https://doi.org/10.5194/egusphere-2024-32
Preprint. Discussion started: 16 February 2024

Brief communication: A low-cost surface vehicle for studying the near-terminus region at tidewater glaciers

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Abstract. The oceanic region at the terminus of tidewater glaciers is under-explored, yet the processes occurring there are critical to our understanding and assessment of climate-change-induced ice loss. This region is hazardous for humans to directly access, necessitating exploration using unmanned robots. This paper discusses the design, development and deployment of a low-cost remote-controlled surface vehicle for in-situ studies in the near-terminus region. The robot is instrumented with passive acoustic, conductivity-temperature-depth and video recorders, and is able to profile short transects in the proximity of, or even at, the terminus region.

1 Introduction

Ocean forcing and atmospheric-driven ice-sheet melting have been significant drivers of ice loss at tidewater glaciers and polar ice sheets in recent years (Slater and Straneo, 2022). At tidewater glacier termini, ice is lost through submarine melting and calving activity, though there is uncertainty on their relative contributions and spatial variability at different locations across the glacier face (Wengrove et al., 2023; Benn et al., 2007). The region near the glacier front, where these ice-loss processes take place, is under-explored with many unknown physical parameters of interest that need to be measured and bounded in order to better understand these processes. For example, at locations where melt water is discharged subglacially, turbulent plumes are generated which locally increase the submarine melt by upto an order of magnitude as compared to regions outside the plume (Fried et al., 2015; Motyka et al., 2003; Wagner et al., 2019). There is considerable uncertainty in the location, size and discharge rate of these discharge plumes, as well as their impact on the melt rate, which complicates assessment of ablation at the termini. The topological morphology of the submerged part of the terminus is relatively unstudied (Rignot et al., 2015). Submarine melting releases bubbles which generates a depth-dependant sound in the glacial bay (Vishnu et al., 2020), which has been confirmed with experimental studies using sampled blocks of glacier ice (Vishnu et al., 2023). By using environmental and acoustic propagation physics-based modeling, the sound produced at the glacier terminus can be estimated from ambient sounds recorded in the outer bay (Vishnu et al., 2021, 2024), but these estimates, as well as the sound's depth-dependence, have not been confirmed with in situ near-terminus measurements. In addition, the bubbles produced during terminus melting may be entrained in the meltwater, enhancing the melt rate (Wengrove et al., 2023) and further distorting the acoustic field, but the density and production rate of bubbles in this region remains unquantified.

Unmanned robots have been successfully used for under-ice operations at polar regions previously (Freitag et al., 2016; Meister et al., 2019; Ressel et al., 2014). Robot operations at glacier termini near the grounding line have been few, because of the danger from calving activity in these regions. Calving additionally complicates accessibility at the terminus by choking the glacier bay with thick ice-mélange, preventing surface movement. Examples of prior robot operations in this region include the use of surface vehicles for bathymetry and hydrographic measurements (Wagner et al., 2019; Kimball et al., 2014; Carlson et al., 2019; Bruzzone et al., 2020), autonomous underwater vehicles for sonar, video and oceanographic observations (Howe et al., 2019; Stevens et al., 2016), and drone-deployed autonomous conductivity-temperature-depth (CTD) profilers operating near the terminus (Poulsen et al., 2022). Due to the hazards involved in operating near the glacier terminus, simple, robust and low-cost robotic systems capable of making measurements allow for low-risk studies at the terminus, because damage or loss of equipment would not incur significant monetary losses. With this in mind, we developed a low-cost, remote-controlled surface vehicle named a “glacial ablation monitoring robot" (GLAMOR), for in-situ studies in the near-terminus region. The vehicle was deployed during field trials in Hornsund fjord, Svalbard, during July 2023. This paper discusses the design, development, and deployment of this vehicle and its sensor payloads.

2 Methods

2.1 Development requirements and principles

The GLAMOR was developed with the aim of collecting acoustic, oceanographic and video data near the terminus. The primary mission requirements were that (1) it would be remote-controlled with a range of at least 200 m so that the operator could be stationed outside the dangerous calving zone (2) it would be low-cost, and there would be multiple backup systems, (3) it would be a low-weight system for easy deployability, handling, and retrieval in the glacial bay, (because conditions in the bays are often unpredictable and require deployment flexibility). The system would need to be robust in terms of (1) mechanical stability, in order to handle the changing marine environment with floating ice, currents, and calving, (2) control systems, with on-oboard automated return to a safe home-point or, to preset station points upon loss of communication with the operator, (3) thruster operation, to avoid getting stuck (4) a streamlined body with few concave edges which increase the chance of line entanglement. Additionally, it was desired to have a modular vehicle which was configurable to allow additional sensor payloads of our choice.

