Performance of an AUV Navigation System at Arctic Latitudes

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***Abstract*— In October of 2001 the Monterey Bay Aquarium Research Institute (MBARI) operated an AUV in the Arctic at latitudes exceeding 80°. The navigation instruments consisted of a ring-laser gyro INS coupled with a DVL and GPS, a separate fiber-optic based gyro-compass, and a traditional flux-gate AHRS system. The instruments were tested on deck, in open water, and under ice. This paper describes the performance of these instruments at high latitudes.**

***Index Terms*— Arctic Regions, Mobile Robot, Underwater vehicles, Inertial Navigation, Sonar Navigation, AUV, INS, Gyrocompass.**

I. Introduction

RECENTLY there has been increased interest in Arctic oceanography, in large part due to the apparent decrease in ice thickness. The Navy has suspended scientific use of under-ice capable submarines (SCICEX), leaving the development of Autonomous Underwater Vehicles (AUVs) as a primary means to collect oceanographic data over large areas and depths, and in a relatively short amount of time [1]. One of the most significant challenges of an Arctic-capable AUV is to navigate under the ice accurately enough to make its data scientifically valuable.

In October of 2001 MBARI operated an AUV in the Arctic at latitudes exceeding 80°. There were two objectives. First was to perform engineering tests in preparation for the future Atlantic Layer Tracking Experiment (ALTEX) mission [2]. These tests included evaluating the three on-board navigation instruments mentioned in the abstract, and described further below. The second objective was to take scientific measurements of nitrate concentration, salinity, temperature, and ice draft in the area between Svalbard and Greenland.

The ALTEX mission requires a vehicle that must travel on the order of 1000 km, and dive to 1,500 meters, under ice, without external navigation aids such as sonar transponders fixed at known locations. We hope that the ALTEX mission ultimately leads to commercialization and production of vehicles that are capable of routinely performing autonomous surveys covering large parts of the Arctic basin.

In the past there have been other high-latitude under-ice AUV missions such as UARS [3], Odyssey II [4], Theseus [5], and recently Autosub in the Antarctic. Both Theseus and Autosub employ an Inertial Navigation System (INS) aided by Doppler sonar.

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The navigation instruments included a ring-laser gyro Inertial Navigation System (INS) coupled with a Doppler Velocimeter Log (DVL) and Global Positioning System (GPS) receiver, a separate fiber-optic based gyro-compass Attitude and Heading Reference System (AHRS), and a traditional magnetic flux-gate AHRS system. For under-ice missions, the DVL was pointed upward to measure velocity with respect to the ice.

The operational procedure consisted of a ship-board GPS-aided INS alignment, launch of the AUV, execution of a series of preprogrammed missions, and finally recovery of the AUV and downloading of the data.

Navigation at Arctic latitudes was a challenge for all three of these instruments. The compass had difficulty determining heading because the Earth's magnetic field lines were nearly vertical. The ability of the two inertial instruments to align to north was inherently reduced as a function of secant of latitude.

This paper discusses the performance of the three navigation instruments and briefly describes the Arctic tests.

II. Vehicle Description

The AUV hull shape is a Series 58 Model 4154 Gertler, with cylindrical mid-sections inserted at the point of maximum diameter. It is .53 meters (21") in diameter, and had a length ranging from 4.25 m to 5.96 m depending on the number of mid-sections. See Fig. 1. The AUV was statically ballasted with a residual buoyancy of approximately 50 Newtons during the October 2001 sea trials.

Fig. 1. Engineering ALTEX AUV in the Arctic

A 2 degree-of-freedom gimbaled ring-wing tail provides control in both vertical and horizontal directions. The control system consists of outer and inner PID loops, for both heading and depth [6].

A fractional horsepower DC brushless motor with a 10:1 reduction gear box provides propulsion. For the sea trials, the energy source was a 3 kwHr silver-zinc battery, which gave about 9 hours of continuous run time at a cruising speed of 1.54 m/s (3 kts). The vehicle consumed about 225 watts, with 150 of that devoted to propulsion.

III. Objectives and Requirements

The objectives and requirements of the future ALTEX mission and the October 2001 sea trials are slightly different.

A. ALTEX Mission

The primary objective of the ALTEX mission is to track and quantify the Atlantic seawater layer that enters the Arctic basin through the Fram strait. This will ultimately provide a better understanding of the changes taking place in the Arctic such as the thinning of the sea ice.

The ALTEX mission currently plans to follow the 1300-meter isobath [2]. This serves as an aid to navigation through the use of a sonar altimeter. An INS will provide the primary navigation. The proposed route begins North of Svalbard and goes Eastward, passes North of Franz Josef Land, and finally turns South toward the Kara Sea. The length is approximately 1000 km.

Ice-penetrating buoys will provide increased navigation accuracy in post processing. The vehicle will carry twelve buoys, and will launch one approximately once each day underneath either a lead or an area that has ice less than a meter thick. The buoy will melt through the ice by mixing seawater with Pyrosolve-Z, a heat-producing compound, in the nose cone. The buoy then deploys both GPS and ARGOS antennas, and reports it's position and other data. There is no communication between the vehicle and the buoy once it is launched. The buoys can only show where the vehicle was; they cannot correct it's course during the mission. See [7] for details.

The required real-time positional accuracy of the AUV is on the order of 50 kilometers. However, the position must be recoverable to within 500 meters after post processing of the data transmitted by the ice buoys. The overall real-time navigation requirement is consequently on the order of 5 percent of distance traveled (DT). The vehicle will not be able to surface during the mission, so GPS fixes will be unavailable. The bottom will be out of DVL sonar range for much of the mission, eliminating the possibility of directly measuring velocity with respect to the Earth. Under these conditions, this is a challenging requirement, particularly given that the navigation system must compensate for motion of the water mass.

B. October 2001 Sea Trials

The general objective of the October 2001 sea trial was to test the operation of the entire system in its intended environment. This included launch, recovery, and operation in below freezing, low light, high latitude, and high wind conditions, where the vehicle must travel under the ice. The following sub-systems were explicitly tested:

1) Navigation.
2) Guidance, control, and propulsion.
3) Arctic science sensors.
4) Penetrating-ice buoys.

In order to validate the arctic sensors, Conductivity, Temperature, and Depth (CTD) measurements from the vehicle were compared to data taken from an instrument lowered from the ship.

A specific requirement for the October 2001 engineering deployment was that the relative position error of the navigation system must be less than the size of the lead (opening in the ice) where the vehicle was launched from. Leads range in size from mere fissures to many square kilometers. During this trip we restricted operations to leads of at least 1 km by several km. Our position error requirement was a circle of diameter 400 meters, 95% Circular Error Probable (CEP). See Appendix I for a definition of CEP.

A mission length of approximately 5 km was necessary to obtain adequate science and engineering data. This translated into an overall navigation requirement of $400/(2.08*5000) = 3.8\%$ where the 2.08 converts from 95% CEP to typical units of 50%. See Eqn. 6.

The navigation instruments we had available to us before the sea trials were:

1) Kearfott and RD Instruments Seadevil DVL/INS/GPS integrated inertial navigation unit.
2) Ixsea Octans Gyrocompass.
3) Crossbow DMU-AHRS, which measures magnetic heading. This is our standard heading reference, and was already built into the vehicle.
4) Litton LN-250 Inertial navigation unit.

