Design and deployment of a four-degrees-of-freedom hovering autonomous underwater vehicle for sub-ice exploration and mapping

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Abstract: This paper describes the 2008 and 2009 Antarctic deployments of the National Aeronautics and Space Administration ENDURANCE autonomous underwater vehicle (AUV). The goal of this project was to conduct three autonomous tasks beneath the ice cap 4 m thick of West Lake Bonney: first, to measure the three-dimensional (3D) water chemistry of the lake at prespecified coordinates; second, to map the underwater face of the Taylor Glacier; third, to chart the bathymetry of the lake bottom. At the end of each mission the AUV had to locate and return through a hole in the ice slightly larger than the outer diameter of the vehicle. During two 10-week deployments to Antarctica, in the austral summers of 2008 and 2009, ENDURANCE logged 243 h of sub-ice operational time, conducted 275 aqueous chemistry sonde casts, completed a 3D bathymetry survey over an area of 1.06 km^2 at a resolution of 22 cm, and traversed 74 km beneath the ice cap of West Lake Bonney. Many of the characteristics and capabilities of ENDURANCE are similar to the behaviours that will be needed for sub-ice autonomous probes to Europa, Enceladus, and other outer-planet icy moons. These characteristics are also of great utility for terrestrial operations in which there is a need for an underwater vehicle to manoeuvre precisely to desired positions in 3D space or to manoeuvre and explore complicated 3D environments.

Keywords: autonomous, robotic, under-ice exploration, autonomous underwater vehicle, Antarctica, West Lake Bonney, Taylor Glacier, navigation, bathymetry, aqueous chemistry

1 BACKGROUND

The Environmentally Non-Disturbing Under-Ice Robotic Antarctic Explorer (ENDURANCE) project was funded by the National Aeronautics and Space Administration (NASA) Astrobiology Science and Technology for Exploring Planets (ASTEP) [**1**] programme in order to test fundamental concepts relating to autonomous under-ice science and exploration that will be relevant to future missions to the outer-planet icy moons such as Europa and Enceladus. The project was also supported by the National Science Foundation (NSF) Office of Polar Programs which arranged for deployment of the robot, its development team, and the science team to Antarctica in the austral summers of 2008 and 2009.

The ENDURANCE vehicle (Figs 1 and 2) is an axisymmetric four-degrees-of-freedom autonomous underwater vehicle (AUV) descended from the Deep Phreatic Thermal Explorer (DEPTHX) architecture that was developed as a three-dimensional (3D) simultaneous localization and mapping (SLAM) testbed [**2–11**]. ENDURANCE [**12–15**] is unusual in the world of autonomous undersea devices in that it actively controls motion in all four degrees of freedom: *X*, *Y*, *Z*, and yaw. It is ellipsoidal with a major axis of 2.13 m, a minor axis of 1.52 m, and a

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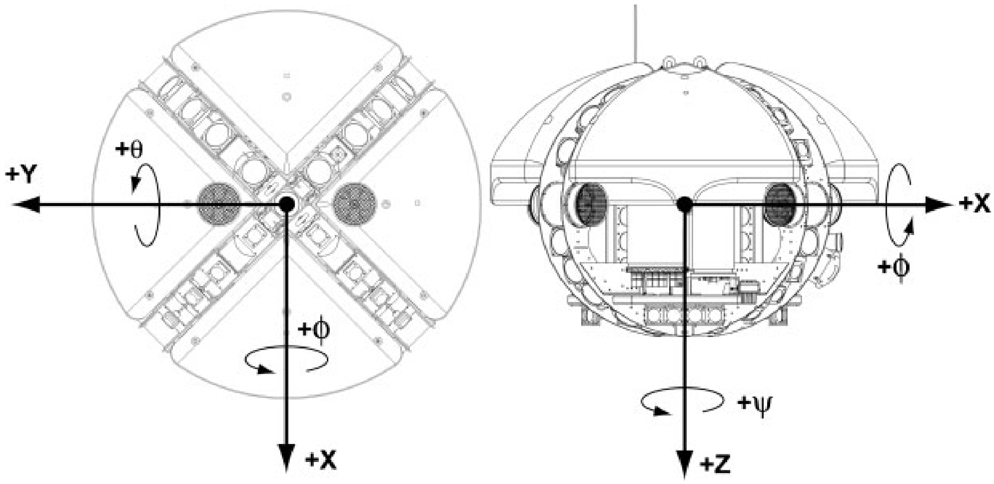


Fig. 1 Vehicle-centric coordinate system for DEPTHX. The overall diameter (major ellipsoid axis) is 2.13 m and the height (ellipsoid minor axis) is 1.52 m. The vehicle dry mass in air is 1272 kg. It is neutrally buoyant under water

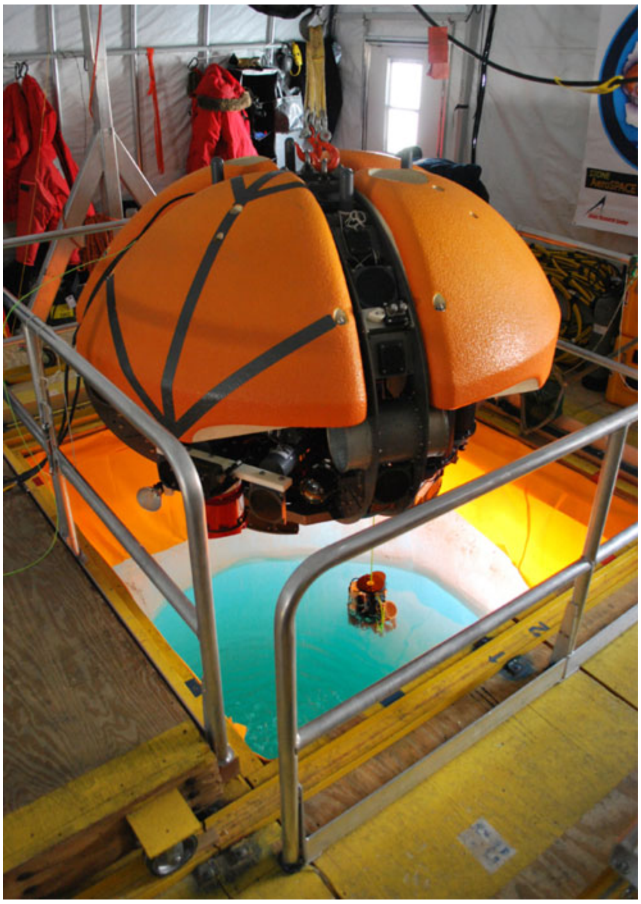


Fig. 2 The AUV ready for deployment down the melt hole. To ensure that the AUV had sufficient energy reserves for each mission, it was kept on charge through the sonde calibration cycle. The vehicle was then lowered into the water, the sonde 'homed', and the charging cables freed to allow it to begin its journey

mass of 1.27 t (see Table 1 for more specifications). The vehicle was designed and developed at Stone Aerospace [**16**] in Austin, Texas, USA.

In 2008 the vehicle was deployed to its field location at West Lake Bonney (WLB) in Taylor Valley, Antarctica [**12–15**, **17**]. In 2009 the vehicle was retrofitted with a new set of batteries that enabled it to explore the entirety of WLB in addition to the narrows leading to East Lake Bonney (ELB). The scientific goals of both field campaigns were as follows:

(a) to characterize the aqueous chemistry of the lake in a full 3D way via automated sub-ice sonde casts (a subset of these sonde casts would be repeated in both the 2008 and the 2009 field deployments to determine how the lake may be changing from year to year);

Table 1 ENDURANCE vehicle specifications and onboard instrumentation

Dimensions	Ellipsoidal: major axis, 2.13 m; minor axis, 1.52 m
Mass	1 t with science payload
Onboard power	5 kW h
Depth rating	1 km
Service range	5 km
Maximum transit speed	0.3 m/s
Nominal navigation accuracy	0.04% of distance travelled
Station-keeping accuracy	±5 cm X, *Y*, *Z*
Onboard instrumentation	Honeywell inertial reference unit Honeywell ring laser gyroscope RDI Doppler velocity log Paroscientific depth sensor Imagenex 100 m and 200 m sonars Imagenex DeltaT multi-beam Sonardyne inverted ultra-short baseline system

(b) to create a high-resolution 3D map of the underwater interface between Taylor Glacier and WLB and, if possible, to image the glacier face;
(c) to create a high-resolution bathymetric map of the lake floor.

The primary engineering goal was to assess and improve the vehicle's ability to deploy autonomously down a melt hole 4 m deep with a diameter only slightly larger than itself, to ranges as far as 2.5 km from the melt hole, and to return home safely at the end of the mission. During the course of the two field seasons the team learned a great deal about how to operate this unique sub-ice science platform in the target environment.

2 ENDURANCE 2008 AND 2009: FIELD SUMMARY

Logistics were driven by the size and mass of the ENDURANCE vehicle. Two separate helicopter sling loads were required to transport the AUV and seven more to transport the ENDURANCE field structure, which included a segmented structural foundation and moon pool, a large polar haven habitat, and a mobile rail-guided gantry to hoist the vehicle for launch and retrieval down a access hole of 2 m diameter melted in the lake ice. It took 7 days from the first helicopter drop on the lake to achieve operational status.

Once up and running, the AUV was configured to handle one of the three mission classes (profiling, wall mapping, or bathymetry). At the beginning of each mission, all navigational and scientific instruments were calibrated and the vehicle was commanded to descend through the melt hole (Fig. 2). Missions would last as long as 9 h and would be up to 4.2 km in length (see Tables 2 and 3 for a summary of all sub-ice missions at WLB). Although the vehicle is autonomous, it was extremely advantageous to have it trail a 0.9 mm reinforced fibre-optic data thread behind it. For ENDURANCE a custom-designed, slightly positively buoyant jacketed fibre was used; a bare fibre could have been substituted for much longer-range missions. This link allowed Mission Control (situated in the ENDURANCE polar haven) to monitor not only the status of all systems in the vehicle, but also to view the 3D environment, live images from the robot's three separate colour cameras, and measurements from the sonde package in real time. In the actual operations under the ice 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 sonar data. In addition, the ability to track the sonde measurements made it possible to maximize the quality of scientific data obtained in areas of interest. Limnologists and microbiologists watching incoming data at Mission Control were able to identify previously unknown anomalies and to request that the vehicle deviate from its scripted mission and investigate such areas in better detail.