2.2 Vehicle description and capabilities

The GLAMOR is built by modifying an off-the-shelf Chasing F1 Pro surface robot originally designed for fish-finding (Chasing, 2023). The vehicle is controlled over WiFi at both 2.5 GHz and 5 GHz bands. Vehicle control and navigation is performed either via a hand-held remote-controller or an app installed on a cellphone. The vehicle also has an onboard line winch with a maximum length of 20 m and a terminal end that can be attached to an underwater camera with real-time video monitoring. Additionally, lightweight sensors can be attached to the winch line and used for depth-profiling. The winch has a vertical speed of about 0.3 m/s. The navigation system does not allow pre-programming of survey tracks, but does allow the setting of GPS waypoints during a mission in order to allow the GLAMOR to return to a chosen location. These waypoints can be used for repeating survey tracks done in previous mission iterations.

During initial tests conducted at a reservoir in Singapore, the range of the WiFi remote control system was found to be inadequate for the required operation. The 2.5 GHz band provided around 83 m of operational range, and the 5 GHz band provided 120 m range in calm sea-surface conditions. In order to extend the range of operation, the operator receiver was supplemented with a directional WiFi antenna (TPLink). Tests with the extender provided an operational range of more than 300 m in calm conditions, which was deemed adequate for the safety of the system and operator.

The Chasing cellphone app displays the GPS coordinates of the vehicle, but does not provide a method to log the GPS data during vehicle missions. In order to provide this capability, we developed custom optical character recognition software to extract GPS data from screen recordings of the Chasing app running on the cellphone. The character recognition algorithms extract the GPS data while post-processing the app recordings after mission operation.

2.3 Sensor payloads

The sensors mounted directly onto the GLAMOR included:

1. CTD logger: A mini stand-alone CTD from Star-ODDI with in-built power was used (StarODDI, 2023). More details on this are given in Appendix C, and a close-up photo in Fig. B2.

2. Underwater camera: The Chasing system is provided with an underwater pan-and-tilt camera that can be operated via the app software. More details are given in Appendix D.

In addition, the GLAMOR was able to tow a sensor payload behind it. Two examples of sensors mounted in this way include the following:

1. Passive acoustic recorder: A passive ultra-light stand-alone acoustic recorder (PULSAR) was developed to record near-terminus acoustics in order to validate the magnitude of sound generated at the glacier face, study its spatial variability, and correlate it with other physical parameters. The PULSAR was mounted onto a custom-built buoyancy collar towed behind GLAMOR. Additional details of the PULSAR system are available in the appendix, and a close-up photo in Fig. B2. The buoyancy collar consisted of dual foam floats cross-connected by a PVC pipe, below which the PULSAR was mounted at the desired recording depth. The system was mechanically stable, and allowed for towing by the GLAMOR at its highest speeds. The tow rope connection between the GLAMOR and PULSAR was about 1 m, to minimize the chance that the tow rope could become entangled in the thrusters and to minimize acoustic interference from the thrusters. Previous studies indicated that the sound of melting glacier ice is loudest near the sea surface, and reduces with depth down to about 13 m (Vishnu et al., 2023). With this in mind, the PULSAR was positioned so that the hydrophone depth was approximately 2 m below the sea surface.

