SUB-ICE EXPLORATION OF WEST LAKE BONNEY: ENDURANCE 2008 MISSION

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ABSTRACT

ENDURANCE (Environmentally Non-Disturbing Under-ice Robotic Antarctic Explorer) is a highly maneuverable, hovering autonomous underwater science platform descended from the DEPTHX vehicle, both of which were developed under NASA ASTEP funding. ENDURANCE had the specific mission of descending through a 5 meter deep melt hole in the ice cap of West Lake Bonney, Taylor Valley, Antarctica and conducting three autonomous science tasks: 1) measuring the 3D water chemistry of the lake; 2) mapping the underwater face of Taylor Glacier where it enters the lake; 3) charting the bathymetry of the lake bottom; and then 4) returning safely on its own to the melt hole – barely 0.25 m larger in diameter than the vehicle – from more than 700 m radial range and rising up the hole to be retrieved for data download and servicing for the next mission. Many features of ENDURANCE represented signficant changes and improvements over its highly successful predecessor craft. Included among these was the development of an automated sub-sea servo winch and sonde payload with nine water chemistry probes, high definition imaging system, and bottom ranging altimeter. A specialized ice-picking behavior was developed to maximize cast initial proximity to the underside of the ice sheet and to reduce power consumption during casts. The navigation system was comprised of a three layer filter utilizing high grade dead reckoning, ultrashort baseline localization, and machine vision. Also new were web-based glacier imaging systems and a 120-degree swath high resolution multi-beam mapping sonar system – used for both lake bottom and glacier face mapping. All of these systems, following several days of initial shakedown in the -4C water, worked flawlessly for the duration of the expedition, producing 108 sonde casts spread over 80% of the lake area (2.5 km length x 1.25 km width x 40 m depth); greater than 100 million 3D sonar hits across the Taylor glacier; and more than 400 million bathymetric 3D hits on the lake bottom. A total of 95 hours of operation beneath the ice were logged along with 19 kilometers of cumulative traversed distance under the ice cap. The vehicle successfully demonstrated autonomous melt hole location, position lock and auto recovery on a routine, daily

basis. A custom magnetic beacon tracking system was developed that enabled real-time surface position fixes to be established on the vehicle – a powerful new feature that allowed for precisely geo-referencing all water chemistry samples. 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, Enceladas, and other outer planet watery moons.

1.0 Introduction:

The ENDURANCE (Environmentally Non-Disturbing Under-Ice Robotic Antarctic Explorer) Project was funded by the NASA ASTEP program in order to test fundamental concepts relating to autonomous under-ice science and exploration that will be relevant to future lander missions to the outer planet watery moons such as Europa and Enceladus. The project was further supported by the NSF Office of Polar Programs which arranged access for the robot, its development team, and the science team to Antarctica in the austral summer of 2008.

ENDURANCE is an axi-symmetric 4 degree-of-freedom autonomous underwater vehicle (AUV) descended from the DEPTHX architecture that was developed as a SLAM (simultaneous localization and mapping) testbed [2-10]. ENDURANCE is unusual in the world of autonomous undersea devices in that it can actively control precise motion in all 4 degrees of freedom (X,Y, Z, and yaw). The vehicle was designed and developed at Stone Aerospace (www.stoneaerospace.com) in Austin, Texas. It is ellipsoidal with a major axis of 2.13 m, a minor axis of 1.52 m and a mass of 1.35 metric tonnes.

During November and December 2008 ENDURANCE was fielded to West Lake Bonney (WLB) in Taylor Valley, Antarctica [1, 11-13]. The scientific purpose of this mission was to:

• Characterize the aqueous chemistry of the lake in full 3D via automated sub-ice sonde casts

• Create a high resolution 3D map of the underwater interface between Taylor glacier and West Lake Bonney and, if possible, to image the glacier face.

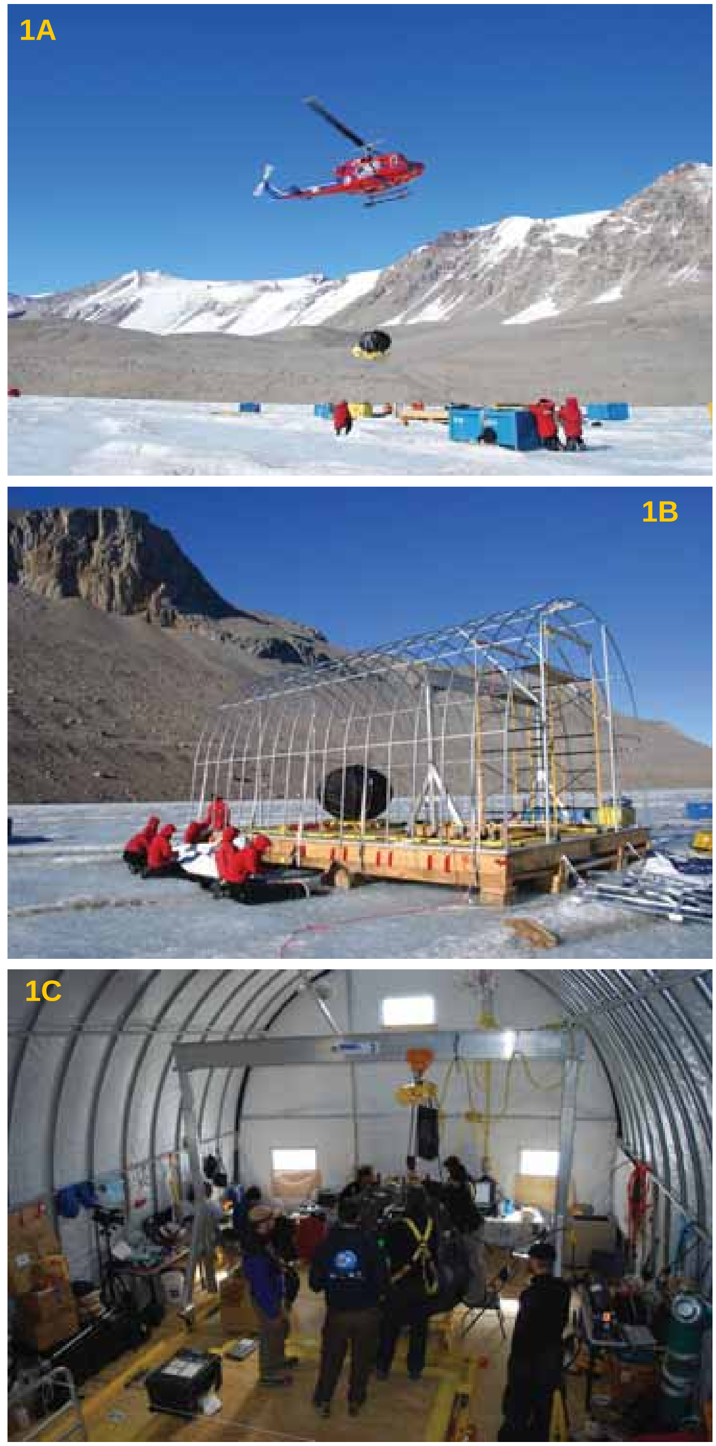


Figure 1: 2008 Ops: The “Bot” and the “Bot House” come together at WLB. The vehicle weighs 1,350 kg and had to be transported in two separate helo loads. A custom structural segmental platform with a moon pool, a large Weather Haven, and a rail-guided gantry are necessary to launch the bot.

• Create a high resolution bathymetric map of the lake floor

• Do all of this when deployed down a 5 meter-deep melt hole in the ice cap barely larger in diameter than the vehicle, to ranges as far as 500 m or more in radius from the melt hole and return home safely following each mission.

The expectation from the science community prior to departure was that the datasets that would result from this project, if successfully obtained, would be unique and would presage a new paradigm in which an entire sub-glacial body of water could be characterized in 3D and used as a large-scale temporal sensor of environmental change.

During the course of the expedition we learned a great deal about how to operate this new, unique programmable sub-ice autonomous science platform in the target environment. We will first discuss the field logistics of working at Lake Bonney with an AUV and will then discuss the specific results for the three main science objectives in 2008.