The ENDURANCE vehicle is composed of several subsystems implemented using a combination of hardware and software. The following sections present a description of each major subsystem together with a list of problems encountered in the field and the solutions devised to deal successfully with these issues.

2.1 Navigation and control

In order to complete its missions successfully, ENDURANCE had to be able to navigate successfully beneath the ice. The most critical objective of the vehicle navigation was to find, return to, and rise up the melt hole at the conclusion of every mission. The thick ice cap precluded surfacing for Global Positioning System (GPS) fixes or the deployment of acoustic positioning arrays. Only on-board sensors and fiducials at the melt hole itself could be used to determine the position of the vehicle relative to the 2 m hole, from distances of up to 2 km. A secondary navigation objective was to provide spatial coordinates for the acquired scientific data.

Three hierarchical navigation systems were used to determine the vehicle position and to ensure successful return to the melt hole. For basic navigation throughout the lake, a dead-reckoning system was employed. This consisted of a ring-laser gyroscope inertial measurement unit (IMU) to determine vehicle orientation, a pair of redundant pressure sensors to determine the depth under the water line, and an acoustic Doppler velocity log (DVL) to determine the vehicle velocity over the bottom. Since the dead-reckoning system relies on integration of vehicle velocities to determine position, it suffers from an inherent drift error, proportional in expectation, to the total distance travelled. For the planned trajectories of up to 4 km, it was not expected that the dead-reckoning system would return the vehicle to the melt hole location with sufficient precision by itself. Indeed, for 2008 the demonstrated 1σ dead-reckoning error was around 0.13 per cent of the distance travelled, with some end-of-mission errors near 4 m (Fig. 3(A)).

Table 2 Summary of 2008 ENDURANCE missions in WLB, Antarctica

Dive number	Mission type	Brief description	UTC enter water*	UTC exit water*	Time under water (hh:mm)	Number of sonde drops	Traverse distance (m)	Number of bathymetry points ($\times 10^6$)	Web link for further mission details
1	Engineering shakedown 1	Ballasting, basic navigation	5 December 2008 04:59 am	5 December 2008 09:11 am	04:12	0	0	0	http://www.stoneaerospace.com/news-/news-antarctica08-Dec4.php
2	Engineering shakedown 2	Testing navigation subsystems	5 December 2008 10:35 pm	6 December 2008 06:40 am	08:05	0	0	0	http://www.stoneaerospace.com/news-/news-antarctica08-Dec4.php
3	Engineering shakedown 3	Longer-distance navigation test	7 December 2008 03:45 am	7 December 2008 07:54 am	04:09	0	856	0	http://www.stoneaerospace.com/news-/news-antarctica08-Dec7.php
4	Aborted sonde	Aborted because of ballast (could not ice pick)	9 December 2008 07:25 am	9 December 2008 09:00 am	01:35	0	0	0	
5	Profiling 1	F6, F5, F4, G3, F3, E4, E5, E6	9 December 2008 10:23 pm	10 December 2008 04:48 am	06:25	8	998	32.6	http://www.stoneaerospace.com/news-/news-antarctica08-Dec10.php
6	Aborted profiling	Aborted because no data were received from the Tritech altimeter	11 December 2008 12:23 am	11 December 2008 04:24 am	04:01	0	528	0	
7	Profiling 2	D5, D4, E3, D3, C3, C4, C5	11 December 2008 09:40 pm	12 December 2008 02:50 am	05:10	7	1 252	20.7	http://www.stoneaerospace.com/news-/news-antarctica08-Dec12.php
8	Profiling 3	B4, A4, B5, A5, A6, B6, C6, D6, F6	12 December 2008 10:58 pm	13 December 2008 04:01 am	05:03	9	1 383	34.4	http://www.stoneaerospace.com/news-/news-antarctica08-Dec13.php
9	Profiling 4	G6, G5, G4, H4, H5, H6, H7, H8, H9, H10, G9, G8, G7, F6	14 December 2008 09:08 pm	15 December 2008 03:12 am	06:04	14	1 544	40.2	http://www.stoneaerospace.com/news-/news-antarctica08-Dec15.php
10	Profiling 5	D7, C7, B7, A7, B8, B9, C9, C8, D8, E8, F7, F6	15 December 2008 10:44 pm	16 December 2008 04:20 am	05:36	12	1 490	33.2	http://www.stoneaerospace.com/news-/news-antarctica08-Dec16.php
11	Aborted profiling	Aborted because of negative ballast (could not ice pick)	16 December 2008 11:00 pm	17 December 2008 12:15 am	01:15	0	382	0	
12	Profiling 6	F8, F9, F10, F11, F12, E13, D13, D12, E12, E11, E10, F6	17 December 2008 02:00 am	17 December 2008 07:31 am	05:31	12	1 712	40.7	http://www.stoneaerospace.com/news-/news-antarctica08-Dec17.php
13	Profiling 7	G11, G12, F13, G13, H13, H12, H11, G10, F6	17 December 2008 11:20 pm	18 December 2008 04:41 am	05:21	9	1 761	37.3	http://www.stoneaerospace.com/news-/news-antarctica08-Dec18.php
14	Engineering calibration	Patch test	18 December 2008 10:30 pm	18 December 2008 11:34 pm	01:04	0	228	0	
15	Glacier front 1	Northwest radial probing + sonde: X1T, X2T, F6	19 December 2008 02:19 am	19 December 2008 08:40 am	06:21	3	1 177	38.9	http://www.stoneaerospace.com/news-/news-antarctica08-Dec19-20.php
16	Glacier front 2	Centre radial probing of icebergs + sonde: X4T, X5T, X7, X7T, F6	20 December 2008 09:20 pm	21 December 2008 05:12 am	07:52	5	1 354	31.7	http://www.stoneaerospace.com/news-/news-antarctica08-Dec21.php
17	Glacier front 3	Southwest radial probing of icebergs + sonde A4, A3, A2T, B3, C2T, F6	21 December 2008 11:00 pm	22 December 2008 05:30 am	06:30	6	1 874	43.6	http://www.stoneaerospace.com/news-/news-antarctica08-Dec22.php

Table 2 (continued)

Dive number	Mission type	Brief description	UTC enter water*	UTC exit water*	Time under water (hh:mm)	Number of sonde drops	Traverse distance (m)	Number of bathymetry points ($\times 10^6$)	Web link for further mission details
18	Glacier front 4	Main south-to-north high-definition sweep + sonde F6	23 December 2008 01:15 am	23 December 2008 05:37 am	04:22	1	1440	22.1	http://www.stoneaerospace.com/news-/news-antarctica08-Dec23.php
19	Glacier front 5	Proximity operations (wall following + mosaic)	23 December 2008 09:12 pm	24 December 2008 02:30 am	05:18	0	1047	18.9	http://www.stoneaerospace.com/news-/news-antarctica08-Dec24.php
				Total	**93.90**	**86**	**19026**	**394**	

*Note that the dates listed are local time in Taylor Valley, Antarctica, and are usually 1 day ahead of Coordinated Universal Time (UTC) time.

To assure vehicle recovery, two additional navigation systems were added: an acoustic beacon system, and a visual melt hole detection and homing system. The visual homing system was developed specifically for ENDURANCE for the final stages of vehicle recovery and is described in more detail in section 2.6. The acoustic beacon system is an inverted ultra-short baseline (iUSBL) system, which allows the vehicle to determine the range and bearing to a transponder beacon suspended directly below the melt hole. The range on this system is limited to a maximum of 1 km and is heavily dependent on the acoustic environment and multi-path sources (see Fig. 3(B) for performance results in 2008 at WLB). Errors in the bearing angle measurement of the iUSBL mean that absolute accuracy falls off with increasing range. This system was used to apply corrections to the dead-reckoned position during approach to the melt hole using a Kalman filter.

Vehicle control on ENDURANCE operates in various modes depending on the operating conditions and motion objectives. The two primary control modes are open-water transit and open-water station keeping. Additional modes include wall following and visual homing (see section 2.2 and section 2.6 respectively).

Figure 4 describes the basic control flow for ENDURANCE. During station keeping, the controller block uses proportional–integral–derivative loops to hold the desired pose. The resulting desired force and yaw moment on the vehicle are then converted into vehicle-relative coordinates, passed through a dead-band filter which smooths control and reduces energy usage, and converted into individual thruster components by the thruster matrix. This matrix can be changed on the fly in response to sensed thruster outages. The vehicle can still be effectively controlled with up to three of the six thrusters disabled. All control modes include the dead-band and thruster matrix components.