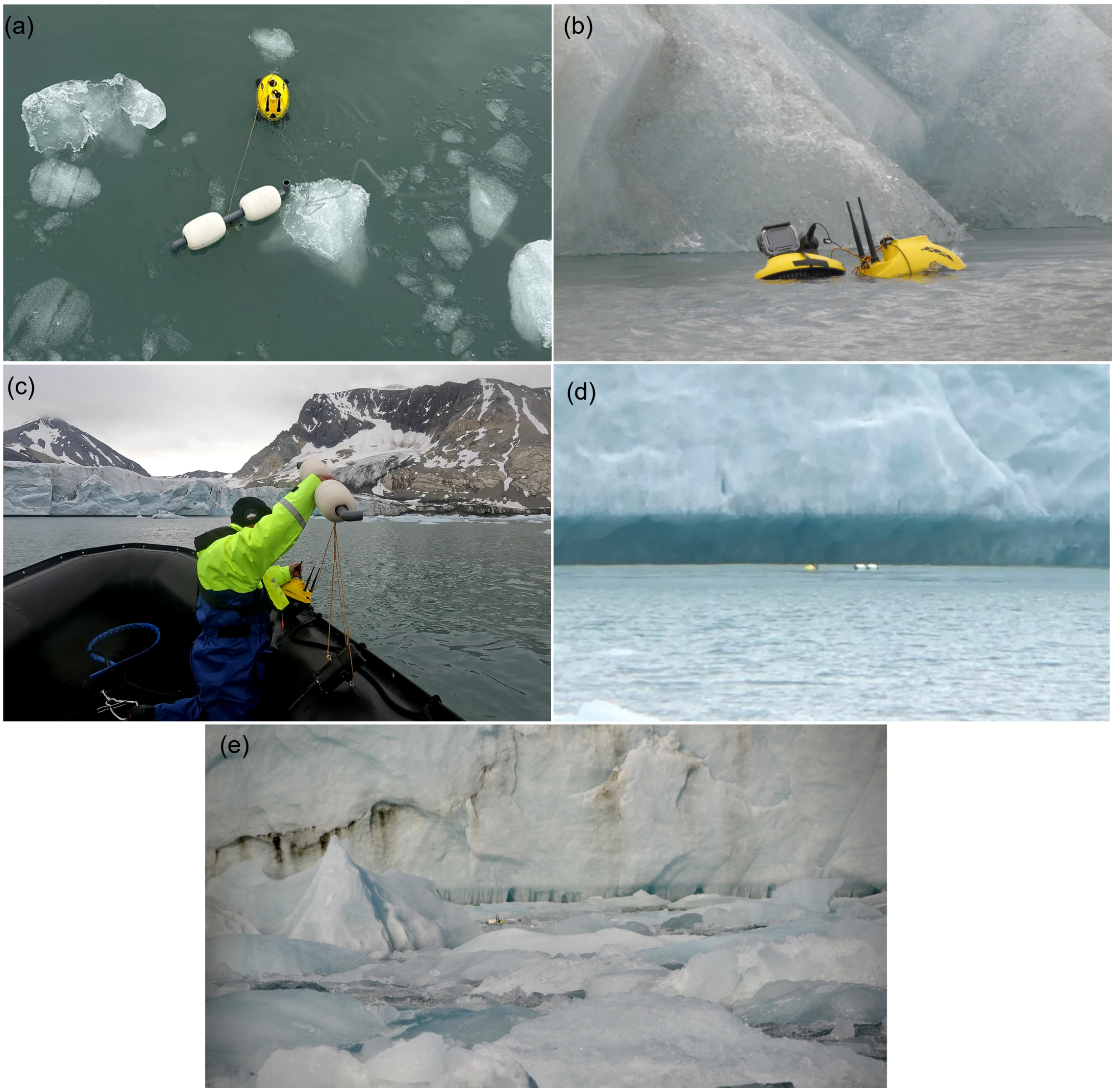

Figure 1. GLAMOR with (a) the buoyancy collar with PULSAR mounted below it, (b) a towed payload module with GoPro mounted on it scanning a bergy bit, (c) photo of deployment procedure, (d) example where the GLAMOR was beneath a glacier's overhang (e) where it was close to the terminus surrounded by thick ice-mélange.

2. Surface-mounted camera: A battery-powered GoPro camera was attached onto a towed-payload module above the surface, providing video footage of the terminus regions traversed by the GLAMOR.

Table A1 gives details on the endurance of the different subsystems of the GLAMOR.

https://doi.org/10.5194/egusphere-2024-32
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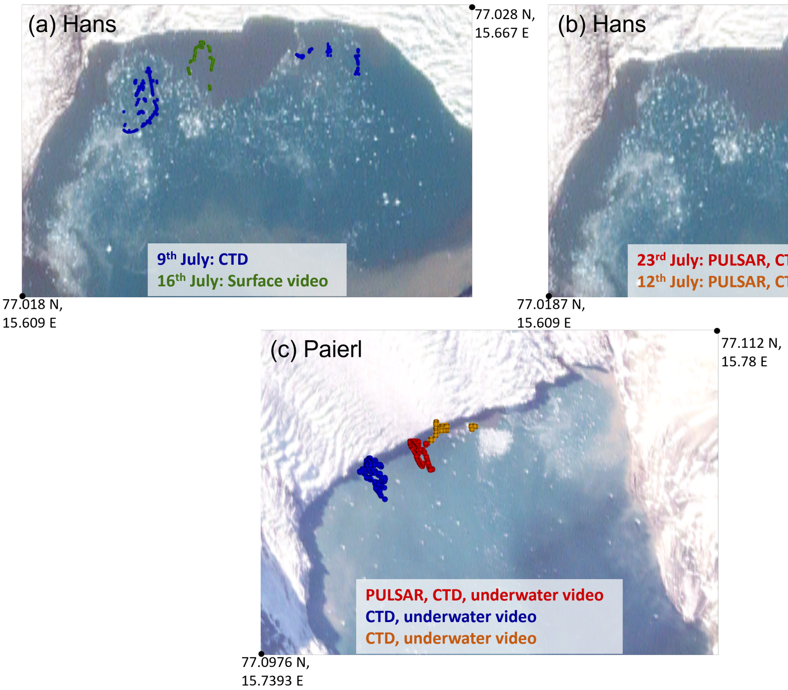

