Ice Profiling Sonar for an AUV: Experience in the Arctic

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***Abstract*- The harsh environment and limited resources available in the Arctic region make collection of most scientifically relevant data in the area difficult and/or expensive. The Monterey Bay Aquarium Research Institute (MBARI), along with other partners, has developed an autonomous underwater vehicle (AUV) specifically designed to withstand the difficult environment in the Arctic and capable of collecting a variety of scientific data. This tool has the potential to replace capabilities previously supported by the US Navy SCICEX cruises which used submarines for measuring and monitoring Arctic oceanographic properties. Scientific access to Navy submarines has been severely restricted over the last several years, with the future prospects for continued support uncertain. Ice draft data was one important piece of data historically collected by the submarines that MBARI's AUV now has the potential to provide. This ice draft data has particular value to climatologists and Arctic scientists who are striving to evaluate the impact of global climate on the thickness and extent of the Arctic ice sheet.**

This paper will examine the ice draft data collected by the ALTEX AUV during its engineering test cruise in the Arctic in October 2001. A description of the experiments and the general performance of the vehicle will be presented along with the scientific instrumentation layout of the AUV. Further, the modifications made to the ASL Environmental Sciences Ice Profiler™ instrument to support vehicle operations in real-time will be described. The use of this real-time data to drive vehicle decision making during missions will be addressed as well. The data acquisition and processing techniques used to determine ice draft will then be outlined, followed by samples of the ice draft data itself and estimates of its accuracy and repeatability. The conclusion will include lessons learned and future plans for the ice profiling science payload.

I. INTRODUCTION

The Arctic region presents a most inhospitable environment for collecting relevant scientific information about the ocean. It is the Arctic Ocean, however, that has extraordinary potential for unraveling the mysteries of global climate change [1] [2]. One of the significant components of the Arctic region contributing to the global energy balance is its ice cover [3]. Using satellite technology, the ice coverage has been monitored and shows significant variation year-to-year. In order to understand the details of the Arctic Ocean mixing process and their impact on the deep ocean water masses, however, the ice thickness also needs to be thoroughly examined.

The Monterey Bay Aquarium Research Institute (MBARI), along with numerous industry and international partner, has been developing an autonomous underwater vehicle (AUV) capable of operating in this harsh region. The vehicle's specific mission is to gather information about the warm Atlantic Layer water mass entering the Arctic Ocean through Fram Strait. The experiment designed to accomplish this mission is known as the Atlantic Layer Tracking Experiment, or ALTEX [5]. To successfully complete this mission, the AUV has been designed for long duration unattended operations which require portions of the data to occasionally be stored on internal buoys that are released, burn through any ice cover, and transmit the acquired data to shore. These buoys have a limited capability for burning through the ice, however, and so the vehicle must be capable of finding regions of thin or no ice cover where the buoys can be launched. To meet this need as well as to demonstrate the ability of this type of autonomous platform for gathering long tracklength ice cover data, an ice profiling sonar has been integrated into the science payload of the ALTEX AUV.

An autonomous underwater platform capable of extended missions and able to measure not only water mass properties, but also ice thickness, would provide the additional attraction of replacing the extremely successful, but no longer feasible US Navy SCISEX cruises [4]. The purpose of this paper is to present the results from the first Arctic engineering test of this platform, paying particular attention to the ice profiling sonar and its capabilities. The performance of the AUV's navigation systems will be addressed in a separate paper at this conference [6], as will a description of the general Arctic experience with this platform [7].

This paper will describe the basic AUV platform and its performance during the ice profiling missions. It will then present details about the science payload section of the AUV, as well as specifications for the Ice Profiler™ ice profiling sonar. The modifications made to the system to support real-time ice sonar data acquisition and AUV operational decision making will also be presented. Finally, the algorithms used to generate estimates of ice draft both in real-time and using post-processing software will be outlined along with the presentation of the ice draft results from one the missions.

