however to verify that M28 was functioning.

As mentioned in Section II, the horizontal geometry and vertical offset between the transponder on the AUV should be considered, both in terms of navigation performance and coverage. In [5] and [8] the floating lines from anchors to transponders were 100-200 m. Such vertical offsets are good for coverage but not ideal for high-fidelity navigation due to currents potentially causing unknown transponder position biases. As described in Section III-A, the navigation requirement for the campaign in this paper was tight, and while currents were not an issue, the transponders were required to be accurately deployed and georeferenced. Any error in the transponder position would potentially absorb the acceptable limit of 2 m (95%) uncertainty margin. Since the ice was fixed however, it was sufficient to measure the position of each transponder once with an RTK GNSS solution. The resulting accuracy of the transponder positions was 2-3 cm (95%).

E. Lessons learned and points of note

In the previous sections the experimental setup and primary objective were described. While most parts of the mobilization and operations went smoothly and as expected, some challenges had to be dealt with. Not surprisingly, many of these are likely attributed to the mix of freshwater, ice, snow and extreme cold. As a simple example, a smart-phone would shut down after just 40 s in open air. The vehicle once assembled is vacuumed to 0.6 bar which is then used during mission to monitor for the potential presence of a hull leak. The vacuum pump is a standard single phase AC motor driven pump. The starting of this motor uses a capacitor which due to its decreased efficiency coupled with increased oil viscosity the motor simply hummed when powered. By manually spinning the motor whilst the unit was energized brought it to life, but this clearly highlights the need for warmth for what would have been previously considered a basic piece of equipment sure to cause no issues. Two propane heaters were soon used inside the base camp tent in order to get the temperature to a more manageable value for both the equipment and personnel, 10°C was attainable and considered a minimum. Compared to initially working close to ambient, this significantly reduced the number of unexpected issues. Simple steps like preventing direct contact between the equipment and the ice also helped. With close to 0°C in the water and -40°C in still air, having a somewhat heated base camp for equipment was essential. This in turn brought other points to the forefront; propane heaters which rely on an internal fan in conditions where power may be intermittent need to be avoided. The loss of generators one evening set the project back 12 h, mainly to get the internal AUV electronics back to a warm enough level to operate.

The previous leads into a more serious example related to the set temperature restriction for charging of the AUV lithium batteries. The batteries are split into several modules, each housing a unique charge controller. It turned out that the lower temperature controller limit was set to a conservative 12°C. The vehicle has no cooling, using the housing as a heat sink and in normal operating conditions the concern is keeping the vehicle cool. With this project the opposite was encountered, and all electronics had to be switched on and wherever possible a load created to introduce heat. While far from instant, this together with the heated environment inside the tent gradually allowed the charging to commence. Generally, and with reduced current, charging of lithium batteries can safely be done down to about 0°C. With the extreme temperatures, the battery controller limit and charge current could have been more thoroughly thought through before mobilizing on the ice.

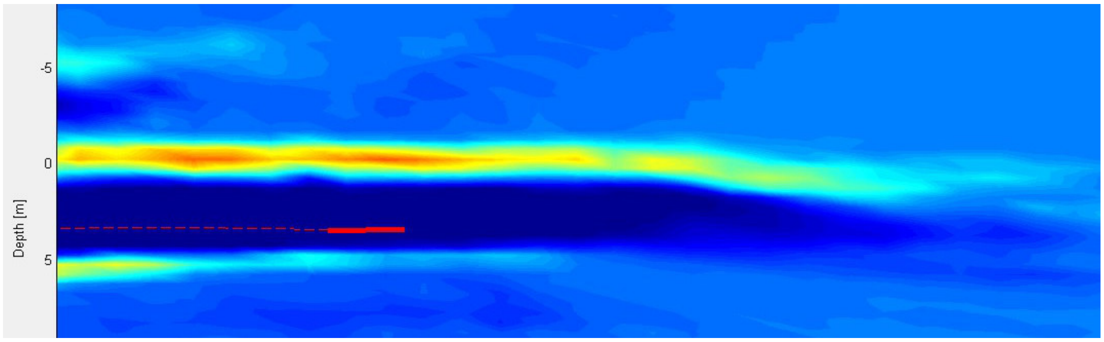


Fig. 8: FLS data showing both lake floor and underside of ice with the vehicle ”threading the needle”.