Figure 2. GPS tracks of GLAMOR deployments at (a) and (b) Hans glacier terminus, and (c) Paierl glacier terminus. The background maps were obtained from Planet labs PBC (2024), under a CC BY-NC-SA 2.0 license.

2.4 Deployment

Here, we describe the deployments at Hornsund fjord, Svalbard. GLAMOR was deployed in the bays of two tidewater glaciers, Hans and Paierl (Fig. 2). It was deployed from a Zodiac boat crewed by three people. With a boat driver, GLAMOR pilot, and one crew spotting to aid vehicle deployment/retrieval, visually monitoring the robot during missions and ensuring WiFi connectivity via the directional antenna.

Immediately prior to deployment, the PULSAR and CTD were switched on to record data continuously until retrieval at the mission end. The PULSAR was mounted onto the buoyancy collar, and the CTD onto the vehicle winch. The WiFi connectivity from cellphone to the WiFi antenna, and antenna to GLAMOR was checked, and screen recording of the phone app was started for data logging and later post-processing of the GPS data.

The GLAMOR and sensor payload were transported by Zodiac boat to as close a location of interest at the terminus as safely possible. Locations along the glacier terminus picked for deployments were primarily where surface expressions of subglacial discharge outflows were observed, or severe undercutting at the terminus ice face was observed. The motivation here was to try and record the spatial variability in the acoustic and thermohaline signature in these melting zones, which may be caused due to the presence of a discharge plume which may increases localized melting (Motyka et al., 2003). The surface track of the sensor-traversed area was planned such that we would be able to cover at least the width of the surface expression of the

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plume. One of the dominant factors in determining the deployment location was the presence of thick ice-mélange, because the GLAMOR's progress through mélange was very slow or sometimes impossible (eg. Fig. 1(e)). Thick ice melange also made retrieval risky because it can also hinder the Zodiac's navigation. During GLAMOR missions, line of sight from the WiFi antenna to the GLAMOR was preferred for robust connectivity, but not entirely necessary.

During operation, robot transects were planned so that they would span some distance along-fjord (perpendicular to the terminus face), as well as parallel to the terminus ice face. The small surface expression of the GLAMOR and sensor payload often made visual tracking of the vehicle difficult and required of the use of binoculars to provide feedback to the pilot on the vehicle's movement. Surface currents induced by strong glacier outflows also sometimes impeded the vehicle's mobility and presented a challenge to operation, but this was mitigated via a combination of appropriate choice of deployment location and careful navigation. During the deployment and the sensor scan, safe GPS homing points were set by the pilot for the GLAMOR to automatically return to in case of the loss of WiFi connectivity. At points of interest, the vehicle was stopped and allowed to drift, and the winch was lowered so that a CTD profile and subsurface video profile of the location could be obtained.

At mission end, retrieval was accomplished by piloting the GLAMOR away from the terminus and towards a surface location where retrieval could be done safely and conveniently by the zodiac crew. When visibility of GLAMOR was not clear, the automatic return-to-home functionality was used to initiate the vehicle's navigation away from the terminus until it was visible.

3 Results

Data was collected from eleven transects over six deployment days, each spanning around 200 m in length within 50 m of the terminus. In three of these transects (e.g. shown in Fig. 1(d), Fig. 2(b) and (c)), GLAMOR was operated directly beneath the overhang at the glacier face.

1. Acoustic data: The system was able to successfully collect acoustic data from the terminus region. An example of a recorded timeseries from the PULSAR is shown in Fig. 3(a). In order to characterize the impulsiveness of the timeseries, a symmetric α stable probability density is fit to the data (Glowacki et al., 2018). In this example, a best-fit α value of 1.88 was obtained which suggests more impulsiveness in the noise because of the close proximity to the terminus face.