II. PLATFORM AND EXPERIMENTS

A. Experiments and General AUV Performance

The objective of the ALTEX test cruise in October of 2001 was to perform engineering tests on each subsystem of the autonomous underwater vehicle (AUV) in preparation for a final 1000 km + autonomous mission to be conducted in 2003 or 2004. Goals for this testing included:

- Operation of the vehicle from the USCGC Healy in the ice pack
- Demonstration of high-latitude navigation
- Testing of the data buoy information transfer and launch system
- Collection of oceanographic sections with both the AUV and a CTD rosette
- Collection of ice draft profiles with the AUV

The cruise took place in the waters West and North of the islands of Svalbard in the Arctic Ocean (Fig. 1). After some initial testing in the waters near Tromso, Norway, where the ship departed, there were a total of nine days of AUV in-water missions. The modular science payload section located at the nose of the vehicle was used during all the missions conducted, even if the purpose of the testing was not specifically to collect oceanographic data. Three days of testing were dedicated to under-ice operations, resulting in the collection of numerous multi-kilometer long sections of ice draft.

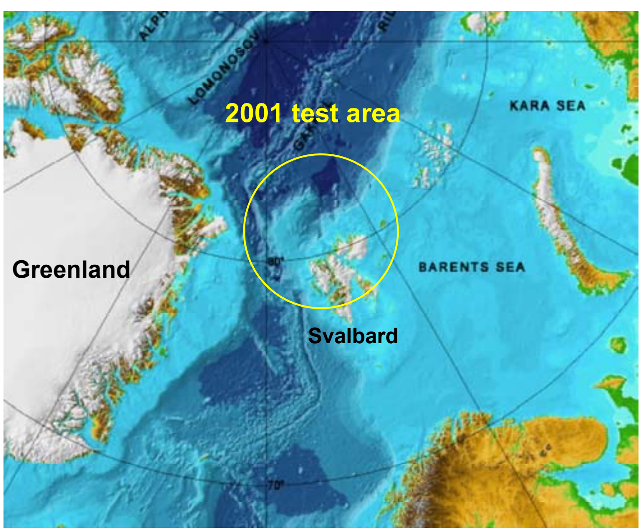

Fig. 1. ALTEX October 2001 test cruise area of operations. Map credit: www.ngdc.noaa.gov/mgg/bathymetry/arctic/provisionalmap.html

The ice profiling test missions were specifically designed to optimize the performance of the Ice Profiler™ ice profiling sonar (IPS) located in the modular science section of the vehicle. They typically consisted of launching the vehicle in a relatively ice free lead, having it dive to between 30 and 50 meters depth, then running it on a straight and level course at approximately 1.5 m/s (the nominal speed of the AUV) under an ice covered region. Some missions were simply 'out-and-back' missions where the vehicle would run a straight course out for some predetermined amount of time, then turn 180 degrees and return to its starting point. Other missions were run in a triangle pattern.

The AUV's general performance was good. There were some difficulties with system and software integration, in particular of subsystems that arrived later than expected and so were not available for testing prior to the cruise. However, once these issues were addressed and the general operation of the vehicle in the difficult conditions of the Arctic in October was practiced, numerous successful missions were completed. These missions addressed each of the testing goals presented above, although this paper will only focus on ice profiling missions. Fig. 2 shows the assembled vehicle on deck following a recovery. During typical successful missions the vehicle was able to maintain heading to within +/- 0.5 degrees, and maintain commanded depth to within +/- 50 centimeters, which is approximately the diameter of the vehicle.

Fig. 2. AUV recovery onboard USCGC Healy October 2001 (photo by Todd Walsh, ©MBARI)

B. Science Instrument Layout

The payload system was designed to provide high quality oceanographic water column science data, complemented by ice draft profiling capabilities. The sensor suite specifications were established based on extensive discussion with the ALTEX science team who defined the measurement needs of the ALTEX project. The resulting modular science payload section of the AUV contains the following instruments (Fig. 3) [sampling rates are listed in square brackets]:

