GOATS 2000
September 25 – October 12, 2000
AUV Operations Report

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I Summary

During the fall of 2000 the MIT AUV Lab deployed two Odyssey IIc class AUVs to Elba Italy. The AUVs were equipped and operated to support the Generic Oceanographic Array Technology (GOATS) 2000 field experiment. GOATS is an Office of Naval Research Joint Research Project that includes contributors from NATO SACLANTCEN, the MIT Department of Ocean Engineering, the MIT Sea Grant College Program, and others. The MIT AUVs were the primary mobile sensor platform for multi-static acoustic experiments. These efforts included study of buried objects and scattering from sand ripples.

GOATS 2000 provided a total window of 18 days for AUV operations. During these 18 days; 4 days were spent repairing and/or maintaining the SACLANTCEN acoustic acquisition system (the AUV payload), 2 days were lost to poor weather, 1 day was lost due to AUV equipment/software failures, 7 days were spent perfecting precise AUV navigation (and other science supporting AUV technologies) and 4 days were spent performing multi-static surveys. A total of 67 AUV missions were launched. Of these missions, 78% (52 total missions) were completed as planned. The remaining 22% of the missions (15 total) aborted due to safeguards in the AUV control software or failed due to errors in the mission code.

GOATS 2000 served as an important demonstration of several new capabilities of the Odyssey IIc AUV. Notable achievements included high precision long baseline (LBL) navigation using a Kalman filter approach, first operational use of an acoustic modem to telemeter AUV status, and microsecond timing accuracy on the AUV for improved data quality. This experiment was also only the second science mission using new AUV software derived from the MIT led Atlantic Layer Tracking Experiment (ALTEX) project. While an earlier effort did use the new code for basic oceanography this was the first project to use sophisticated waypoint behavior and closed loop navigation control.

The MIT AUV Lab considers GOATS 2000 a successful field operation. Many problems were encountered and resolved. Significant engineering goals were achieved and valuable scientific data was collected. Without the use of AUVs this data would not be available. In this, the AUV Lab has fulfilled its mission to develop and operate autonomous underwater vehicles to meet challenging and unique scientific requirements.

II Team

The GOATS 2000 team representing MIT included

Core personnel present for experiment duration:

Prof. Henrik Schmidt - Team Leader
Justin Manley - Operations Manager
Jerome Vaganay - Navigation and Tracking
John Rieffel - AUV Pilot and Software Engineer

and support personnel present for various phases of the experiment:

Prof. John Leonard - Navigation, Mission Planning, and AUV Software
Matt Grund - Acoustic Communications
Don Eickstedt - Graduate Student, AUV Software
Joe Edwards - Graduate Student, Data Processing
T.C. Liu - Graduate Student, Precision Timing
Rick Rikoski - Graduate Student, Navigation and Software
Irena Veljkovic - Graduate Student, Geographic Information Systems

III Vehicles

The Odyssey II class autonomous underwater vehicles were chosen as the mobile sensor platform for the GOATS'98 experiment because of their flexible architecture and proven performance. These vehicles have logged many hundreds of dives in over 20 field deployments. The Odyssey *Xanthos* used in GOATS'98 has logged close to 500 successful dives. A substantial fraction of the vehicle is dedicated to wet volume, which enables the Odyssey II vehicles to support a wide range of payload systems. Those fitted in the past include CTD, ADCP/DVL, ADV, side-scan sonar, USBL tracking systems, OBS, and several video systems. The core vehicle has a depth rating of 6,000 m, weighs 120 kg, and measures 2.2 m in length and 0.6 m in diameter. It cruises at approximately 1.5 m/s with endurance in the range of 3-12 hours, depending on the battery installed and the load. Included in the core vehicle are the guidance and navigation sensors necessary to support autonomous control: attitude and heading, pressure, altimeter, and LBL acoustic navigation.

