

Performance of an AUV Navigation System at Arctic Latitudes

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Abstract—In October of 2001 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. This paper describes the performance of these instruments at high latitudes.

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 [9]. 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°. The objective was to perform engineering tests in preparation for the future Atlantic Layer Tracking Experiment (ALTEX) mission [4]. These tests included evaluating the three navigation instruments described below. A second objective was to take scientific measurements of nitrate concentration, salinity, temperature, and ice draft in the area between Svalbard and Greenland.

The ALTEX 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 beacons. A desirable outcome of the ALTEX is to ultimately produce vehicles that are capable of 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 [5], Odyssey II [3], Theseus [2], and recently Autosub in the Antarctic. Both Theseus and Autosub employ an Inertial Navigation System (INS) aided by Doppler sonar.

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 is a challenge for all three of these instruments. A compass has difficulty determining heading because the Earth's magnetic field lines are nearly vertical. The ability of the two inertial instruments to align to north is 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 gimballed 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 [7].

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 12 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 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 can be achieved by allowing the vehicle to follow a 1300-meter isobath [4]. This can serve as an aid to navigation through the use of a sonar altimeter. An INS will provide the primary navigation.

The required real-time positional accuracy 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. Thus, a reasonable position error requirement is 400 meters, 95% Circular Error Probable (CEP). Mission length must then be limited so that the total position error does not exceed 400 meters. See the appendix for a definition of CEP.

A mission length of approximately 5 km is necessary to obtain adequate science and engineering data. This translates into a navigation requirement of

$$\frac{(400)}{(2.08)(5000)} = 3.8\% \quad (1)$$

where the 2.08 converts from 95% CEP to typical units of 50%. See Eqn.7.

In this 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. Motion of the local ice pack is then irrelevant since the DVL senses motion with respect to the ice.

Heading misalignment error was not explicitly accounted for during these sea trials as it tends to cancel for trajectories that form a closed loop.

Under good conditions, DVL dead-reckoning accuracy is less than 1% DT, presuming an ideal heading reference [6], and continuous bottom tracking. Thus, an upward-looking DVL combined with an accurate heading reference appear to easily meet the 3.8% DT requirement for the October sea trials. However, the vehicle must pass under open water in the lead before reaching the ice, and may well pass under another lead or broken ice cover while on its mission. This decreases the accuracy of ice-aided navigation, effectively making the 3.8% DT requirement more challenging. The use of an INS is necessary to provide an accurate and stable heading reference at that latitude. One must bear in mind that the penalty for missing the lead on the return leg is the probable loss of the vehicle and its data.

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

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

The INS/DVL, mounted inverted so the DVL will ping off the ice, easily meets the 3.8% DT requirement when under ice. Subsequent sections discuss the INS/DVL performance in detail.

The Ixsea Gyrocompass has a heading accuracy specification of $0.2^\circ / \cos(\lambda)$, rms, where λ is latitude. At $\lambda = 82^\circ$, the heading error is 1.4° rms, which translates into a cross-track error of 2.5% DT, rms, or 3.0% DT CEP, assuming an equal standard deviation in the along-track axis. See Eqn 8. Combined with the DVL, this is also

a possible navigation solution for the sea trials, provided we don't operate much above 82° of latitude. The Gyrocompass is not feasible for ALTEX class vehicles that are expected to operate in the Arctic basin without latitude restrictions.

The Earth's magnetic field had an inclination of approximately 83.5° in the test area on October 2001, rendering standard magnetic compass operation unreliable. However, it is possible that comparison of the magnetometer output against an on-board magnetic field model could produce a feasible heading estimate, as long as the inclination doesn't get close to 90° . Although this method is not generally applicable to eventual ALTEX class vehicles that may operate in areas where the field lines are essentially vertical, it still could be useful as an aid in parts of the Arctic basin.

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 [1]. 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 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 INS/DVL 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



Fig. 2

KEARFOTT AND RDI SEADEVIL INTEGRATED INS/DVL/GPS

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.

