SUB-ICE EXPLORATION OF AN ANTARCTIC LAKE: RESULTS FROM THE ENDURANCE PROJECT

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Abstract

The ENDURANCE autonomous underwater vehicle was developed and deployed to explore and map a unique environment: the waters of Lake Bonney in Taylor Valley, one of the McMurdo Dry Valleys of Antarctica. This permanently ice-covered lake presented several unique challenges and opportunities for exploration and mapping with an AUV. ENDURANCE was successfully deployed in 2008 and 2009, completing the first full synoptic 3-D chemical profile and high-resolution 3-D geometric mapping of such a body of water.

Following the 2008 campaign, several upgrades were made to the vehicle to improve its exploration capabilities. The most significant of these was replacement of two battery packs. The improved energy capacity of these batteries coupled with analysis of in-situ transit speed efficiency tests resulted in an almost tripled range of the vehicle. This fact, combined with a longer fiber-optic data tether, enabled vastly more ambitious missions during the 2009 campaign. In addition, operational changes were made in 2009, including a super-ballasted mode to enable the vehicle to operate within the super-saline lower lake layers and investigate previously inaccessible areas of the Taylor Glacier face.

ENDURANCE successfully navigated in the presence of ice cover and large density gradients—including precise approach and negotiation of narrow passageways—and demonstrated autonomous melt hole location, position lock and auto recovery on a routine, daily basis. It performed general automated mapping and profiling surveys, as well as detailed studies of localized phenomena, operating in an extreme, remote, unknown environment. Post-processing of the data gathered on the two campaigns has made available a never-before-seen level of detail greatly enhancing the understanding of the lake biogeochemistry. The ENDURANCE project has demonstrated new underwater mapping capa-

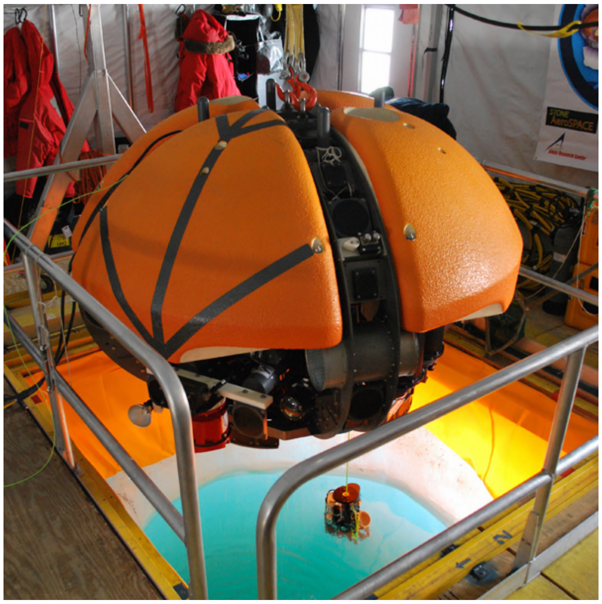


Figure 1: ENDURANCE in position over the Lake Bonney deployment melt hole. The drop sonde can also be seen suspended below the vehicle in a partially deployed position as part of the instrument calibration.

bilities to enhance the understanding of extreme, unique environments. Many of the characteristics and capabilities of ENDURANCE—now successfully demonstrated in complex under-ice settings beneath West Lake Bonney—are the types of behaviors that will be needed for sub-ice autonomous probes to Europa, Enceladus, and other outer planet watery moons.

1 Introduction

The Environmentally Non-Disturbing Underwater Robotic ANtartctic Explorer (ENDURANCE) AUV [1, 2, 3] (see Fig. 1) is a highly maneuverable, hovering autonomous successor to the DEPTHX [4, 5] vehicle, modified to operate in the environment of a permanently ice-covered lake in the Antarctic Dry Valleys. Over the course of two campaigns in the austral summer seasons of 2008–2009 and 2009–2010, this vehicle was deployed in Lake Bonney in Taylor Valley in the Transantarctic Mountains. These campaigns fully explored the west lobe of the lake, and made brief forays into its east lobe.

During the two 10-week deployments to Antarctica, ENDURANCE logged 243 h of sub-ice operational time, traversing a cumulative total of 74 km beneath the ice cap of Lake Bonney. It conducted 275 sonde profiling casts covering the entire west lobe, including short forays through the lake narrows into the east lobe, and several high-resolution profiling runs near the glacier face to localize inflows to the lake. ENDURANCE completed a full 3D bathymetry and glacier face geometry survey over a horizontal area of 1.06 km^2 at an average raw resolution of 22 cm, including detailed scans at less than 3 m range of the glacier grounding line obscured from the surface by overhanging ledges. Finally, ENDURANCE demonstrated routine automated docking into a deployment/recovery melt hole 0.25 m larger in diameter than the vehicle.

ENDURANCE was operated in several modes during these campaigns. These included both down-looking and forward-looking multi-beam sonar configurations for different mapping tasks, a super-ballasted configuration for two missions penetrating into the super-saline lower lake layers near the glacier front, and supervised and fully autonomous modes employing a fiber-optic data line as needed.

In addition to underwater imagery and full synoptic profiles of numerous biophysical parameters of the lake [1], a primary goal of the ENDURANCE project was a bathymetric map of the lake and 3-D geometry of the face of the Taylor Glacier forming its western boundary. The navigation system deployed on ENDURANCE ensured the vehicle was able to meet and exceed the technical goals of traversing the entire west lobe without a loss of vehicle, demonstrate fully autonomous science missions—from deployment to recovery—in the extreme environment of the lake, and fulfill the scientific goals of gathering synoptic biophysical data sets and producing a full high-resolution sonar map of the entire 3-D lake geometry.

1.1 Related Work

A variety of robotic vehicles have been deployed for under-ice operations. The Theseus AUV [7] demonstrated early autonomous under-ice cable-laying. The ALTEX [8] successfully gathered mid-water data under Arctic sea ice. The Autosub AUV [9] has performed a number of missions under sea, fast, and shelf ice. The SeaBED [10] and Puma and Jaguar [11] AUVs have explored geothermal vents in the Arctic ocean. The key differences between these vehicles and ENDURANCE are the very restricted operating volume in Lake Bonney (between 3 and 12 m depth), the difficult acoustic environment (smooth ice above and a severe halocline below), the requirement to perform precision operations under the ice and near the glacier face, and the

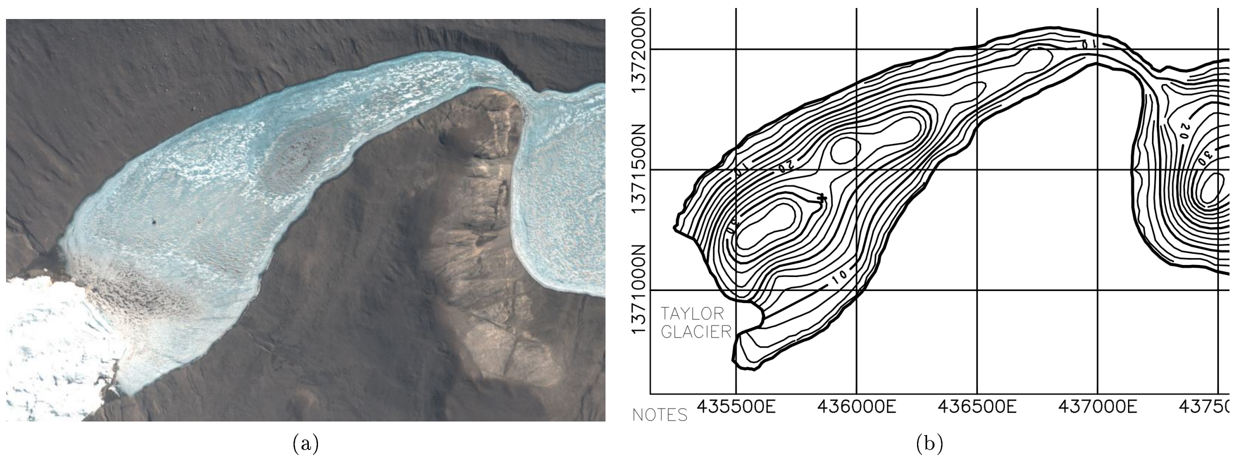


Figure 2: Views of the west lobe of Lake Bonney. (a) Satellite view, the Taylor Glacier is the white ice at the lower-left, the west lobe is in the center, and the end of the east lobe is visible at left. (b) Extant bathymetry prior to ENDURANCE campaigns, grid is in UTM (meters), contours are at 2.5 m intervals, excerpted from [6]. This map is based on discrete soundings and ice-penetrating radar scans in the peripheral, shallow areas. The resulting smoothing and interpolation artifacts are evident.

extremely limited water access (a hole only 20 cm—10%—larger than the vehicle diameter) which demands very robust navigation and an auto-docking capability.