Two Odyssey IIc class AUVs were used in GOATS 2000. These vehicles were both built as Odyssey IIb class vehicles in 1995 and during the spring and summer of 2000 both vehicles were significantly modified to meet the Odyssey IIc standard. This upgrade added a new Main Vehicle Computer (MVC) based on the industry standard PC104 platform. This MVC runs code that evolved from the original Odyssey model but is now significantly improved. The code is compiled and run on the PC104 using the QNX real-time operating system. Fluxgate motion sensors were replaced with the Crossbow Technologies? DMU-AHRS attitude heading reference system, which yields improved performance in a smaller form factor. Other systems, previously optional, now standard on the Odyssey IIc include Freewave? RF modems used for mission programming and data quality control and GPS receivers for surface navigation fixes.

Xanthos served as the primary vehicle for GOATS 2000 and was equipped with the same sensor used in GOATS '98, an 8-element array mounted on the nose in a `swordfish' configuration. In addition, a Roxann bottom classification pinger was installed along with the array for Rapid Environmental Assessment missions. Both sensors were controlled by an acquisition system, separately housed in the vehicle's wet volume, which required 100 W of power and generated data at a rate in excess of 5 Gbyte/hr. This system, the heart of the scientific payload for the experiment, acquired signals from the

TOPAS parametric source, and the Roxann echosounder. It also interfaced to the MVC and the high precision clock installed in *Xanthos*. This clock consisted of a PC104 card GPS receiver and a Rubidium oscillator. The GPS Receiver synchronized the Rubidium clock with GPS time, broadcast by the GPS satellite constellation, and maintained it to within 1 microsecond.

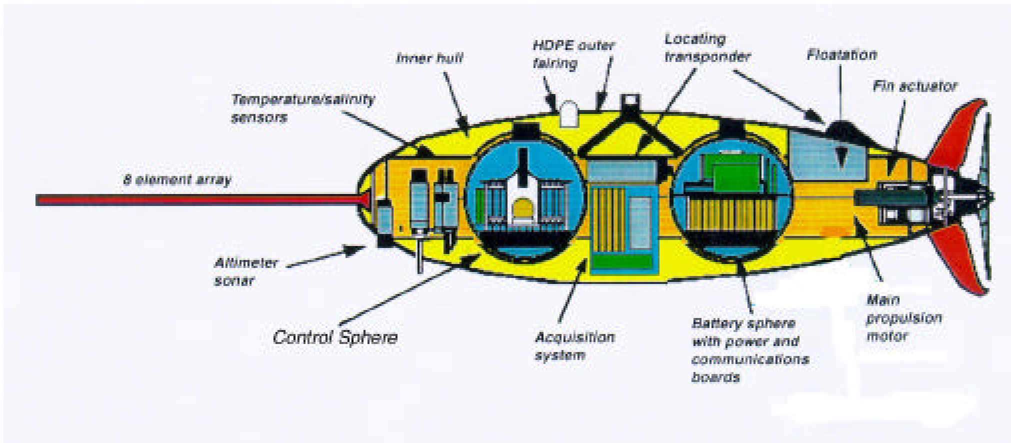

Fig. 1 A cross-section of *Xanthos* as configured for GOATS 2000.

The second AUV was named *Borealis*. It was equipped similarly to *Xanthos*, but instead of the data acquisition system and array, it carried a sub-bottom profiler manufactured by Edgetech? . This system consisted of processing electronics, contained in their own pressure vessel and mounted transversally between the AUV spheres, an acoustic projector mounted in the nose, and two acoustic receivers mounted on the underbelly of the AUV. *Borealis* was not equipped with a GPS/Rubidium clock. Due to technical problems, explained below, *Borealis* was unable to successfully collect sub-bottom data during the science surveys.

Fig 2. *Borealis* equipped with the sub-bottom profiler

Further demands placed on the AUVs by this experiment led to the inclusion of several sensors from within the Odyssey family of supported devices. These were a 200 kHz altimeter and an LBL acoustic navigation system. The altimeter enabled the AUV to survey at constant altitude (3-5 m) above the sea floor during the REA component of the field experiment and to avoid equipment placed on the bottom in the vicinity of the target field during the multi-static acoustics component. The LBL system allowed *Xanthos* to use a closed loop control algorithm based on a Kalman filter. This allowed the AUV to follow waypoint-defined surveys for data collection.