The navigation error of the DVL/INS is less than 0.05% DT under good conditions where the DVL has continuous bottom track [8]. Mounting the DVL/INS inverted so the DVL will ping off the ice should then easily meet the 3.8% DT requirement. However, the navigation error may be larger than 0.05% DT because the AUV must start in open water where the DVL can't initially sense motion with respect to the ice, and the AUV may also pass under other leads or broken ice cover while on its mission. During these periods the navigation error is limited by the free inertial drift rate of the INS, which is less than 1 nautical mile per hour. Another source of error is that the ice may be slowly moving due to the wind. Subsequent sections discuss the observed DVL/INS performance in detail.

In the case of return missions under the ice, operation of the DVL off the underside of the ice is an advantage because the lead and support ship are approximately fixed with respect to the ice. Gradual motion of the local ice pack is then irrelevant since the DVL senses motion with respect to the ice.

The AUV operates by traveling between sets of geo-referenced waypoints. The control algorithm uses the navigated position to compute the perpendicular distance of the AUV from the track line connecting the two waypoints. It then trims the vehicle heading to null this cross-track error.

In addition to the nominal waypoint navigation algorithm, the AUV can operate using a simpler, less accurate mode where it navigates using only heading and time. The operators select heading durations before the mission by dead reckoning predictions. This is referred to as navigation by setpoints. A principal source of error, in this case, is the motion of the water with respect to the ice. If we assume this is no more than 10 cm/second in the worst-case direction, our position error requirement implies a heading requirement of $((400 - 0.1 * 5000/1.5)/5000/2.08/1.18) \approx 0.0054$ radians or $0.31°$ rms. Here we additionally assume equal standard deviations in the along-track and cross-track axes. See Eqns. 6 and 7.

Under good conditions the DVL/INS will provide a stable non-magnetic heading reference accurate to $0.03°$ rms [8], thus enabling the use of setpoints in the Arctic, under the above assumptions. Setpoint navigation turned out to be crucial during the sea trials.

The AUV navigation algorithm did not explicitly account for heading misalignment error in the setpoint mode, as it tends to cancel for trajectories that form a closed loop. All trajectories necessarily formed a closed loop during the sea trials, since the AUV always had to return to the lead. The eventual ALTEX mission will use only waypoint navigation. In this case, heading misalignment of the DVL/INS as a unit may affect the control error of the AUV, but not navigation error.

The Ixsea gyrocompass, combined with the DVL, was also a candidate for navigation during the sea-trials. This would permit a DVL-aided dead-reckoning type algorithm, which would produce a position estimate. The DVL would again be mounted facing up so that it could measure velocity with respect to the ice. This algorithm would then account for lateral as well as forward motion. A significant source of error for this arrangement would be the misalignment between the DVL and the gyrocompass, since they are separate instruments.

Navigation error due to the DVL alone, presuming continuous ice tracking, is less than 1% DT, CEP. This results from the specification of $\pm 0.4\% \pm 2$ mm/second, one sigma, per axis, for the 300 kHz DVL [9].

The gyrocompass has a heading accuracy specification of $0.2°/\cos(\lambda)$, rms, where λ is latitude. At $\lambda = 82°$, the heading error is $1.4°$ rms, which translates into a position error of 3.0% DT CEP, again assuming an equal standard deviation in the along-track axis. This heading error is not necessarily constant like a misalignment angle. A complete error analysis of navigation by combining the gyrocompass and the DVL was beyond the scope of this project, however, given the errors discussed above, the overall error may have been acceptable as long as we restricted operations to below $82°$ of latitude.

The Crossbow magnetometer was already built into the AUV and was included during the sea trials.

The Earth's magnetic field had an inclination of approximately 83.5° in the test area on October 2001. Consequently, the strength of the horizontal component of the field was reduced to less than 12% of its low-latitude value. Additionally, the vehicle needed only to pitch 6.5° in the plane of the magnetic field lines for the heading signal strength (the horizontal component in the vehicle-fixed body frame) to go to zero. For these reasons standard magnetic compass operation was considered unreliable.

Fig. 2. Kearfott and RDI Seadevil Integrated DVL/INS/GPS

Another problem was that the declination changed rapidly over relatively short distances; it was about 4.6 degrees per 100 km in the test area. However, it is possible that comparison of the magnetometer output against an on-board magnetic field model could produce a feasible heading estimate at times when the instrument has adequate signal strength. This method could be useful as a heading aid. Employing an on-board magnetic field model has the disadvantage of first requiring the vehicle location to determine heading.

The engineering team selected the Kearfott Seadevil as the primary means of navigation, since the Gyrocompass and the magnetic compass cannot operate in large areas near the pole and hence are not generally suitable for Arctic navigation.

The LN-250 arrived too late to be tested in the vehicle, and was only briefly bench-tested aboard the ship.

IV. Navigation Instruments

The primary navigation system was a Kearfott and RD Instruments Seadevil, which includes an INS mechanically coupled to a DVL, and a GPS receiver [10]. The INS is based on a 3-axis ring-laser gyro with a path length of 24 cm. Figure 2 shows the instrument.

The INS contains a gyrocompass algorithm as part of its Kalman Filter. This is independent of the Ixsea Gyrocompass, which is a completely separate instrument that propagates heading but not position.

Recent increases in computational capacity now permit implementation of optimal estimation in the real-time implementation of the INS, and effectively merge the alignment and navigation phases. The parallel development of complementary navigation sensors such as the Global Positioning System (GPS) and Doppler Velocity Logs (DVL) sets the stage