2.0 ENDURANCE 2008: Field Summary

Logistics in 2008 were driven by the size and mass of the ENDURANCE vehicle. Figure 1 shows details of setting up at West Lake Bonney. Two separate helo sling loads were required to transport the bot and seven more to transport the "bot house", which included a segmental 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 the melt hole. It took 7 days from the first helo drop on the lake to achieve operational status.

Once up and running, the bot was programmed for one of the three mission classes (profiling, wall mapping, bathymetry) and following navigation sys-

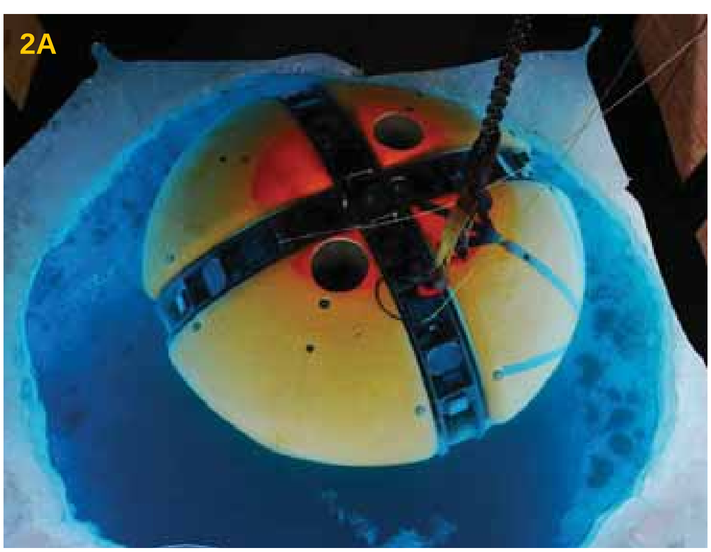


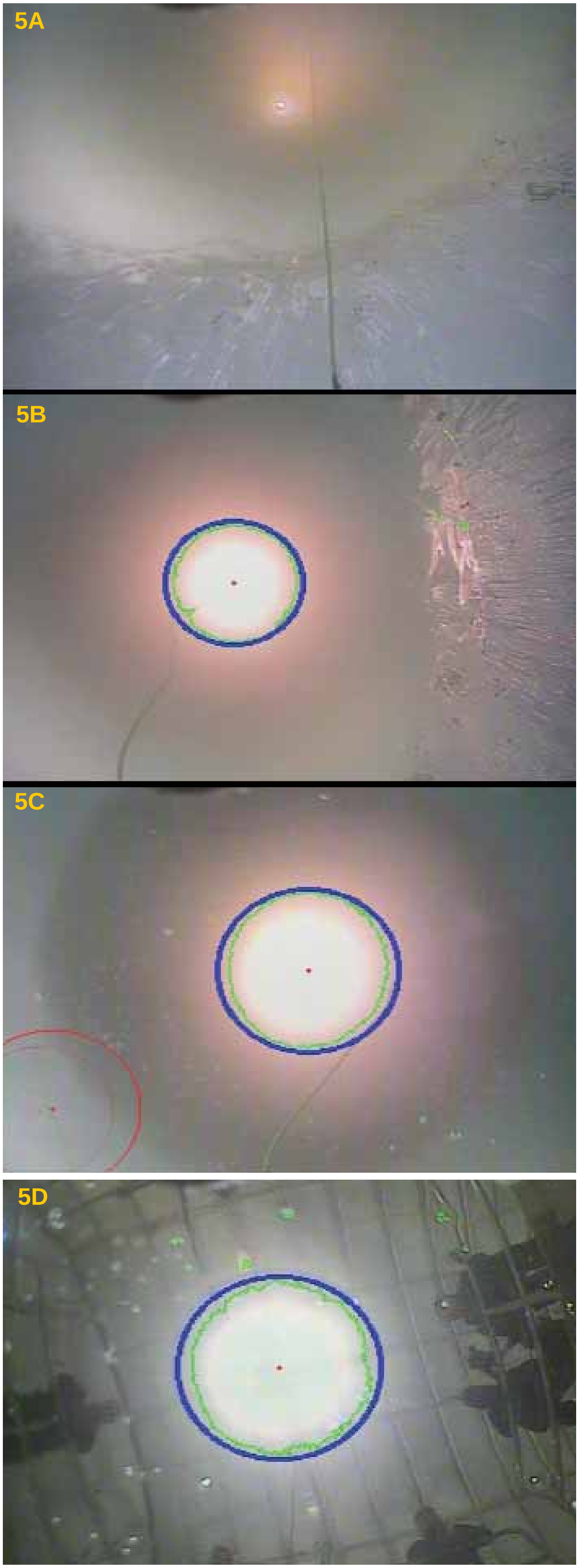
Figure 2: Mission Operations: 2A) launching the bot down the melt hole; 2B) mission control; 2C) data fiber tending

Figure 3: Primary navigation sensors: 3A) IMU/RLG ; 3B) resonant oscillator depth sensors; 3C) iUSBL

Figure 4: Emergency Recovery Beacon: 4A) onboard magnetic field generator; 4B) surface tracker in use on WLB

tem initialization and instrument calibration it was launched down the melt hole (Figure 2A) on missions that lasted as much as 8 hours in duration (see Table 1 for a summary of all sub-ice missions in 2008 at WLB).   Although the vehicle is autonomous we found it extremely advantageous to have it trail a 0.9 mm reinforced fiber optic thread behind it (Figure 2C). This allowed Mission Control (Figure 2B) to monitor not only the status of all systems in the vehicle, but also to visualize what it was seeing in 3D geometry as well as live images from three separate color cameras.   In the actual operations under the ice this supervisory capability proved crucial on several occasions to preventing the loss of the vehicle.

In order to collect science data the robot had to be able to successfully navigate beneath the ice and find its



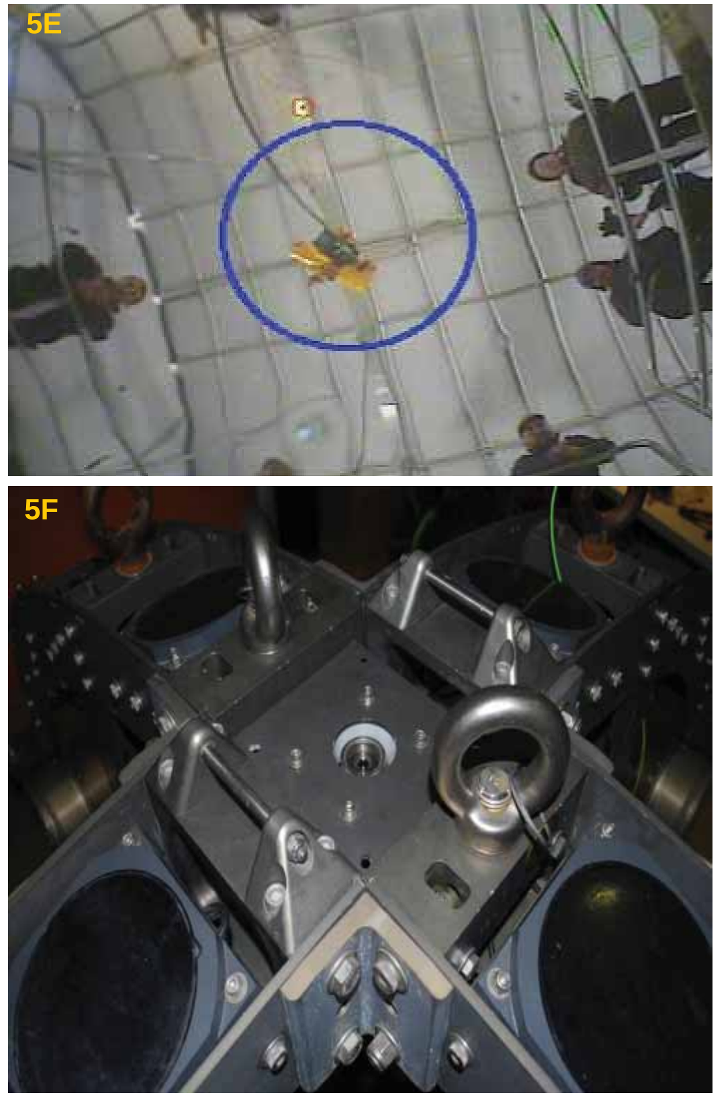


Figure 5: Final Stage Return-to-Melthole Navigation: 5A through 5E) machine vision frame captures of the auto location and return system in action on Mission 5; 5F) the zenith-pointing machine vision camera.