Thermohaline data: The system was able to obtain CTD profiles in the near-terminus region. Profiles were obtained both horizontally (along the glacier face and perpendicular to it), as well as vertically down to depths of 20 m using the GLAMOR's winch. The data clearly showed the presence of a near-surface, cold, glacially-modified, water layer of low salinity due to ice melt, stratified above the warmer and more saline Atlantic waters. It should be noted that the Star-ODDI miniature CTD was removed from its manufacturer-provided secondary plastic housing and attached directly to GLAMOR winch line to significantly improve its sensor response time and accuracy (which was then comparable to data obtained from a Valeport CTD sensor.).

Underwater video: In total, eleven vertical profiles were done with the underwater video camera. The camera had an infrared light, which was crucial for visibility at depths greater than 5 m. This was useful in capturing the presence of suspended bubbles at depths down to 20 m (Fig. 3(d)). This observation holds significance in the context of modeling ablation at the terminus, as

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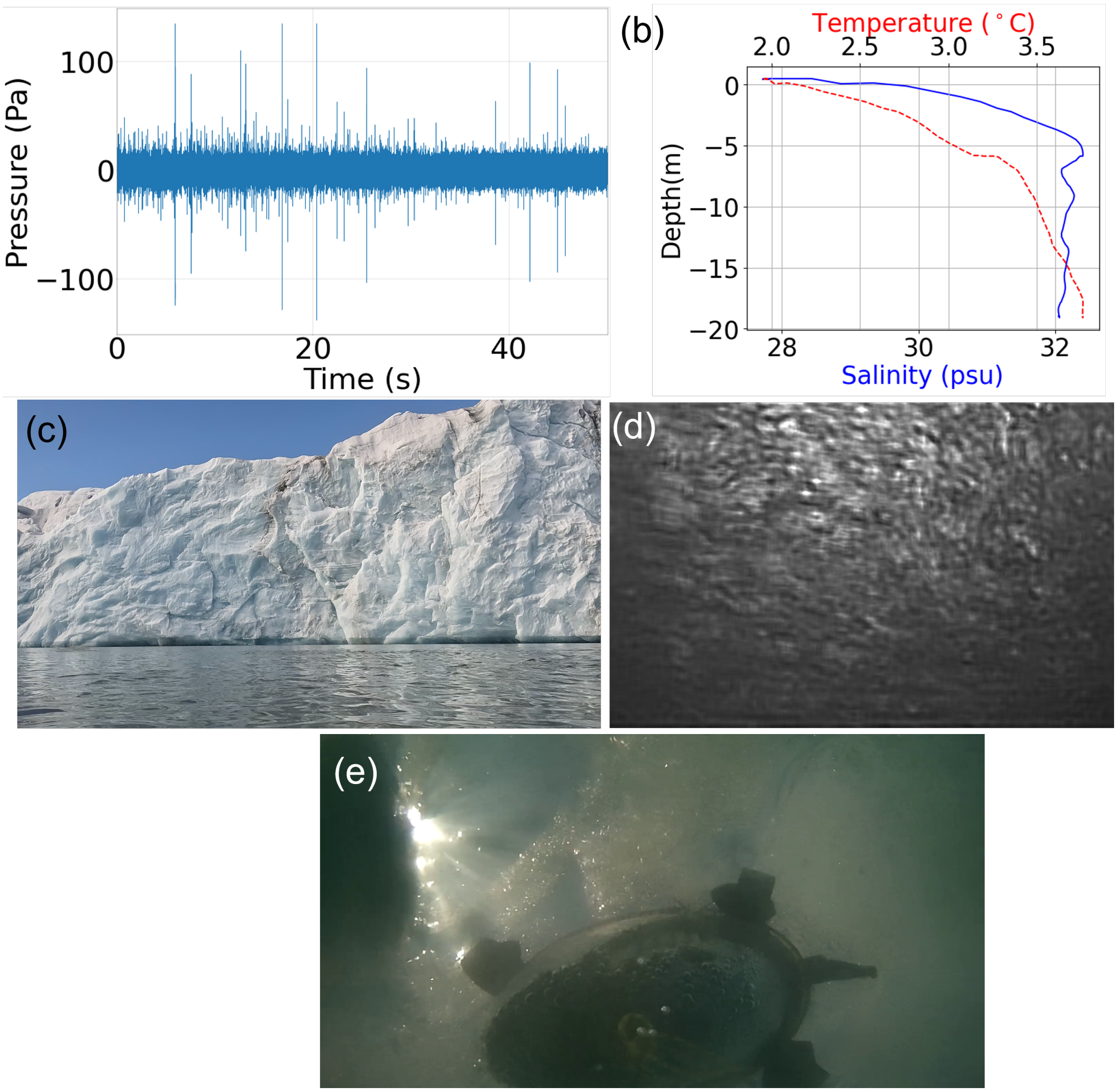