For transit to distant goal locations, trajectory generation and cross-track control components are added to the basic station-keeping control. In order to provide a consistent depth and heading to science sensors during transit, motion is divided into three phases in the trajectory generator: the vehicle first dives or ascends to the desired depth while maintaining horizontal position, then turns to face the target position, and finally transits along a horizontal line to the target while maintaining heading. During both the descent and the transit phases, the cross-track error controller balances desired motion towards the goal with reducing deviation from a

Table 3 Summary of 2009 ENDURANCE missions in WLB, Antarctica

Dive number	Mission type	Brief description	UTC enter water	UTC exit water	Time under water (hh:mm)	Number of sonde drops	Traverse distance (m)	Number of bathymetry points ($\times 10^6$)	Web Link for Further Mission Details
1	Engineering shakedown 1	Systems test. On hoist, no flotation	1 November 2009 23:29:00	2 November 2009 1:33:00	2:04	0	0	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov1.php
2	Engineering shakedown 2	Full checklist run-through. Flotation attached. Ballasting	3 November 2009 3:54:00	3 November 2009 6:42:00	2:48	0	0	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov4.php
3	Engineering shakedown 3	Ballasting, navigation checkout, visual homing test	3 November 2009 22:30:00	4 November 2009 6:01:00	7:31	0	81	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov4.php
4	Engineering shakedown 4	DeltaT resolution test	5 November 2009 3:05:00	5 November 2009 6:23:00	3:18	0	175	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov5.php
5	Engineering calibration 1	DeltaT forward-looking and navigation calibration run	5 November 2009 23:40:00	6 November 2009 4:58:00	5:18	0	1 104	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov6.php
6	Profiling 8	Profiling of the southwest quadrant. {E5, E4, D4, C3, D3, E3, F3, F4}	6 November 2009 22:42:00	7 November 2009 6:45:00	8:03	8	2 475	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov7.php
7	Profiling 9	Profiling of the north side. {F5, G5, G4, G3, H4, H5, G6, H6, G7, H7, H8, H9, H10, G10, G9, G8, F8, F7, F6}	8 November 2009 22:15:00	9 November 2009 10:03:00	9:50	19	3 000	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov9.php
8	Aborted profiling 10	Profiling of the northeast side. Mission aborted owing to cPCI Ethernet hub power failure. {F10, G11}	11 November 2009 1:36:00	11 November 2009 7:00:00	1:21	2	497	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov11.php
9	Profiling 11	Profiling of the northeast side. Ended with ultra-short baseline calibration run. {G12, G13, F14, F15, F16, G16, G15, G14, H13, H12, H11, F13, F12, F11, F9, E7, D7, D6, E6, F6}	12 November 2009 23:18:00	13 November 2009 7:11:00	7:53	20	3 347	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov13.php
10	Profiling 12	Profiling towards narrows. {E17, E18, E19, D21, E20, F19, F18, F17, E16, E15, E14, D14, F6}	15 November 2009 2:47:00	15 November 2009 9:50:00	7:03	13	3 339	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov14.php
11	Profiling 13	Profiling of the south side. Ended with visual homing experiments. {D5, C4, B3, A2, A3, A4, B4, C5, B5, A5, A6, B6, C6, C7, B7, A7, B8, B9, C9, C8, D8, F6.}	15 November 2009 23:21:00	16 November 2009 11/16/2009 5:46:00	6:25	22	2 731	10.3	http://www.stoneaerospace.com/news-/news-antarctica09-Nov16.php
12	Profiling 14	Profiling behind the limno hut. {E10, E11, E12, E13, D12p, D13, D12, D11, C10, D10, D9, E9, F6}	17 November 2009 1:27:00	17 November 2009 6:48:00	5:21	13	1 930	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov17.php
13	Profiling 15	First narrows run into the east lobe. {NR2, NR3, NR4, NR6, NR8, NR7, NR5, NR1}	18 November 2009 2:31:00	18 November 2009 8:50:00	6:19	8	3 900	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov18.php
14	Engineering 1	Ultra-short baseline calibration, visual homing, and subhalocline ballasting preparation	19 November 2009 1:25:00	19 November 2009 4:59:00	3:34	0	1 012	0	

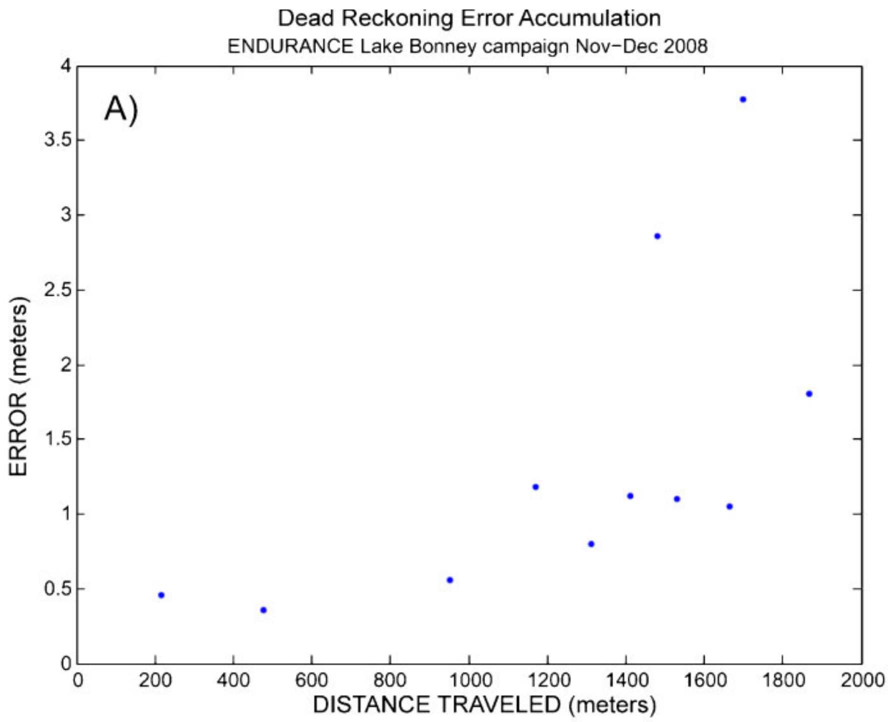
Table 3 (continued)

Dive number	Mission type	Brief description	UTC enter water	UTC exit water	Time under water (hh:mm)	Number of sonde drops	Traverse distance (m)	Number of bathymetry points ($\times 10^6$)	Web Link for Further Mission Details
15	Engineering 2	Subhalocline ballasting, transit efficiency tests	20 November 2009 3:02:00	20 November 2009 4:50:00	1:48	0	350	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov20.php
16	Aborted	Spooler slip ring problem	20 November 2009 21:11:00	20 November 2009 21:30:00	0:19			0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov21.php
17	Profiling 16	High-resolution profiling near the glacier. 40 casts performed; data from 25 were corrupted. Glacier imaging with DeltaT. Acquired some camera images of the glacier face. {BF1 to BF14, BF16}	21 November 2009 3:21:00	21 November 2009 11:20:00	7:59	15	1 857	7.4	http://www.stoneaerospace.com/news-/news-antarctica09-Nov21.php
18	Profiling 17	Re-do of high-resolution profiling near the glacier. {BF10, BF12 to BF39, F6}	23 November 2009 2:55:00	23 November 2009 9:00:00	6:05	30	1 582	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov23.php
19	Profiling 18	Glacier-front exploration. Profiling near the glacier face resulting in the discovery of locations with temperatures lower than 5 °C. Test surfacing at the glacier melt hole using visual homing. {F6, E3, BF13, BF16, BF15, BF24, BF25, BF34, BF35, BF40, BF41, BF42, BF43, BF44, BF45, B3, F6}	24 November 2009 2:04:00	24 November 2009 7:30:00	5:26	19	1 739	0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov24.php
20	Glacier front 5 (subhalocline)	Subhalocline exploration of the glacier front. Side sweep close to the glacier face to obtain comprehensive DeltaT imaging. Profiled at L1	24 November 2009 22:28:00	25 November 2009 6:02:00	7:34	1	1 509	2.7	http://www.stoneaerospace.com/news-/news-antarctica09-Nov25.php
21	Glacier front 6–bathymetry 1 (subhalocline)	Subhalocline exploration of the glacier front. Attempt to capture visual imagery of the grounding line. Obtained good camera images of the nose of the glacier. Side-mounted DeltaT scan of the south shore of the lake in autonomous mode (with communications connected). Profiled at {F6, GMHO9, BF35x}	26 November 2009 0:10:00	26 November 2009 7:30:00	7:20	3	2 768	11.0	http://www.stoneaerospace.com/news-/news-antarctica09-Nov26.php
22	Bathymetry 2	Sideward-looking DeltaT scan of the North shore in autonomous mode (with communications connected). Testing of automatic profiling. Profiling at F6	26 November 2009 22:55:00	27 November 2009 4:20:00	5:25	1	3 653	14.9	http://www.stoneaerospace.com/news-/news-antarctica09-Nov27.php

Table 3 (continued)

Dive number	Mission type	Brief description	UTC enter water	UTC exit water	Time under water (hh:mm)	Number of sonde drops	Traverse distance (m)	Number of bathymetry points ($\times 10^6$)	Web Link for Further Mission Details
23	Bathymetry 3	Sideward-looking DeltaT scan behind the limno hut. Communications-disconnected autonomous mode, but manual recovery up the melt hole. Testing of automatic profiling. Profiling at F6	28 November 2009 23:12:00	29 November 2009 4:16:00	5:04	1	2 733	12.5	http://www.stoneaerospace.com/news-/news-antarctica09-Nov29.php
24	Bathymetry 4	Downward-looking DeltaT scan on the northwest side, including patch tests. Communications-disconnected autonomous mode. Testing of automatic profiling. Profiling at F6	30 November 2009 1:55:00	30 November 2009 7:55:00	6:00	1	3 591	2.2	http://www.stoneaerospace.com/news-/news-antarctica09-Nov30.php
25	Bathymetry 5	Downward-looking DeltaT scan of the south side. Autonomous mode with communications connected. Tested automated profiling with commands from the system executive. Profiled at F6	30 November 2009 22:38:00	1 December 2009 4:54:00	6:16	1	3 525	11.8	http://www.stoneaerospace.com/news-/news-antarctica09-Dec1.php
26	Profiling 19	Second narrows run. Autonomous mode, with communications connected going out to the narrows. Manual from then on. Profiling at {NR1, NR2, NR3, NR4, NR5, NR6, NR7, NR8, F6}	1 December 2009 23:43:00	2 December 2009 6:24:00	6:41	9	4 383	21.3	http://www.stoneaerospace.com/news-/news-antarctica09-Dec2.php
27	Bathymetry 6	Downward-looking DeltaT scan behind the limno hut and north side. Automated mode with communications connected. Finished with theautonomous patch test– ultra-short baseline navigation run. Profiled at {ACO1, ACO2, BA80}	2 December 2009 22:28:00	3 December 2009 4:45:00	6:17	3	3 730	26.9	http://www.stoneaerospace.com/news-/news-antarctica09-Dec3.php
				Total	**149**	**189**	**55 011**	**121**	

*Note that the dates listed are local time in Taylor Valley, Antarctica, and are usually 1 day ahead of Coordinated Universal Time (UTC) time.