ENDURANCE is a descendant of the DepthX vehicle [4, 5]. A simultaneous localization and mapping (SLAM) algorithm using sonar sensors was successfully tested on DepthX in the confines of flooded shafts [12]. However, the lack of physical features over vast areas of the lake, and the significant acoustic multipath due to the ice roof and the water density profile make sonar SLAM unsuitable in Lake Bonney. Thus ENDURANCE relied on more traditional methods of underwater navigation, and the full 3-D map was created in post-processing.

The primary contribution of this work is a successfully deployed robotic system integrating several novel and existing technologies, and techniques for exploring and for collecting scientific data from an ice-covered lake. ENDURANCE demonstrated routine, automated visual homing and docking system, enabling fully autonomous vehicle operations in this difficult environment while ensure recovery of the vehicle. ENDURANCE employed traditional IMU/DVL dead-reckoning navigation, demonstrating its successful use at high latitudes and in an acoustically difficult environment. The presence of an ice cover led to the development of a method to correct navigation error using GPS and a magnetic beacon system. Due to the complex geometry present at the glacier front, the acoustic sonar data gathered by ENDURANCE represents fully 3-D surfaces for which non-traditional representations and methods were applied for processing. Finally, the development and deployment of an automated spooling profiler enabled fully autonomous science the first repeated 3-D synoptic profiling of such a body of water.

2 Background

2.1 Lake Bonney

Lake Bonney presents a unique and challenging environment for autonomous exploration by a robotic vehicle. The general geometry of West Lake Bonney is shown in Figure 2. The lake lobe is approximately triangular, with the "base" of the triangle formed by the face of the Taylor Glacier and the deltas of two glacial streams. Its "apex" is formed by the mouth of the Bonney Riegel Narrows separating the east and west lobes. The maximum lake width is ∼800 m, while the distance from the glacier to the Narrows is ∼2000 m. The maximum lake depth is ∼42 m, the maximum depth at the glacier face is ∼25 m and in the Narrows ∼16 m. The lake is covered by perennial ice whose summertime thickness ranges from a completely open moat at the lake margins to a seasonally-varying 3–4 m in the lake interior.

An additional primary physical feature of Lake Bonney is its unique, highly stratified chemistry. The west lobe comprises three distinct layers. At

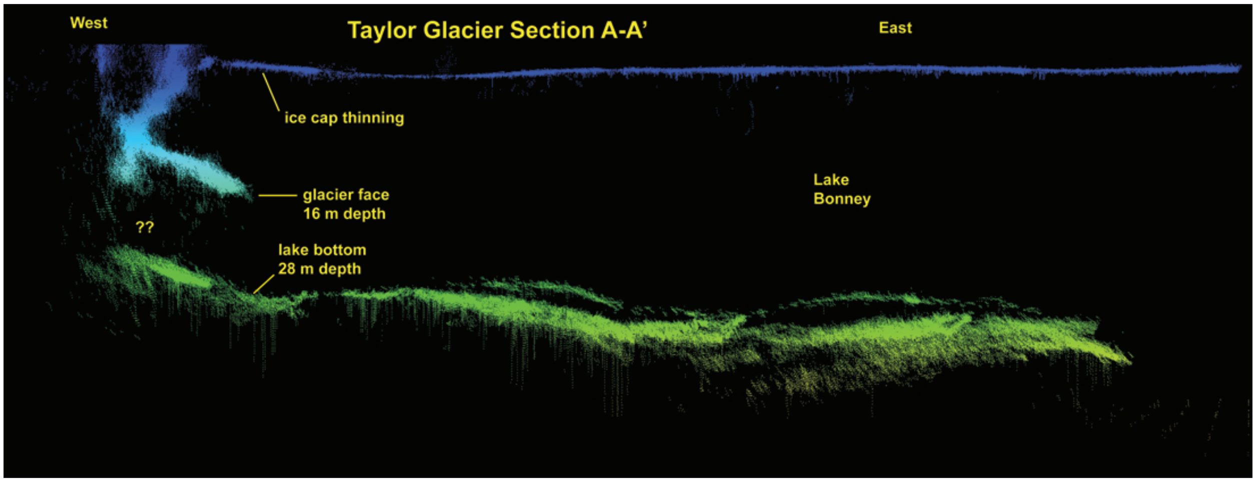


Figure 3: Cross-section of 2008 Lake Bonney sonar returns taken above the halocline near the glacier face. The lake bottom is in green, the glacier front in blue, and the ice cover above in purple. The ledge protruding from the glacier at 16 m is clearly visible, along with the gap in data of the recessed area hidden behind it. A primary goal of the 2009 campaign was to explore this scientifically important location.

the bottom, extending up to a depth of ∼15 m, sits a hypersaline body of water which has had minimal external interaction since the formation of the perennial ice cover [13]. The salinity of this layer ranges from around twice that of seawater at the top to 4–5 times seawater at the greatest depths. On this dense saline layer floats a freshwater lens of around 10 m thickness composed of annual meltwater inflows. The ice cover forms the top-most layer.

To protect the unique Lake Bonney environment and to obtain reliable water chemistry data, disturbance of the lower saltwater layers was to be kept at a minimum during operations. Hence, the vehicle was restricted to the upper freshwater layer. However, the first campaign in 2008 revealed a complex 3-D morphology at the glacier, including a large recessed area hidden under an ice shelf near its base (see Fig. 3). Exploration of this area—including the scientifically interesting glacier grounding line—was not immediately possible, as it required the vehicle to travel into the hypersaline lower lake layer. As the changes in vehicle buoyancy in the denser water were greater than the available ballasting could accommodate, and pending a review of the environmental effects and potential dangers to the vehicle of such a sub-glacial mission, exploration of this area was postponed until 2009 (see Sec. 2.5).

2.2 Goals

The ENDURANCE project had several primary goals:

- the creation of a high-resolution, 3-dimensional map of the entire western lake lobe geometry, including the glacier face;
- detailed investigation (visual, geometric, biophysical) of the lake-glacier interface, including the glacier grounding line at the lake floor;
- two large-scale 3-D synoptic surveys of the lake chemical, physical and biological profiles comparing year-to-year changes;
- demonstration of automated technologies to complete the above scientific missions in a remote, extreme environment.

2.3 Challenges

The Lake Bonney environment presented several unique challenges. First, the ice cover on Lake Bonney required that the vehicle be deployed through a melt hole in the lake ice (see Fig. 1). The logistics of melting a hole large enough for the vehicle and setting up deployment, retrieval, and recharge and maintenance equipment in a safe, covered space necessitated that the vehicle start and terminate its missions at a single, fixed location on the lake (for the sub-halocline glacier face missions in 2009, an additional melt hole was created near the glacier face, see Sec. 2.5). These melt holes represented small but critical targets with which the vehicle had to dock to complete any mission. This fact, combined with the extent of the lake, required that the

Table 1: ENDURANCE vehicle specifications

Dimensions	Ellipsoid major axis (diameter): 2.13 m Ellipsoid minor axis (height): 1.52 m
Mass	1.3 t including science payload
Depth rating	1000 m (excluding payload)
Onboard power	2 × 2.5 kW h lithium-ion rechargeable battery packs
Thrust	6 electric thrusters @ 110 N nominal thrust
Service range	5 km
Maximum transit speed	0.3 m/s
Cruise speed	0.24 m/s
Onboard instrumentation	Honeywell inertial measurement unit (IMU) RDI Doppler velocity log (DVL) 2 Paroscientific pressure depth sensors 32 Imagenex 100 m sonars 24 Imagenex 200 m sonars Imagenex DeltaT multi-beam sonar Sonardyne inverted ultra-short baseline (USBL) transceiver

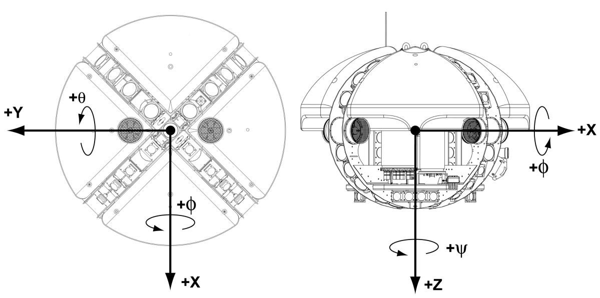


Figure 4: Schematic of ENDURANCE vehicle indicating vehicle axes.

vehicle perform navigation over a distance of several kilometers and return to within a few meters of the melt hole in a fail-safe manner. Further, after returning to within a few meters of the melt hole, the vehicle was required to locate it and ascend to recharge its batteries and download data.