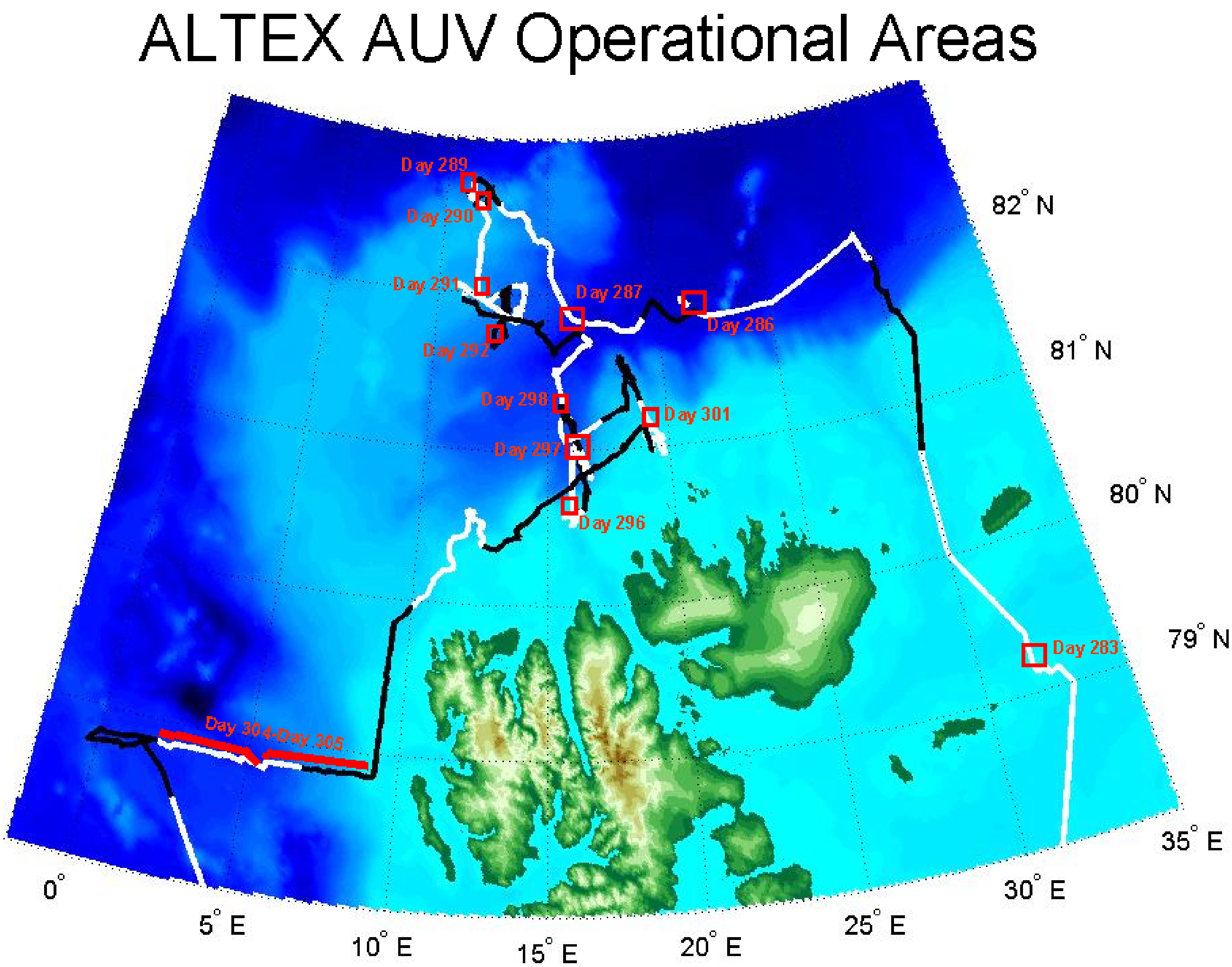

Fig. 3. Ship's Track in the Vicinity of Svalbard, 11 Oct to 2 Nov 2001

for a synergistic combination of these three sensors and their embedded computers. This combination of sensors minimizes the alignment-to-north limitation in the polar region. This type of multiple sensor DVL/INS configuration was developed by Kearfott and RD Instruments.

The objective of the integrated system design is to provide the best estimate of position, velocity, and attitude by combining information from the three sensors. The GPS receiver provides long-term position accurate to within 10 meters when four or more satellites are in view. The DVL provides velocity accurate to within 1 cm/s when in "bottom track" and accurate velocity with respect to the water mass when in "water track." The INS provides very accurate short-term changes in velocity and attitude, with position and velocity error less than 1 Nautical Mile per Hour (NMH) and 1 m/s long term, following alignment. At lower latitudes, the integrated system provides accurate attitude with position error less than 10 m when GPS satellites are in view, and position error growth less than 0.05% of distance traveled (DT) when GPS data is not available, and the DVL is providing bottom-track data.

The challenge of accurate heading alignment of the inertial sensors in a polar region remains today, if the classic gyrocompass mechanization (detection of the earth's rotation vector) is utilized. When external information (position and velocity data from GPS or DVL sensors, for example) is available, a more general Kalman Filter estimation algorithm performs the alignment rather than a classic gyrocompass mechanization. Combining the information content of the inertial sensor with that of the external sensors results in an integrated sensor system providing position, velocity, and attitude worldwide.

At high latitudes where gyrocompassing is less accurate, the Kalman Filter aligns the INS sensor axes to the geographic frame computationally by comparing the errors in navigation data determined by the unaligned INS to data provided by the GPS. If the GPS is unavailable, the Kalman Filter uses the DVL. Once the inertial sensor orientation is determined, highly accurate underwater operation (without the aid of data from the GPS receiver) continues by combining velocity data developed by the DVL sensor with the INS sensors. If the DVL maintains bottom-lock, the position error growth will be less than 0.05%DT.

In the case where the INS uses its gyrocompass algorithm for alignment, rather than GPS, both the alignment-to-north accuracy and the navigation accuracy decrease proportional to the secant of latitude. For a gyrocompass alignment at $80°$ latitude, position error growth would be approximately 0.3% DT, and at $85°$ it would be 0.6% DT.

The AUV also carried an Ixsea Octans Gyrocompass, which is a separate AHRS instrument. It contains accelerometers and fiber-optic gyros, and computes heading but does not propagate position. It also outputs attitude angles and angular body rates.

The third on-board instrument was a Crossbow DMU-AHRS magnetic compass. It consists of a triad of flux gate magnetometers, accelerometers, and piezo-electric gyroscopes. The instrument computes magnetic heading based on magnetic field, and pitch and roll attitude measurements from the accelerometers. The heading is gyroscopically stabilized.

V. Results of Arctic Sea Trials

Figure 3 shows the path of the support ship Healy during the sea trials, annotated with day-of-year (DOY) number at the locations where the AUV was either deployed or operated on deck. In subsequent data plots the DOY is in the title, permitting the reader to locate the area where the vehicle was operated. The field team did not deploy the AUV after day 298 due to high winds, cold, and darkness.

The darker blue areas show deeper water, with the Fram strait running north/south along the prime meridian. The lighter area to the northeast of Svalbard is the Yermak Plateau.

A. DVL/INS Moving-Base Alignment and Navigation Accuracy During On-Deck Tests

A goal of the navigation tests was to demonstrate the performance of the integrated DVL/INS/GPS system in the Arctic region. The initial concern was the ability to align the INS sensors to north using the GPS navigation system, instead of the classic gyrocompass technique used statically at lower latitudes. To provide a benchmark, Kearfott performed real-time mechanization simulations of the as-implemented alignment mechanization. Simulated was a boat in the polar region performing a box maneuver. The simulations indicated a desired alignment accuracy of less than 2 milliradians could be achieved in less than one hour under the simulated conditions. Initial testing was performed on October 14, 2001, north of Svalbard, on deck. Fig. 4 shows the path of the ship. Figures 4, 5, 6, and 7 are from the same experiment and share the same time axis.

Fig. 5 shows the time history of the three attitude states estimated by the Kalman Filter for two sequential alignments that correspond to the tracks in Fig. 4. It consists of the X and Y level axes error, and heading error standard deviations. The three alignments started when the standard deviations were off-scale in the plots and concluded by periods of pure inertial navigation. Changes in vehicle motion aids the alignment algorithm, and the impact on alignment by vehicle dynamics can be dramatically seen at 50 minutes by the 35-degree turn resulting in tilt and heading accuracy improvement of 75% in the level axes (0.2 to 0.05 milliradians) and 50% in the heading axis (6 to 3 milliradians).