way back to and rise up through the melt hole at the conclusion of every mission, frequently from distances of more than 700 m from the melt hole. We developed four separate systems to improve the probability of success. The dead reckoning system consisted of a ring-laser gyro IMU (Figure 3A), a pair of fine resolution depth sensors (Figure 3B), and a doppler velocity log (Figure 9). Through significant refinement between June of 2007 and November of 2008 we were able to reduce total dead reckoning 50% circular error probable (CEP) return error to 0.1% of distance traveled during under-ice operations. To this sensor suite we added an inverted ultra-short baseline (Figure 3C) iUSBL system, which allowed the vehicle to determine a range and heading vector back to a beacon that was suspended directly below the melt hole and just

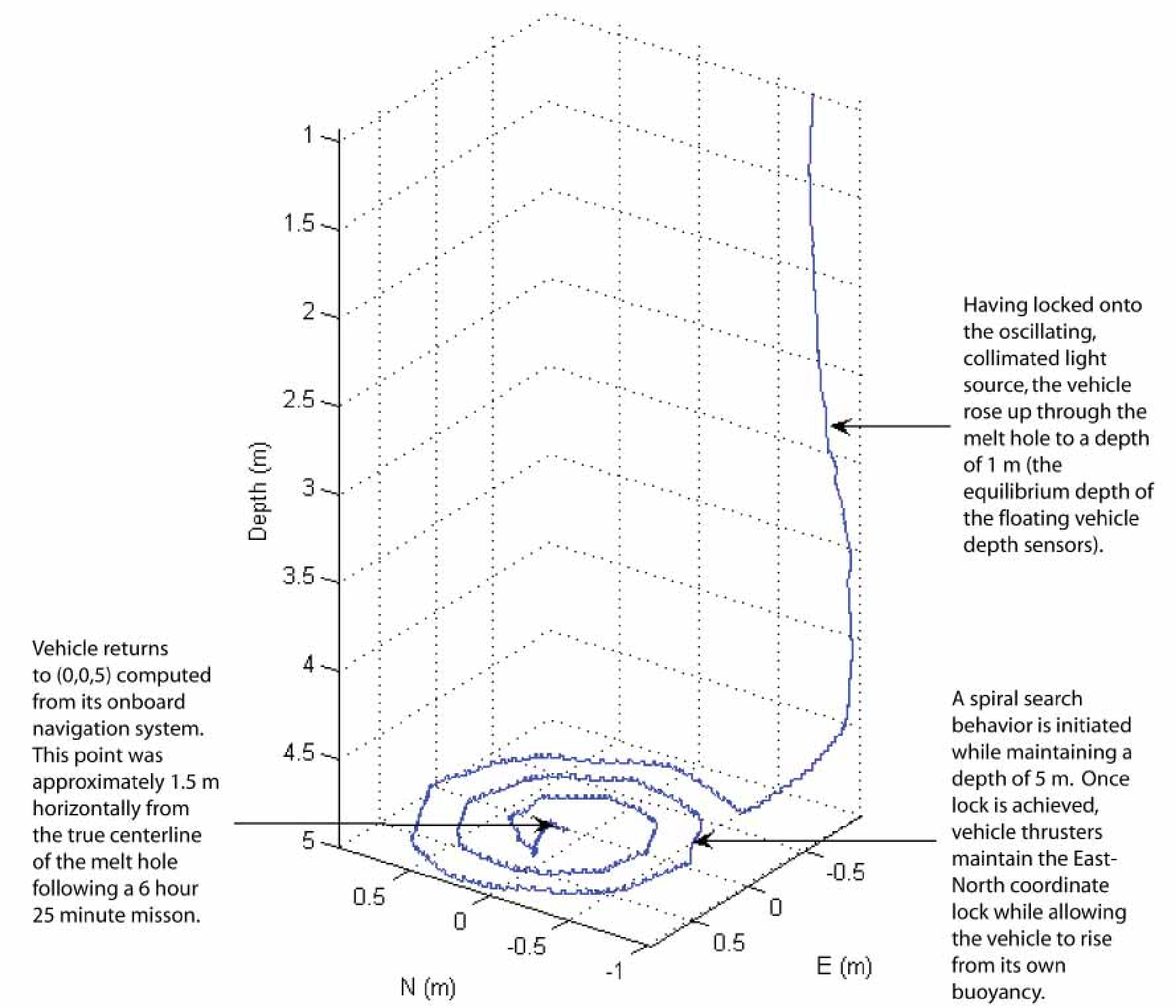
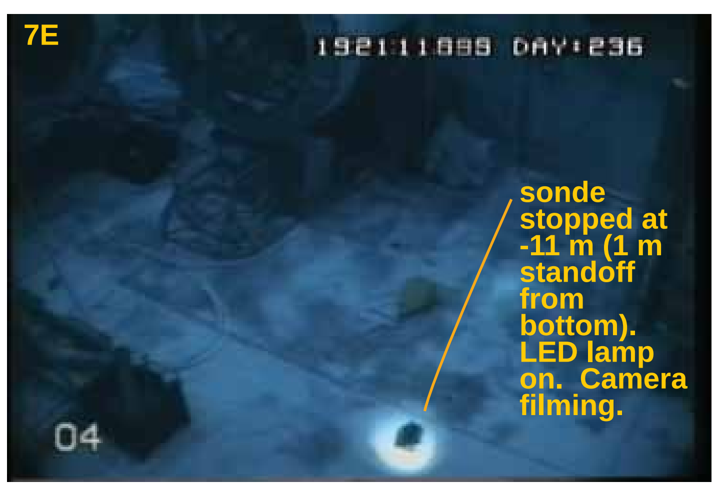


Figure 6: MatLab 3D plot of the auto-return-to-melt-hole system system in action during Mission 5. Coordinates are vehicle-centric (where the vehicle believes it is located relative to its initial starting position, including error) while the overhead collimated light oscillator represents the true centerline of the melt hole.

above the chemocline (the vehicle operated predominantly at a depth of 6 m, just below the ice cap and just above the chemocline at 14 m depth). These two measurements were weighted and a final position estimation made.

A custom-designed magnetic field generator was developed for ENDURANCE (Figure 4A) for use in locating and recovering the vehicle in the event of a total power failure during a mission. This was field-tested in Wisconsin in February of 2008. An observation was made then that it might be possible to track the vehicle in real-time under the ice. At WLB this idea was turned into industrial practice (Figure 4B). With this capability we not only knew where the vehicle was at all times, we were further able to precisely mark the position of a sonde drop. The surface fix was then recorded with cm-level GPS in order to permanently geo-reference the data set. Under typical weather conditions at WLB the surface horizontal detection range from the receiver to the vehicle was between 300 to 500 meters radius. This capability was also used on two occassions to re-initialize the guidance fix on the robot during a mission. Due to poor visibility in the lake, yet faced with a desire on the part of the science team to attempt to image the the underwater Taylor glacier where it intersects West Lake Bonney, we allowed the vehicle to effectively go to zero standoff distance from the glacier on two occassions. As expected, the dead-reckoning navigation solution eventually dropped out because of loss of doppler velocity lock (we were also beyond iUSBL

Figure 7: ENDURANCE Profiler (auto-deployed sonde and servo-spooler) System: 7A) the Profiler science payload showing deployed sonde; 7B through 7E) The Profiler in action at Johnson Space Center; 7B) the vehicle maneuvers 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; 7C) the sonde begins its descent; 7D) the sonde at 8 m depth; 7E) the sonde, at 1 m bottom altimeter standoff, powers up its light and takes a few seconds of high def video before rewinding.



range). Although we were able to move the vehicle safely back from the glacier and re-acquire velocity (using the onboard video cameras and a joystick control override for guidance), the navigation solution was compromised. To resolve the problem the beacon team vectored the robot back to a known GPS fix location in real-time and the fix was uplinked via the fiber optic thread. Both missions resumed and completed normally. The point here is that a robust method has been developed for dealing with an under-ice emergency that otherwise would have led to a loss of the bot. See reference [12] for further detail on the general navigation system for ENDURANCE.