ALTEX AUV Operational Areas

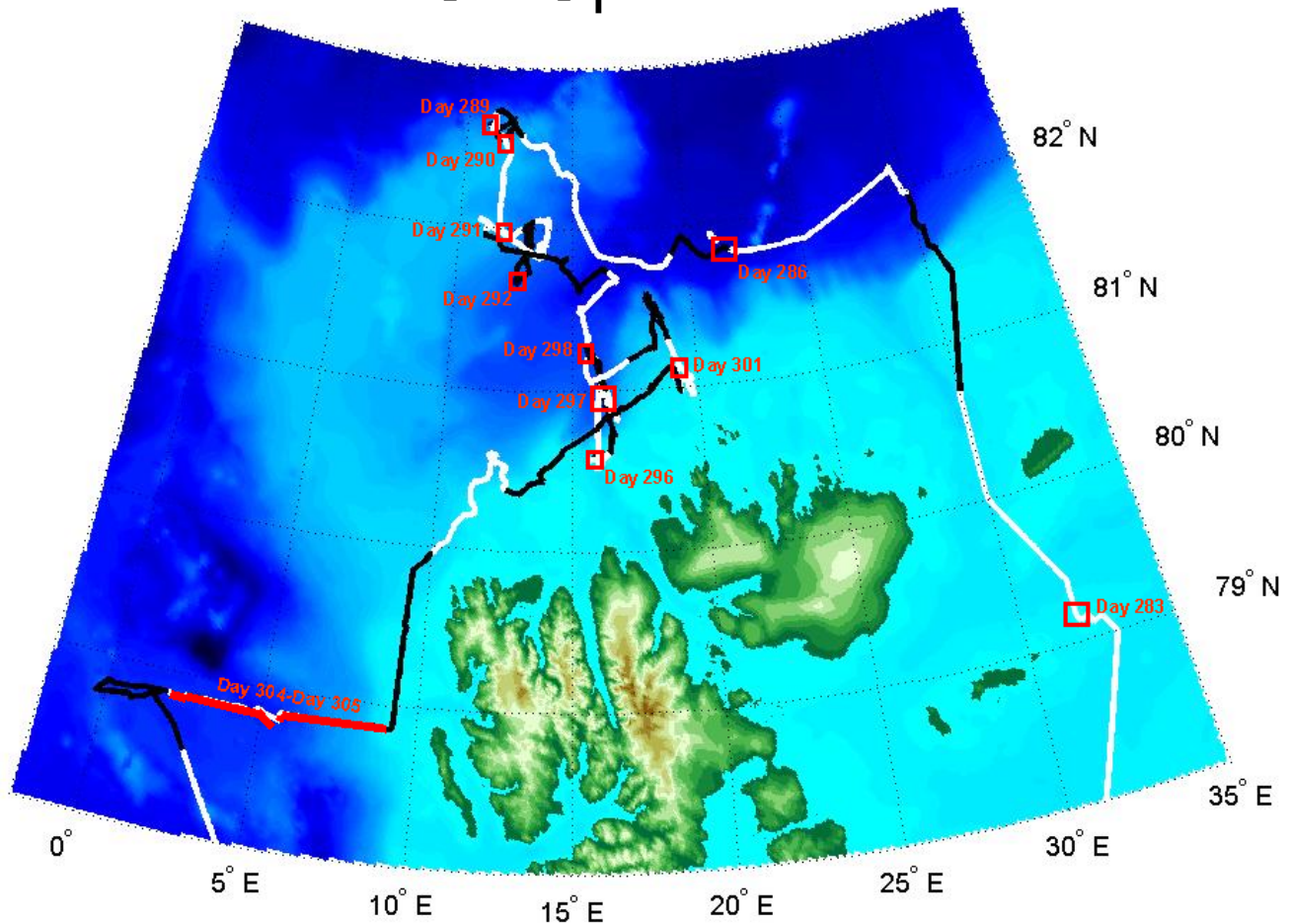


Fig. 3

SHIP'S TRACK IN THE VICINITY OF SVALBARD, 11 OCT TO 2 NOV 2001

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. INS/DVL Moving-Base Alignment and Free-Inertial Propagation

A goal of the navigation tests was to demonstrate the performance of the integrated INS/DVL/GPS system in