Figure 3. Sensor measurements using the GLAMOR: (a) 50-s acoustic timeseries, (b) Temperature (dashed) and salinity (solid) data from one transect, low-pass filtered to remove oscillations, (c) a video frame from the surface-mounted GoPro, (d) processed image from underwater camera showing bubbles in the water and (e) upward-pointing view from the camera at a depth of 0.5 m, showing the GLAMOR surrounded by ice-mélange.

bubbles are shown to increase the melt rate (Wengrove et al., 2023). The near-surface video from 0.5 m depth can also enable estimation of size distributions of bubbles that reach the surface, adding to an understanding of bubbles in the near-terminus region.

Surface video: Two deployments were done to obtain in-air GoPro video data using the GLAMOR. On one run, a growler was surveyed with video, and one run was near the terminus region where we scanned along the terminus to obtain video with the aim of studying the surface morphology of the glacier front (Fig. 2(a), Fig. 3(c)).

4 Discussions

The GLAMOR system provides a robust and low-cost option for studying the glacier terminus-ocean interface. This can help elucidate ice-ocean interactions in this infrequently studied region, including but not limited to: the thermohaline properties, the size and velocity of turbulent plumes and subglacial discharge, the sound produced at the terminus, the distribution of bubbles released due to melting, and the underwater morphology of the ice front. Furthermore, GLAMOR enables sensing of the near-terminus region via different modalities (e.g. vision, acoustics, temperature, salinity), which can be integrated and compared for a more comprehensive study of the glacier terminus region.

Despite challenges posed by the rigors of the glacier environment, including calving activity, low temperatures, the presence of ice-melange and rapidly-changing weather conditions, all of which affected both vehicle control and navigation, the vehicle was able to successfully achieve its mission parameters. In comparison to other robot-based survey approaches in the literature, the system does not require drone-based deployment as done by Poulsen et al. (2022), and is smaller and more portable than some of the other attempts reported (Wagner et al., 2019; Bruzzone et al., 2020). Though the vehicle itself cannot directly access the subsurface region as AUV-based field surveys can (eg. Howe et al. (2019); Stevens et al. (2016)), this allows it to be controlled remotely, keeps the navigation and control systems simple and allowing real-time video streaming. Consequently, this enables adaptive maneuvering of the vehicle to survey regions of interest. Furthermore, through effective design and planning, sensing of the underwater regions of interest was possible through a combination of placement of sensors at the right depth and use of the winch. The overall cost of the GLAMOR system (including underwater camera and winch) was USD 1200, and, with the addition of the STARODDI CTD and the PULSAR systems, the total system's cost was approximately USD 4000 excluding the cost of the GoPro camera and man-hour costs for development. In this sense, it was able to achieve its objective of affordability and portability, which was our primary objective and comparable to that of Carlson et al. (2019).

Careful planning and testing of the system to understand its limitations beforehand was crucial to helping achieve these goals. Some additional system parameters that helped support the mission objectives include:

1. The GLAMOR provided good mechanical stability, and its ellipsoidal hull design worked very well in the environmental conditions encountered. This design ensured that when the vehicle was contacted by floating ice from the sides, rather than getting crushed or submerged, it was pushed upwards from the water and stayed afloat. There were a few cases where large ice blocks calved from the terminus nearby (as close as 100 m), creating large swells and thick melange, but the vehicle was able to stably and safely ride through these surface hazards.

2. Though there was occasional loss of WiFi connectivity to the vehicle, particularly in cases where icebergs blocked the line-of-sight from the pilot, the automatic homing system of the robot helped quickly regain control and visibility of the craft.

3. The real-time video stream from the vehicle provided some sense of surroundings for the pilot to control the vehicle, and also provided immediate access to the underwater video data, which was one of the objectives of the campaign. By creating a screen recording of the Chasing app we ensured that we had a backup of the video data and GPS locations, even in case of the vehicle getting irretrievably lost or damaged.