IV. Field Experimental Results

A. Threading the Needle

The aforementioned Smart Pig had raised some concern over burial close to the shore, hence it was also desirable to survey this area. While it posed a greater operational risk to the AUV, the integration of FLS allows very shallow operation with a good degree of safety. With a high degree of trust in the vehicle it was decided to give it a try. While the post-mission inspection seen in Fig. 8 indicated a slightly braver mission than what the operator had anticipated, the vehicle operated without any issues and collected the desired data as planned.

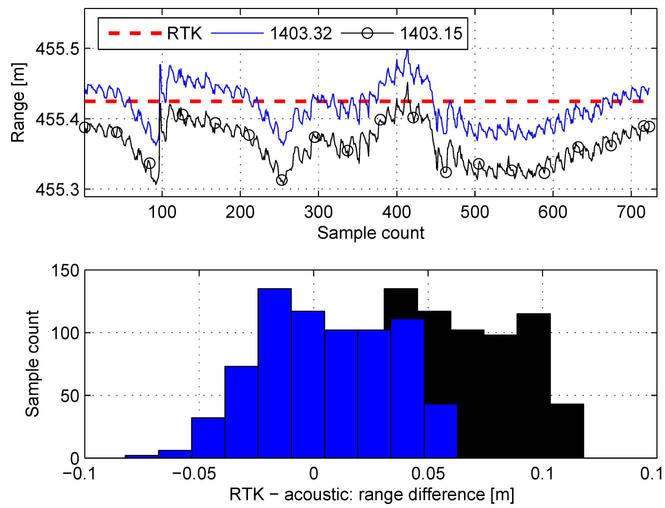
B. Base to transponder acoustic ranging

The localization of the transponders as well as the cPAP30 transducer was as previously discussed accurately done using RTK GNSS. Using this data a consistency check could be done by comparing the RTK-derived slant ranges with those acoustically measured with the cPAP30. In addition to the signal detection of the acoustic message, the calculation of range from time is entirely dependent on knowing the sound speed. Using the measured or known salinity, temperature and pressure, the sound speed at the AUV operating depth of around 4 m was calculated to be 1403.15 m/s with a standard deviation of 0.3 m/s over the course of the entire campaign.

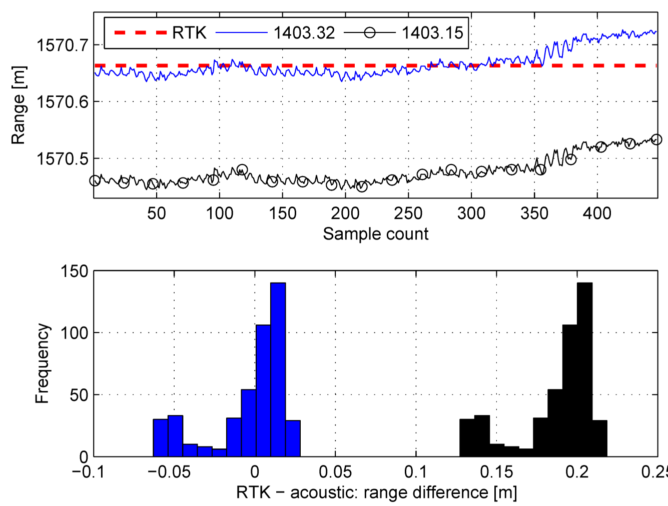
To establish a base line, 500-700 range interrogations were done for both the M40 and M47 transponders. As shown in Fig. 9 the consistency between the measured and derived ranges was very good, with a difference in the sub-decimeter range. The adjusted sound speed scaling was also reasonable as it was observed that the sound speed increased slightly with reduced depth. Based on the results it was concluded that the accuracy of the UTP transponder localization and the acoustic ranges derived were well within the requirements.