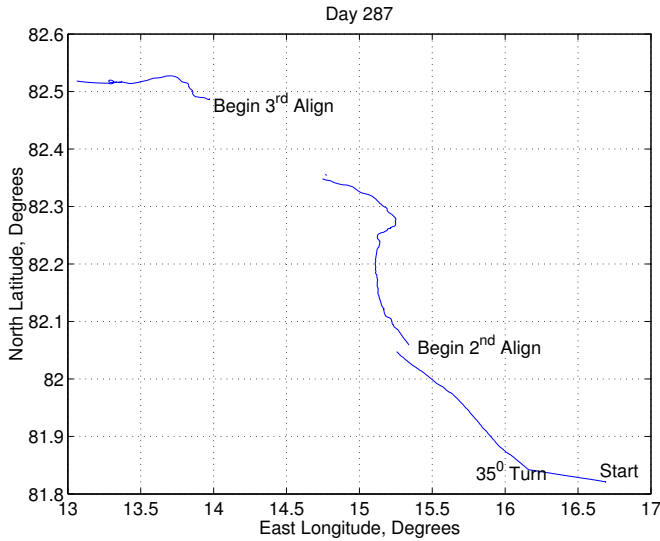


Fig. 4
OCTOBER 14, 2001, TEST TRAJECTORY

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.

Fig. 5 shows the time history of the three attitude states estimated by the Kalman Filter for three 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).

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 the GPS aid and operate the INS in the pure inertial mode. This was done 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

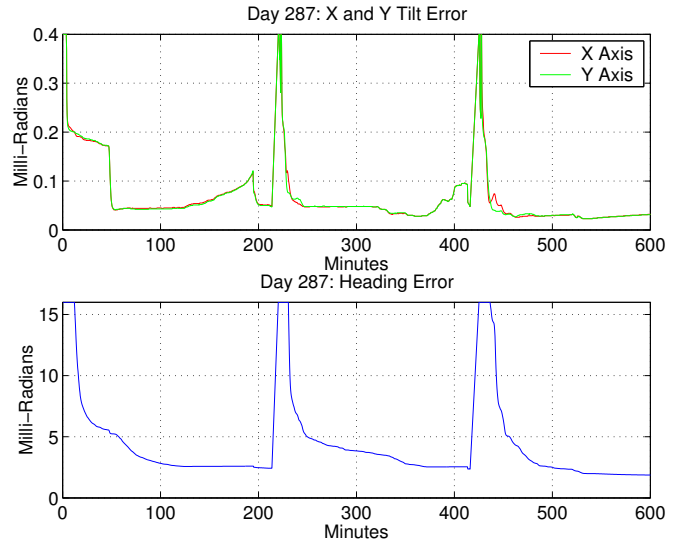


Fig. 5
STANDARD DEVIATION OF THE ATTITUDE ERROR ESTIMATES

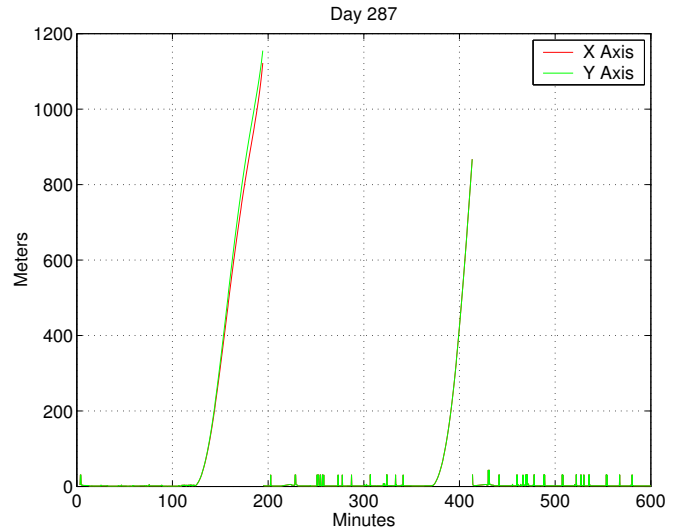


Fig. 6
STANDARD DEVIATION OF THE POSITION ERROR ESTIMATES

Fig. 6, illustrating slightly better than a 1 NMH estimated error (1.22 km/axis).

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.