A final system installed on the AUVs for GOATS 2000 was the Utility Acoustic Modem (UAM) developed by the Woods Hole Oceanographic Institute (WHOI). This system was used to provide telemetry from the AUVs back to the R/V Alliance during AUV missions. Using the UAM small packets containing the coordinates of the AUV and some basic status information were sent from the AUV to the ship every 20 –30 seconds depending on mission configuration. These transmissions allowed the support boat to standoff from the AUV, and remove its acoustically noisy signature from the survey area.

IV Operating Procedures

During GOATS 2000 a basic AUV mission consisted of several steps.

<u>Mission Planning</u> – in this phase the objectives of the mission were defined, survey patterns were developed and converted into AUV mission files using a MATLAB based software tool, the acoustic systems schedule was created, missions were simulated and then run on deck to verify their stability.

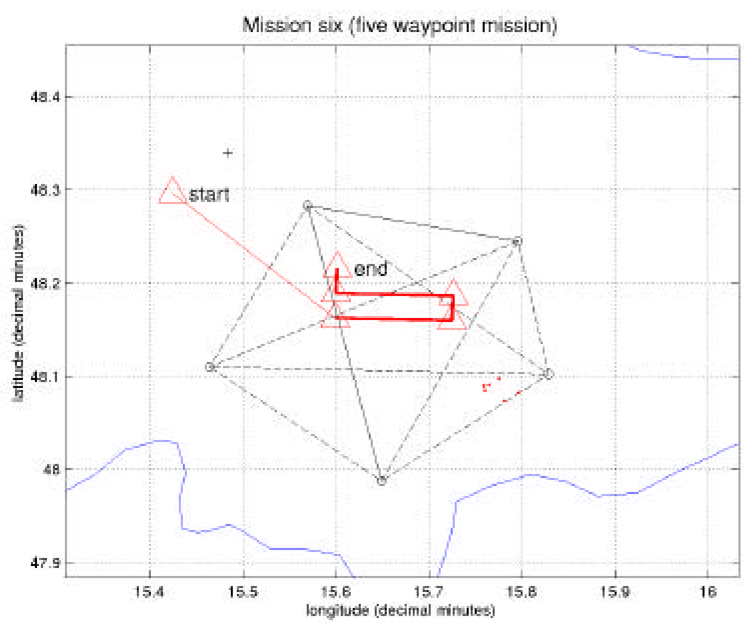

Fig 3. The MATLAB Mission Planning Tool

Pre-launch – The lack of an embedded processor in the acoustic acquisition system required a complicated pre-launch procedure. The AUV was powered on while connected to the acquisition system control PC. This was necessary so the system settings could be loaded and the instrument activated. A notable complication of this step was the need to connect the control PC to the AUV tether while both were powered down, and then power the control PC followed by the AUV. Failure to follow this procedure would crash the system and require a complete restart of the pre-launch procedures. From this point on the AUV could not be powered down or the instrument settings would be lost and the AUV would have to be recovered to deck to reprogram the sensor. Fortunately the other required pre-launch procedures could be carried out simultaneously using the RF modem. During these tests all instruments are interrogated and their functionality verified, the actuators are indexed, mission files are verified, and all tracking and safety systems are activated and tested. These are standard Odyssey procedures. For GOATS 2000 two extra steps were required, a GPS fix, which set the MVC clock to GPS time, was confirmed and the stable lock-in of the Rubidium Oscillator was also confirmed. These steps were required to verify the precise timing of the data sets collected by the AUV. This entire process had to be completed as quickly as possible because the high power draw of the acquisition system limited vehicle operations to 1.5 hours per battery charge.