C. Single-transponder navigation

As mentioned earlier in this paper, it was of eminent importance to the end-customer to be able to collect payload data to a hydrographic standard. While having been used routinely for open water surveys, the use of UTP single-transponder navigation had not been attempted earlier under ice with the KM AUVs. Five dives (excluding test runs) were completed successfully, which covered the required survey area, about



(a) M40 transponder.



(b) M47 transponder.

Fig. 9: Comparison of RTK-derived ranges and acoustic ranges; showing very good agreement.The adjusted sound speed is 1403.32 m/s, and the left most histograms correspond to this sound speed. The reason for the drift slight from sample 350-450 for the M47 is unknown but is currently being investigated. The observed small oscillations in acoustic range are due to clock drift between cPAP and cNODE, influencing the interpolation between samples in the signal processing.

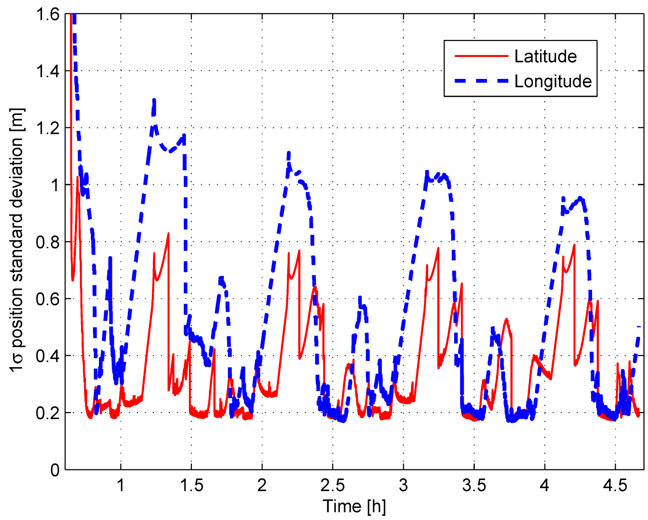
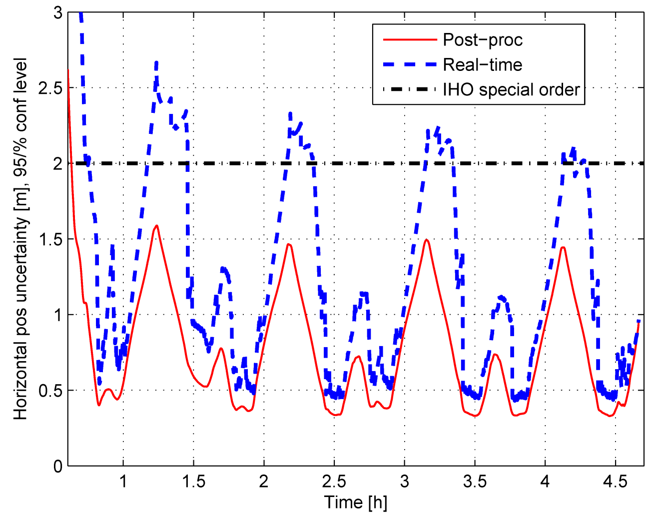


Fig. 10: Real-time position standard deviation (1σ) for Mission_170117_3 (reciprocal-lines) in Fig. 12.