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

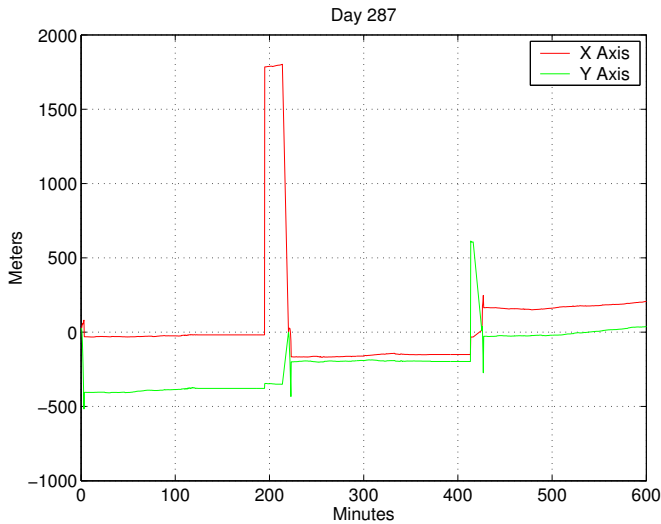


Fig. 7
POSITION ERROR ESTIMATES

observations to 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 (prior to initialization and start of the third alignment at 420 minutes).

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.

B. INS/DVL Water-Tracking Performance

The second operational need is for the INS/DVL 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 INS/DVL 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 INS/DVL must be

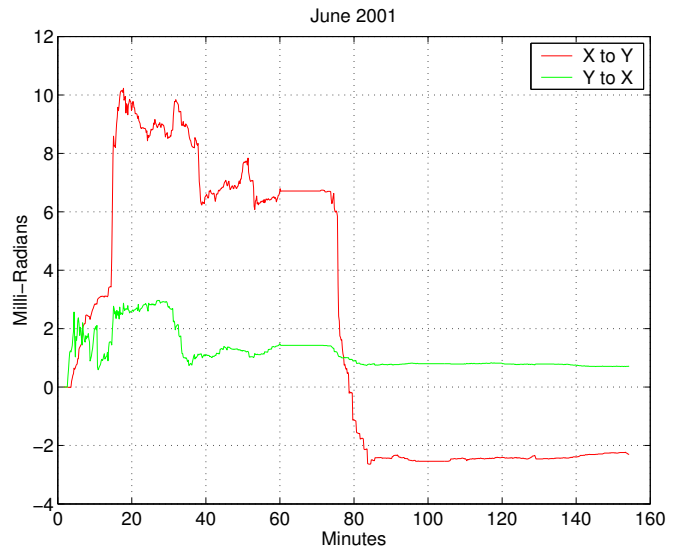


Fig. 8
DVL TO INS ALIGNMENT ESTIMATES

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 INS/DVL 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 INS/DVL 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 INS/DVL 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

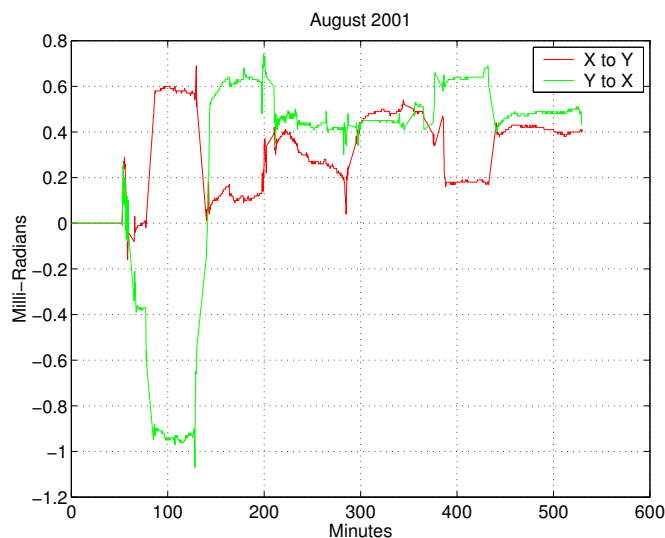


Fig. 9
DVL TO INS MISALIGNMENT ESTIMATES

the change in estimated misalignment angles with the assumption that the final estimate of Fig. 8 is perfect. The data in August is a 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 INS/DVL 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, a significant part of the time was spent in water track mode.