Launch – Upon completion of pre-launch checks the AUV is lifted by a ship's crane. It is attached with a quick-release line, which is detached once the AUV is floating on the water's surface. The bow of the AUV is secured with a tag line that is thrown to the waiting workboat upon AUV release. The workboat then tows the AUV to its dive site and notifies the AUV pilot. The pilot launches the mission via the RF modem and the mission begins.

Fig 4. *Xanthos* is launched

Fig. 5 *Xanthos* is towed to dive site

Mission Completion – Once the mission was launched the AUV submerged and executed the programmed behavior. When possible, while underway, the AUV was visually tracked by the workboat. During science surveys the workboat shut down its engine and did not follow the AUV. This provided a quieter environment for the multi-static acoustics. The AUV position and status was transmitted to the ship via the UAM. The position was plotted in MATLAB for comparison with the intended course. This real time feedback replaced the ultra-short baseline (USBL) acoustic tracking used in previous Odyssey missions. Upon completion of the mission the vehicle surfaced and re-established contact with the pilot via the RF modem. At this point, to confirm successful completion, the pilot reviewed a sample of the mission log. Once the mission was confirmed successful, further missions could be launched using the RF modem. Survey missions averaged about 15 minutes in duration. Up to four consecutive surveys were performed during GOATS 2000.

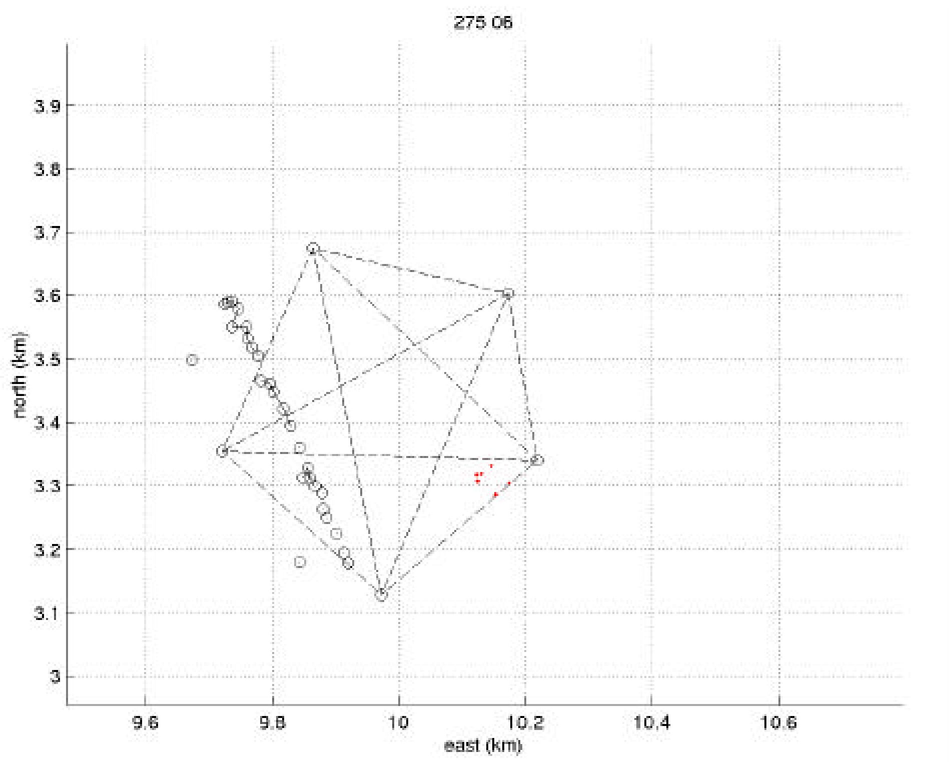

Fig 6. The MATLAB AUV Telemetry Plot

Recovery – After all missions were completed the workboat took the AUV under tow and brought it back to the ship. A pick pole was used to attach a line to the AUV lift point from a distance. This line was attached to the ship's crane and the AUV was lifted to deck. Once on deck it was rinsed with freshwater and returned to the ship's garage. The AUV was opened and the acquisition system was removed to facilitate data downloading directly to the system's control computer. The AUV mission data was then downloaded via an Ethernet connection to the ship's network. The AUV batteries were removed and set to charge and the mission cycle was complete.