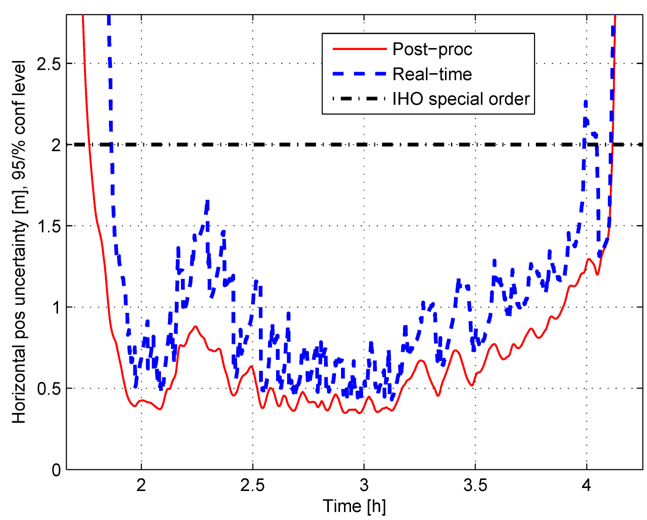
65 km in total length. Two mission examples are shown in Fig. 12, including UTP transponder placement and range fixes (where ranges were actually applied by the INS). While it was not consequential for the success of the campaign, the absence of the faulty M28 transponder resulted in a 100% coverage gap in the northernmost part. This again led to a slightly higher navigation uncertainty than what could have been the case; both due to aiding coverage and since the inclusion of the M28 would have meant a better overall geometry.

The obtained navigation performance for the reciprocal-line mission and the lawn-mower mission are shown in Fig. 10 and Fig. 11a, and Fig. 11b, respectively. The range-derived horizontal fixes were given a weight (bias) of 0.5 m (95%) in the Kalman filter (KF). The other sensors had KM standardized settings. While no continuous reference solution was available (e.g. USBL), the covariance information has been shown to be reliable, or even slightly on the conservative side, as discussed in Section III-B. As can be seen from Fig. 11, both missions resulted in post-processed (NavLab [21]) navigation performance within the IHO Special Order specification. This was also the case for the other three missions. Using NavLab is a standard step for all the HUGIN and MUNIN AUVs when creating the final data product.

Comparing the two missions, it is clearly seen that the lawn-mover mission has a more uniform performance, without the periodic uncertainty growth seen in the reciprocal-line mission. While a lawn-mower pattern is generally favorable, then main reason is the better UTP geometry, as seen in Fig. 12. As discussed in Section II, the covariance should ideally be compressed such that it becomes circular (to the extent possible). As illustrated in Fig. 10, the longitudinal uncertainties grow larger than the latitudinal. The four tops correspond to the four pairs of reciprocal-lines passing by the transponders, and not surprisingly, with the highest uncertainty on the lines closest to the transponders. Again, had the M28 transponder been functional at e.g. (2500N, -500E), the geometry and performance would have been improved further.



(a) Mission_170117_3 (reciprocal-lines).



(b) Mission_170115_2 (lawn-mower).

Fig. 11: Real-time and post-processed navigation performance for the example missions in Fig. 12. Both missions show performance better than the IHO Special Order specification. Since the covariance is not circular when doing range aiding (or for autonomous AUV missions in general), the 95% position numbers were derived by determining a circle with radius R such that the probability of samples associated with the covariance ellipse falling within the circle equal is equal to 95%.

D. Pipeline survey

Determination of pipeline burial depth with SBP is somewhat subjective given that the propagation speed in the medium is unknown. Given the relatively short ranges the propagated error tends to be within tolerance for most operations, however the absolute depth of seafloor still had to be given. Using the IHO S-44 Special Order specification as reference, and given a mean depth of 10 m, the permissible total vertical uncertainty (TVU) was around 26 cm (95%).

The TVU is the accumulation of absolute and relative uncertainties, where the absolute uncertainty is related to the depth of the AUV relative to some datum and the relative uncertainty is related to the MBE footprint depth relative to the AUV. While not directly quantifiable at site, the combination of