An additional challenge was posed by the presence of the halocline. In addition to limiting the vehicle operating envelope, the large density gradient induced significant beam bending in the multiple acoustic instruments used by the vehicle. This affected both navigation and mapping (see, e.g., Sec. 4.1.2 and Sec. 5.1.1).

2.4 ENDURANCE Vehicle

The physical and operational features of ENDURANCE have been described in detail elsewhere [1, 2, 14, 15, 3]. For completeness, the primary characteristics of the vehicle are briefly summarized again here. An overview of vehicle specifications and hardware is provided in Table 1.

The ENDURANCE vehicle (Figs. 1 and 4) is an axisymmetric four-degree-of-freedom autonomous underwater vehicle. It is equipped with 6 thrusters divided into two independent control and power modules of 3 thrusters each. Redundant pairs of thrusters in each axis ensure full vehicle controllability for any single failure, while nonlinear controllability and the ability to transit are ensured given failure of either thruster bank.

ENDURANCE is equipped with two battery packs supplying power to the thrusters and other vehicle subsystems. A PC-104 stack holds the primary vehicle processor and a separate sonar processor with attached storage, allowing ENDURANCE to perform advanced behaviors and gather data completely autonomously.

For certain operations, an additional measure of safety is provided by a custom-designed, slightly positively buoyant jacketed 0.9 mm reinforced fiberoptic data connection allowing operators to "look over the shoulder" of the robot and manually intervene if necessary. In actual operations under the ice at Lake Bonney, this supervisory capability proved crucial on several occasions to prevent the loss of the vehicle and to allow the team to tune instrument parameters (e.g. multi-beam range gating and gains) to obtain the best-quality data. Limnologists and microbiologists watching data coming in over the fiber were able to identify previously unknown anomalies and to request that the vehicle deviate from its scripted mission and investigate such areas in more detail.

Navigation on ENDURANCE [14] is provided by dead-reckoning using a down-looking Doppler velocity log (DVL) and an inertial measurement unit (IMU), along with redundant pressure depth sensors. Operationally, this on-board navigation is complemented by an active magnetic beacon (originally intended as an emergency locator) allowing the vehicle to be localized from the surface to within 0.2 m. At Lake Bonney, this allowed periodic location fixes to be taken and subsequently surveyed with a real-time kinematic GPS. These fixes were used to precisely determine the locations of sonde profiles, and to post-process navigation data for calibration and improved accuracy, as described in Sec. 4.1.

To ensure vehicle return, the it is equipped with an inverted inverted ultra-short baseline (iUSBL) transducer to allow for absolute position fixes relative to a transponder. At Lake Bonney, the transponder was hung from the deployment melt hole, giving a secondary position reference for the navigation system when near the hole [2].

ENDURANCE is equipped with several independent sonar systems. A bank of 100 m and 200 m pencil-beam sonars enable 4-π-steradian sonar awareness and proximity stand-off and wall-following behavior in unknown environments. The primary mapping unit on ENDURANCE is a 480-point multi-beam sonar with a 120°× 3° field of view. This unit could be mounted in both forward-looking and down-looking configurations to ensure full coverage of the lake geometry.

In order to map the 3-D biophysical parameters of Lake Bonney, ENDURANCE is equipped with a small instrument sonde that could be reeled out to the lake bottom as the vehicle hovered above the halocline. The sonde and its associated servo-controlled spooler are known together as the “profiler” [16]. The sonde comprises nine physical and biological probes—sonde depth, temperature, electrical conductivity, ambient light (photosynthetically active radiation), turbidity, chlorophyll-a, dissolved organic matter, pH, and redox—which gather data in real time during both the descent and the ascent phases of each cast.

ENDURANCE also carries 300 W of high-intensity discharge (HID) lighting and 3 cameras: one primary forward-looking camera, one camera mounted upward-looking along the vehicle centerline intended primarily for visual docking (see below) but also used to collect science data on the lake ice, and one camera angled downward on the sonde to collect lake-bottom imagery (for sample images from each camera, see Fig. 16).

For the 2009 campaign, the reach of the vehicle when operating in monitored mode (via the fiber) was extended while avoiding entanglement with known obstacles between the melt hole and target locations by sinking a long PVC pipe through a small hole drilled in the ice to act as a diverter. The vehicle could then pass to the side of the pipe away from the obstacle and turn to maneuver “behind” it, as seen from the melt hole. This procedure enabled the vehicle to pass through the Narrows into East Lake Bonney while maintaining the safety and oversight provided the data connection.

Several operating behaviors of ENDURANCE were important to its success at Lake Bonney. Of primary importance was the ability to “ice pick” by stopping, shutting off thrusters and floating to sit on the ice ceiling on specially-designed Delrin feet [14]. Another critical behavior was the auto-docking capability in which the vehicle searched for and ascended the two melt holes providing access to the lake using a novel vision-based docking algorithm that uses a blinking light source for docking Sec. 3. An additional behavior is the wall stand-off and

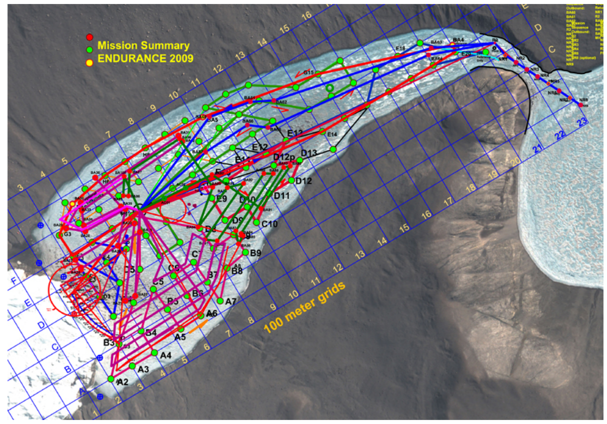


Figure 5: Summary view of all 2009 ENDURANCE mission trajectories.

wall-following mode. It was envisioned that this capability would be used for automated mosaicking of the glacier face, and several transits employing this operating mode at the glacier were performed [14]. However, the lack of visibility, and areas of significant relief encountered during these trials precluded significant use of this behavior in the field.

2.5 Missions

ENDURANCE operated 3 distinct classes of science missions at Lake Bonney:

1. Profiling missions primarily characterizing the water chemistry.
2. Bathymetry missions primarily scanning the lake bottom with the multi-beam sonar.
3. Glacier exploration involving close approaches and scanning with multiple sensors.

Fig. 5 shows the trajectories of all 2009 missions.

Profiling involved transit to pre-defined sampling points, ice-picking at the points, and deploying the drop sonde. For the overall synoptic lake profile, a 100 m grid aligned with the long axis of the lake was used. Additional high-resolution grids with 25 m spacing and covering much smaller areas of around 150 m × 150 m were used to investigate sites of potentially more dynamic flow near the glacier, and a single line of profile points spaced at 50 m was run through the Narrows and into the east lobe.