V Hardware Report

In general the Odyssey hardware systems functioned well. There were no problems attributable to the actual Odyssey hardware design during GOATS 2000. However, a series of problems were experienced due to the age of the systems used. These problems never prevented an operation from occurring on a planned day but they did cause launch delays. On at least two occasions a series of morning runs were postponed till the afternoon due to hardware failures. These delays represented a loss of approximately four hours of survey runs. Xanthos was the primary vehicle used in this experiment and its long service history, nearly 500 missions, is clearly the root cause of the hardware failures experienced in GOATS 2000. Problems faced include:

Worn fin actuator gear – This was the most obvious age related failure. Due to the subtle wear pattern this problem required three separate cycles of tailcone disassembly, inspection, and reassembly before it was identified and corrected. This failure was responsible for the loss of one morning's surveys and required a total repair time of approximately 10 man-hours.

Thruster control board short – This was another subtle failure mode. A loose circuit board, which is actually a hardware modification from the original Odyssey IIb design, caused the MVC to intermittently lose communications with the thruster. This failure required extensive troubleshooting which was made especially difficult by the lack of knowledge on the part of the AUV team. The thruster controller is a legacy system employing an arcane communications protocol (known as a SAIL loop) to communicate with the MVC. The current staff of the AUV lab was not involved in the design and construction of this system and lacked the experience of the original system designers. Eventually, careful disassembly and reassembly of the system resolved the short and resolved the problem. This failure also delayed a morning survey and required approximately 15 man-hours to correct.

Long baseline navigation serial communications failure – This proved to be a simple case of a broken connection. The symptom arose during vehicle checks during a weather day. Careful inspection and troubleshooting of the system led to the broken connection that was attributable to the significant number of times this connector had been cycled. This diagnosis and repair required approximately 5 man-hours.

General serial communications failures – Several systems, including the acoustic acquisition system, communicate with the MVC using RS-232 serial protocol. This protocol calls for the use of three signal wires, one of which is ground. The original Odyssey design uses two serial wires and ties all serial grounds to the AUV power ground. In theory this is a fine concept but after many years of use the actual wiring in the vehicle has become somewhat more complicated. Apparently ground-loop errors are now present as both the SACLANT acquisition system and the WHOI UAM required installation of the third ground wire for proper serial communications. This solution was simple to implement, requiring roughly 1 man-hour each, but was only attempted after significant time was wasted troubleshooting software. The underlying problem here is that the actual wiring in the AUVs has deviated from documented designs. The entire wiring bus of the AUVs will be removed and reinstalled with a full three wire RS-232 bus to ensure such failures do not appear again.

Overloading the AUV power electronics – The SACLANT acquisition system draws roughly 100 watts. This high power demand put exceptional strain on the AUV power systems. Two significant failures can be attributed to the inefficient design of the system. Early in the experiment the system was damaged and drawing 25-40% more power than usual. This was not known and the AUV was operated on deck while running the system. Safe operating time for the batteries was based on the standard power specifications and was therefore incorrect. The high power draw over drained the battery pack and damaged nearly 50% of the cells. This eliminated one of the two AUV battery packs and prevented dual vehicle operations or double use of one vehicle in a given day. This significantly reduced the operational capabilities of the MIT AUV team until replacement cells could be brought from the US during the last week of the cruise. A second problem caused by the high power demands of the system was the failure of a 24 volt DC/DC converter providing power to the acquisition system, as well as the AUV control electronics. This failure happened during the last few days of the cruise and had been observed in GOATS 98. The DC/DC converters are designed to handle such a load but can only do so for a limited amount of time. After several weeks of use the converter failed and needed to be replaced. As the converters are mounted deep under the other control electronics this repair required 10 man-hours to complete. Power electronics were also the root problem preventing sub-bottom profiler surveys using *Borealis*. While the standard current draw of the instrument was within tolerance of the AUV power circuits, the instantaneous peak was well over the 5 amp fuses on the AUV battery pack. This extra safeguard is not present on the shore power supplies so the failure was not observed during the deck testing of the instrument integration into the AUV. The problem was only observed just as Borealis was being prepared for a sub-bottom profiler survey mission. A current limiting device was fabricated to overcome this problem. Unfortunately, after development of this solution the remaining ship time had to be allocated to other tasks and the opportunity to test this new instrument was lost.