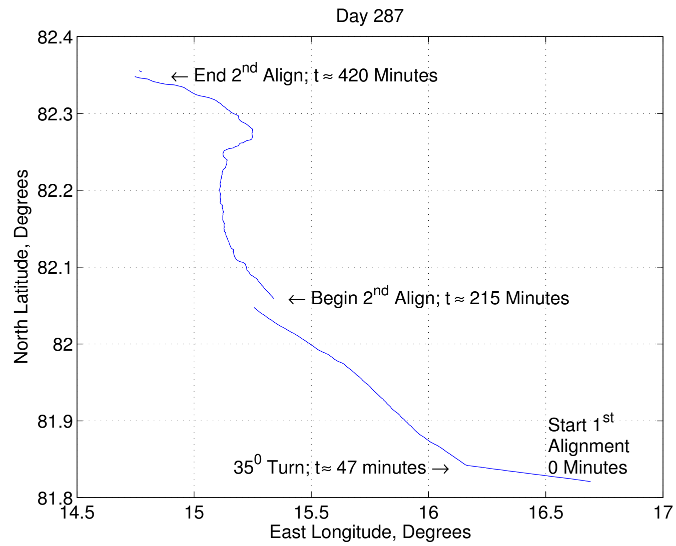

Fig. 4. October 14, 2001, Test Trajectory

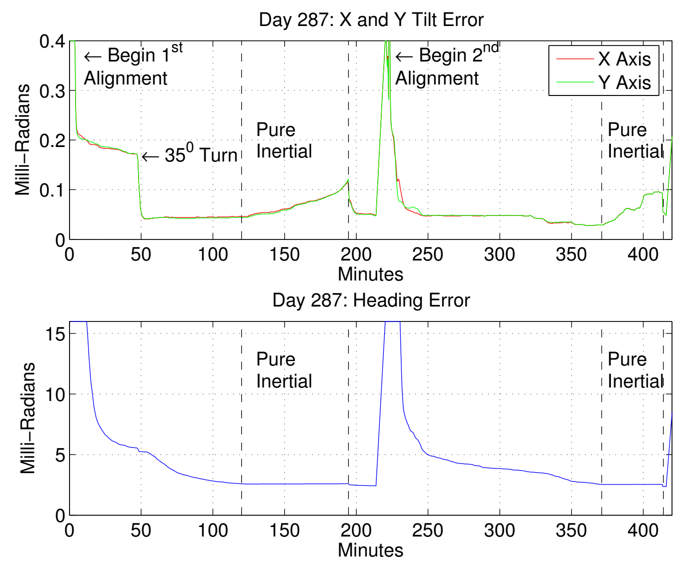

Fig. 5. Standard Deviation of the Attitude Error Estimates

The next step was to verify the heading accuracy predictions without a reference source of vehicle heading. The approach taken was to first let the INS align using position and velocity from the GPS, then upon completion of alignment remove GPS and operate the INS in the pure inertial mode for a period of time. When the GPS was reconnected, the measured position error was compared with the predicted error for consistency. This in turn inferred consistency of the heading error estimate.

The INS was operated in the pure intertial mode for approximately one hour, following each of the first two alignments of Fig. 5, by removing the GPS antenna. The position error growth predicted by the Kalman Filter for these tests is shown in Fig. 6, illustrating slightly better than a 1 NMH estimated error (1.22 km/axis).

At the end of the two pure inertial periods (at about 190 and 410 minutes in the data recording), the GPS antenna was reconnected. The Kalman Filter utilized GPS observations to

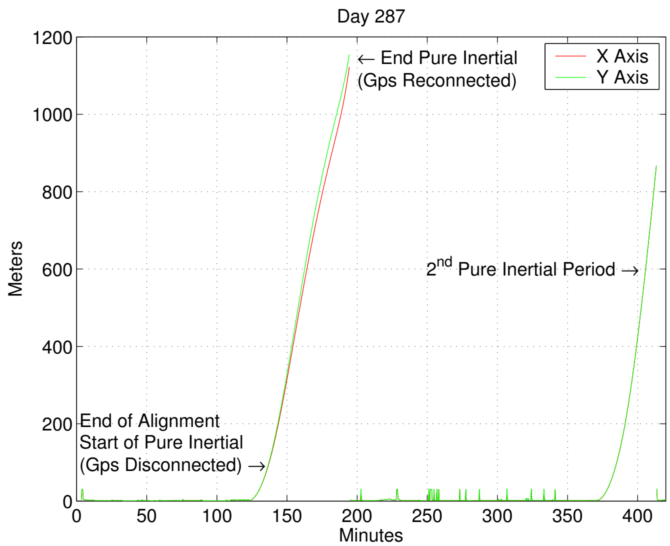

Fig. 6. Standard Deviation of the Position Error Estimates

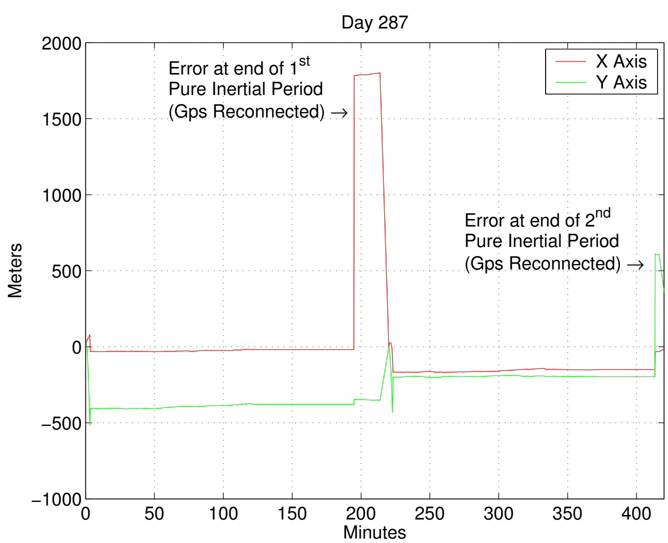

Fig. 7. Position Error Estimates

correct for the position and velocity errors developed during the pure inertial periods. This is illustrated in Fig 7 by the step changes of the Position Error Estimates. At 190 minutes the X axis estimate changed from near zero to about 1800 meters (prior to initialization and the start of the second alignment at 220 minutes). At 410 minutes the Y axis estimate changed from about -200 meters (accumulated during the initial coarse align mode where heading was unknown) to about +600 meters.

The first test resulted in a position error of less than 1 NM and a velocity error of less than 20 cm/sec (0.6 f/s) after 70 minutes. This demonstrated performance of about 0.9 NMH. The second test resulted in a position error of less than 0.4 NM, and a velocity error of less than 30 cm/sec (1 f/s) after 45 minutes This demonstrated performance of about 0.7 NMH.

For the tests, the position error performance demonstrated is consistent with the 1 NMH predicted by the Kalman Filter. This confirms that the heading alignment is also consistent with the 2 milliradian heading accuracy indicated by the Kalman Filter covariance solution.

Pure inertial navigation performance can be characterized in terms of nautical miles per hour (NMH) 50% probable circular position error rate (CEP) determined mainly by the quality of the inertial sensors (gyros and accelerometers). The most common INS quality level is known as medium accuracy or a 1 NMH system. This is the quality of the INS within the DVL INS.

B. *DVL/INS Water-Tracking Performance*

The second operational need was for the DVL/INS to navigate with DVL velocity aiding, following loss of the GPS signal when the vehicle submerges. There were several confidence building steps required for the DVL/INS system prior to Arctic testing. First, the misalignment angles between the INS and the DVL needed to be accurately calibrated. Second, the algorithm had to demonstrate proper performance when aided by water-mass velocity, since the altitude of the vehicle in the Arctic was expected to exceed the DVL's range. Finally, the DVL/INS must be able to operate while the DVL is tracking the bottom of the ice pack. The first two steps were accomplished in the waters off California in the summer of 2001.

The DVL/INS is constructed such that the mechanical alignment angles between the INS sensor axes and the DVL sensor axes are small. For a standard, separately packaged two-sensor configuration, the estimated initial alignment angles are approximately 2.5 degrees with a standard deviation of approximately 0.5 degrees. The major horizontal navigation error contributors are the DVL X axis velocity data coupling into the inertial Y axis, and the DVL Y axis velocity data coupling into the inertial X axis. This sensitivity is represented by the "X to Y" and "Y to X" misalignments of the DVL sensor X and Y axes to the inertial sensor X and Y axes, as shown in Fig. 8. The DVL/INS alignments were determined to be within about 3 milliradians $(0.15°)$. This was verified by testing in June 2001 near RDI in San Diego, CA.