- Dual Seabird conductivity and temperature sensors (SBE 4C and 3F) [4 Hz]
- WET Labs light scattering sensor (LSS) [4 Hz]
- Seabird dissolved oxygen sensor (SBE 43) [4 Hz]
- ASL Environmental Sciences Ice Profiler™ [1 Hz]
- MBARI In-Situ Ultraviolet Spectrophotometer (ISUS) used to measure dissolved nitrate concentrations in the water column [0.25 Hz]
- Datasonics altimeter used as a forward looking sonar (PSA-916) [5 Hz]
- Two Seabird pumps (SBE 5T 2000 rpm)
- Two MBARI flow meters [4 Hz]

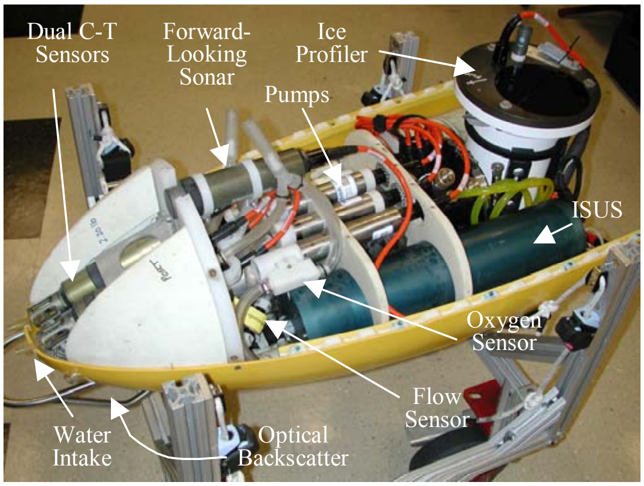

Fig. 3. Science payload instrument layout. (photo by Nicole Tervalon, ©MBARI)

The dual conductivity and temperature sensors, oxygen sensor, ISUS, the pumps, and the flow meters are all part of a pumped water flow system. The primary pumped system contains in order, starting at the water intake port, a temperature sensor, conductivity sensor, oxygen sensor, ISUS, a pump, and finally the flow meter. The secondary system contains a temperature sensor, conductivity sensor, a pump, and finally the flow meter. The ice profiling sonar and the forward looking sonar are mounted within the fairing and operated through it, with the understanding that their attenuation through the ABS fairing is minimal. The LSS protrudes approximately one inch outside the fairing on the forward underside of the nose section. A welded stainless steel cage protects the water intakes and LSS. The Seabird SBE25 data acquisition boardsets used to sample and digitize the majority of the sensor outputs are housed in a large titanium pressure vessel located forward of the ice profiling sonar and underneath the pumps.

The IPS, with its narrow beam transducer and specialized hardware and software, detects the time-of-flight of an acoustic signal generated by its transducer and reflected off the underside of the ice. This time-of-flight information along with knowledge of the sound speed profile of the water column, the depth of the instrument package, and the atmospheric pressure, are used to generate ice draft estimates. The conductivity and temperature sensor data collected during each mission allow for accurate real-time measurements of the sound speed profile of the water column, thus improving the accuracy of the ice draft estimate as compared with moored ice sonars. The specifications for the Ice Profiler™ are as follows:

420 kHz transducer
1.8 degree beamwidth at –3 dB
Integral Paroscientific pressure sensor
Integral tilt sensor
Internal data storage
Real-time output of all internally stored variables
200 PSIA pressure rating
24 Volt DC power input via wet cabling

The IPS system was originally designed to collect data in a moored configuration. The following section will describe some of the modifications that were implemented by ASL Environmental Sciences and MBARI to support the use of the system on board the AUV.

III. REAL TIME ICE DRAFT GENERATION

A. IPS modifications to support real-time data acquisition

A number of modifications to the Ice Profiler™ firmware were necessary to support operations on the ALTEX AUV.

Under normal operating conditions, the IPS is setup to log data internally during one or more phases of a deployment. A phase is a set of operating parameters that will govern the behavior of the IPS during a defined period of time. The phases are provided to allow for different setup parameters to be used at varying times during the year as environmental parameters or scientific needs change. After the usual months- to year-long deployment, the instrument is retrieved and data is offloaded from a serial communications port. The data can then be analyzed on a desktop PC using software provided by ASL Environmental Sciences. For the ALTEX AUV operations, multiple phases of operation are not necessary due to the short duration of even the extended day missions, so the ability to program multiple phases was removed. The unit is instead setup prior to each day's operation on deck with the parameters for each mission.