Though early tests of the automated profiling system failed at Lake Bonney due to difficulties of the sonde sonar altimeter determining termination of the cast on the soft Lake Bonney bottom sediments—requiring manual intervention for most

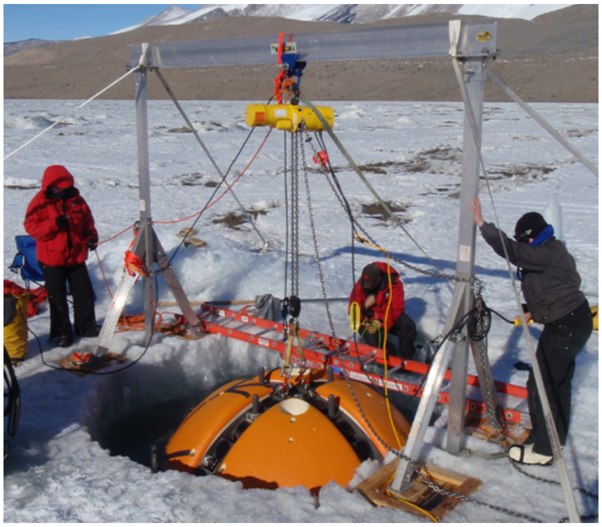


Figure 6: ENDURANCE surfaced at secondary melt hole in preparation for ballasting for sub-halocline operations.

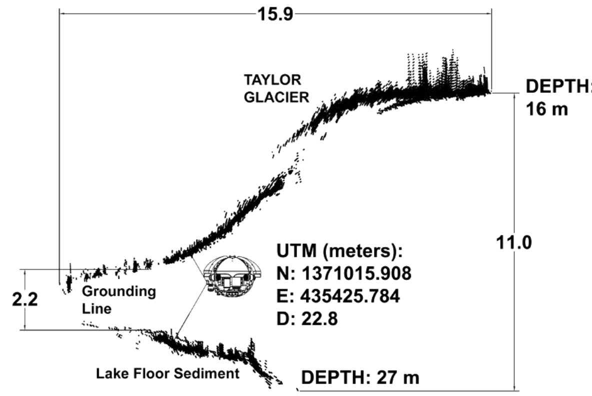


Figure 7: Schematic view of sub-halocline exploration, including raw multi-beam sonar data. The overhanging ledge of glacier ice is visible at top-right at a depth of 16 m (cf. Fig. 3). Due to the limited clearance, ENDURANCE was unable to fully penetrate to and image the glacier grounding line, but was able to establish its depth and general geometry using the multi-beam sonar.

profiling—modifications made in 2009 enabled fully autonomous science missions. These involved fusing measurements from multiple sources, including a DVL measurement of initial altitude, measurements of the sonde tether pay-out, and the flaky sonde altimeter to arrive at a reliable, robust criterion for termination of the sonde cast.

Bathymetry missions were run with the multi-beam sonar in both forward- and down-looking configurations. Bathymetry data was collected on profiling missions, though in this case trajectories naturally could not be optimized for overlap and crossing as required for ideal mapping. Dedicated missions with down-looking sonar was used to fill in gaps in the the bathymetry acquired during profiling. The lake margins were fully mapped using the forward-looking configuration and driving the vehicle "sideways" with the sonar fan pointed to shore.

In 2009, glacier exploration involved a special super-ballasted configuration allowing sub-halocline exploration. As the interactions of the glacier and any potential sub-glacial inflow sites with the lake waters were of primary interest to the project, a mission design including extra ballasting of the vehicle to penetrate the halocline was included in the 2009 campaign. This permitted the vehicle to scan the glacier geometry and grounding line underneath the overhanging ledge on the glacier face mentioned in Sec. 2.1.

The density change in the lower water layers required the addition of ~110 kg ballast to the vehicle. As this quantity of ballast is more than the available vertical thrust on the vehicle, sub-halocline missions were divided into two phases. The vehicle first deployed in the normally-ballasted configuration suitable for the freshwater layer and transited to a secondary hole melted into the ice cap near the glacier face (see Fig. 6). It located and docked with this hole using the visual docking system, and was loaded with the required ballast. A lifting tether attached to a pulley over the hole was attached to the vehicle and used to lower it through the halocline to the new neutral depth without requiring vertical thrusters. This tether remained attached to the vehicle as it explored the glacier face at this new depth, and was used to retrieve the vehicle through the secondary hole at the end of the mission. The ballast was then removed, and the vehicle freed to transit back to the main melt hole in the middle of the lake for recovery and recharge as normal.

Using this procedure, ENDURANCE performed two dives below the Lake Bonney halocline at the glacier face, and successfully penetrated underneath the glacier (see Fig. 7). The resulting high resolution sonar mapping scans, biophysical profiling, and visual imaging of the sub-glacial cavity helped to establish the scientifically interesting physical geometry and dynamics of this location, including the depth of the glacier grounding line and sub-glacial inflows.

2.6 Data Processing

ENDURANCE gathered approximately 240 GB of raw data over the two campaigns, including bathymetry, visual imagery, and sonde and navigation data. A significant component of the ENDURANCE project consisted of processing the raw data into visualizable and scientifically-usable results. Significant processing and visualization work was performed for three classes of data:

- full 3-D sonar bathymetry,
- 3-D biophysical profile data, and
- upward-looking visual imagery for sediment analysis.

The data processing flow for the sonar bathymetry is sketched in Fig. 8. The navigation correction components are described in Sec. 4.1, and the sonar correction and processing components are described in Sec. 5.1. Gathering, processing and visualizing the biophysical data is discussed in Sec. 5.2.

3 Homing and Autonomous Docking

A novel vision-based docking algorithm was developed to enable the vehicle to locate and ascend the melt hole after reaching the nominal home position. For this, a downward-facing blinking light is suspended centered above the melt hole.

The autonomous docking then procedes as follows. When the vehicle reaches the melt hole, a search behavior is initiated in which the vehicle moved in an outward spiral pattern to look for the light. Next, after the light is detected, an ascent behavior is initiated. Here the vehicle ascends the melt hole while keeping the light centered in the upward camera images. The ascent controller uses a PD control law for lateral velocity control and a PID control law for vertical velocity control. The control law attemps to center the light source in the image, thereby centering the robot on the light source. For vertical control, a non-zero velocity is commanded only when the light is sufficiently centered in the image. The ascent controller stopps when the vehicle reaches the water surface.

These controllers require accurate detection and tracking of the target light source in the camera image. Frames are captured at the camera frame rate of around 6 Hz, and then processed by low-level vision routines (built on the OpenCV image processing library [17]) to identify high-contrast contours as candidates for the target light. These contours are then filtered based on their roundness and size to eliminate obvious false positives. For each candidate contour that passes the filters, the center and radius of the bounding circle is passed to the light tracking algorithm.

One of the requirements for the light detection algorithm is that it should perform robustly in the presence of ambient light sources, such as direct light from the sun and indirect reflections from the ice. To distinguish the target light source from these persistent sources, the algorithm tracks a unique blinking signature of the target. The applied solution does not require synchronization between the camera and light, and makes only the straightforward assumption that the vehicle does not move too quickly frame to frame. The details of this algorithm are discussed in [15] and [2].

The vision-based docking algorithm was successfully employed a total of 18 times for ascent and descent in the 2008 campaign. Quantitative and qualitative results showed that the algorithm acquired and detected the blinking light quickly and did not lose track of the light once it was acquired. Further, it rarely misclassified non-target light sources and maintained an accurate estimate of the target center. Results also showed that the ascent/descent controller was sufficiently precise to keep the vehicle centered more than 90% of the time. While we have not performed quantitative analysis of the data from the 2009 campaign yet, qualitatively similar results to that of 2008 were obtained in roughly 15 ascents in 2009. These included the completely automated transition from end-of-mission to docking and recovery as part of completely automated science in the Lake Bonney environment.