The accumulated position error over the entire test was 130 meters. 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 INS/DVL 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 INS/DVL system also estimates water current, as shown in Fig. 11.

During testing in the Arctic region on October 24, 2001, the INS/DVL 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.

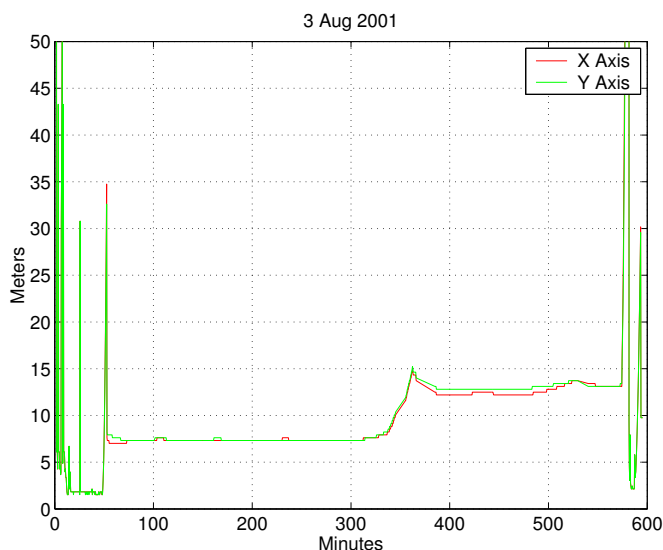


Fig. 10
STANDARD DEVIATION OF THE POSITION ERROR ESTIMATES

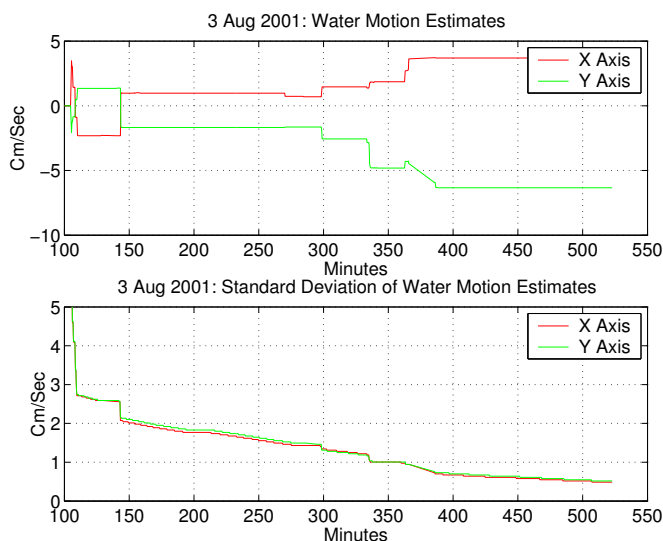


Fig. 11
DVL TRACKING DATA AND WATER MOTION ESTIMATE

The INS/DVL 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 the initial water-mass motion estimate, the INS/DVL position track was consistent with that of the carrying ship. The INS/DVL 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