Control sphere overheating/clock failure – The Rubidium oscillator used for the precise timing generated a great deal of heat. As the control sphere seal is a result of a vacuum, this heat was very hard to dissipate while the vehicle was on deck. Usually precautions were taken to avoid the sphere reaching greater than 45? C, and never more than 50? C, at which point the oscillator, DMU-AHRS, and potentially the MVC could be irreparably damaged. In once case the AUV was prepared for launch following the pre-launch procedure described in section IV. Unfortunately the launch had to be delayed as the R/V Manning occupied the survey area. Not wishing to repeat the arduous pre-launch procedure, and accepting the report that the Manning would clear the area immediately, the AUV was left on and awaiting launch. Eventually the AUV spent nearly 30 minutes powered on, while on deck. It was then launched, but as the mission was being executed the Rubidium clock stopped responding to the MVC and the mission crashed. This was a result of the sphere reaching a critical temperature. After this event the clock never returned to its regular operating condition and was no longer available for data collection. Fortunately this transpired on one of the last days of the cruise and the remaining time was used to perform Roxann surveys that did not require precise timing.

VI Software Report

The primary role of the Odyssey IIc vehicles in GOATS was to navigate in the vicinity of the TOPAS tower and gather, via the nose-mounted SACLANT Acoustic Array, the results of the tower's ensonification of the surrounding sea-floor and the targets therein. The software used on the Odyssey IIc AUVs during GOATS 2000 was primarily the core ALTEX vehicle software written in collaboration by MBARI, MIT, and Bluefin Robotics. The need in GOATS for functionality not supported by the current framework, however, necessitated several significant departures from the code and its architecture.

Inspired and influenced by the Odyssey II software, the ALTEX software has been completely re-written from the ground up in POSIX-compliant C++. The ALTEX software is currently compiled for the QNX operating system and run on the PC104-based Main Vehicle Computer (MVC) within the Odyssey IIc control sphere. The control software of the vehicle is based upon the Layered Control scheme developed on the Odyssey II's by Jim Bellingham and the MIT AUV Lab. Layered Control involves the interaction of several concurrent "behaviors". Each concurrent behavior of a Layered Control architecture is responsible for meeting a certain goal (maintaining a depth envelope, following a survey line or homing in on a waypoint, for instance) and each is independently capable of issuing commands to the vehicle's dynamic control system. When the commands of two behaviors conflict, for instance when the target of a waypoint behavior is deeper than what the depth envelope behavior is trying to maintain, the dynamic control command of the higher-priority behavior (in this case, depth envelope), overrides all conflicting commands. This interaction of simple behaviors can lead to the relatively complex actions needed by an intelligent AUV.

The two software elements most crucial to the needs of GOATS 2000 that were not supported by the current ALTEX core software were accurate LBL navigation of the vehicles and the precise (microsecond, GPS-accurate) timing and scheduling of acoustic events. The Scheduler, perhaps the single most important addition to the software, was responsible for triggering events that occurred at specific times during the 10-second "timeline" established for GOATS. The implementation of this timeline was crucial for the coordination of acoustic events both locally (on the AUV-mounted acoustic array), and on the TOPAS tower. SACLANT's acoustic acquisition system, the central AUV instrumentation of the experiment, was largely autonomous, but required two communications from the AUV's MVC. Early in the 10-second cycle, the MVC triggered the acquisition system via a serial string containing elapsed mission time (in seconds) along with vehicle telemetry (UTM coordinates, roll, pitch, yaw, etc). Once the acquisition system had been triggered, the MVC sent, via the Rubidium oscillator clock card, a GPS accurate TTL-pulse "timestamp". Several seconds into the 10-second timeline, the TOPAS tower would ensonify the region of interest and log its own GPS accurate time of events. An accurate version of acoustic events could then be produced by combining in post-processing the vehicle's telemetry information with the timestamps on the acquisition system and the TOPAS timing logs.