Improvisations we envision to this system include:

1. An independently-powered GPS module with satellite communications transmitter located on top of the vehicle, which can provide a constant update of its location. This would allow us to locate the vehicle even in scenarios where connectivity to the GLAMOR is lost, as long as it is floating on the surface. For example, during one of the deployments, the GLAMOR got trapped in a thick ice-mélange (Fig. 1(e)), ran out of battery, and had to be abandoned. However, within 24 hours, it was pushed pushed by tidal currents to a nearby beach with all its sensors intact and recording, providing about 22 hours worth of data. While this clearly demonstrated the mechanical stability and robustness of the system, it also showed the importance of having a redundant GPS beacon which would have allowed us to locate and retrieve the vehicle as soon as it was free of the ice-mélange.
2. Painting the foam floats on the buoyancy collar a more prominent color (e.g. red, orange), which would also make it easier to spot and distinguish visually from ice, snow, and reflections on the water surface.
3. Real-time streaming of other recorded data, such as the acoustics and CTD data, to the operator, which would provide valuable assistance in piloting the vehicle and also ensure that valuable mission data would be available immediately even if the vehicle were to be lost.
4. Incorporating other measurement systems that may be of interest, including but not limited to turbidity sensors and depth-finding sonars. Other sensors can be mounted onto the GLAMOR as long as they are autonomously powered and recording and do not disrupt the stability and navigation capabilities of the vehicle.

Furthermore, the limited length of the winch means that we cannot get a full picture of the thermohaline properties down to larger depths at the terminus. The maximum winch length could also be a limitation in locations where the maximum acoustically active depth at which underwater melting produces sound significantly exceeds 20 m. It has been shown in previous work (Vishnu et al., 2023) that at Hans glacier in Hornsund fjord, the maximum acoustically active depth of melting glacier ice blocks is about 13 m. As such, a winch line depth of 20 m was deemed adequate to capture the information necessary to study the sound produced at the glacier termini in the region studied in our field trials.

Appendix A: Specifications of Chasing vehicle

The Chasing F1 Pro is 278 × 154 × 215 mm in dimensions, and is powered by a rechargeable battery with capacity of 51.8 Wh. The vehicle has a plastic ellisoidal hull housing the electronics. It is capable of speeds of upto 0.5 m/s while towing the buoyancy collar, and each battery has about 3 hours of endurance when continually thrusting. The system also has an

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Subsystems	**Power source**	**Battery endurance**	**Data storage device**	**Recording duration**
Navigation, control	Chasing battery	3 hours	-	-
Underwater camera	Chasing battery	(dependent on navigation speed)	Chasing SD card	Around 500 hours (continuous video recording)
PULSAR	Power bank	3 days (continuous recording)	Dedicated SD card	30 days (continuous recording)
GoPro camera	GoPro battery	2.5 hours (continuous recording)	Dedicated SD card	6 hours
CTD sensor	Internal battery	5.5 days (for sampling interval of 1 Hz)	Internal EEPROM storage memory	24 hours (continuous recording at 1 Hz)

Table A1. Endurance specifications of different subsystems

underwater light and a bow light, and comes with a towable payload attachment (originally meant to carry fish feed). The complete system weighs less than 2 kg, making deployment and retrieval easy.

During testing, we found that the Chasing's battery holder was not mechanically stable and did not have a mechanism to lock the battery solidly into place. Thus, the battery containment was reinforced with waterproof tape for strength and to ensure the battery stayed in place.

Appendix B: Development and specifications of PULSAR

The PULSAR was a stand-alone acoustic recorder, fabricated from a single HTI 96-min hydrophone and a Loggerhead Systems acquisition board capable of autonomously acquiring acoustic data at 96 kHz sampling rate. The hydrophone had a sensitivity of -180 dB re 1V/μPa, and a preamp with a gain of 16.8 dB. The board had a 256 GB SD card to store the recorded data, and was powered by a USB power bank, providing an endurance of upto 3 days of continuous recording. The entire system was fit into a 7.6 cm diameter Blue Robotics watertight bottle and was negatively buoyant.

Prior to the deployments, the acoustic interference from the thruster operation was characterized in a test tank (Supplementary Fig. B1). The interference peak at 81 dB re1μPa^2/Hz at a frequency of approximately 2 kHz, which overlaps with the frequency band of interest for submarine melting (1-3 kHz) (Vishnu et al., 2020). The acoustic interference's magnitude and center frequency increased with increasing thrust, by an average of 3.1 dB within the 1-3 kHz band. In (Vishnu et al., 2020), the power spectral density (PSD) of sound from the terminus melting was measured to be around 100 dB re1μPa^2/Hz at 2 kHz at the Hans glacier, and that of a nearby growler was found to be 105 dB re1μPa^2/Hz at a range of approximately 20 m. Thus, based on the tests, the magnitude of the thruster sound during operation was not expected to be significant compared to the overall sound from submarine melting, especially if recorded from near the terminus. Nevertheless, the thrusting was