4 Navigation

The previously discussed environmental and logistical constraints at Lake Bonney placed demands on the vehicle navigation and mapping capabilities. The vehicle was required to achieve high precision navigation (less than 0.1 % of distance traveled for operations in the field, and less than 0.5 m absolute error for post-processed mapping data) while remaining confined to the freshwater lens between the halocline and the ice roof. Access to the water was limited to the deployment melt hole (and the auxiliary melt hole for the two missions near the glacier face). This precluded any on-board GPS or long-baseline (LBL) acoustic aiding. Instead, a survey-grade IMU was fused with DVL for dead reckoning,

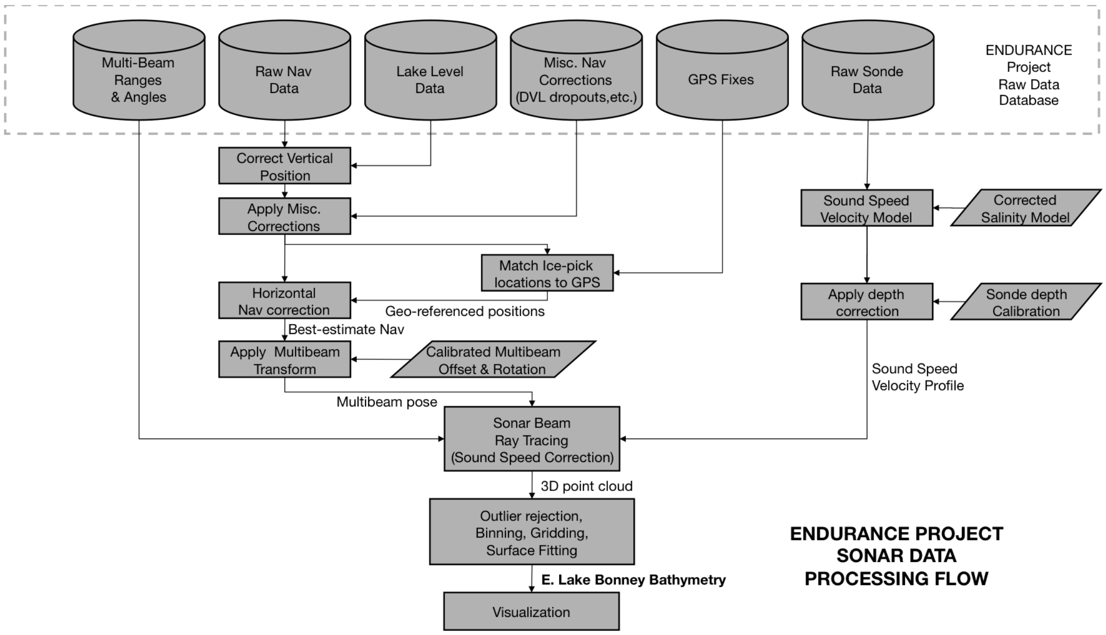


Figure 8: ENDURANCE sonar bathymetry data processing flow.

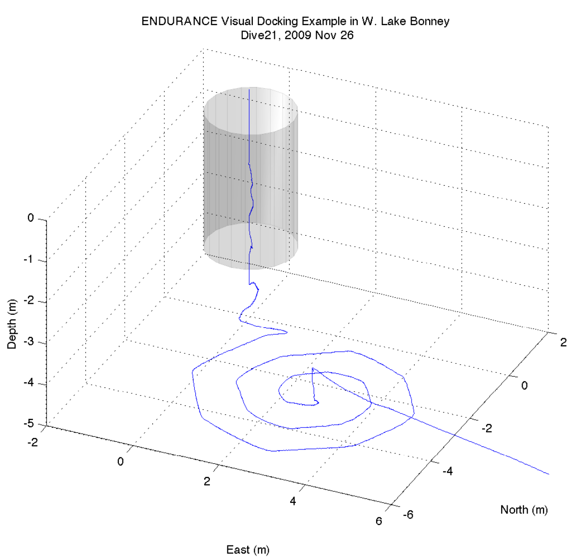


Figure 9: Example of autonomous visual docking at the deployment melt hole (represented by the gray cylinder). The vehicle trajectory is indicated by the blue trace. The vehicle arrives at the presumed location of the melt hole, which, due to navigation errors, is not the true location. It begins an outward spiral search until identifying the blinking light in the upward-looking camera. It then centers on the light and moves up the melt hole to be recovered.

and aided by an iUSBL beacon at the deployment melt hole to guarantee recovery. This system guaranteed navigation accuracy and—along with the visual docking system—vehicle return for operations in the field, and is further described in [14]. For navigation system calibration and post-processing of navigation data, the active magnetic beacon system and GPS was used to obtain offline vehicle location fixes from the surface to achieve the desired absolute mapping errors.

4.1 Navigation Correction

To obtain the best possible basis for vehicle science data, particularly mapping sonar readings, the online navigation was corrected in post-processing. Two complementary corrections were applied. First, the vehicle vertical position (from pressure depth readings) was corrected, taking into account the highly-variable water density, as well as the varying lake surface height. Next, the horizontal positions (from online dead-reckoning) were calibrated and corrected using the magnetic beacon surface fixes as absolute references. The resulting data provided navigation solutions with estimated maximum absolute position errors of ∼0.5 m throughout the lake.

4.1.1 Vertical (pressure-depth) correction

The online vertical navigation derived from hydrostatic pressure is subject to two primary error sources: (1) the varying lake water level and freshwater layer thickness (on the order of 1 m) due to melt water inflow and evaporation/ice ablation, determined by daily level readings; and (2) the unusual water density profile due to the extreme salinity, determined by a measuring tape calibration of the sonde pressure sensor. These corrections also affect the measured locations of the biophysical data collected by the sonde (described in Sec. 5.2).

The lake level readings are referenced to the level on a datum day (10 December 2008) which is taken as the zero reference level for all data. The depth calibration was performed on a different day (29 November 2009). Thus, correcting vertical position proceeds in 3 steps:

1. Offset the raw recorded vehicle depths to the lake level on the calibration day[1].
2. Correct depths using the calibration profile.
3. Offset depths back to the level on the datum day.

As a result, all depths are corrected to a vertical offset in true meters from the lake level on the datum day.

4.1.2 Horizontal (dead-reckoning) correction

Two primary sources of error are present in the dead-reckoned navigation:

- systematic or bias error in the form of misalignment of the DVL and IMU, and a scale error in DVL velocity;
- random-walk drift error due to integration of noise velocity (and to a much lesser extent orientation) noise in the process of obtaining the dead-reckoned position.

To eliminate systematic error, a calibration of the DVL orientation and scaling was performed. To eliminate drift error, the calibration-corrected positions were adjusted to match the GPS truth points by minimizing a square-error criterion which accounted for the various measurement errors.

DVL scaling In addition to customary scale errors in the DVL velocity measurement [18], the

[1]The halocline absolute altitude is assumed to remain constant (set by the outflow lip level in the Narrows). It is the amount of fresh water above this level which varies, so that the calibration profile applies only for the lake level of a single day.

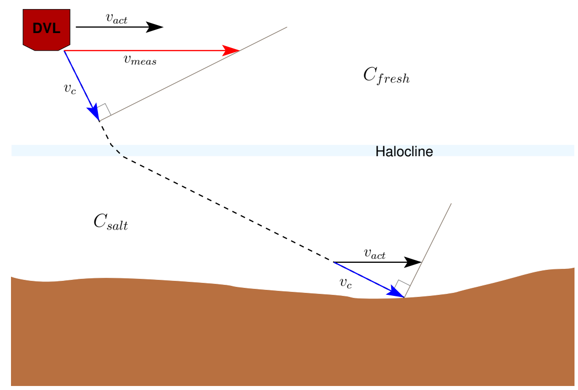


Figure 10: Additional DVL scale error introduced by Lake Bonney environment: schematic of one DVL sonar beam. The actual DVL velocity is v_{act}. The Doppler shift in the beam is induced by the velocity component v_c along the (bent) beam at the lake bottom. This in turn causes the velocity v_{meas} derived at the DVL transducer and based on the outgoing beam angle to be scaled.

Lake Bonney environment presented a particular constant scale error which could thus be considered systematic: bending of the DVL beams at the halocline. Fig. 10 shows a schematic of the effect of the halocline on one of the DVL beams. It follows directly from Snell's Law that the velocity v_{meas} measured at the DVL is scaled from the actual velocity v_{act} of the DVL according to

$$v_{act} = \frac{C_{fresh}}{C_{salt}} v_{meas},$$

where C_{fresh} and C_{salt} are the speed of sound in the freshwater and saltwater layers, respectively. In the west lobe of Lake Bonney, $C_{fresh} \approx 1410$ m/s and $C_{salt} \approx 1530$ m/s, so that it would be expected that to recover actual DVL velocity (and hence dead-reckoned distance) from the measurement would require scaling by a factor of 0.92. The actual scaling, including all scale errors and determined via the global calibration based on location fixes discussed below, was 0.934, and was thus likely dominated by this effect.