The ten-second timeline of the experiment was (roughly) as follows:

Time (in seconds)	Event
0.0	AUV pings LBL transducer at 9 hertz
~0.0	TOPAS receives ping
~2.0	AUV sends "Acquire" command to Acquisition system.
~2.2	Acquisition System begins acquiring hydrophone data
~2.5	AUV stops listening for LBL returns
~2.5*	TOPAS ensonifies region
~3.0*	AUV clock card sends TTL Pulse
~9.7	Acquisition System stops acquiring

The times of the two events marked with asterisks, the TOPAS ensonification and the TTL pulse, were both recorded with microsecond accuracy by GPS-synched clock cards.

Also crucial to the GOATS experiment was the integration of Long Baseline (LBL) Navigation. LBL Navigation allowed for precise (meter resolution) localization of the vehicle and (as a result) acoustic data gathered by the SACLANT acquisition system. The precision of LBL navigation was augmented by Jerome Vaganay's adaptive Kalman filter based navigation algorithm which, once "trained" (by post-processing the results of early vehicle trials) was able to take into account and correct for errors caused by both external (currents) and internal (instrument calibration errors) biases of the system. Like the Scheduler, the integration of the LBL board set and Vaganay's algorithm were performed largely by graduate student Don Eickstedt.

It was in the testing and tuning of this precise navigation that the most significant bug in the core code was identified. During a waypoint mission, and while using LBL to navigate, the AUV failed to deviate from its course towards the waypoint. Even after moving significantly past the waypoint the AUV failed to turn, and only gave up that heading upon that way-point behavior timing out. This was a perplexing fault but after investigation it was determined that there was an error in the “circular way-point” behavior algorithm.

To prove the point, a piece of Matlab code was used to perform the same calculation as the original core code. This Matlab code connected the commanded start (blue square) and way-point (red circle) with a blue line, and for a grid of hypothetical 'current x,y' (triangles) drew a RED vector indicating the new bearing computed by the vehicle. The green lines indicate the new bearings computed by making a minor change to the code. The resulting plot shows that once the vehicle misses its waypoint it keeps going rather than circling back to the waypoint. Once this error was understood, it was corrected and waypoint behaviors were completed properly.