The data flow in the ALTEX AUV requires science sensors to stream data for logging on the main vehicle computer (MVC) through a serial or ethernet port. This data can then be used by other tasks running on the MVC to produce more integrated data sets, navigation, and other decision-making processes. For this environment, the IPS was modified to supply a coded data stream via the serial communication link directly to the MVC. The data stream, providing updates at a frequency of 1Hz, contains all the information that is normally logged on the device in coded format. The MVC task managing the data link to the IPS decodes the messages, logs the data, and is able to provide the latest science data values to other tasks running on the system.

B. Real-time data use to support vehicle decision making

The task running on the MVC that manages communications with IPS also makes the ice draft data available to other processes on the MVC. The data that is shared is used to control other aspects of the AUV mission, such as guidance and control, and payload delivery (to the data buoys).

A unique aspect of the ALTEX vehicle is the ability to launch specially designed data buoys. Periodically, science data is downloaded to a data buoy and the buoy is launched from the vehicle with the purpose of transmitting the science data to shore stations via satellite communication. The buoys were designed to burn through ice up to a meter thick in order to deploy the communication antennae. The AUV guidance and control (GNC) software is responsible for finding an area to launch buoys with an appropriate probability of making it to the surface. With real-time IPS ice draft data available to it, the GNC software was created to find large areas of surface ice of suitable thickness under which to launch data buoys.

IV. ICE DRAFT COMPUTATIONS AND DATA

A. Ice draft calculation

Ice draft is defined as the distance from the bottom of the ice to the mean surface water level, while ice thickness is the total distance from the bottom to the top of an ice floe. Ice thickness can be computed from a measurement of ice draft if one knows or can estimate the density of the ice itself. The ice measurements described in this paper are focused only on the generation of an ice draft estimate.

The calculation of ice draft from an underwater platform is fundamentally simple; it is the difference between the distance from the platform to the underside of the ice, and the distance from the platform to the mean water level. However, the measurement of these distances is not trivial. A detailed description of the error budgets associated with these measurements when made from AUV and submarine platforms is included in [8].

B. Real-time ice draft estimates

The data collected by the ice profiling sonar is stored both in the IPS memory, and on MVC hard disk. This redundancy allows for real-time generation of ice draft estimates that can be used for vehicle control and decision making, as described in the previous section. To calculate these estimates onboard the AUV, a program was written by ASL Environmental Sciences based on their already well established post-processing algorithms. Combined with an estimate of the atmospheric pressure and a water column conductivity-temperature-pressure profile (CT profile), this program decodes the real-time output from the ice profiling sonar and generates an ice draft estimate. The software necessary to achieve this real-time control as described in the previous section, was not ready to be tested at the time of the cruise, but future tests are anticipated prior to the final ALTEX deployment.

The accuracy of the real-time estimate is limited by accuracy of both the atmospheric pressure input and the CT profile input. The CT profile is generated by a program which uses the calibrated real-time output from the Seabird SBE 25 boardset and knowledge of the AUV mission plan to determine the most recent vertical profile performed by the AUV. This is coupled with an AUV mission plan which is designed to run straight and level for a preset amount of time, ascend to a safe distance below the ice cover, and then return to the nominal operational depth. The ascents allow the science sensors to collect accurate profiles of the water column. They can be programmed to occur as often as deemed appropriate given the anticipated ice cover conditions, or possibly based on some adaptive program which recognizes possible changes in the water mass properties which would indicate the need to re-profile. Currently, the CT profile data is not post-processed in any way (except to calibrate the sensor data), so inaccuracies associated with plumbing lags, detection of erroneous data spikes, etc. are expected. This will cause some errors in the resulting ice draft estimate, but these are expected to be small compared with the errors that expected to accumulate in the atmospheric pressure predictions.