The DVL/INS was tested in August 2001 near MBARI on Monterey Bay, CA. The day-to-day and in-run changes in these important parameters were verified to be small as shown in Fig. 9. The Kalman Filter error states were initialized to 1 milliradian. This estimate of the standard deviation was confirmed during several tests. The Kalman Filter estimates of the key X to Y alignment angles were less than the 1 milliradian initial standard deviation during the testing program.

Figures 8 and 9 are of the same parameters. Figure 8 is the estimated misalignment angles starting from the assumption that during manufacture the two sensors were perfectly aligned. The Fig. 8 June 2001 data is the estimated full magnitude of the manufacturing error, which is less than 3 Milli-Radians after the filter achieves steady-state, at 90 minutes. The Fig. 9 August 2001 data is the change in estimated misalignment angles with the assumption that the final estimate of Fig. 8 is perfect. The data in August is a

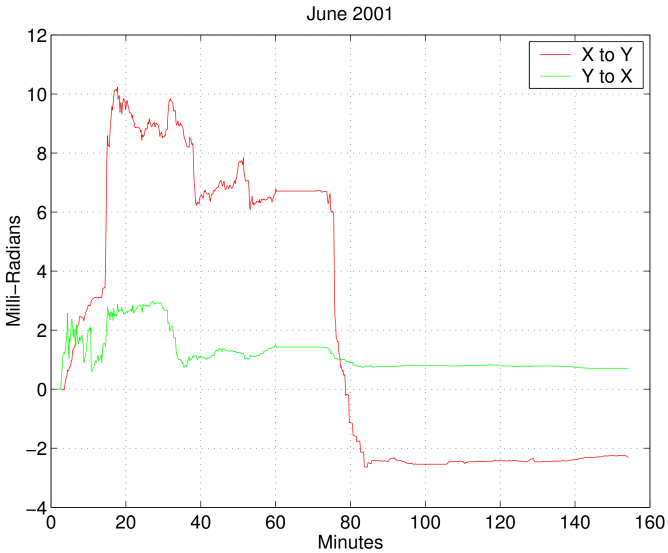

Fig. 8. DVL to INS Alignment Estimates

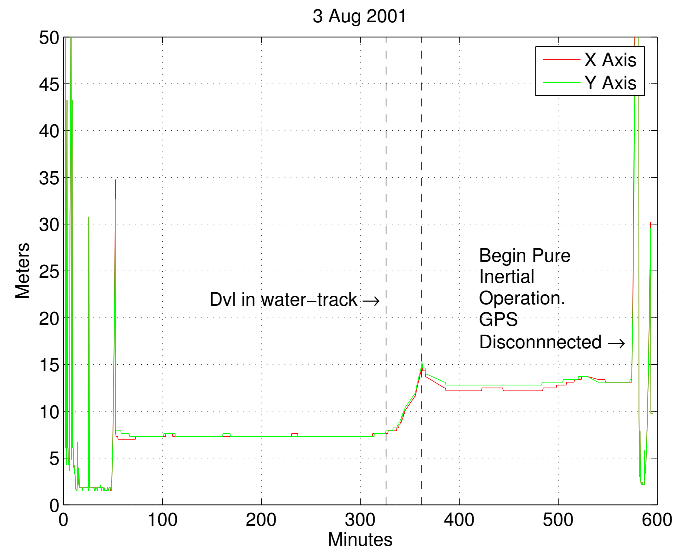

Fig. 10. Standard Deviation of the Position Error Estimates

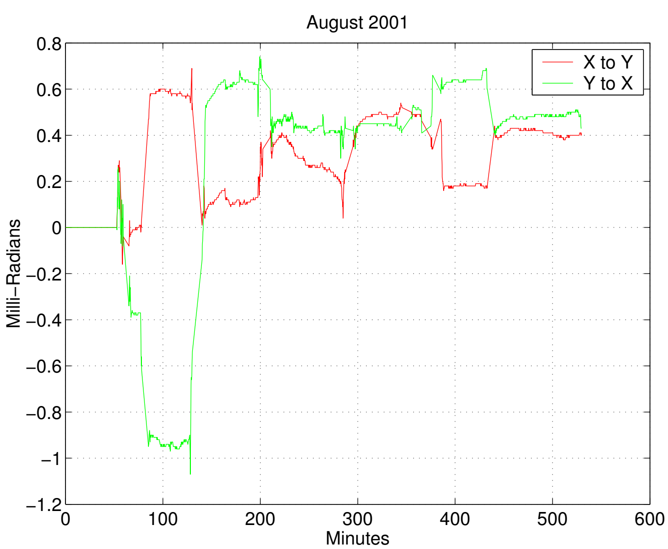

Fig. 9. DVL to INS Misalignment Estimates

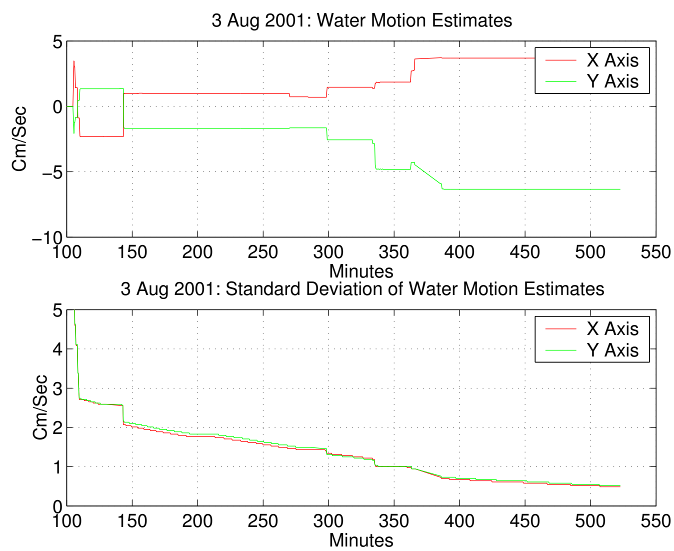

Fig. 11. DVL Tracking Data and Water Motion Estimate

measurement of the error in the June 2001 estimate plus any change since the June 2001 estimate, which is less than 0.5 Milli-Radians.

The second capability verified on Monterey Bay, CA is the ability to utilize DVL water-track velocity information as observations to the Kalman Filter and to maintain precision navigation for an extended period of time. On August 3, 2001, the DVL/INS was aligned using GPS on board the carrying ship prior to placement in the water and operated 8 1/2 hours in the water using DVL data. Due to the depth of Monterey Bay, the DVL spent a significant part of the time in water track mode. Figures 10 and 11 show results from this test.

The accumulated position error over the entire test was 130 meters (not shown). The Kalman Filter's estimate of position error was about 70 m per axis after 580 minutes of recorded data. See Fig. 10. The estimated position error increases at about 360 minutes of recorded data, where water-track data was exclusively used for almost 30 minutes. For the final 7 minutes of operation, the DVL/INS operated without either DVL or GPS aiding. Most of the estimated error developed during these final minutes of pure inertial operation prior to the availability of GPS data for observations.

The DVL/INS system also estimates water current, as shown in Fig. 11 for this mission.

During testing in the Arctic region on October 24, 2001, the DVL/INS was aligned in similar fashion using GPS aiding on-board the carrying ship prior to placement in the water. During the alignment on-board the ship, the Kalman Filter received an estimate of water mass motion of 61 cm/sec (2 ft/sec) in a S/SW direction. This is clearly incorrect as the vehicle was not yet in the water.