During the longest missions (1700 to 1900 meters traverse) the cumulative navigation error resulted in the vehicle being within 2 meters from melt hole centerline 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 VGA video camera (Figure 5F) to search for the presence of an oscillating, collimated light source. The algorithm segments the video frame into candidate intensity sources (green boundaries in Figure 5) and then

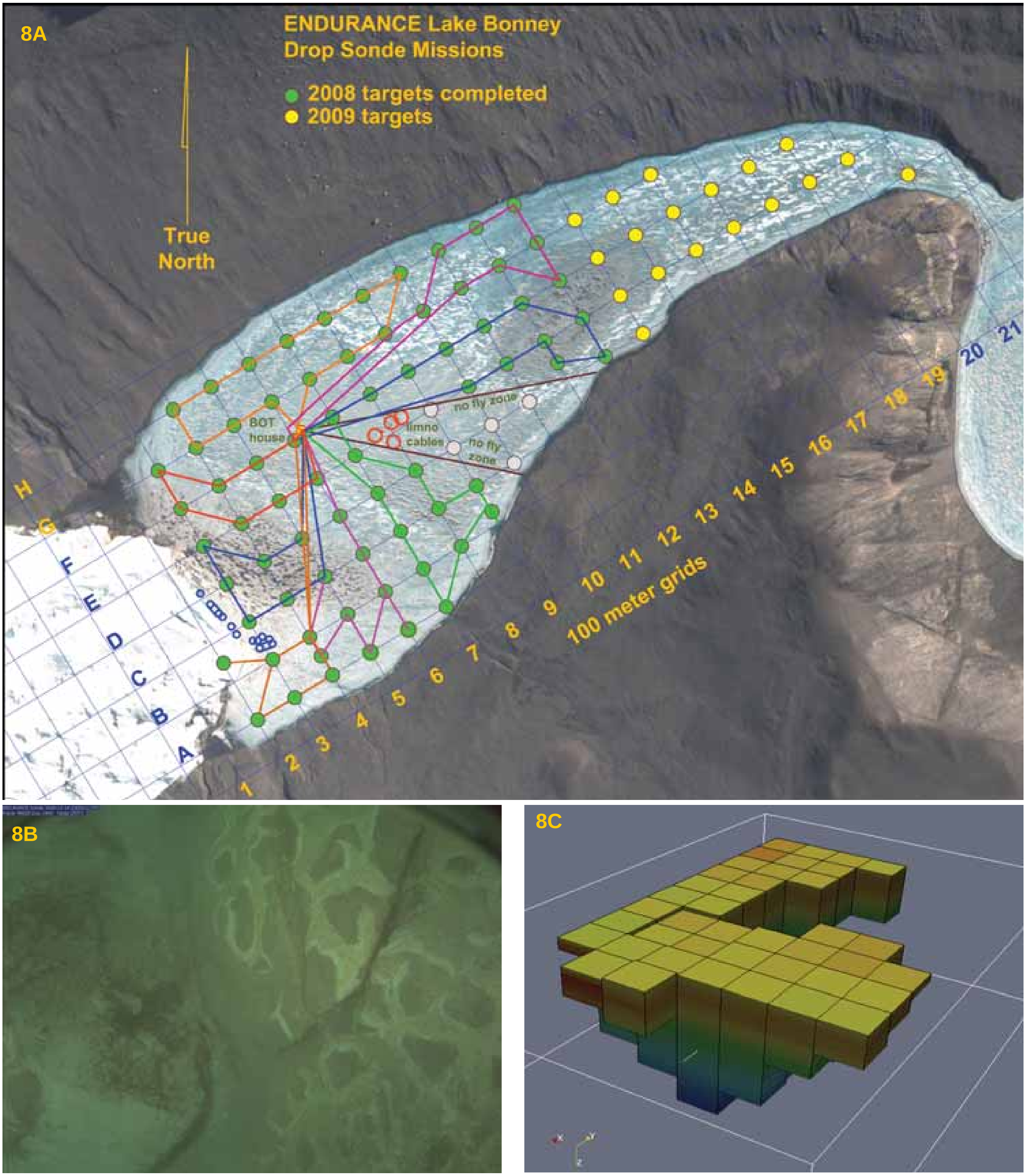


Figure 8: Production Sonde Missions at WLB: 8A) Green circles mark the locations of successful sonde drops during the 2008 season. Because of logistics and time limitations a decision was made to carry out all science missions in 2008 from a single melt hole. Red circles mark hanging cables from legacy instrumentation - an additional hazard to vehicle operations that had to be avoided. The vehicle power supplies were pushed to the limit to obtain the eastern-most 14 sonde drops; 8B) bottom bio-mats from a typical shallow depth sonde video bottom capture (in this case for station H6); 8C) preliminary 3D temperature distribution for WLB.