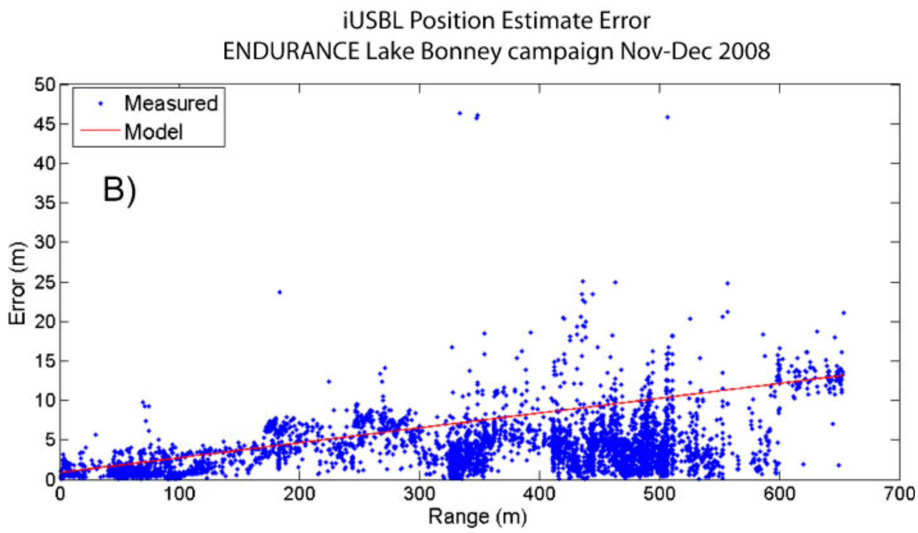


Fig. 3 ENDURANCE performance at WLB in 2008: (A) dead-reckoning navigation error as a function of distance travelled as determined upon return to the melt hole in 2008, where the 1σ error was 0.13 per cent of the distance travelled; (B) iUSBL navigation error as a function of range from transponder where the 1σ error was $0.9\,\text{m} + 0.019 \times \text{range}$

straight-line path. If, during transit, vertical or yaw deviation from the desired path becomes too large, the trajectory starts again from the descent phase.

2.2 Proximity operations

In order to operate in close proximity to walls in its subterranean environment, a wall detection and wall-following capability was developed for DEPTHX [**2–11**]. This capability has been extended and employed on ENDURANCE for glacier face mapping in WLB. The wall-following capability relies on an array of pencil-beam sonars on one quadrant of the vehicle, spanning a 90° view in the horizontal and vertical planes. The wall data sensors (camera, lights, and multi-beam sonar) are mounted facing outwards from the centre of this quadrant.

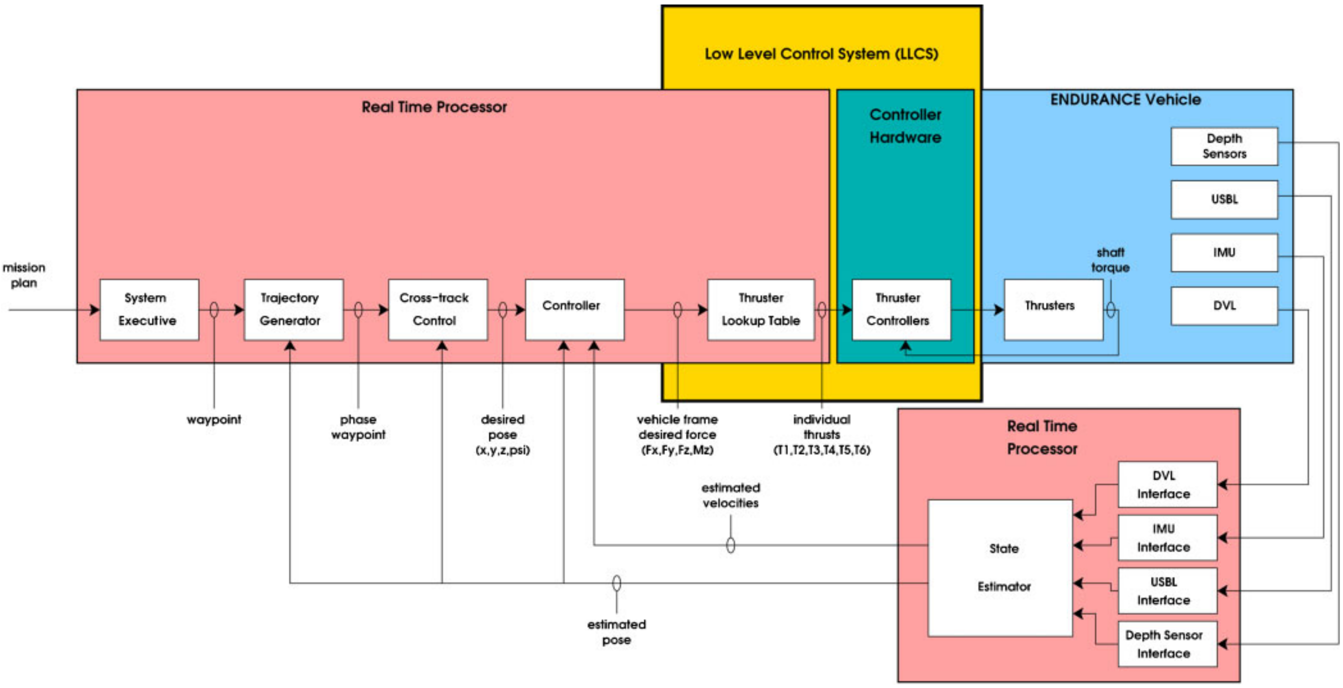


Fig. 4 ENDURANCE control system for under-ice transit and station keeping

In wall-following mode, points representing the hit locations from the pencil-beam sonars are tracked in a coordinate frame attached to the vehicle. As the vehicle moves, dead-reckoned position changes are used to update the positions of points in the vehicle frame. The number of points tracked is limited so that, as new points are added, the oldest points are deleted. At every time step, a vertical plane is fitted to this local collection of points, and the desired incremental motion is calculated parallel to this plane. In addition, errors in the range to the plane and the deviation of heading from the plane normal are calculated. These relative motion terms are fed to a motion control module and controlled with proportional–derivative controllers. Depth control is via the precision depth sensors used for normal control modes.

The wall-following behaviour was successfully field tested in a flooded quarry in Austin, Texas, USA, and the NASA Neutral Buoyancy Laboratory in Houston, Texas, USA. It was employed to follow a portion of the Taylor Glacier face at WLB in 2008, but poor visibility limited the amount of data gathered.

2.3 Assured recovery and ground truth

To ensure that the vehicle could be located and recovered in the event of a total power failure during a mission a custom-designed through-ice location system was developed for ENDURANCE. This system consisted of two components. First, a 20 mW magnetic field generator was pendulum mounted within the vehicle frame such that it generated a field that always presented a null-field axis perpendicular to the surface of the ice. The magnetic field was modulated at 3.5 kHz and the generator was a self-contained system enclosed in a waterproof housing. Second, the surface-based element of the system consisted of a phase-locked loop receiver set that could be operated either digitally or via audio feedback. The direction of the vehicle from the receiver could be audibly detected by sweeping a loop antenna until the received signal strength approached a null. The intersection of the two null planes thus indicated the vehicle position. This system was field tested at ice-covered Lake Mendota, Wisconsin, USA, in February 2008 and fully implemented during the WLB deployments. Under typical weather conditions at WLB the surface horizontal detection range from a receiver unit to the vehicle was between 300 m and 500 m. The tracking system, operated at a higher power, has been shown to penetrate up to 1200 m of rock, water, or ice and thus may have potential for tracking under much thicker ice shelves.

Although originally designed as an emergency recovery measure, this location system also proved useful in providing ground truth for the vehicle navigation data. This capability allows science data to be accurately georeferenced. During the initial

Lake Mendota field tests an observation was made that, beyond simply locating the stationary vehicle under ice, it was possible to track the vehicle in real time and this became part of the standard mission procedure at WLB. It was found that the vehicle could be effectively located by a two-person crew in which one person tracked the velocity vector of the vehicle and a second person tracked the position from a point approximately 50 m orthogonal to the velocity vector. With this capability the vehicle's location could be known at all times and the team tracking of the AUV was able to mark sonde cast locations precisely. These surface location fixes were recorded with a centimetre-level real-time kinematic GPS in order to georeference the data set permanently and to serve as a basis for establishing ground truth for the AUV's navigation fix.

This capability was also used on two occasions to re-initialize the guidance fix on the robot during a mission. Because of poor visibility in the lake (typically less than 2 m owing to ultra-fine suspended glacial sediment) and yet faced with a desire on the part of the science team to attempt to image the underwater Taylor Glacier where it intersects WLB, the vehicle was allowed (in 2008) effectively to go to zero stand-off distance from the glacier on two occasions. As expected, the dead-reckoning navigation solution dropped out because of loss of the Doppler velocity lock; the vehicle was also beyond iUSBL range. Although Mission Control was able to move the vehicle safely back from the glacier and to re-acquire velocity using the on-board video cameras and a joystick control override for guidance, the navigation solution was compromised. To resolve the problem, the surface tracking team vectored the robot back to a known GPS fix location in real time and the fix was uplinked via the fibre-optic thread. Both missions resumed and completed normally. The vehicle location system thus allowed the development of a robust method for dealing with an under-ice emergency that otherwise would have led to a loss of the AUV.