The DVL/INS was placed in the water and operated for 10 3/4 hours using DVL water track data. 6 1/2 hours of data were recorded during this test. Following compensation for

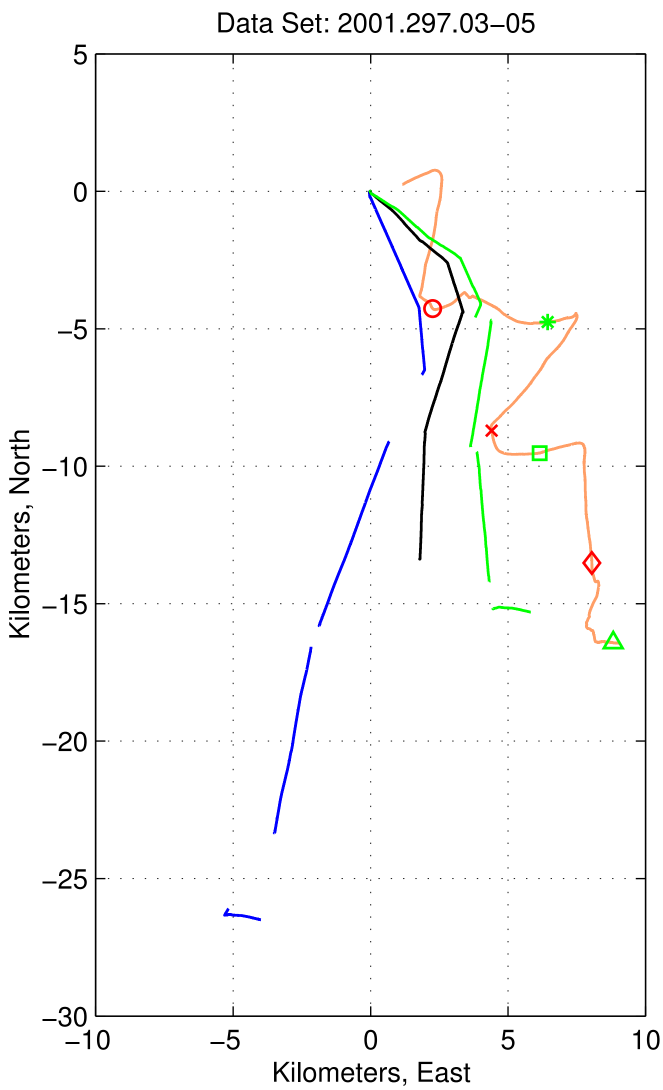

Fig. 12. Various Position Tracks, Including the DVL/INS and the Support Ship

the initial water-mass motion estimate, the DVL/INS position track was consistent with that of the carrying ship. The DVL/INS and the carrying ship's relative position track, shown in Fig. 12, illustrates the position errors during the 6 1/2 hours of data accumulated during 10 3/4 hours of operation in the water utilizing DVL water track aiding. The erroneous water motion estimate was partially due to the on-deck INS alignment procedure necessary on this expedition. The GPS receiver in the DVL/INS typically receives a signal from an antenna mounted on the vehicle whenever the vehicle is on the surface. In the Arctic the GPS antenna did not receive a signal, consequently the antenna was manually connected to the DVL/INS while on deck, and disconnected prior to launching the vehicle into the water. Under normal conditions the DVL data would not be processed while on the deck, and the DVL/INS would receive GPS data in the water until the vehicle submerged. This would permit estimation of the water motion while the vehicle is under water.

The tests shown in Fig. 12 consisted of three consecutive southward legs. The vehicle was programmed to repeatedly dive to 500 meters, then climb to 5 meters while maintaining a constant heading. The DVL/INS was pointed down, and the vehicle was operating in open water.

The four blue leftmost North/South segments in Fig. 12 show the uncorrected vehicle track as measured in real time by the DVL/INS. The four green North/South tracks that are second from the right show the post-processed vehicle track after removal of the erroneous water motion estimate. The rightmost track is the ship position, with annotations showing the position at the start and stop of each AUV leg.[1] The triangle at the bottom of the ship track shows the vehicle on the deck of the ship, and corresponds to the fourth (eastward) leg in both the real-time and the post-processed vehicle track. This indicates that the vehicle was set to the East by about 4 km by the current, and is consistent with the general idea that the Atlantic water flows North through the Fram Strait and sweeps to the East around the top of Svalbard.

We consider this to be good navigation performance by the DVL/INS. The challenge was that the vehicle was out of range of the ice or bottom and GPS data was not available when the vehicle was in the water on the surface. Under these circumstances it is not realistically feasible to inertially sense water current motion much less than 1 NMH with an instrument that has the required size and power, and is available generally.

Also, on this day the INS was aligned to within 1 milliradian, which is extremely good performance at this latitude.

The third North/South track, second from the left, shows the vehicle position re-created by dead-reckoning using the DVL data and the INS heading. This was done as a comparison. It unfortunately does not include vehicle motion in between the legs, because the on-board software does not log data unless a mission is running.

C. Comparison of DVL/INS, Gyrocompass, and Magnetic Compass Heading Error

Figure 13 shows the difference between the three different heading sources for the second leg of the day 297 tests, which are in Fig. 12. The lower strip shows the vehicle's pitch angle. The reason for the commanded depth oscillations, or yoyos, was to take CTD data, but the effect of the pitch angle on the navigation instruments is interesting (many other missions were straight and level flight). The INS was predicting a heading error of 1 milliradian rms during this mission, and therefore is considered to be "truth." The top strip of Fig. 13 shows both the magnetic heading minus the INS, and the Gyrocompass minus the INS.

It is not possible to state the absolute error between the various heading sources as they were only aligned mechanically to $\pm 5^\circ$. However, the transient behavior is enlightening.

The magnetic heading varies by 3° depending on the pitch angle, most likely due to the local magnetic inclination of 83.5°. During the previous leg, the magnetic heading had an

[1] The circle shows the ship's position at the end of the first leg. The star and x, and the square and diamond, show the position at the beginning and end of the second and third legs, respectively.

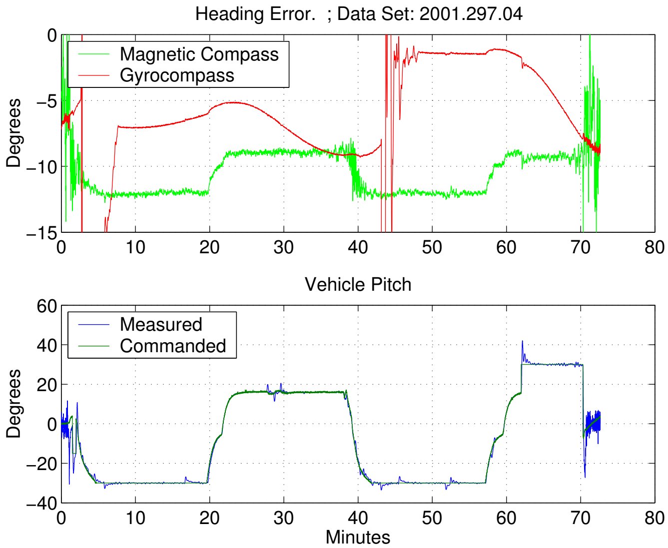

Fig. 13. Gyrocompass and Magnetic Heading Error, Day 297

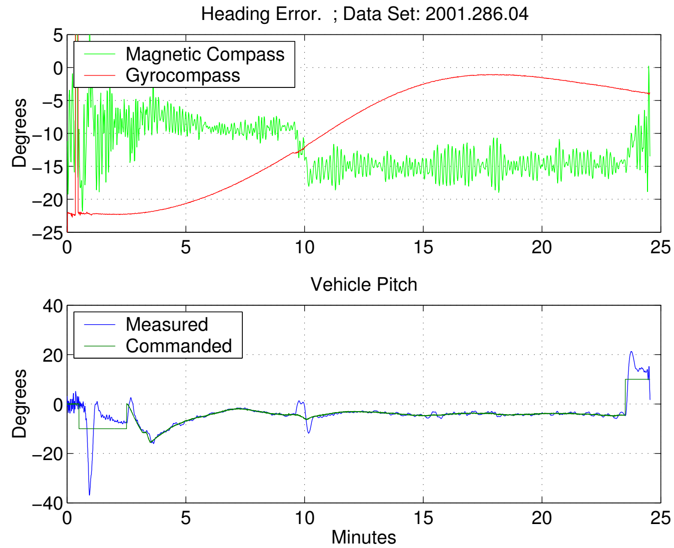

Fig. 14. Gyrocompass and Magnetic Heading Error, Day 286

$8°$ pitch dependence, and on the third leg the dependence was nearly absent at $.25°$.