GPS truth measurements The melt hole locations and the magnetic beacon system provided the opportunity to globally fix the vehicle position in absolute coordinates using available real-time kinematic GPS survey equipment. The error in measured GPS locations was estimated at less than 5 cm by the RTK/GPS system, and it thus provided anchor points with which to constrain the vehicle trajectory in a navigation post-processing procedure.

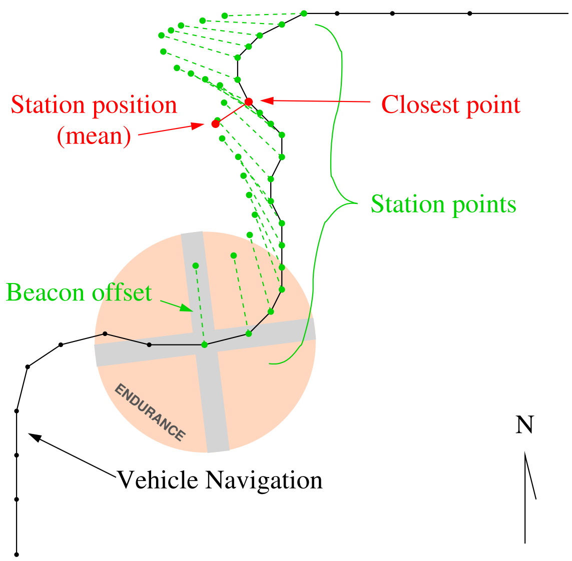


Figure 11: Example of station definition for ice picking. The dead-reckoned measurements of the vehicle trajectory are shown in black. The points chosen to define the station are in green, along with the position of the magnetic beacon (offset from the vehicle center), which is the actual point measured by the GPS fixes. In this example, upon reaching the target location, the vehicle drifts for some time before vertical motion (out of the plane of the figure) ceases and ice picking is determined to have started. During the course of the picking and obtaining the magnetic beacon fix (~1-5 min), the vehicle skids slowly along the ice roof before diving and resuming its course eastward toward the next waypoint. The actual station position is the position that would be measured with a GPS magnetic beacon fix, shown in red. For ice-picking, this is assumed to be the mean of the beacon position during the episode. The uncertainty in the measurement includes the spread in the station points. Also in red is the closest point on the dead-reckoned vehicle trajectory. The absolute measurement update of is applied to this point.

The first step in correcting navigation data is to match the GPS-localized points representing truth measurements to the corresponding vehicle navigation points. This proceeds according to the following steps:

1. Apply several preliminary corrections based on known events and problems.
2. Identify portions of the navigation data, termed *stations*, which are potential locations where a GPS measurement, termed a *truth point*, was taken.
3. Match the stations and truth points.

Preliminary corrections included manual corrections for navigation drift when the vehicle was briefly recovered and in air during dives early in the campaign, for two incorrect initializations due to vehicle software failures, and for one case of unexplained intermittently spurious DVL readings over the course of a minute in an otherwise routine Dive 17 in 2009. They also corrected for incomplete calibrations of the DVL and IMU alignments used in the online navigation calculation for the first half of the 2008 season and half of one dive in 2009.

Stations are the portions of the vehicle navigation data at which GPS truth points for vehicle position are available. Stations fall into four types. Each type represents a different vehicle behavior (most of which can be automatically identified), and potentially a different point on the vehicle being measured (either the vehicle center, or the magnetic beacon position). Table 2 explains the different station types. Figure 11 shows an example of the definition of a station for the complicated but common case of ice picking.

Stations in the vehicle navigation and GPS truth points were matched automatically by finding the closest truth point for every station, according to the horizontal Euclidean distance, or manually. After all stations were matched to corresponding truth points, the dead-reckoned navigation was corrected by the procedure outlined in Section 4.1.2.

Navigation instrument calibration Calibration of the dead reckoning system was performed in the field for each campaign following one or more calibration runs. First, to eliminate as much effect of dead-reckoning drift as possible, an initial correction was made by forcing the recovery location to match the deployment location (enforced by the melt hole), and smoothing the trajectory as described below. Subsequently, after all stations in the

Table 2: Station Types

Station Type	Station Description	GPS Measurement Type	Range of navigation points	Measured point on vehicle
Launch	Vehicle is under melt hole and dead-reckoning has just been reset.	Melt hole	Single point at navigation reset	Center
Recovery	Vehicle has come up melt hole to a depth of less than 2 m.	Melt hole	Single point at depth= 2 m	Center
Ice picking	Vehicle is resting on the underside of ice.	Magnetic beacon fix	Duration at ice-bottom depth with velocity below a threshold	Magnetic beacon
Stationkeeping	Vehicle is holding station somewhere in the water column.	Magnetic beacon fix	Time spent stationkeeping	Magnetic beacon

GPS Measurement The type of measurement for the truth point. The bothouse melt hole location was determined before melting began. The glacier hole center location was determined by fitting a circle to a set of measurements taken around the periphery of the hole after it was completed. The magnetic beacon null axis was located during ice picking and stationkeeping, and the position above the ice flagged and later surveyed with a real-time kinematic GPS (see Sec. 4.1.2).

Range The range of the time series of vehicle navigation points used to determine the station position. For stations (such as ice picking) where the truth measurement was taken over a period of time, navigation points for the period are averaged together to determine the position to match with the truth point. The statistical standard deviation of the averaged points is taken as the uncertainty standard deviation for the estimation.

Point on vehicle The location on the vehicle which is measured by the truth point. For melt hole measurements, the center of the vehicle aligns with the truth point, for beacon measurements, the axis of the magnetic beacon aligns with it.

Table 3: Sources of uncertainty in final ENDURANCE navigation.

Source	Measurement Description	Standard Deviation
Misalignment of DVL and IMU	From calibration of Sec. 4.1.2.	0.025° (residual error)
DVL scale factor	From calibration of Sec. 4.1.2.	0.03 % (residual error)
DVL+IMU dead-reckoning drift	Via integration of velocity in online Kalman filter.	From online Kalman filter covariance
Magnetic beacon localization	Measured by localizing magnetic null axis with hand-held antennas and marking position with ice drill and flag.	Estimated: 0.15 m
Melt hole passage	Determined by passage of vehicle through narrow, fixed melt hole location at deployment/recovery.	Estimated: 0.15 m
GPS	Measured with real-time kinematic GPS surveying equipment, used to localize beacon flags and melt holes.	Average reported by system: 0.02 m

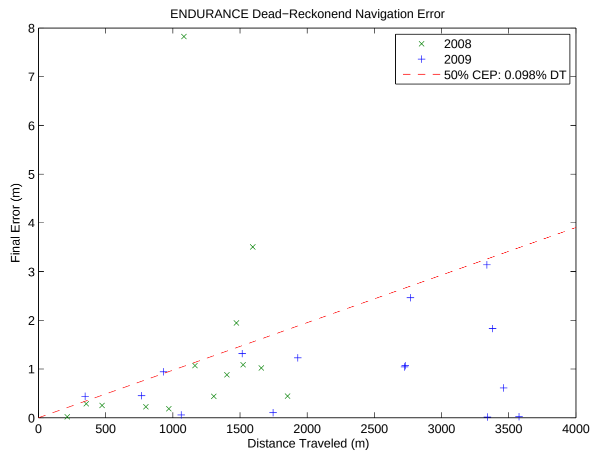


Figure 12: Actual dead-reckoning performance of ENDURANCE vehicle in Lake Bonney, based on error at return to deployment melt hole. The 50 % circular error probable (CEP), assuming symmetric binormal distribution of position errors, is 0.098 % of distance traveled.

run(s) were matched to GPS truth points, the calibration of the DVL orientation with respect to the IMU and of the DVL velocity scaling was extracted in the form of the best-fit similarity transform aligning the station and GPS positions determined using a singular value decomposition method [19].