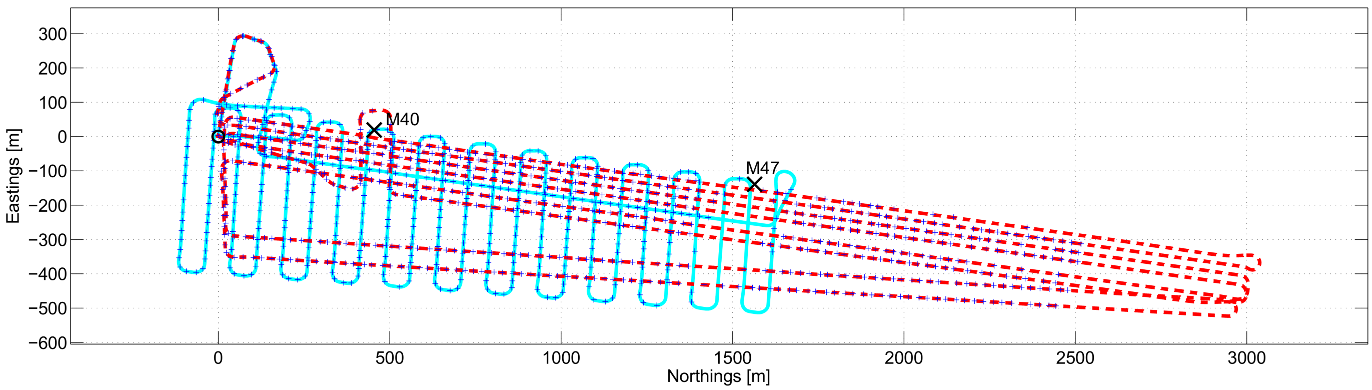


Fig. 12: Example missions; Mission_170115_2 (lawn-mower) shown as solid cyan, and Mission_170117_3 (reciprocal-lines) shown in dashed red. The ice hole is at the origin. The deployed transponder are shown as M40 and M47. The blue + markers show the horizontal position fixes derived from the UTP ranges; decimated such that only fixes more than 20 m apart are shown (showing 462 out of 1255 for Mission_170115_2 and 693 out of 1981 for Mission_170117_3).

factory calibrated components, excellent orientation accuracy, and good control on the sound speed would results in small relative uncertainty contributions. Working on the lake there was no tide and with RTK GNSS, the start point (determined as water level flush with top of ice) could be referenced to the clients chosen ellipsoid to 5 cm (95%). The dominating vertical factor in this paper was the vehicle depth calculation from the pressure sensor readings. The raw pressure readings are influenced by atmospheric changes. However, once accounted for the latter introduces very little error. The pressure sensor used has a full scale (FS) to 700 m depth, which given the accuracy of 0.01% of FS adds a further 7 cm of uncertainty (1σ). For the UNESCO formula [24] itself is stated to have an uncertainty of 10 cm (1σ). Given the above and with tight controls in place, it was possible to maintain acceptable TVU throughout. As for the total horizontal uncertainty (THU), the driving factor in this paper was the absolute positioning of the AUV relative to the ellipsoid. As discussed in Section IV-C the navigation accuracy was within the acceptable limit. See also [25] for a further discussion on THU in AUV missions.

In terms of the survey the mission plans were run two fold, long runs along pipe route to establish a bathymetric surface whilst other missions involved transects separated by 50 m to establish depth of burial, as illustrated in Fig. 13. As seen in Fig. 14 the pipes have been visualized beneath the bathymetric surface where the SBP transect shows a cross section of the pipeline burial route. Note three pipes lie in a bundle to the west whilst a further two sit to the east. The three together are difficult to distinguish in the SBP echo-trace due to the strong response given that all lie within the main beam pattern simultaneously. Interestingly the second echo shown lower in the image shows the dropped signal strength and gives clear definition on the three individual lines.

V. Conclusions and Future Work

This paper has reported what appears to be the first commercially delivered under-ice survey carried out by an AUV. Unlike many previous reports on under-ice AUV missions, the mobilization and operations were low-logistics and truly COTS, that is, without any under-ice-adaptations being made. This operations described a unique situation for a commercial client meeting a time sensitive deadline. The success of this project has opened a new operational envelope for commercially deliverable datasets by surveying under-ice to hydrographic standards with no support vessel.