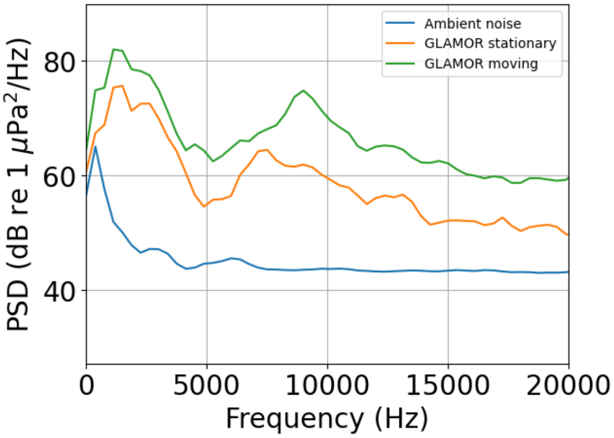

Figure B1. PSD of recorded noise from GLAMOR during tests when it was stationary and moving.

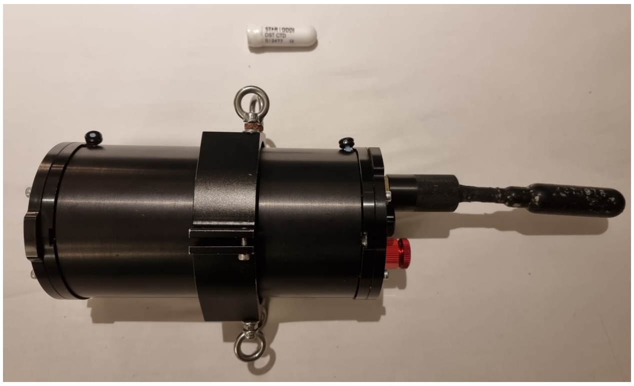

Figure B2. Close-up photo of the PULSAR with hydrophone attached, and the CTD.

periodically stopped and the vehicle was allowed to drift in order to minimize interference from the thrusters during acoustic recordings.

Appendix C: Specifications of CTD

A CTD sensor from STARODDI was used (StarODDI, 2023). It has a cylindrical shape and is small enough (5 cm length, 1 cm dia) and light enough (21 g in air, 13 g in water) to be attached to the GLAMOR winch system. The CTD comes with a polyurethane plastic protective housing, a separate communication box and SeaStar software that can be used to download recorded data onto a computer, and to pre-program the sensor to turn on at a pre-set date and time, and fix the measurement frequency. A measurement frequency of 1 Hz was selected (which was the highest setting available). The conductivity sensor has a range of 3-68 mS/cm, resolution of 0.025 mS/cm and accuracy of 1.5 mS/cm. The temperature range is -1 to 40°C, with a resolution of 0.032°C, accuracy of ±0.1°C, and a response time constant of 20 seconds. The STARODDI is available with several standard depth ranges, of which we opted for a depth range of 100 m with a resolution of 0.03 m and accuracy of ±0.6 m.

Appendix D: Specifications of underwater camera

The camera captures photos at a resolution of 1920×1080, and can record video in either 1080P or 576P resolutions at 30 frames per second (Chasing, 2023). It has a pan angle of ±173°, tilt angle range of $-27°$-75°, field of view of 164.6°, focal length of 2.7 mm, lens aperture of 5.4 mm and ISO range of 100-102400. The camera footage is transmitted in real-time to the operator. This camera cannot be directly replaced by other commercially available cameras this time. Thus, using a separate underwater recording camera would require mounting an autonomous battery-powered camera onto the GLAMOR system separately, without the possibility of real-time viewing.

Author contributions. BK, TSP, HV and MC developed and tested the initial GLAMOR system control and communication in tank, pool and lake tests. BK and HV tested the CTD system. TSP, BK and HV developed and tested the PULSAR system and its frame. DS, MC and HV developed and tested the GoPro mounting frame. HV, MC and DS undertook the field trials at Hornsund with GLAMOR. HV wrote the manuscript, with contributions from MC, DS, and BK.

Competing interests. The authors declare that they have no competing interests.

Acknowledgements. We acknowledge the funding support from the INTERACT III Transnational Access grant under the European Union H2020 Grant Agreement No.871120, for the travel and logistics for the campaign. We thank the Polish Polar research station for helping with administration of the funds, as well as facilities during the campaign. We are grateful to Matthias Hoffmann-Kuhnt for his help in making the PULSAR frame, Oskar Glowacki for piloting the Zodiac during two of the deployments, Grant Deane for discussions in planning the vehicle, and Hayden Johnson, Elizabeth Reed-Weidner and Satchel Birch for help in testing the equipment at the field. We also acknowledge the crew of the M/V Ulla Rinman for their support towards our experiments, and thank Paulina Lewinska for the photo in Fig. 1(b).

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