Drift error correction A linear information filter formulation representing a linear-least-squares optimization weighted by measurement uncertainty estimates was used to eliminate online drift error in the dead-reckoned measurement. Measurements consist of relative incremental motions measured by the dead-reckoning system, and of absolute measurements in the form of GPS/magnetic beacon fixes or occurrences of the vehicle passing through a melt hole. The uncertainty associated with each of these measurements is described in Table 3. Absolute measurements are used to fix the position of the stations described in Sec. 4.1.2. Relative measurements connect the vehicle trajectory between stations. The resulting navigation is a smooth optimal estimate of the vehicle position at every point in time.

4.2 Results

The existence of the melt hole allows the total random-walk drift of the dead-reckoning system on ENDURANCE to be determined precisely, as the location of system initialization and termination must necessarily coincide. The 2008 and 2009 campaigns showed that this drift was extremely low (see Fig. 12). Indeed, the iUSBL system proved of minimal operational utility for the ENDURANCE missions (particularly since the magnetic beacon system was able to track the vehicle).

Far from the deployment hole, the DVL alignment and scale errors were of the same order as dead-reckoned navigation errors (see first two entries in Table 3).

The maximum error estimated for the corrected navigation by the filtering of Sec. 4.1.2 was 1.2 m, with 94 % of vehicle positions having estimated errors of less than 0.5 m.

5 Data Processing

5.1 Underwater 3-D Geometry

The sonar mapping at Lake Bonney required full 3-D capabilities as the glacier face was an important focus of the study, and indeed turned out to contain significant overhangs and cavities. Creating the full high-resolution map of the lake and glacier face geometry followed the data flow shown in Fig. 8. The sonar data processing built upon the corrected navigation data.

5.1.1 Sonar data processing

A sound speed model based on temperature and salinity as measured by the ENDURANCE profiler was selected for the hypersaline lower lake water layers [20]. It was determined that variation of the sound speed profile throughout the lake was sufficiently small that a single profile could be assumed for the entire west lobe, and a second one for the data collected in the small portion of the east lobe.

Next, the raw sonar data were processed. This required correcting the raw returns to take into account the significant refraction effects generated by the large halocline. Utilizing components from the open source MB-System software [21], and based on the lake sound speed profile, the sonar beam paths were ray traced through the water column to identify the true beam hit points. The ray-traced data were then cross-referenced with the navigation data to produce a raw 3-D point cloud of the entire lake, consisting of approximately 256 million individual data points. To obtain the final 3-D surface, the point cloud was gridded and noise-filtered using an octree clustering algorithm, generating a final

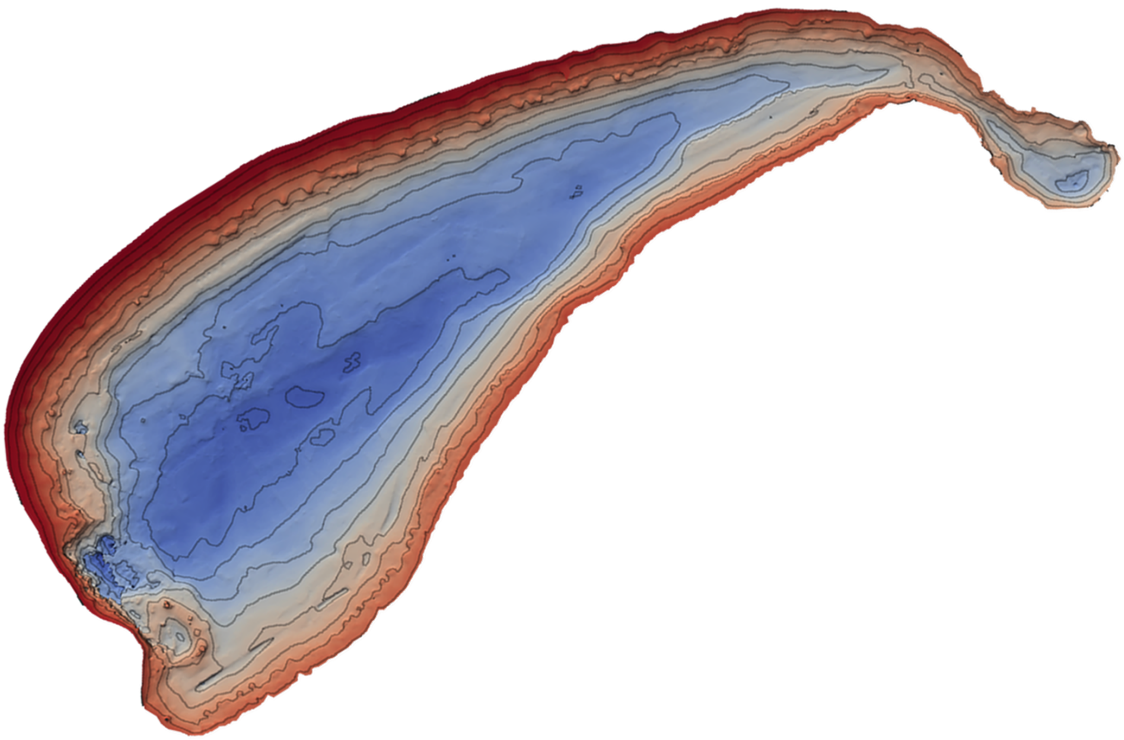


Figure 13: The final mesh generated through poisson reconstruction contained about 500 000 vertices and 800 000 faces.

nearly-homogeneous point cloud of about 1 million points. A modified poisson surface reconstruction algorithm [22] was used to generate a mesh of the entire lake, capturing the full 3-D details of the glacier region with a final resolution down to 50 cm.

Given the special data processing requirements associated with the ENDURANCE dataset, an *ad-hoc* toolset was developed to process the sonar data [23]. This toolset allowed the entire data processing pipeline to be run automatically, while allowing user control of several fundamental data processing parameters. It was therefore possible to easily go from raw sonar and navigation data to the final mesh using different sets of parameters, compare the results and choose the set of options leading to the better reconstruction.

5.1.2 Results

Fig.13 shows the result of surface reconstruction from the aggregate sonar data collected in the 2008 and 2009 ENDURANCE missions.

Finally, the two missions to the Narrows provided some historical contrast. In 1903, Captain Robert Falcon Scott's party first passed over Lake Bonney and through the Narrows. In addition to

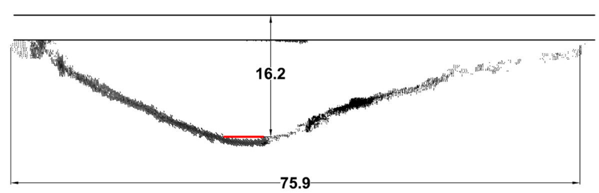


Figure 14: Cross-section of bathymetry at historical minimum width of the Narrows. Scott's measurement is shown in red, at the resulting required depth relative to the modern lake level of 16.2 m.

taking several black-and-white photographs, they also measured the narrowest width of ice in the passage. With this crucial measurement and the high-resolution multi-beam measurements acquired by ENDURANCE, it became possible to demonstrate that the level of Lake Bonney had risen by more than 16 m since Scott's team passed through (see Fig. 14).