A vital part of the the campaign was the ability to deliver datasets which were compliment with the IHO S-44 Special Order specification. All the missions successfully achieved this by utilizing UTP single-transponder navigation; despite one of the transponders failing. This shows the strength of UTP in its ability to utilize each transponder independently. Future work should include algorithms or tools for optimal placement (geometry) of a transponders given a desired missions plan.

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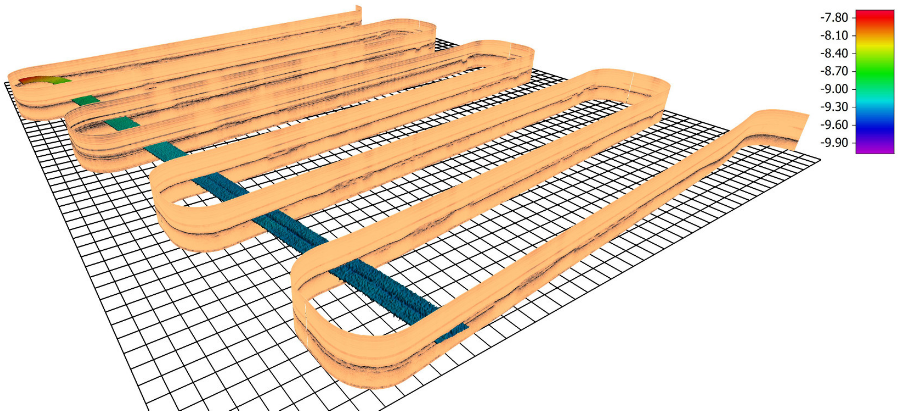

Fig. 13: Two types of mission; one for bathymetry running along the pipe route whilst the transects show cross lines to establish depth of burial

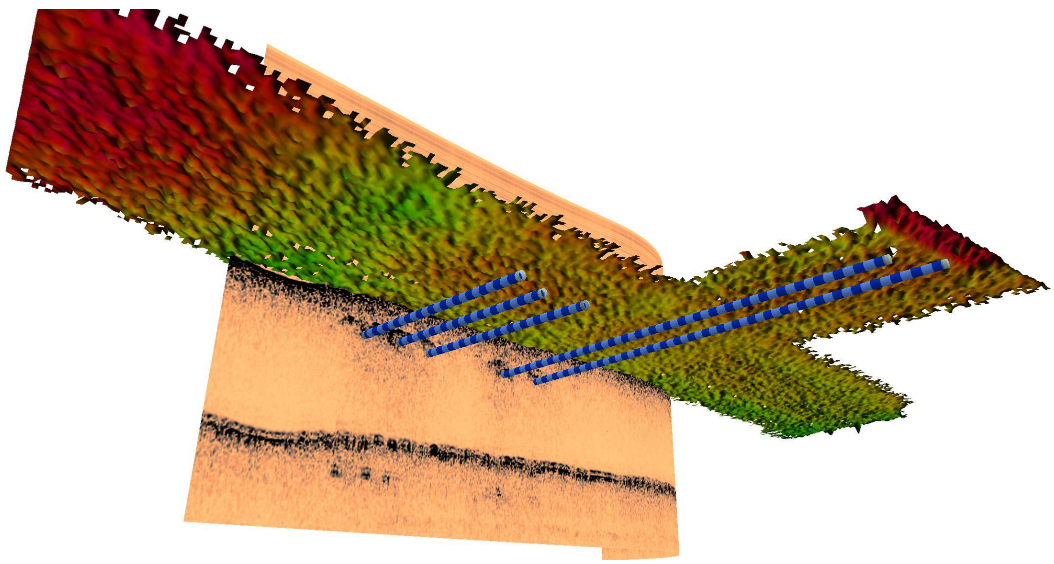

Fig. 14: Payload data showing the buried lines in the SBP data. The pipe detections seen in the lower part of the picture are from the second echo. Overlaid bathymetry showed that the area overall was fairly flat.

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