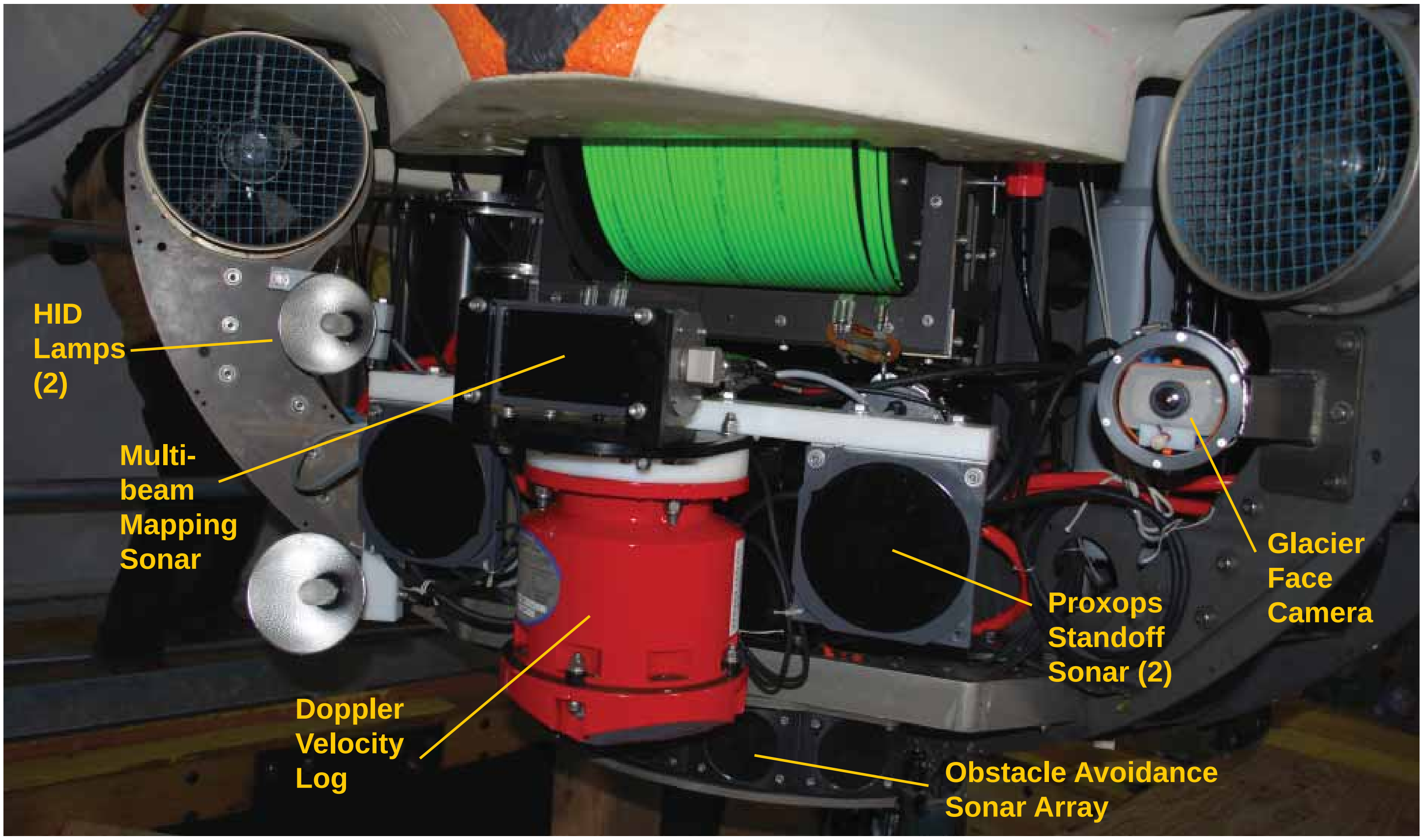
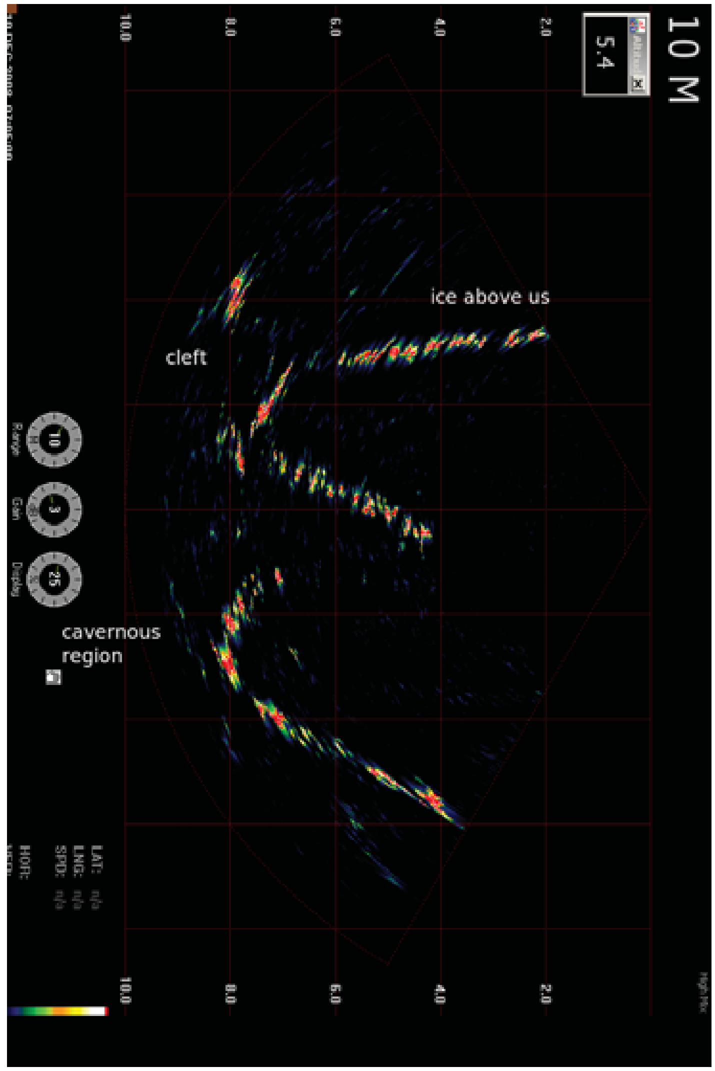


Figure 9: Glacier mapping and imaging array

analyzes the frequency spectra. If it finds one that matches the pre-set frequency of the overhead beam (blue perimeter in Figure 5) it locks onto 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 Figure 5 is taken from Mission 5 live video and shows (5A) the vehicle crossing the melt hole edge and the first appearance (but not detection) of the light source; (5B) positive lock is acquired on the light source; (5C) the bot is rising up the hole; (5D) first breaking surface; and (5E) the entire crew watches as it surfaces, with no human at the wheel. The same sequence is shown from the viewpoint of the vehicle 3D trajectory in Figure 6. During the course of 19 sub-ice missions to WLB in 2008, there were only two failures of the machine vision system to automatically bring the bot up the hole. These were the last two missions. During the final week of the project the water visibility degraded rapidly from glacial runoff to the point where the bot could not see the light from the bottom of the melt hole (see Figure 10B). In both cases, we used the magnetic beacons to vector the vehicle to centerline. See reference [11] for further details.

2.1 Sonde Casts: These were the primary science objective of the 2008 season. A mission scenario was developed wherein the robot would descend through the melt hole in the ice cap of West Lake Bonney (approximately 0.25 m larger in diameter than the vehicle) and then cruise with the top of the vehicle hovering approximately 1 meter below the ice cap. A geo-referenced sampling grid was designated at 100 meter centers over the entire surface of the lake [see Figure 8]. 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% on early missions but gradually reduced to less than 10% for the last missions as we came to exactly quantify power consumption rates) for emergency return to the melt hole. The robot was then programmed to maneuver successively to these points, station-keep at each location, rise to the ice roof where it would then "ice pick" (rest quiescently on the underside of the ice pack based on buoyancy alone) to conserve energy, and then subsequently reel out the sonde payload. The sonde was a cluster of 9 aqueous water chemistry probes which gathered data in real-time during both the descent and ascent phases of each cast. A cast ended when the down-looking



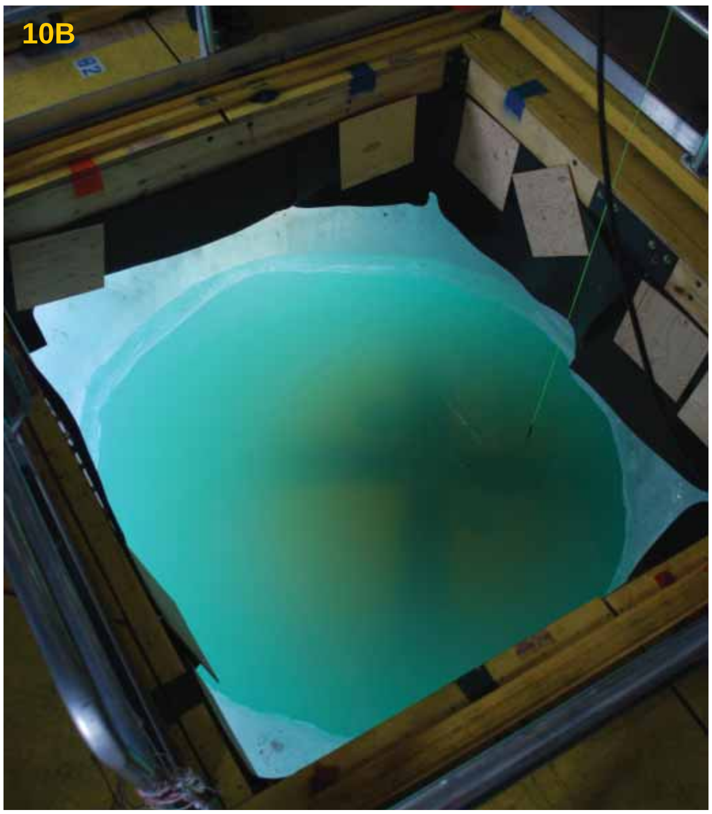


Figure 10: Glacier Mapping Part 2: 10A) the guts of the glacier face imager; 10B) WLB visibility as of December 20, 2008 - compare to Figure 2A; 10C) image frame of underwater Taylor glacier taken from a standoff distance of less than 1 meter. Closer approaches resulted in loss of navigational lock due to being under the minimum return distance for several sonar systems; 10D) typical multi-beam profile of Taylor Glacier showing upper face / shelf and lower over-hung region.

sonde altimeter (a tight beam single-point sonar) indicated a depth of 1 meter 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 meter altitude on the ascent phase. Once the sonde docked with the parent vehicle, ENDURANCE would drop off the ice cap and cruise at 5 to 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 behavior described above.