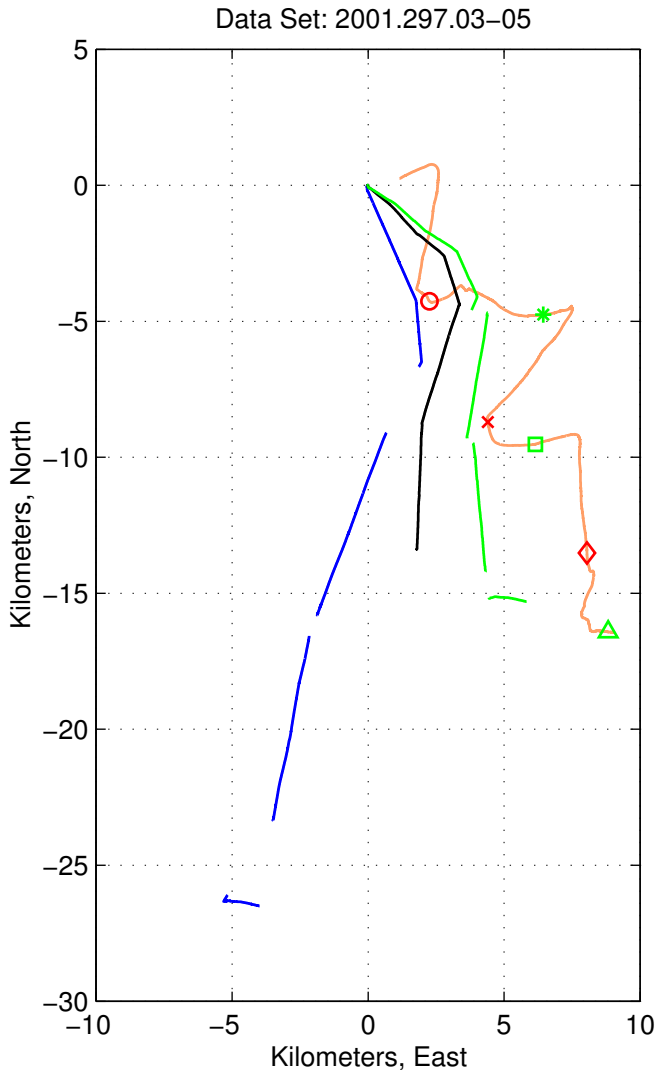


Fig. 12

VARIOUS POSITION TRACKS, INCLUDING THE INS/DVL AND THE SUPPORT SHIP

the INS/DVL 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 INS/DVL 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 INS/DVL 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 INS/DVL was pointed down, and the vehicle was operating in open wa-

ter.

The four blue leftmost North/South segments in Fig. 12 show the uncorrected vehicle track as measured in real time by the INS/DVL. 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 INS/DVL. 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 generally available.

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 INS/DVL, 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 shown 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, which is the case in Fig. 14. 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, due to the local magnetic inclination of 83.5° .

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.

During the previous leg, the magnetic heading had an 8° pitch dependence, and on the third leg the dependence was nearly absent at $.25^\circ$.

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 $.17^\circ$ (10 minutes of arc) over the short length of the mission, at that location and time.

The Crossbow was calibrated with the vehicle in the water under nominal operating conditions in Monterey Bay. 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° . Both the INS and the Gyrocompass were reporting themselves aligned, 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 Shuler 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.

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 its 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