2.4 Machine vision homing

During the longest missions (up to 4.4 km traverse) the cumulative navigation error generally caused the vehicle to be under 2 m (and many times significantly less) from the melt hole centre-line at the conclusion of a mission. At this point, a machine vision algorithm took over control of the vehicle. The system uses a zenith-pointing video graphics array camera (Fig. 5) to search for the presence of an oscillating collimated light source. The algorithm segments the video frame into candidate intensity sources (green boundaries in Fig. 5) and then analyses the frequency spectra. If it finds one that matches the preset frequency of the overhead beam (blue perimeter in Fig. 5), it locks on to that source and goes into station-keeping mode in *XY* on that locus while allowing the slight positive buoyancy of the vehicle to allow it to rise up through the melt hole. The image sequence in Fig. 5 is taken from Mission 5 (2008) live video and shows in Fig. 5(A) the vehicle crossing the melt hole edge and the first appearance (but not detection) of the light source; in Fig. 5(B) the positive lock is acquired on the light source; in Fig. 5(C), ENDURANCE is rising up the hole; in Fig. 5(D), ENDURANCE first breaks the surface as the entire crew watches, with no human at the wheel. During the course of 19 sub-ice missions to WLB in 2008, there were only two failures of the machine vision system to bring ENDURANCE automatically up the hole. These were the last two missions. During the final week of the project the water visibility degraded rapidly from glacial run-off to the point where the AUV (at a depth of 5 m) could not see the light from the bottom of the melt hole. In both cases a magnetic beacon was used to vector the vehicle to the centre-line. In 2009, two missions out of 27 were prematurely aborted owing to electrical failures and one fully autonomous mission failed to achieve lock on the final stage light homing beacon, not because of visibility but from human error in the coding of the mission upload file; the command to initiate the homing beacon search behaviour had been accidentally omitted. Otherwise, this homing and autodocking approach has proven highly robust.

2.5 Sonde casts

The primary scientific objective of the Lake Bonney mission was to build a 3D aqueous chemistry map of WLB. Original design concepts for ENDURANCE had the vehicle raster scan the lake at various depths. This was eventually discarded on two counts: first, it would stir up the eons-old stratified layers below the chemocline and, second, it would burn up an inordinate amount of travel time. The first of these was specifically forbidden by the environmental review board and so an alternative approach was needed. The solution involved the development of a small instrument sonde that could be reeled out from the parent vehicle that hovered above the chemocline. The sonde and its associated servo-controlled spooler were known together as a 'profiler'.

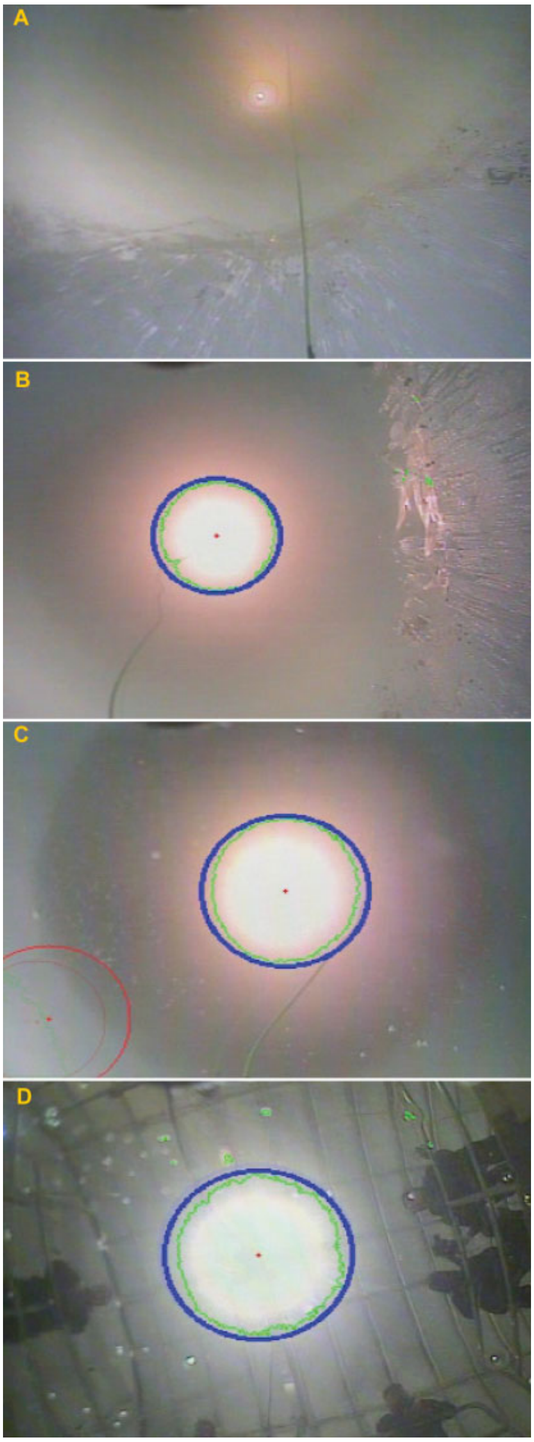


Fig. 5 Final-stage return-to-melt-hole navigation: (A) to (D) show machine vision frame captures of the autolocation and return system in action in WLB, Antarctica. The melt hole is 4 m deep and 1.75 m diameter, allowing horizontal manoeuvring room for ENDURANCE of less than 0.25 m. In (A) the robot has entered into a search pattern in the presumed vicinity of the melt hole; in (B) it detects an oscillating light; in (C) it locks on to the light and powers up through the centre of the melt hole, arriving on the surface in (D) to see the entire team standing around the melt hole; the mission was fully autonomous

With ENDURANCE now equipped with a profiler subpayload, a mission scenario was developed wherein the robot would descend through the melt hole in WLB and then cruise with the top of the vehicle hovering approximately 1 m below the ice cap. A georeferenced sampling grid was designated at 100 m centres over the entire surface of the lake (see the bright green dots in Fig. 6). A typical mission plan consisted of a sequence of grid points that were within the mobility range of the vehicle while leaving some reserve energy margin (about 20 per cent on early missions but gradually reduced to less than 10

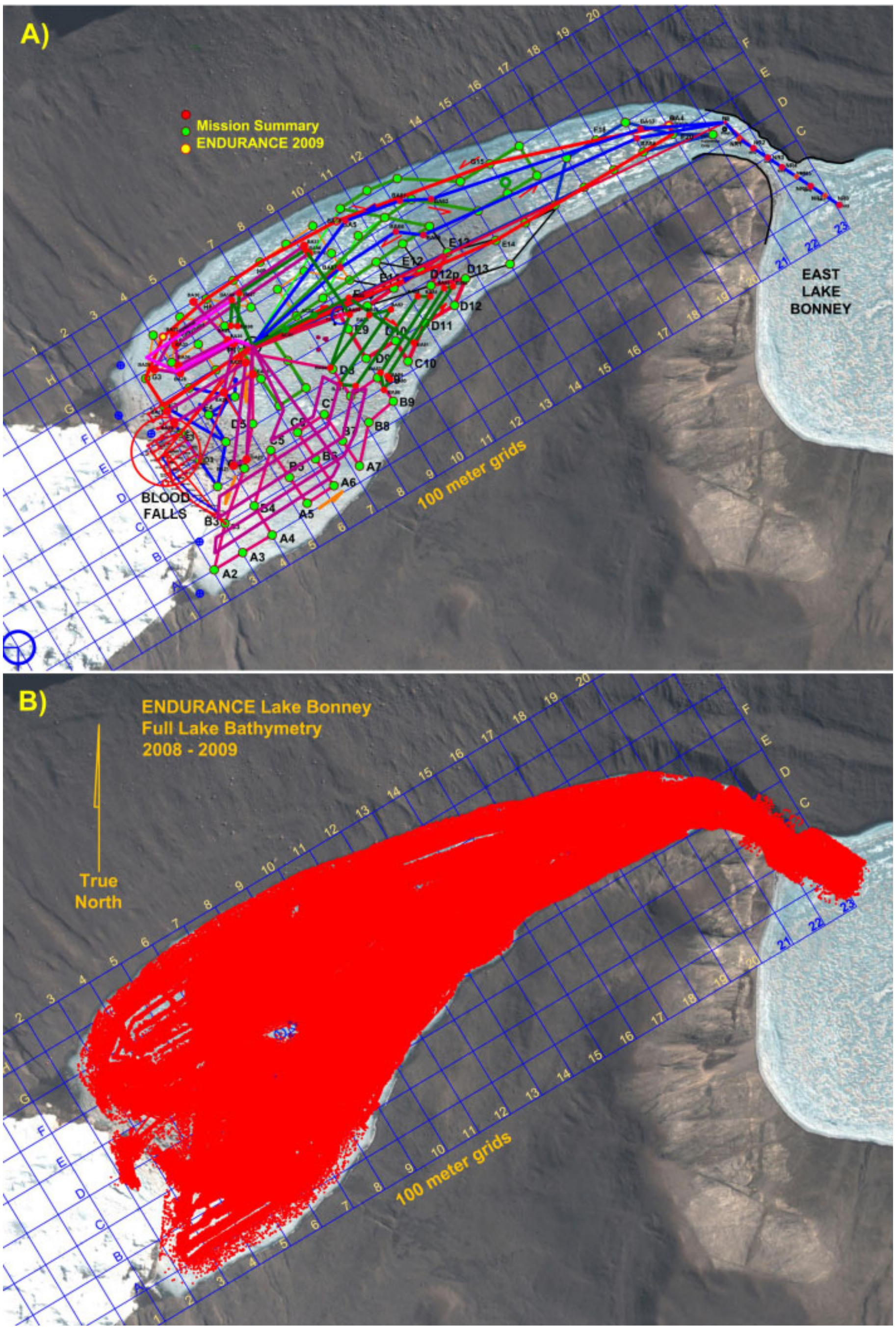


Fig. 6 ENDURANCE campaign overview at WLB. Whereas previous scientific investigations were limited to at most a few measurements from drill holes in the ice per year, ENDURANCE obtained full coverage of the entire lake lobe, including part of the east lobe. (A) Summary view of all sonde profiling, glacier face, and bathymetery mission trajectories for 2009. Green full circles indicate the sonde profiling stations. The area in the red circle is enlarged in Fig. 9. (B) Preliminary (uncorrected) bathymetry points recorded by ENDURANCE, showing that the bathymetry footprint covers the vast majority of the lake in high resolution. Some shallow areas were not completely ensonified owing to navigation constraints or unexpectedly low overlap between bathymetry swaths