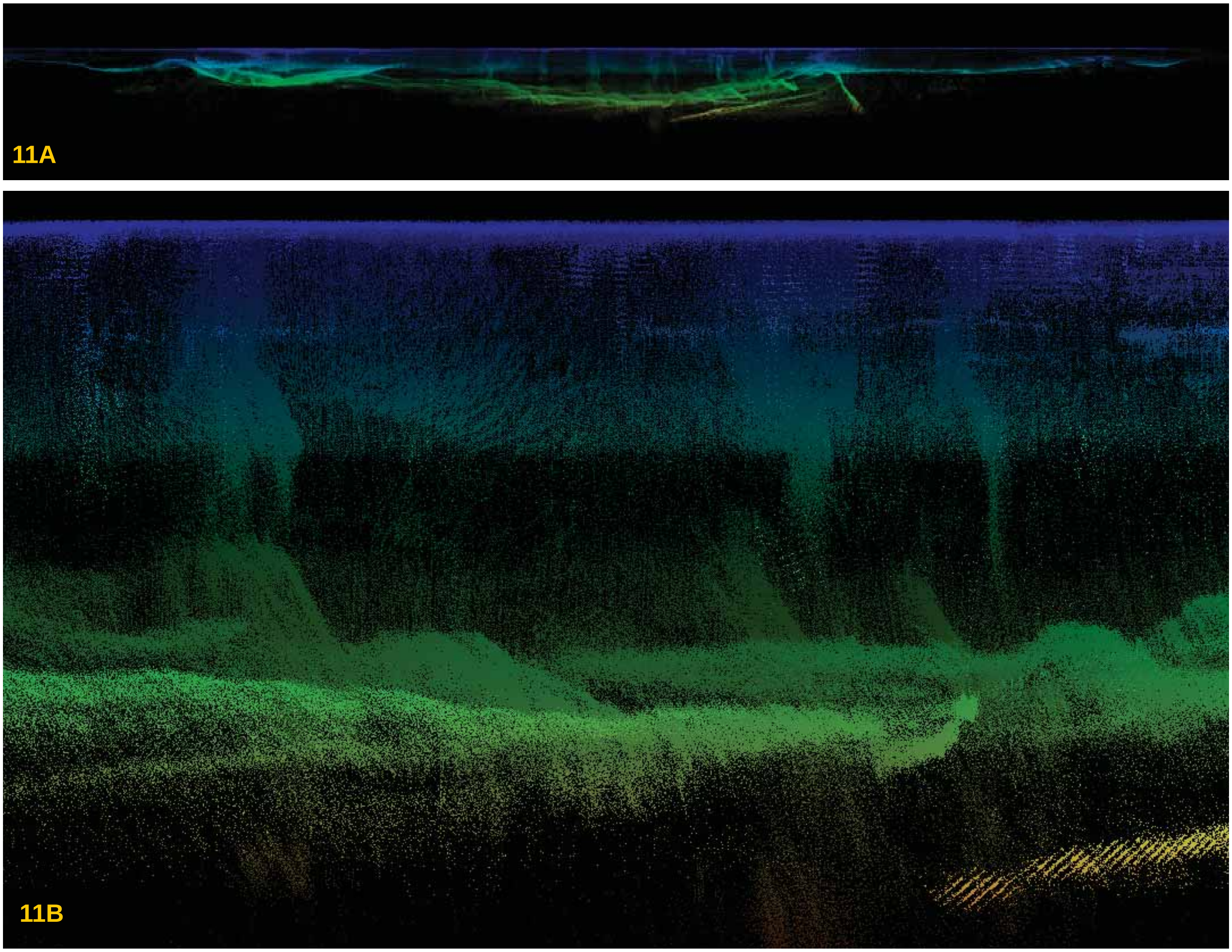


Figure 11: Preliminary Results of Glacier Mapping: 11A) Complete south (left) to north (right) image of underwater Taylor glacier, showing the southern moraine, the central glacier floating on the chemocline at 14 m depth, and the northern moraine. Maximum water depth at centerline was approximately 28 meters. The left-to-right width of the image is 900 meters; 11B) a closeup of the central portion of the image showing the floating glacier (riding on the chemocline, as noted by the under-cut cavity). Camera images validate the presence of the overhang. The strange features descending from the glacier at various points remain to be identified.

Because of the very limited visibility at WLB it was not posible to capture an actual sonde mission on video. But we did film several sonde mission tests at the Johnson Space Center Neutral Buoyancy Lab on August 23, 2008 during the dress rehearsal prior to shipping the vehicle to MCM. A typical sonde seqeuence is shown in Figures 7B through 7E. 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 and takes a sequence of images, then returns to the vehicle.

Sonde Results: In 2008, ENDURANCE performed 108 sonde drops beneath the ice cap at WLB (see Figure 8A). Each included both bottom images (Figure 8B) and 3D lake chemistry data (Figure 8C). While the XY spatial distribution of the sonde grid (Figure 8A) was 100 m x 100 m, the Z (depth) sampling was at 0.1 m spacing. The intricate Profiler system worked reliably on a daily basis, with no operational problems following the initial shake down drop (which identified and led to the field repair of a pair of failed thermistors in one of the servo motor controllers). See www.stoneaerospace.com for a daily blog.

As Figures 8A and 8C show, there were gaps in attaining full-lake coverage in 2008. This was due to our late start and the presence of a significant number of existing permanent instrument cables in the vicinity of the center of the lake. The deployment delay precluded the establishment of a second hole and moving the Bot House to that location. This meant all missions had to run from one melt hole. The sonde drops shown in Figure 8A represent hard limits for the ENDURANCE system (on the two easternmost missions the bot returned with less than 5% reserve power). Secondly, the legacy cables created a fiber snag "shadow zone" where it would have been dangerous to drive the bot for fear of a fiber catch. The team worked straight 16 to 18 hour days attempting to catch up for the lost time due to late deployment. The grid count shown can be considered a maximum possible effort on the part of any field crew operating the vehicle over a 4-week period unless significant changes are made to the operational characteristics of the vehicle (see Section 3 below). See reference [13] for further details on the design of the automatic chemistry Profiler.

2.2 Mapping Underwater Taylor Glacier:

Figure 9 shows the bow instrument suite developed for mapping and imaging the underwater segment of Taylor Glacier. The primary mapping unit is a 480-point multi-beam sonar with a 120x3 degree FOV. In the orientation shown it creates a vertical imaging plane that can be swept across the face of the glacier by maintaining a uniform yaw angle and standoff range. The proxops standoff sonars provide this capability in conjunction with additional data from the obstacle avoidance sonar system. ENDURANCE carried 300 W of HID lighting and a 6 megapixel digital video forward-looking camera (Figure 10A) contained within a dome port pressure housing. The camera contained a network interface that allowed for real-time monitoring of the image at Mission Control and also allowed for remote software toggling of the HID lights.

Glacier Science Results: Glacier exploration began on December 19, 2008. Because of the anticipated arrival of glacier melt runoff due to the late season deployment the sonde missions had been given top priority. The lake visibility (as observed at the melt hole) dropped suddenly on December 19 from approximately 2.5 to 3 m (see Figure 2A for an example of the best visibility that was encountered on the project, on December 6) to less than 30 cm at the melt hole (Figure 10B). Optical images of the underwater glacier (such as the one shown in Figure 10C) were only possible by maneuvering the vehicle to a standoff distance of well under 1 m - a distance under the minimum standoff range required to achieve valid readings on many of our sonar instruments, most importantly the doppler velocity log. When the latter instrument dropped out we lost dead reckoning navigation lock. Similarly, iUSBL navigation was not working at this range (the glacier was more than 400 m from the melt hole and multipath interference between the chemocline and the ice cap degraded that signal as well). Thus, an approach such as shown in Figure 10C was a dangerous undertaking. The initial planning had assumed that visibilty would be unlimited and that low resolution wide field images could be obtained from 20 m standoff and that high resolution images for selected sections could be arranged using proximity operations sweeps at 5 m standoff range. This proved not to be the case (no human diver nor robot or ROV had previously entered WLB so the visibility characteristics of the lake were unknown prior to the ENDURANCE mission). Future optical imaging missions will need to be launched much earlier in the season.