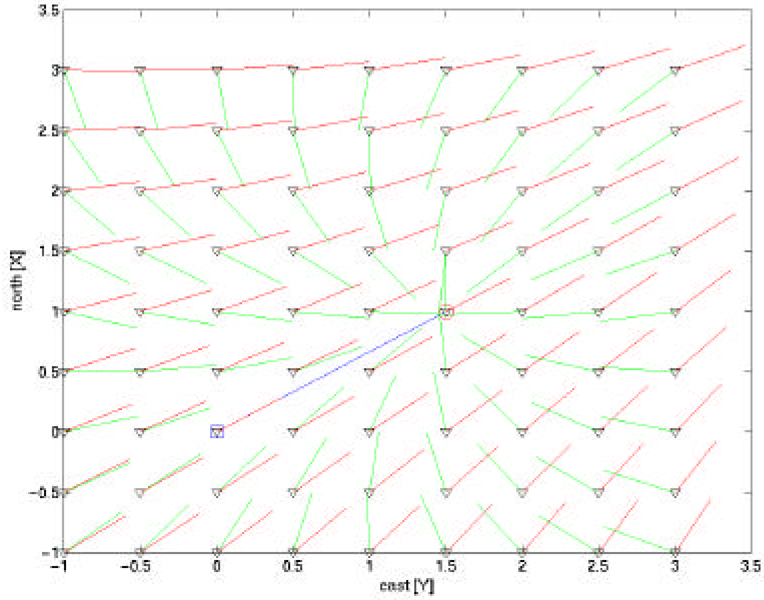

Fig 7. Matlab plot of the waypoint error

A related software issue was the "training" of the Kalman filter. While significant work was done in early trails to properly tune the filter, the currents and conditions for each survey were always unknown. It was discovered that it was wisest to begin the AUV surveys as far from any obstacles, notably the TOPAS tower, as possible. This allowed the filter to acclimate to the local currents and led to much improved performance as the AUV moved closer to the hazardous areas of its survey course. Unfortunately this lesson was only learned by experience as, in one case, the AUV actually struck the TOPAS tower during a survey. Fortunately the hardware was quite robust and no significant harm was done.

One of the difficulties currently inherent in the ALTEX software framework is its lack of approachability to new developers. While Don Eickstedt did an excellent job in writing the majority of the GOATS-specific additions software, the lack of a clean development tools and guidelines was a significant obstacle. Furthermore, attempts at creating a method of changing mission plans mid-mission via the acoustic modem were hindered by the lack of a supporting mechanism in the framework. While this remains one of the weak points of the ALTEX software, it promises to be solved by the current cycle of joint software development between MIT, MBARI and Bluefin.

Mission planning was improved tenfold by John Leonard's impromptu (but well-conceived) MATLAB-based navigation software, which allowed multiple setpoint and multi-waypoint missions to be planned by clicking on appropriate regions of the Map. Moreover, Leonard's software was capable of generating syntactically-correct mission files that could then be downloaded directly onto the vehicle and used immediately -- this feature became particularly useful for some of the longer waypoint missions. Because of the positive experience with Leonard's tool, and the lack of an analogous existing tool for the ALTEX software, significant effort should be applied to creating an "official" ALTEX graphical mission planner.

Aside from the modifications and difficulties noted above, the ALTEX core software behaved quite well and reliably, due largely to its extensive testing on both Odyssey IIc and Odyssey III platforms. Ultimately, the ALTEX software has proven itself as versatile, productive, and stable. Future development of the code promises to improve upon this foundation, while simultaneously extending the versatility of Odyssey IIc and Odyssey III class vehicles as oceanographic tools.

VII Daily Activities

As noted in Section I, above, there were a total of 18 days available for AUV operations in GOATS 2000. Due to various factors a true routine never developed and each day was planned and executed based on the latest conditions. Table 1, below, summarizes each day's activities.

Date	Missions Launched	Success Rate	Comments
Sep. 25	0	NA	Acquisition system under repair, trimmed *Xanthos*
Sep. 26	0	NA	Acquisition system under repair, RF comms testing
Sep. 27	0	NA	Acquisition system under repair, Batteries damaged in deck tests.
Sep. 28	11	72%	Basic trials, waypoint behavior tests
Sep. 29	6	100%	Planning tool development, LBL data collection, UAM trials
Sep. 30	4	50%	LBL data collection, Roxann surveys, UAM telemetry verified
Oct. 1	18	64%	LBL data collection, 100 UAM packets transmitted
Oct. 2	5	80%	LBL data collection, attempted way-point test rudder gear failed
Oct. 3	6	100%	Way-point test complete, observed algorithm error but mission completed successfully
Oct. 4	0	NA	Weather Day
Oct. 5	7	100%	LBL navigated waypoint behavior achieved
Oct. 6	3	66%	Multi-static surveys, thruster wiring fault observed
Oct. 7	5	100%	Multi-static surveys
Oct. 8	0	NA	Weather Day
Oct. 9	1	0%	Sphere overheat and mission crash
Oct. 10	3	33%	Clock failures, Multi-static surveys
Oct. 11	0	NA	Acquisition system under repair, Taipan AUV lost
Oct. 12	2	100%	Roxann surveys, Taipan AUV recovered

Table 1: Daily Activities of MIT AUV Lab during GOATS 2000