per cent for the last missions as the team were able to quantify power consumption rates exactly) for emergency return to the melt hole. The robot was then programmed to manoeuvre successively to these points, to station keep at each location, and to rise to the ice roof where it would then 'ice pick' (rest quiescently on the underside of the ice pack based on buoyancy alone). It was determined that the vehicle's position could be more precisely maintained and less power consumed in ice-picking mode than when station keeping. Performance characteristics of powered station keeping versus passive ice picking are shown in Fig. 7. Once ice picked, the AUV was to reel out the sonde payload. The sonde was a cluster of nine aqueous water chemistry probes (probe depth, temperature, electrical conductivity, ambient light (photosynthetically active radiation), turbidity, chlorophyll-a, dissolved organic matter, pH, and redox) which gathered data in real time during both the descent and the ascent phases of each cast. A cast ended when the downward-looking sonde altimeter (a tight-beam single-point sonar) indicated a depth of 1 m above the lake bottom. At that point a video light was enabled and a high-resolution video camera stored a short video sequence of the bottom sediment. The sonde would then be retrieved, with the video and light being turned off at 2 m altitude on the ascent phase. Once the sonde docked with the parent vehicle, ENDURANCE would drop off the ice cap and cruise at 5–6 m depth to the next grid point. When all sonde points in a mission plan were acquired, the vehicle would then return home using the navigational architecture and melt hole proximity operations behaviour described above. See reference [**15**] for further information on the design of the profiler.

Because of the very limited visibility at WLB it was not possible to capture an actual sonde mission on video but several sonde mission tests were filmed at the Johnson Space Center Neutral Buoyancy Laboratory on 23 August 2008 during the dress rehearsal prior to shipping the vehicle to McMurdo Station. A typical sonde sequence is shown in Figs 8 (A) to (D). The sonde descends to a bottom stand-off distance of 1 m, as measured by a sonar altimeter on the sonde, stops at this location, takes a sequence of images, and then returns to the vehicle.

In 2008 and 2009, ENDURANCE performed 275 sonde drops beneath the ice cap at WLB (see Fig. 6 for a general summary of all missions to WLB in 2009; sonde cast locations appear as green full circles; see references [**12**] and [**15**] for 3D chemistry figures). Each cast included both bottom images and 3D lake chemistry data which are now being processed at the Electronics Visualization Laboratory at the University of Illinois at Chicago. While the XY spatial distribution of the sonde grid (Fig. 6) was $100\,\text{m} \times 100\,\text{m}$, the Z (depth) sampling was at 0.1 m spacing. The intricate profiler system worked reliably on a daily basis. The extent of the sonde casts was not limited to WLB; two missions in 2009 extended through the Bonney Riegel Narrows and 400 m out into ELB. These missions, conducted with a data fibre to allow real-time validation of the sonde casts through the narrows, were particularly complicated owing to the 'dog-leg' 90° channel leading from WLB to ELB (Fig. 6). A poly(vinyl chloride) pipe was temporarily sunk through the ice cap to serve as a fibre diverter for these runs. These two missions, run in the 2009 field campaign and separated by 3 weeks, were fully successful and produced temporal 3D chemistry maps through this area.

Another area of interest with regard to lake chemistry was in the vicinity of Blood Falls [**17**] where one of the sonde casts in 2009 showed the presence of a potentially very cold (less than 0 °C) water source entering the lake at 21 m depth somewhere along the glacier. The below-freezing temperature of the water indicated that this water was not fresh, but instead hypersaline and of particular scientific interest. A refined sonde grid mission (Fig. 9) was planned to localize the plume. This 9 h mission consisted of 39 casts at 25 m intervals leading south of Blood Falls. Figure 9 also provides a description of the typical navigational accuracy achieved during sonde casts. The data from the vicinity of BF35 showed water temperatures at −4 °C. Data collected in a series of sonde casts to the south of this grid detected −5 °C, the coldest recorded temperature in WLB.

2.6 Mapping underwater at Taylor Glacier

The primary mapping unit on ENDURANCE is a 480-point multi-beam sonar with a $120^\circ \times 3^\circ$ field of view. In the forward-looking orientation it creates a vertical imaging plane that can be swept across the face of a glacier by maintaining a uniform yaw angle and stand-off range. ENDURANCE is equipped with several independent sonar systems that enable proximity stand-off behaviour in unknown environments. ENDURANCE carried 300 W of high-intensity discharge (HID) lighting and a 6 megapixel digital video forward-looking camera contained within a dome port pressure housing. The camera contained a network interface that allowed real-time monitor-

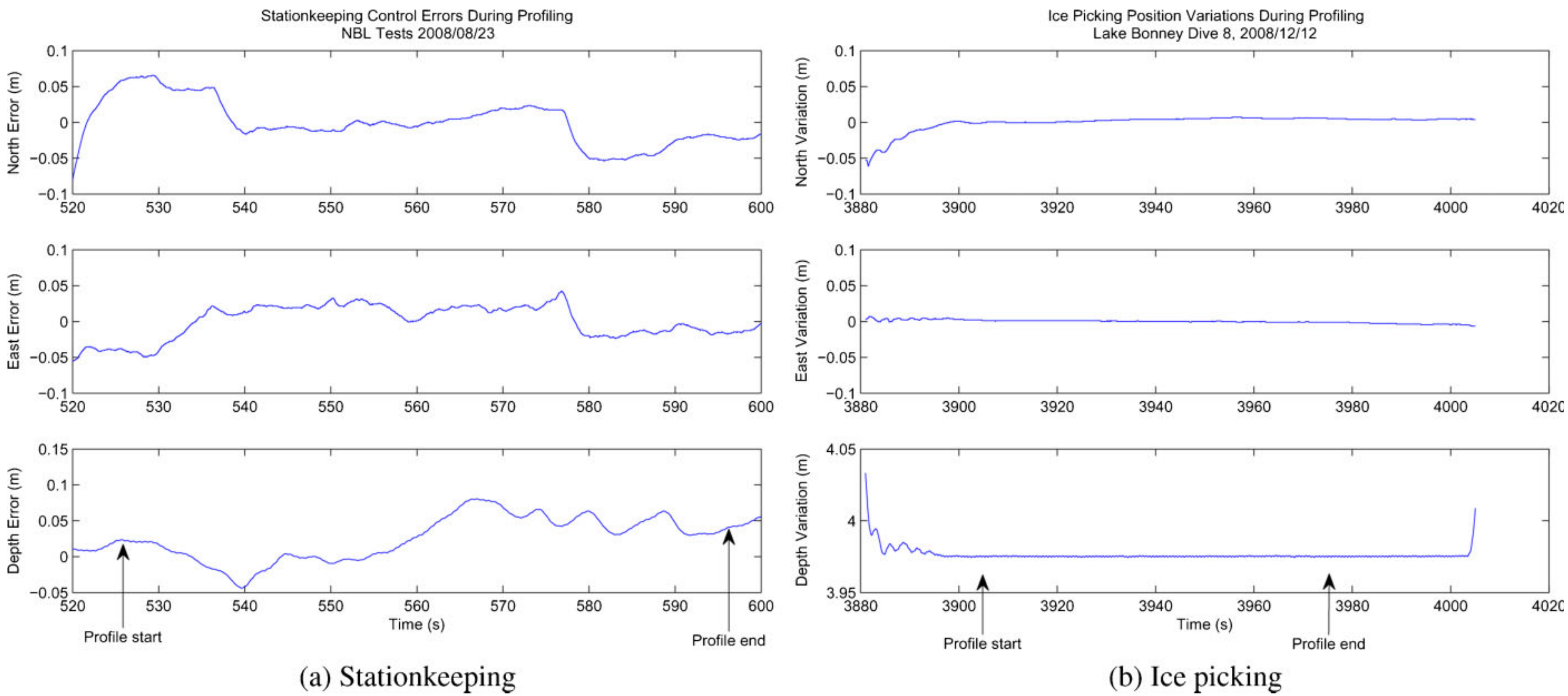


Fig. 7 Typical position-holding performance for ENDURANCE during the 2008 WLB missions: (a) active (powered) station keeping at a pre-programmed position in space; (b) 'ice-picking' behaviour; the vehicle was positively ballasted and, once it achieved a grid locus, it would shut down vertical thrusters while maintaining a horizontal position; once lateral motion was stabilized, the vehicle would shut down the horizontal thrusters as well and settle on the underside of the ice cap; special ice-picking contact posts were developed to minimize the potential for snags