Exploration of the glacier, using the multi-beam and obstacle avoidance sonar array, was further compounded by the discovery of icebergs calving off the glacier face. Positions for these features, which were located approximately 50 m east of the above-water glacier face, were obtained with GPS and superimposed on the tactical map that we were building for the lake. These appear as small dark blue circles in Figure 8A. The initial (conservative) operating assumption was that these would have 90% of their mass underwater and would present significant entanglement threats to the vehicle. We thus executed three exploratory missions that consisted of a series of radial (straight line from the melt hole) approaches punctuated slow vehicle +/- 90-degree yaw rotations every 20 m to gradually fill in the unknown geometry of both the glacier and the underside of the icebergs. During the course of these three missions 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 December 23. The results of all glacier missions are shown in Figure 11A. This image is a 2D planar view of the 3D data set, looking west (end-on into the front

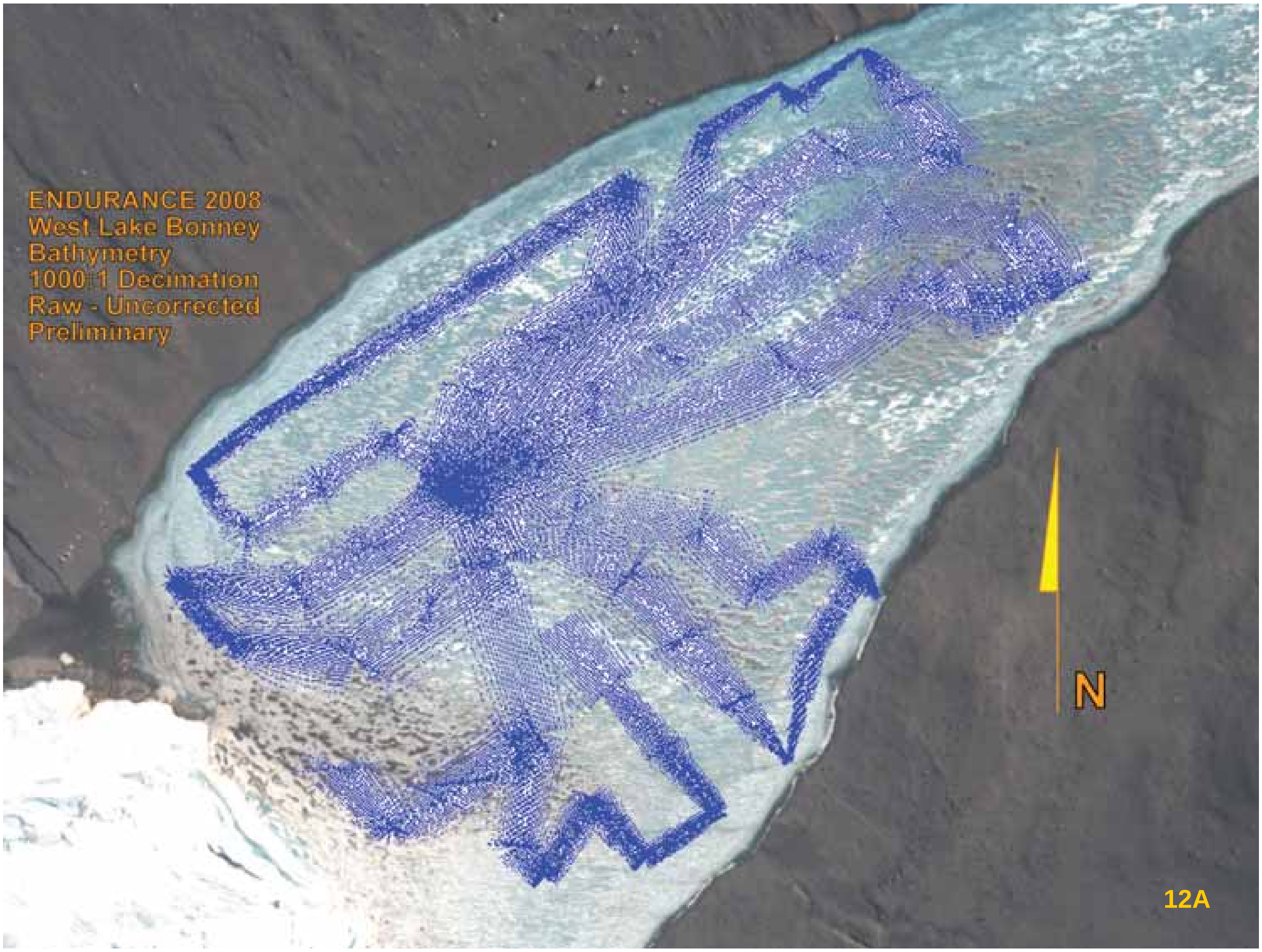
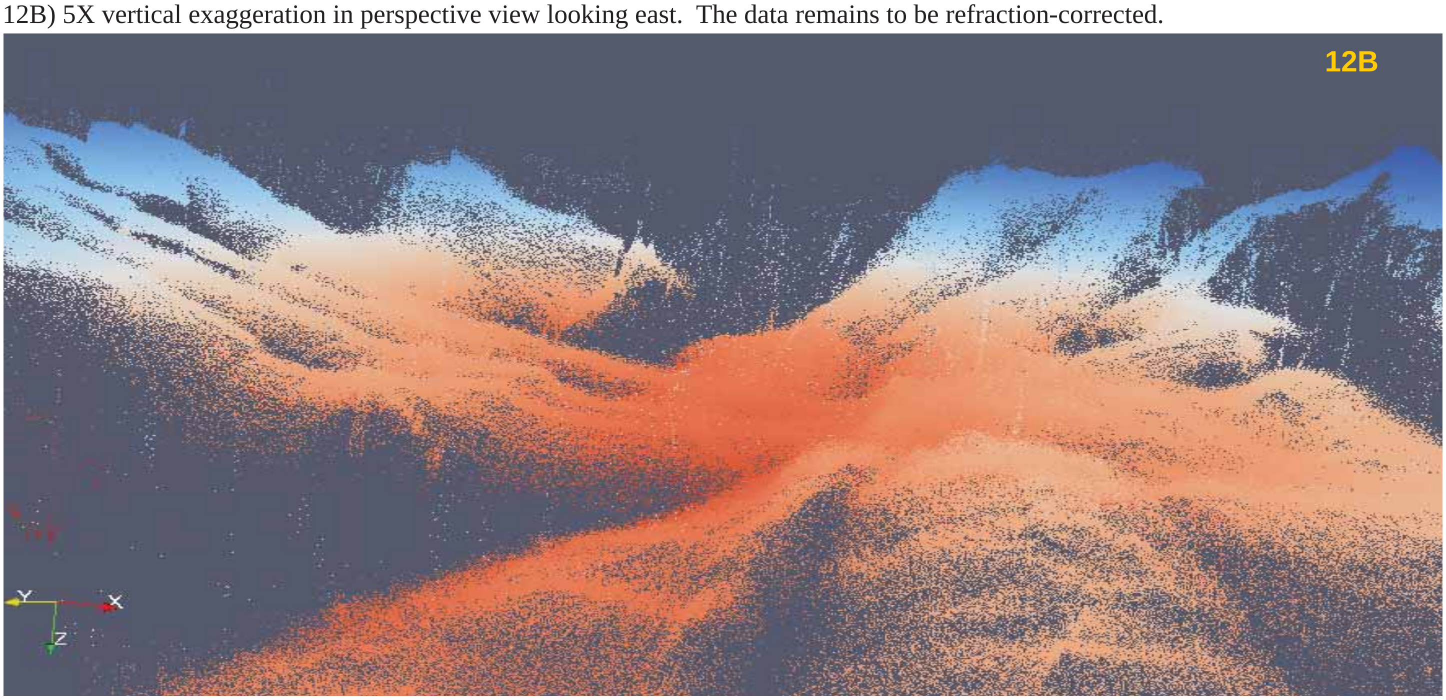