The heading error is also a function of heading angle. The magnetic heading error differs by as much as $2.9°$ when comparing the descending portions of the three legs in Fig. 12. The vehicle was consistently pitched down at $-30°$ during the descending portions. The three legs had commanded headings of $160°, 195°$, and $180°$, respectively, indicating that a change in actual heading of $35°$ can cause the $2.9°$ error in the magnetic heading measurement.

Finally, we computed the magnetic inclination from the gravity and magnetic field vectors measured by the instrument. It deviates by $1.25°$ as a function of vehicle pitch. The IGRF2000 model indicates that the magnetic declination and inclination should be constant to within $.17°$ (10 minutes of arc) over the short length of the mission, at that location and time.

The magnetic compass was not calibrated in the Arctic, but was calibrated shortly before the Arctic tests in Monterey Bay, with the vehicle in the water under nominal operating conditions. Calibration data was not available.

Figure 14 shows heading differences between the three instruments for a mission that consisted of two straight and level legs separated by a turn of $180°$. The vehicle turns at ten minutes. Both the INS and the Gyrocompass were reporting themselves aligned throughout the mission, with the INS's Kalman Filter estimating the heading error at less than 4 milliradians, rms. The magnetic heading error difference was $6°$ after the turn.

The Ixsea Gyrocompass was showing a large amplitude oscillation with a period of 64 minutes (not the Schuler period of 84 minutes). This seems unaffected by the heading change. Figure 13 shows a similar result, although the heading does show a dependence on vehicle pitch angle. The 64-minute period is still apparent. These oscillations are apparently due to high-latitude operation.

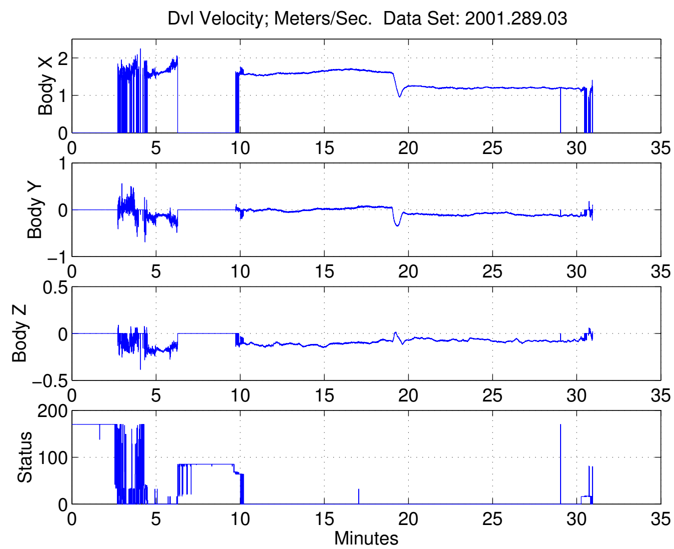

Fig. 15. Velocity of the AUV With Respect to the Ice

D. DVL Ice-Tracking Performance

Figure 15 shows the velocity of the AUV with respect to the ice. This is from an out-and-back mission at 30 meters depth. The vehicle was in straight and level flight, except for the turn at 18 minutes when it reversed it's course. The velocity is coordinatized in the vehicle frame, which is x ahead, y to starboard, and z down.

This data consists of velocity with respect to the ice, and does not contain any information about Earth-referenced ice or water motion. Since the lead and support ship can be considered approximately fixed in the ice, the relative motion of the water with respect to the ice is the dominant cause of position error with respect to the lead.

The bottom strip shows the status flag, which is zero when all four DVL beams report good data. The vehicle began in open water, then passed under some broken ice cover from 3 to 5 minutes, then went under solid ice at 10 minutes. The status flag shows that the DVL got very good data off the ice for the rest of the trip.

The negative value along the body z axis is due to the AUV's nose-down attitude while in straight and level flight.

It is apparent from the top strip that the AUV had a following current (with respect to the ice) during the outbound leg, and the reverse inbound. Further, the y axis shows a small lateral component, and also the possible effect of a heading misalignment angle between the DVL/INS and the vehicle centerline. If one assumes that the velocity difference between the outbound and inbound legs was entirely due to relative water current and heading misalignment, and that the current remained constant during the mission, the heading misalignment angle was $\psi_m = 1.9°$. The speed of the AUV with respect to the ice was 1.41 meters/second, with a following current (outbound) of .21 meters/second. See Appendix II for a derivation.

VI. Lessons Learned

The Arctic trip was challenging in that the vehicle and all of its support gear had to be disassembled, shipped internationally, then reassembled and deployed from a ship of opportunity. It was necessary to bring spares of nearly everything due to the remote location. The field team made a careful and thorough effort to anticipate problems, and their effort was successful in that the vehicle was able to operate at every opportunity permitted by the weather and by the discovery of leads of adequate size. But, with an operation as risky and complicated as this one was, some problems were bound to happen. The list below enumerates some of the navigation-related lessons that the team learned, with the hope that future expeditions can avoid them by being forewarned.

1) Test the final configuration of the GPS system in as realistic an environment as possible. The vehicle-mounted GPS antenna and receiver in the DVL/INS could not obtain a signal in the Arctic. This was found to be related to the type of antenna cable and connector. Following the sea trials, the problem was solved by replacing the antenna with a Bluefin GPS/RF model, and using a D.G. O'Brien connector instead of an Impulse.
   The absence of the in-water GPS signal necessitated an on-deck alignment procedure, where the DVL/INS was connected to an external GPS antenna mounted high on the ship. When the alignment completed, the vehicle was disconnected from GPS and deployed.
2) Arrange to test any ice-specific configurations ahead of time. During the sea trials, the team was unable to properly configure the DVL/INS to operate inverted, so that the DVL could navigate off the ice. This turned out later to be easily correctable with the right set of initialization parameters. The inertial computer had to be configured for the sensors rolled $180°$ from the standard orientation (Y and Z axis gyros and accelerometers measuring oppositely signed rates and accelerations, while the X axis measurements did not change). The DVL computer had to be configured with the four sonar transducers also sensing opposite sign velocities (port/starboard and up/down were reversed while fore/aft did not change). For downward-facing operation, the specfic commands were EA$= 135°$ for the DVL, and VALPHA$= 0°$ for the INS. For upward operation, it is EA$= 45°$, and VALPHA$= 180°$.
   Because of this problem, the field team ended up running the vehicle under the ice using basic dead reckoning with setpoints. The DVL data was logged and was very useful in predicting water and ice motion for subsequent missions. The under-ice mission lengths were still about 5 km, but the vehicle was not allowed to get more than approximately 1.5 km away from the lead.
3) Test any ice-specific operational procedures ahead of time. As described in Section V-B, the DVL/INS initialized with an erroneous water motion estimate, which prevented way-point operation. This was due to the untested on-deck alignment procedure, which was in turn a result of item 1.
4) The USBL was unusable for navigation due to the long transducer pole and ship-of-opportunity constraints. It was only good for approximate real-time tracking.
5) Calibrate the magnetometer on site.