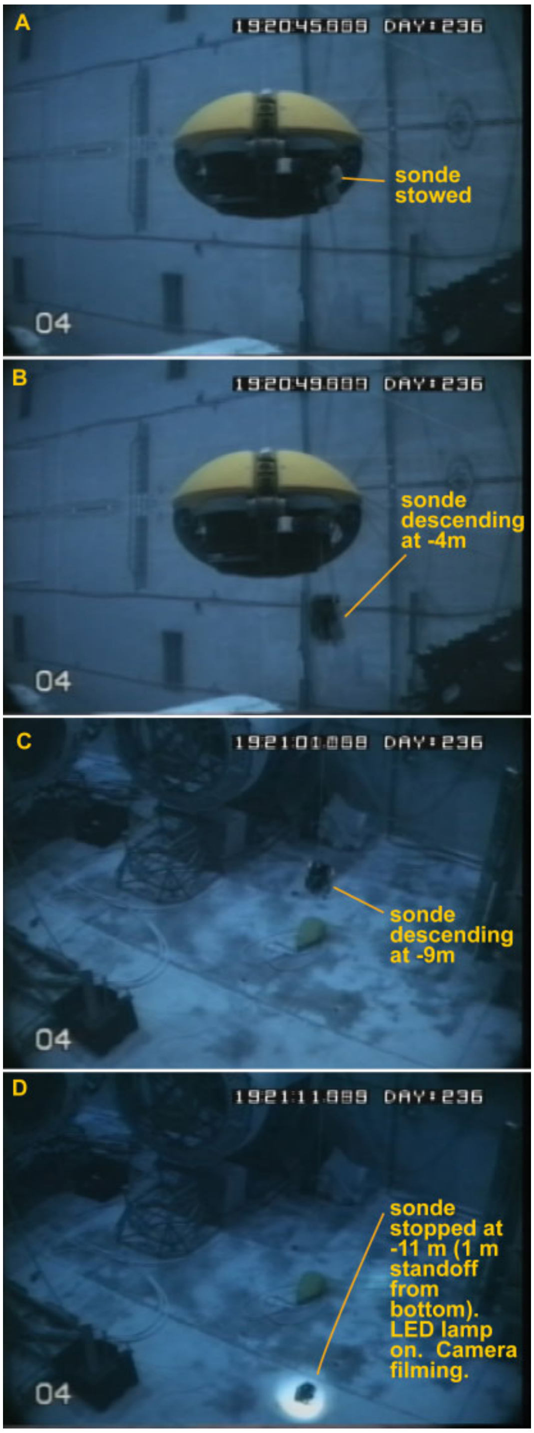


Fig. 8 ENDURANCE profiler (autodeployed sonde and servo-spooler) system in action at the Johnson Space Center: (A) the vehicle manoeuvres to the sonde grid point and hovers in 'station-keeping' mode (in actual practice in WLB it went into 'ice-picking' mode and floated up to the underside of the ice cap for energy conservation while the probe was deployed); (B) the sonde begins its descent; (C) the sonde at 8 m depth; (D) the sonde, at 1 m bottom altimeter stand-off, powers up its light and takes a few seconds of high-definition video before rewinding

ing of the image at Mission Control and also allowed remote software toggling of the HID lights.

Taylor Glacier enters the western edge of WLB and half of it lies above the chemocline interface and the rest below. All imaging in 2008 took place above the chemocline since no one (human or robot) had ever entered WLB and no maps were available upon which to base a subchemocline mission. The plan was to develop a full 3D map of the glacier above the chemocline in 2008 and then to return in 2009 to go underneath the glacier.

Glacier exploration began on 19 December 2008. Because of the anticipated arrival of glacier melt run-off due to the late season deployment in 2008 the sonde missions had been given top priority. The lake visibility (as observed at the melt hole) dropped suddenly on 19 December 2008 from approximately 2.5–3 m to less than 30 cm. Optical images of the underwater glacier [**12**] were only possible by manoeuvring the vehicle to a stand-off distance of well under 1 m, which is the distance under the minimum stand-off range required to achieve valid readings on many of the sonar instruments, most importantly the DVL. When the latter instrument dropped out, the dead-reckoning solution degraded to a pure IMU estimate. Similarly, iUSBL navigation was not working in this range (the glacier was more than 400 m from the melt hole and multi-path interference between the chemocline and the ice cap degraded that signal as well). Thus, an approach such as shown in Fig. 10 was a dangerous undertaking. The initial planning had assumed unlimited visibility and that low-resolution wide-field images could be obtained from 20 m stand-off and that high-resolution images for selected sections could be arranged using proximity operations sweeps at 5 m stand-off range. This proved not to be the case in both 2008 and 2009 and so the optical image data now available for underwater Taylor Glacier are both limited and clustered to a small area near the centre of the glacier where a safe approach could be made.

Exploration of the glacier using the multi-beam and obstacle avoidance sonar array was also complicated by the observation of large masses of ice that had calved off the glacier face on to the surface of the lake ice. Seen from the surface, these 'icebergs' were up to 5 m long and 2 m tall, generating concern that there would be an expression of these masses below the ice cap as well as above. The initial conservative operating assumption was that these icebergs would have 90 per cent of their mass underwater and would present significant entanglement threats to the vehicle. Three exploratory

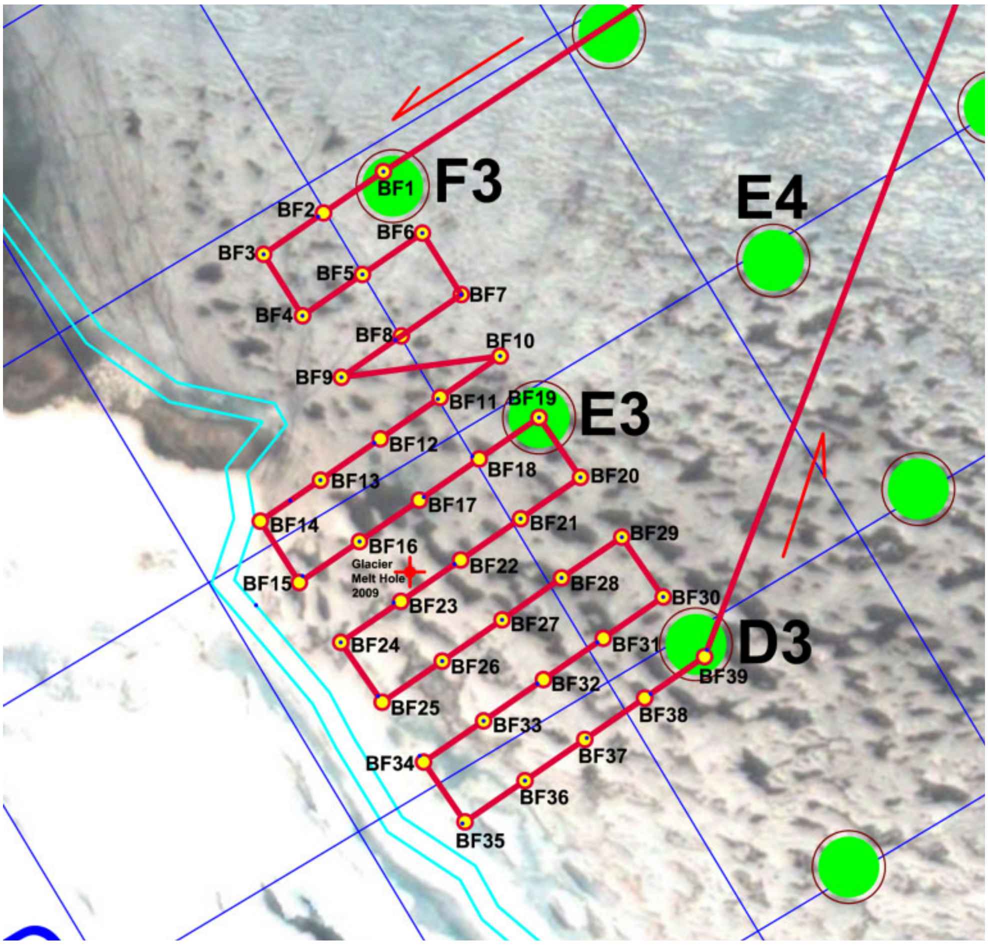


Fig. 9 The mission plan for 21 November 2009 showing a series of 39 fine-grid sonde cast waypoints near Taylor Glacier. The target trajectory is shown in red, with waypoints as yellow-filled red circles. The small blue dots represent the uncompensated real-time kinematic GPS true positions achieved by the AUV (these were obtained by tracking the AUV through the ice cap using a custom-designed localizer). The small red circles are 2.5 m in radius. Most of the blue dots are on target; those that are not are because the vehicle was using 'ice picking' for stabilization when making its chemistry measurements at each waypoint (vehicle position control was shut down for energy conservation at these locations). The underside of the ice was frequently not flat and the robot would slide up to 2 m or more on occasion before stabilizing. The blue dot between BF13 and BF14 was the achieved location of BF14; the glacier prevented a closer approach at that location. Conversely, an auxiliary station was set beyond BF15 since it was possible to approach closer to the glacier at that location. The trajectory shown here represented a 9 h underwater mission time

missions that consisted of a series of radial (straight line from the melt hole) approaches punctuated by slow vehicle $\pm 90^{\circ}$ yaw rotations every 20 m were executed to fill in gradually the unknown geometry of both the glacier and the underside of the icebergs. During the course of these three missions in 2008 it became clear that, while there were significant surface expressions of the icebergs, the under-ice effect apparently was to depress the ice sheet slightly while still maintaining a relatively smooth roof. This opened the way for a full-glacier high-resolution sweep mission on 23 December 2008. The results of all glacier missions are shown in reference [**12**] as a frontal plan view. A more revealing isometric view from 2009 is shown in Fig. 10(A). This is a screen capture from the vehicle situational awareness system, which plots the vehicle in 3D to scale within the context of the map data. In both Fig. 10(A) and Fig. 10(B) it can be clearly seen that the glacier interface to WLB above the chemocline has a pronounced concavity, forming a lip at the 16 m depth level. In 2009 an auxiliary melt hole was