Figure 12: Lake Bathymetry: 12A) Extent of the bathymetric imaging coverage of WLB acquired during the course of all drop sonde missions. The multi-beam mapping system has a 120-degree down-look aperture. Along the central 1/2 of the lake axis the water depth beneath keel was greater than 30 m and the coverage is relatively uniform and dense -- only 1/1,000 th of the points acquired are plotted here. Towards the lake edges the vehicle sometimes had less than 2 m below keel and the scan width comensurately decreased; 12B) 5X vertical exaggeration in perspective view looking east. The data remains to be refraction-corrected.



of the glacier). It was generated by a 1,000 to 1 decimation of the approximately 100 million sonar hits collected. The data presented here are preliminary and have not yet been corrected for sensor alignment nor chemocline refraction. Many morphological features are evident - the south and north moraine deposits are clearly visible underwater; the central portion of the glacier appears to be floating on the chemocline; and there are strange features along the central face that may be associated with deposition of sediment coming off the glacier. Specific missions are planned to return to the area below the chemocline and under the glacier in 2009.

2.3 Bathymetric Mapping of WLB:

There was insufficient time to conduct a complete bathymetric program at WLB in 2008. However, in an effort to begin the process and learn the true lake floor geometry, we re-mounted the multi-beam imaging system into a down-look configuration such that the 120-degree 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, but we have software-designated the "bow" as the forward pointing direction of the multi-beam instrument as shown in Figure 9) towards the next trajectory target point, and then it moves in a straight line to that point. In this configuration, we obtained extensive bathymetric data for WLB for each of the sonde missions (a total of approximately 400 million bottom hits were logged). Furthermore, because all sonde drops were GPS-registered, any navigational error buildup was confined to the distance between sonde grid points. The extent of the bottom coverage obtained is shown in Figure 12A. As expected, the imaging beam width that contacts the floor is a function of the under-keel depth. The swaths down the central (deep) portion of the lake are wide, dense, uniform, and cover large areas at high resolution. Those in the shallow edges have very narrow coverage areas and will require many parallel passes to fill in in the entire floor. Fortuitously, having this initial data will now enable an efficient bathymetric mission to be pre-planned and completed in 2009. Figure 12B shows a sample cross section of WLB looking east from Taylor Glacier. The convex curvature in the individual swath paths is due to chemocline refraction. Patch and crossing tests were performed to account for instrument alignment errors and sonde chemistry measurements provide the needed information for refraction correction; the data shown remain to be corrected for these two factors. Work is currently underway a the time of this writing to make these corrections.

3.0 Conclusions

ENDURANCE was the first entity (human or robot) to enter the sub-ice world of West Lake Bonney. Prior to the WLB2008 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 super-saline chemocline beginning at a depth of 14 meters and continuing to the lake floor at a depth of 40 meters. The presumption was 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. Ultimately we were able to achieve less than 0.1% navigation error from the dead reckoning navigation system using bottom lock configuration for the DVL. Detailed results on the performance of this and the iUSBL navigation system are provided in reference [12]. The melt hole homing stage machine vision algorithm worked spectacularly for all but two missions where the water visibility precluded acquisition of the overhead light beam from the cruising depth of the vehicle. See reference [11] 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 108 successful casts that were used to build iso-surface 3D chemistry maps of the lake. Further details on the Profiler are available from reference [13].

Although ENDURANCE is fully autonomous and its operations were automated, we found it extremely useful to be able to "look over its shoulder" as it con-

Dive Number	Mission Type	Brief Description	UTM Enter Water	UTM Exit Water	Time Underwater	# Sonde Drops	Traverse Distance [meters]
1	pre-test	ballasting, basic navigation	12/05/08 04:59 AM	12/05/08 09:11 AM	04:12		
2	pre-test	testing navigation subsystems	12/05/08 10:35 PM	12/06/08 06:40 AM	08:05		
3	pre-test	longer distance navigation test	12/07/08 03:45 AM	12/07/08 07:54 AM	04:09		856
4	sonde	aborted because of ballast (could not ice pick)	12/09/08 07:25 AM	12/09/08 09:00 AM	01:35		
5	sonde	F6, F5, F4, G3, F3, E4, E5, E6	12/09/08 10:23 PM	12/10/08 04:48 AM	06:25	8	998
6	sonde	D5, D4, E3, D3, C3, C4, C5, C6, D6, F6	12/11/08 12:23 AM	12/11/08 04:24 AM	04:01	9	528
7	sonde	D5, D4, E3, D3, C3, C4, C5, C6, D6, F6	12/11/08 09:40 PM	12/12/08 02:50 AM	05:10	10	1252
8	sonde	C5, B4, A4, B5, A5, A6, B6, C6, D6, F6	12/12/08 10:58 PM	12/13/08 04:01 AM	05:03	10	1383
9	sonde	G6, G5, G4, H4, H5, H6, H7, H8, H9, H10, G9, G8, G7, F6	12/14/08 09:08 PM	12/15/08 03:12 AM	06:04	14	1544
10	sonde	D7, C7, B7, A7, B8, B9, C9, C8, D8, E8, F7, F6	12/15/08 10:44 PM	12/16/08 04:20 AM	05:36	12	1490
11	sonde	aborted because of negative ballast (could not ice pick)	12/16/08 11:00 PM	12/17/08 12:15 AM	01:15	11	382
12	sonde	F8, F9, F10, F11, F12, E13, D13, D12, E12, E11, E10, F6	12/17/08 02:00 AM	12/17/08 07:31 AM	05:31	12	1712
13	sonde	G11, G12, F13, G13, H13, H12, H11, G10, F6	12/17/08 11:20 PM	12/18/08 04:41 AM	05:21	9	1761
14	patch test		12/18/08 10:30 PM	12/18/08 11:34 PM	01:04		228
15	glacier	NW radial probing + sonde: X1, X1T, X1, X2, X2T, X3, X3T	12/19/08 02:19 AM	12/19/08 08:40 AM	06:21	7	1177
16	glacier	Center radial probing of icebergs + sonde: X4, X4T, X5, X5T, X7, X7T	12/20/08 09:20 PM	12/21/08 05:12 AM	07:52	6	1354
17	glacier	SW radial probing of icebergs	12/21/08 11:00 PM	12/22/08 05:30 AM	06:30		1874
18	glacier	Main south-to-north high def sweep	12/23/08 01:15 AM	12/23/08 05:37 AM	04:22		1440
19	glacier	proxops (wall follow + mosaic)	12/23/08 09:12 PM	12/24/08 02:30 AM	05:18		1047
				TOTALS:	**93.9**	**108**	**19,026**

Table 1: Summary of all ENDURANCE Missions at WLB, austral summer 2008

ducted its missions. On two occassions 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 fiber; and once when the vehicle obstacle avoidance standoff routine was over-ridded in order to obtain photos of the glacier. In the first case we were able to program a series of maneuvers that first detected the location of the hanging cable and thence allowed the vehicle to maneuver around it and return home; in the second case the navigation solution was lost when the DVL standoff range dropped below the no-return distance (1 meter) at a location outside of iUSBL reception. We were able to manually maneuver the vehicle to a known GPS point on the surface using a magnetic beacon localizer and uplink those coordinates to the vehicle and reboot the navigation solution. The data fiber (a 1 kilometer long single mode tactical fiber optic thread) was fed and retrieved by a fiber 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 under-side of the ice sheet turned out to be surprisingly smooth. This allowed us to safely work with a floating fiber at distances in excess of 700 meters from the melt hole.

A total of 19 sub-ice missions were logged by ENDURANCE during the WLB2008 mission. The vehicle spent 94 hours below the ice cap and traversed 19 kilometers of lake bed in the performance of drop sonde, lake mapping, and glacier mapping objectives. A total of 108 drop sonde "casts" were successfully completed with no cable snags, spool out or reel-up errors.

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