5.2 Profiling

In order to simplify the analysis of the large set of data generated by the profiling missions, a tool has been developed to assist researchers in visualizing

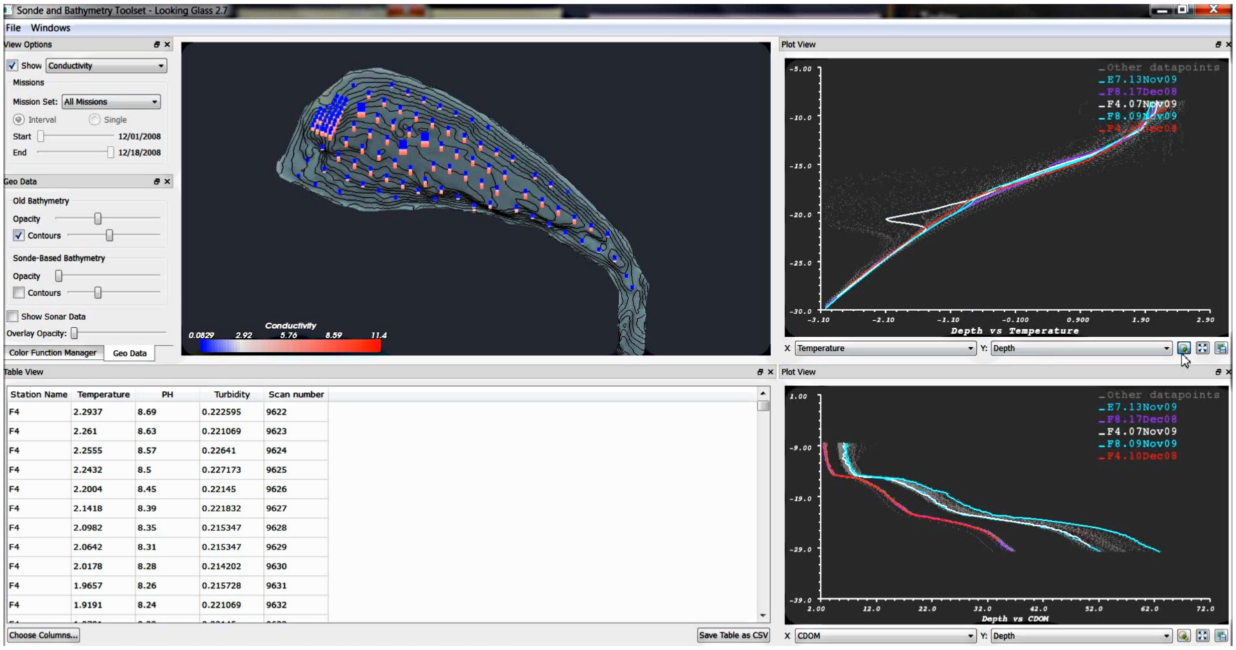


Figure 15: A screenshot of Looking Glass displaying the main 3-D view, two data plots and a tabular view of the selected data.

and querying the dataset. The tool, named Looking Glass [24], represents data collection sites as 3-D columns overlaid on the lake mesh generated by the sonar data (see Fig. 15). The user can pick sonde drop sites by their location or by entering query parameters (such as mission year, day, drop station name, etc.) manually. Selected stations are then represented both in customizable data plots and a spreadsheet view that can then be exported and reloaded into other data analysis programs.

6 Conclusions

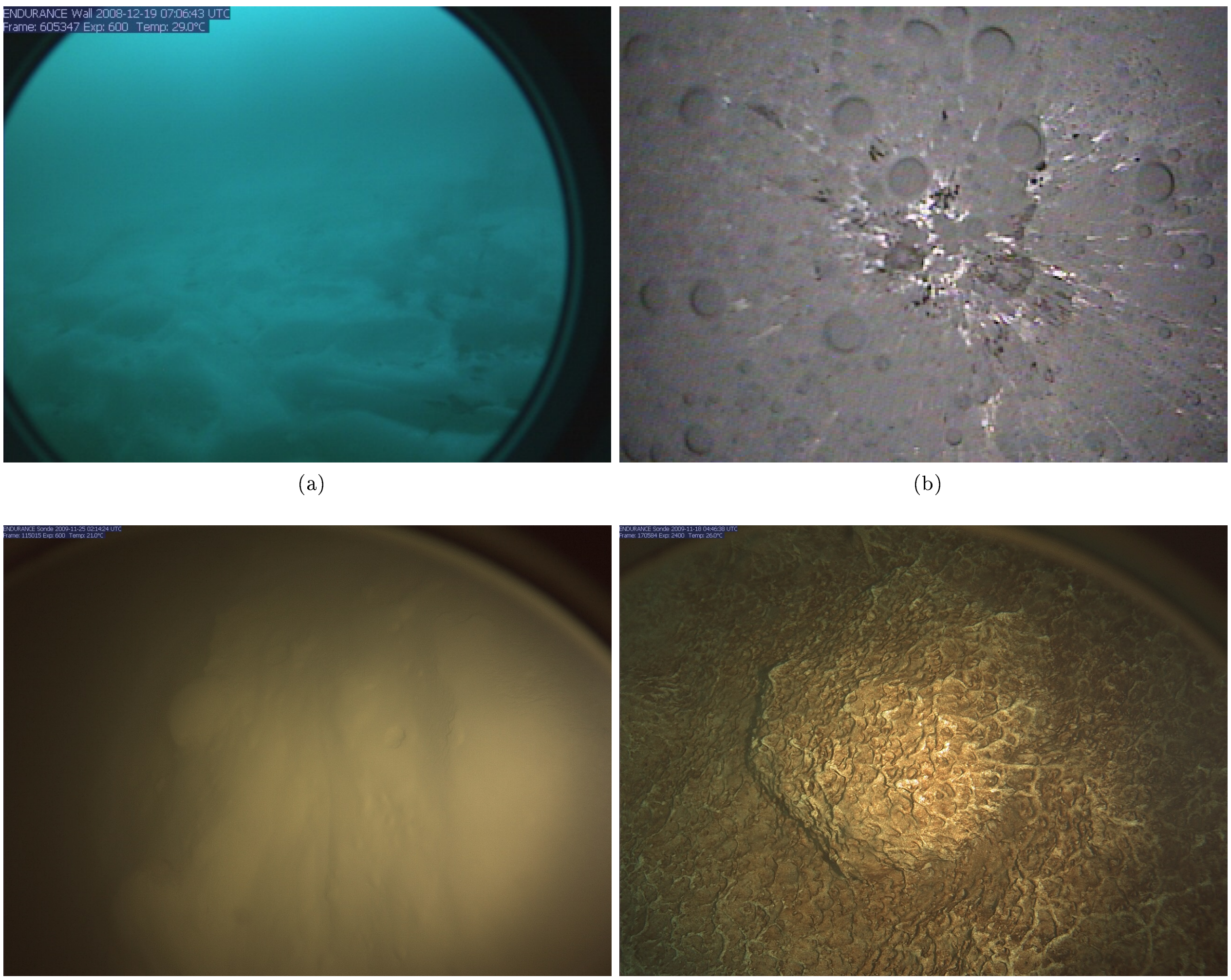
ENDURANCE was the first entity (human or robot) to enter and explore the sub-ice world of West Lake Bonney. It has accumulated a wealth of new knowledge about a previously unknown, remote, and extreme environment, and demonstrated critical technologies for working in such locations.

The physical limitations imposed by the presence of the ice cap led to the development of a visual homing and docking system which was critical to allowing the vehicle to find the deployment melt hole and glacier-face ballasting melt hole used in these campaigns, and enabling completely autonomous missions from deployment to recovery.

At Lake Bonney, the dead-reckoning system with IMU and downward-facing DVL demonstrated a total 50% CEP drift error of about 0.1% of distance traveled. Additional errors due to the misalignment of the IMU and DVL, as well as DVL scaling errors, became significant far from the point of navigation initialization. Despite the limited access from the surface which could enable online navigation correction via GPS fixes or the via the deployment of an LBL, overall navigation errors of less than 0.5 m could be guaranteed throughout the lake for the science data by correcting online navigation in post-processing using surface fixes on the vehicle magnetic beacon. This beacon system has demonstrated penetrations of 400 m in subterranean applications, and has the potential for much greater penetration than the 4–5 m required in Lake Bonney.

Processing the data acquired in these campaigns required extensions to traditional methods. In particular, data acquired with the multi-beam sonar required full 3-D processing to completely represent the Taylor Glacier face. In addition, the sonde data acquired in Lake Bonney represents by far the most numerous and extensive set of profiles of and Dry Valley lake ever taken, requiring new methods of analysis and visualization for researchers.

In the course of the two campaigns, ENDURANCE gathered valuable data and demonstrated autonomous capabilities of great utility for exploration of remote, inaccessible environments, both on Earth and on extra-terrestrial bodies such



(a) (b)

(c) (d)

Figure 16: Images taken by ENDURANCE cameras in Lake Bonney. (a) Taylor Glacier face in forward camera. (b) Lake ice with visible sediments and trapped gasses in upward camera. (c) Sandy lake bottom in sonde camera. (d) Rock covered with bacterial mat in sonde camera.

as Europa or Enceladus.

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