The atmospheric pressure input to the ice draft estimate program is based on weather predictions in the region and initial pressure data collected by the launch ship prior to deployment. The longer the mission proceeds, the worse the pre-programmed atmospheric pressure estimates are likely be. This could be remedied by developing an open-water detection algorithm on the vehicle. When the AUV is swimming under an open water event, the ice draft estimate should be zero. If it isn't, the program could readjust the atmospheric pressure value to force the drafts to zero. Some inherent problems with this type of scheme are fairly obvious, but if long duration AUV missions intending to measure ice draft real-time are to be planned, some kind of mechanism for reducing atmospheric pressure errors must be established.

C. Post-processed ice draft estimates

The ice profiling sonar data collected during the October mission is currently being post-processed. To insure the highest accuracy of the resulting ice draft estimate, algorithms developed by ASL Environmental Sciences are being used for this task. The key pieces of data generated by the IPS are range to the ice, based on an acoustic time-of-flight measurement and a nominal speed-of-sound in the water column, instrument pressure, used to determine depth, and instrument tilts. A general description of the data processing steps followed is:

1. Edit IPS range, pressure, and tilt files to remove out-of-range data and other data anomalies including spikes

2. Establish the atmospheric pressure time series using a combination of meteorological data and other available AUV data collected when the vehicle is floating on the surface
3. Compute a time series of the water level from the IPS pressure file, the atmospheric pressure data, and the latitude of the mission (needed because water density is a function of latitude)
4. Determine the corrected speed-of-sound value for water column from the CT profile data collected by the AUV
5. Generate ice draft estimates as a function of time using the edited IPS range data, water level data, platform tilt data, and corrected speed-of-sound value
6. Establish time series of the ice motion and AUV position
7. Generate ice draft estimate as a function of distance using ice draft time series, ice motion time series, and AUV position time series

The ice motion data was determined by using a time series position of the launch ship which was 'parked' in the ice during the AUV operations. The AUV position was dead reckoned based on approximate measurements from the navigation system of the heading and vehicle speed through the water. The impact of currents on the vehicle position relative to the ice was not included in the calculations. It is known that currents will introduce potential errors in the conversion of time series ice draft data to spatial ice draft data. A mechanism for measuring the speed of the vehicle directly with respect to the ice is under development and was being tested on the cruise, but was not working well enough to be used for determining the spatial ice draft data presented herein.

Fig. 4 shows the results of the above post-processing for one of the under ice missions completed by the AUV. The mission consisted of a spiral dive to 50 meters, a straight and level run for approximately 900 seconds, a 180-degree course change, and finally a straight and level run back to the launch location. The initial portion of the mission when the vehicle tilt was greater than 10 degrees, and the time when the vehicle was turning, are not included in the these plots due to the increased errors in the ice draft estimates caused by these maneuvers. It was not feasible to ground truth the ice sections under which the AUV flew, but Fig. 5 shows a panoramic mosaic photo taken at approximately the same time as the mission was conducted. It is estimated that the error in these measurements is less than +/- 10 centimeters, due to the accuracy of the speed of sound and atmospheric pressure measurements combined with the known performance of the ice profiling sonar.