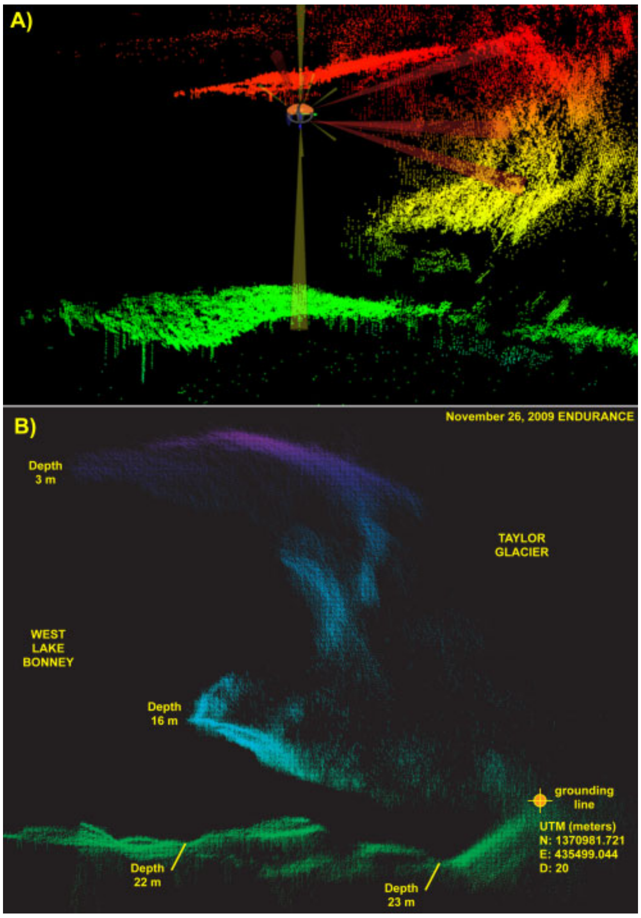


Fig. 10 Results from a typical mission to the underwater face of Taylor Glacier, WLB, in 2009. (A) The bright red points show the underside of the ice cap and the beginning of the top of the glacier. The ice cap thinned as it approached the glacier. The shadows between the green and yellow points highlight the unknown region beneath the glacier as seen in the multi-beam data from above the chemocline at -16 m. (B) With the vehicle reballasted to be neutral beneath the chemocline, at a depth of 20 m, it was possible to explore underneath the glacier and to image the grounding line between the base of the glacier and the moraine–lake bottom. This image shows 3D multi-beam data for a section of the glacier grounding line 10 m wide, looking south. Green represents lake floor sediment; blue is the Taylor Glacier

created immediately adjacent to the glacier and a special environmental waiver was granted to ballast the vehicle to work below the chemocline in the vicinity of the glacier. Figure 10(B) shows the imaging results for the subchemocline missions for a single segment 10 m wide along the glacier front. This shows a gap 40 m deep under the glacier to where the moraine deposits meet the glacier ice at the grounding line. This section is typical of the morphology of the central portion of the glacier where it empties into WLB.

2.7 Bathymetric mapping of WLB

In 2008, owing to a late start in the NSF Antarctic season that year, there was insufficient time to conduct a complete bathymetric mapping programme at WLB. However, in an effort to begin the process and to learn the true lake floor geometry, the ENDURANCE multi-beam imaging system was remounted into a downward-looking configuration such that the 120° swath fan was perpendicular to the motion of the vehicle. In the current ENDURANCE motion control protocol the vehicle establishes the target depth on the trajectory sequence, performs a yaw rotation to align the vehicle 'bow' (there is no preferred yaw angle for forward motion since the vehicle is axisymmetric so that the 'bow' can be designated in software – a very useful tool which allows point-of-view instrumentation to be mounted anywhere on the vehicle) and the vehicle moves along the programmed trajectory to the target point. Since a significant portion of the lake was being traversed to obtain the sonde casts, the team took advantage of this to obtain auxiliary bathymetry data on the same missions. In this configuration, extensive bathymetric data for WLB were obtained for each of the sonde missions (a total of approximately 400×10^6 bottom hits were logged in 2008). Furthermore, because all sonde drops were GPS registered, any navigational error build-up was confined to the distance between sonde grid points.

In 2009 a number of oddly shaped gaps in the bathymetry data for the western two thirds of WLB and a complete lack of data in the eastern third remained owing to vehicle on-board power limitations in 2008. After completing the sonde casts in 2009 (which repeated the measurements obtained in 2008 and thus created a temporal comparison data set between 2008 and 2009, and then extended those into eastern WLB using newly improved on-board power systems), targeted missions were designed to fill in the holes in the bathymetry data. Importantly, almost no coverage existed within 80 m of shore around the entire lake, because the vehicle required a minimum under-keel draft for safety. After working for some time in the vicinity of the glacier in 2009 it was observed that the sideward-looking multi-beam system could be tuned to image directly to shore with little beam distortion from as far away as 80 m. The lack of distortion came from the fact that the chemocline interface was non-existent above 16 m depth and the robot was working in pure fresh water at the lake edges. Within three dedicated missions the entire lake shore was mapped in 2009 at high density. Three further missions filled in the remaining central lake gaps. The overall vehicle trajectories, sonde drop locations, glacier exploration, and bathymetry, are shown in Fig. 6(A). Figure 6(B) shows the resulting bathymetric coverage, not including sideward-looking data from the glacier explorations in 2009 which fill in the gaps on the western edge adjacent to the glacier. A total of more than 500×10^6 measurements are shown in Fig. 6(B). Work is currently under way to correct these data for refraction, accounting for instrument alignment, density, temperature and conductivity stratification effects, and sonde position calibrations. The resulting database will be stored online within the NSF's Long Term Environmental Research database for the Dry Valleys.

Finally, with regards to bathymetry, the two missions to Bonney Riegel Narrows were of some historical interest. In 1903, Captain Robert Falcon Scott's party first passed through the Bonney Riegel Narrows. In addition to taking several black-and-white photographs they also measured the width of the narrowest portion of the ice at that location. This was a crucial measurement from which, together with the high-resolution multi-beam measurements acquired by ENDURANCE, it became possible to demonstrate that the water level in Lake Bonney had risen by more than 16 m since Scott's team was there. See Fig. 11 for the multi-beam cross-section at this location.

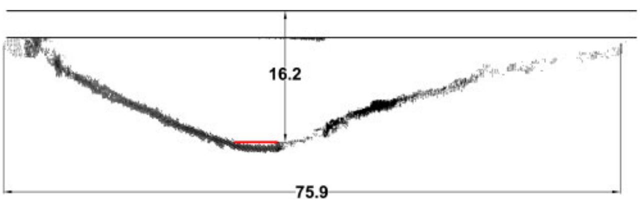


Fig. 11 Lake Bonney water levels: 1903 versus 2009. This computer-generated plot shows a slice through the 3D sonar data acquired by ENDURANCE as it navigated through the Narrows. Captain Robert Falcon Scott's party, whose ice width measurement is plotted to scale here in red, almost certainly stood at this location in 1903. The top horizontal line represents the surface ice cap level today; the second lower horizontal line represents the measured underside of the ice cap today

3 CONCLUSIONS

ENDURANCE was the first entity (human or robot) to enter the sub-ice world of WLB. Prior to the WLB 2008 mission there was considerable concern regarding whether the vehicle would be able to navigate under the ice cap, given that the vehicle would be sandwiched just below the ice and in a freshwater lens that was perched on top of a hypersaline chemocline beginning at a depth of 16 m and continuing to the lake floor at a depth of 40 m. The presumption was that the acoustic navigation sonars would either bounce between the layers or be so severely refracted as to produce large navigation errors. Neither of these proved to be true, although it did take some experimentation with the iUSBL transponder beacon to obtain a workable solution, which ultimately saw the beacon essentially floating on the chemocline as the best configuration for long-range reception (there was still substantial noise in the signal as shown in Fig. 3(B) and therefore the problem of signal bounce is significant at Lake Bonney). Ultimately ENDURANCE was able to achieve less than 0.13 per cent of distance travelled navigation error from the dead-reckoning navigation system using bottom lock configuration for the DVL in 2008. In 2009, some missions achieved errors of 0.04 per cent or less of distance travelled on missions that now extended to 4.4 km in traverse distance. Detailed results on the performance of this and the iUSBL navigation system have been provided in reference [**14**]. The machine vision homing algorithm worked spectacularly for all but two missions in 2008 where the water visibility precluded acquisition of the overhead light beam from the cruising depth of the vehicle and on three missions in 2009, two of which involved electronics failures in midmission and the last involved a mission programming error. See reference [**13**] for further details on this navigation system.

The automated sonde water chemistry profiler system also worked flawlessly following some minor pre-deployment glitches in the servo motors and was used for 275 successful casts that were utilized to build isosurface 3D chemistry maps of the lake. Further details on the profiler are available from reference [**15**].

Although ENDURANCE is fully autonomous and its operations were automated, the team found it extremely useful to be able to 'look over its shoulder' as it conducted its missions (an operations mode referred to as 'supervised autonomy'). On two occasions in 2008 this proved essential to rescuing the vehicle: once when it 'discovered' an unknown legacy instrument cable that was suspended in the lake and wrapped the fibre, and once when the vehicle obstacle avoidance stand-off routine was overridden in order to obtain photographs of the glacier. In the first case it was possible to program a series of manoeuvres that first detected the location of the hanging cable and thence allowed the vehicle to manoeuvre around it and to return home; in the second case the navigation solution was lost when the DVL stand-off range dropped below the no-return distance (1 m) at a location outside iUSBL reception. It was possible to manoeuvre the vehicle manually to a known GPS point under the surface using a magnetic beacon localizer, to uplink those coordinates to the vehicle, and to reboot the navigation solution. The data fibre (a single-mode tactical fibre-optic thread 2.2 km long) was fed and retrieved by a fibre tender from Mission Control. The ice cap at Lake Bonney forms by freezing from underneath (it ablates rapidly on the surface side from sunlight) and thus the underside of the ice sheet turned out to be surprisingly smooth. This allowed work with a floating fibre to be carried out safely at distances in excess of 2 km from the melt hole. Most of the final missions in 2009 were fully autonomous, with no data link from Mission Control.

A total of 19 sub-ice sorties were logged by ENDURANCE during the WLB 2008 mission and 27 sub-ice sorties during the WLB 2009 mission. The vehicle spent 243 h below the WLB ice cap and traversed 74 km of lake bed and glacier face in the performance of drop sonde, lake-mapping, and glacier-mapping objectives. A total of 275 drop sonde casts were successfully completed with no cable snags, spool-out errors, or reel-up errors. The long missions through the Bonney Riegel Narrows were, prior to the 2009 season, considered infeasible. A power systems upgrade in the summer of 2009 combined with extensive vehicle hydrodynamics testing changed that (essentially quadrupling the range of the vehicle) and allowed two missions to proceed through the dog-leg pass and out into ELB, mapping, in the process, the site where Captain Robert Falcon Scott's party took their bathymetric measurements in 1903.

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