VII. Conclusions

The DVL/INS, produced by Kearfott and RD Instruments, proved to be accurate and reliable. In conjunction with external aids such as bathymetry following, it will enable an ALTEX class AUV to perform basin-scale surveys. Items 2 and 3 in Section VI are relatively easily corrected, and are the type of things that the sea trials were designed to detect before committing the vehicle to a long under-ice mission.

The Crossbow magnetometer showed promise as a potential aid, but would require careful calibration on site, and recalibration if any instruments are changed out.

The Ixsea Gyrocompass had large oscillations, and was not used for navigation.

Acknowledgments

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Appendix I
Review of CEP Criterion

The Circular Error Probable criterion is a way of expressing two-dimensional miss distance as a single statistic. The key assumption is that the component X and Y axis errors are independent Gaussian random variables. Here we will also make the simplifying assumption that they have equal variance

σ^2, although this is not strictly necessary. See [11], page 366, and [12].

Since we are really concerned with radial error, it makes sense to define a new random variable that combines the error in each axis into a miss distance,

$$R = \sqrt{X^2 + Y^2}. \tag{1}$$

The random variable R has the well-known Rayleigh density function as long as the component Gaussian densities are independent. The Rayleigh distribution function (p.195, [13]) is given by

$$P_R(r) = 1 - \exp\frac{-r^2}{\overline{R^2}}, \tag{2}$$

where $\overline{R^2}$ is the mean-square value,

$$\overline{R^2} \triangleq E\{R^2\}. \tag{3}$$

Beware that $\overline{R^2}$ is *not* the variance, because the Rayleigh density has a non-zero mean. Also,

$$\overline{R^2} = 2\sigma^2. \tag{4}$$

It is common to set the left-hand side of Eqn. 2 to a value P_o, such as 50% or 95%, and solve for the corresponding radius r_o,

$$r_o = \sqrt{\ln\left(\frac{1}{1-P_o}\right)\overline{R^2}}. \tag{5}$$

This means that for an arbitrarily large number of trials, P_o of the results will fall within radius r_o.

Several useful numerical relationships from Eqn. 5 are:

$$r_o(95\%) \approx 2.08\, r_o(50\%); \tag{6}$$
$$r_o(50\%) \approx 1.18\,\sigma. \tag{7}$$

APPENDIX II
DERIVATION OF ICE-REFERENCED VELOCITY AND HEADING MISALIGNMENT ANGLE

This section derives formulas for relative water motion, and misalignment of the DVL/INS to the vehicle centerline, based on the DVL data. The derivation makes the simplifying assumptions that: the relative motion of the water with respect to the ice is constant throughout the mission; the ice is a rigid sheet; the AUV maintains a constant heading on the outbound leg, and then maintains the reciprocal heading inbound; the errors apparent in the DVL data are entirely due to water motion and misalignment angle.

Let the velocity of the water with respect to the ice be given by ${}^I\vec{v}^{\,W}$, and the velocity of the AUV with respect to the water be given by ${}^W\vec{v}^{\,B}$. Then the velocity of the AUV with respect to the ice is

$${}^I\vec{v}^{\,B} = {}^I\vec{v}^{\,W} + {}^W\vec{v}^{\,B}. \tag{8}$$

The velocity measured by the DVL is then

$$\begin{aligned} {}^I\vec{v}^{\,B}_{DVL} &= T_{DVL/B}\; T_{B/I}\;\; {}^I\vec{v}^{\,B}_I && (9)\\ &= T_{DVL/B}\; T_{B/I}\;\; \left({}^I\vec{v}^{\,W} + {}^W\vec{v}^{\,B}\right)_I. && (10)\end{aligned}$$

The subscript I on the rightmost vectors means they are coordinatized in the I frame. This reference frame is assumed to be fixed in the ice, with x along the direction of the AUV's outbound leg, and z down. The DVL frame, referred to by the subscript DVL on the leftmost vector, is displaced about the vehicle z axis by a small misalignment angle ψ_m. Thus, considering only the horizontal plane,

$$T_{DVL/B} \approx \begin{bmatrix} 1 & \psi_m \\ -\psi_m & 1 \end{bmatrix}, \tag{11}$$

where $T_{DVL/B}$ is a direction cosine matrix that takes a vector from the B frame to the DVL frame. All reference frames here are right handed.

The B reference frame is the SNAME standard vehicle axes; x ahead and z down.

Both ${}^I\vec{v}^{\,B}$ and $T_{B/I}$ change sign when the AUV turns from the outbound to the inbound leg, but are constant otherwise. On the outbound leg, $T_{B/I}$ is the identity, and

$${}^W\vec{v}^{\,B}_I = \begin{bmatrix} v \\ 0 \end{bmatrix}. \tag{12}$$

Let the components of ${}^I\vec{v}^{\,W}_I$ be given by

$${}^I\vec{v}^{\,W}_I = \begin{bmatrix} v_x \\ v_y \end{bmatrix}, \tag{13}$$

and for the outbound leg, let

$${}^I\vec{v}^{\,B}_{DVL} = \begin{bmatrix} v_{ox} \\ v_{oy} \end{bmatrix}. \tag{14}$$

Substituting Eqn. 11 through Eqn. 14 into Eqn. 10 gives

$$\begin{bmatrix} v_{ox} \\ v_{oy} \end{bmatrix} = \begin{bmatrix} 1 & \psi_m \\ -\psi_m & 1 \end{bmatrix}\begin{bmatrix} v_{ox}+v \\ v_{oy} \end{bmatrix} \tag{15}$$

for the outbound leg. Changing sign on ${}^I\vec{v}^{\,B}$ and $T_{B/I}$, and making the same substitutions yields an equation for the inbound leg,

$$\begin{bmatrix} v_{ix} \\ v_{iy} \end{bmatrix} = \begin{bmatrix} 1 & \psi_m \\ -\psi_m & 1 \end{bmatrix}\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} v_{ox}-v \\ v_{oy} \end{bmatrix} \tag{16}$$

Equations 15 and 16 contain four scalar equations with the four unknowns v, ψ_m, v_x, and v_y, and may be solved:

$$v = \frac{v_{ox}+v_{ix}}{2}; \tag{17}$$
$$\psi_m = -\frac{v_{oy}+v_{iy}}{v_{ox}+v_{ix}}; \tag{18}$$
$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} \approx \begin{bmatrix} 1 & -\psi_m \\ \psi_m & 1 \end{bmatrix}\begin{bmatrix} \frac{v_{ox}-v_{ix}}{2} \\ \frac{v_{oy}-v_{iy}}{2} \end{bmatrix}. \tag{19}$$

Then, averaging the data in Fig. 15 for the two straight and level legs, separately, gives:

$$v_{ox} = 1.617; \tag{20}$$
$$v_{oy} = 0.01248; \tag{21}$$
$$v_{ix} = 1.199; \tag{22}$$
$$v_{iy} = -0.1045. \tag{23}$$

These are in meters/second. Substituting the values in Eqns. 20 through 23 into Eqns. 17 through 19 gives the values stated in Section V-D, as well as the lateral water current in the ice-fixed frame;

$$v_y = 0.065 \text{ meters/second.} \tag{24}$$

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