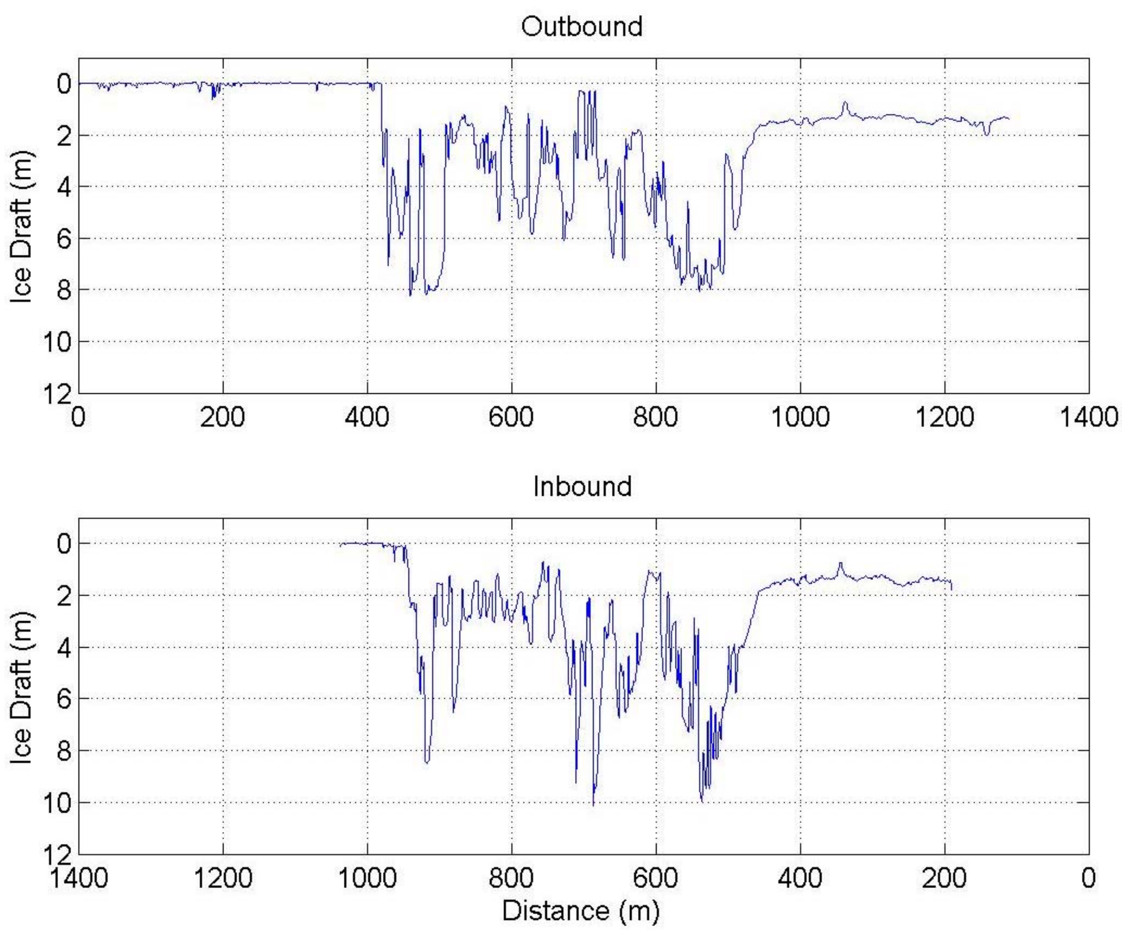

Fig. 4. AUV post-processed ice draft for mission 2001.290.08, ALTEX cruise, 17 October 2001

Fig. 5. Panoramic mosaic photo of ice conditions during mission 2001.290.08. Arrow represents approximation of outbound mission trajectory. (photo by Todd Walsh, ©MBARI)

Given the proximity to the lead from which the AUV was launched as well as the evidence from the panoramic photo taken near the time of deployment, the draft values estimated do indeed appear to be representative of the environment in which they were collected.

IV. CONCLUSIONS

MBARI conducted its first high-latitude test of the ALTEX AUV in October 2001 from the USCGC Healy in the region North and West of Svalbard. The nine days of AUV in-water testing that were accomplished have provided invaluable data regarding both the engineering performance metrics of the vehicle as well as the science sensing capabilities of the platform. In conjunction with CTD casts performed throughout the cruise, they also have the potential to add further information to the growing body of knowledge about the Arctic Ocean circulation and ice cover.

The ice profiling sonar collected numerous under ice profiles that are in the process of being analyzed. While ice coring for the purpose of ground truthing the collected data was not feasible during the cruise, the combination of satellite imagery, visual observation, and confidence in the Ice Profiler™ reliability will still make the collected profiles very useful. Future deployments of the system are expected to increase confidence in its accuracy. Furthermore, with additional development of the long duration AUV platform, the reality of using AUVs to monitor ice thickness is coming more and more into focus.

It is hoped that this effort to accurately measure ice drafts from an autonomous platform continues with the recommendation that future testing be performed in regions where adequate ground truthing can be collected. Additionally, extensive 20+ kilometer missions should be run to allow more traditional statistical comparison between this platform's data and historical data collected by other ice monitoring platforms such as moorings and submarines.

ACKNOWLEDGMENTS

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