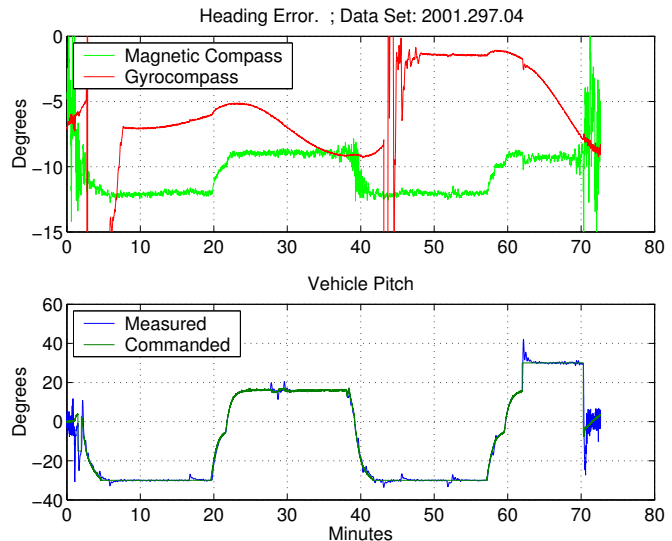


Fig. 13

GYROCOMPASS AND MAGNETIC HEADING ERROR, DAY 297

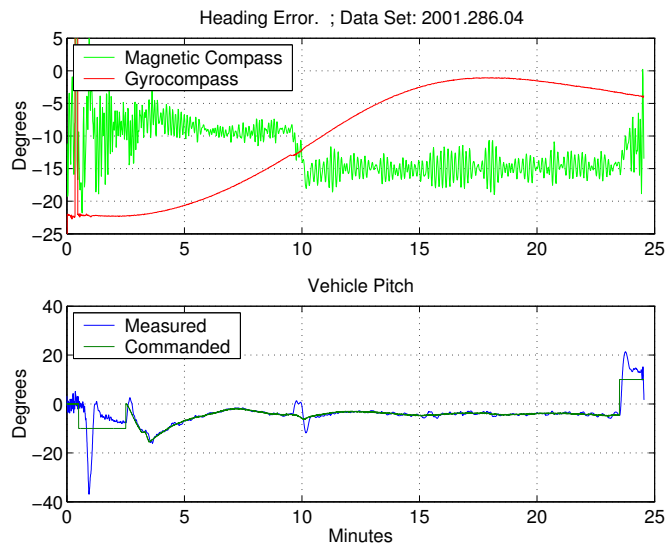


Fig. 14

GYROCOMPASS AND MAGNETIC HEADING ERROR, DAY 286

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 INS/DVL 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 $\psi_m = 1.9^\circ$. The speed of the AUV with respect to the ice

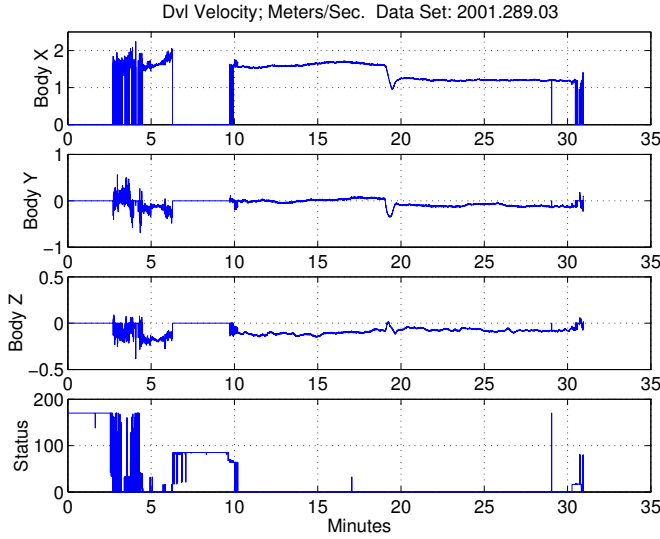


Fig. 15
VELOCITY OF THE AUV WITH RESPECT TO THE ICE

was 1.41 meters/second, with a following current (out-bound) of .21 meters/second. See the Appendix, Section B, 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 GPS system in as realistic an environment as possible. The vehicle-mounted GPS antenna and receiver never could obtain a signal in the Arctic with the vehicle in the water. It worked routinely in Monterey Bay.
2. Test any ice-specific configurations ahead of time, such as the orientation of the instruments. The team was unable to properly configure the INS/DVL 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. Because of this problem, the field team ended up running the vehicle under the ice using basic dead reckoning. 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. The INS/DVL 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 INS/DVL, 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. We are currently working with Ixsea to resolve these issues.

ACKNOWLEDGMENTS

The ALTEX development was supported by the National Science Foundation under grant number OPP-9910290. The ALTEX work at MBARI was also supported through the Packard Foundation, and through the National Ocean Partnership Program under contract N00014-98-1-0814, administered by the Office of Naval Research.

Many people made this project possible. Special thanks go to the Arctic AUV field team: Jim Bellingham, Drew Gashler, Bill Kirkwood, Rich Henthorn, Rob McEwen, D.J. Osborne, Farley Shane, Mark Sibenac, Mark Talkovic, Hans Thomas, and Todd Walsh.

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 of equal variance σ^2 . 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,

$$R = \sqrt{X^2 + Y^2}. \quad (2)$$

The random variable R has the well-known Rayleigh density function as long as the component Gaussian densities

have equal statistics and are independent. The Rayleigh distribution function (p.195, [8]) is given by

$$P_R(r) = 1 - \exp \frac{-r^2}{\overline{R^2}}, \quad (3)$$

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

$$\overline{R^2} \triangleq E\{R^2\}. \quad (4)$$

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

$$\overline{R^2} = 2\sigma^2. \quad (5)$$

It is common to set the left-hand side of Eqn. 3 to a value P_o , such as 50% or 95%, and solve for the corresponding radius r_o ,

$$r_o = \sqrt{\ln \left(\frac{1}{1 - P_o} \right) \overline{R^2}}. \quad (6)$$

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

Also, one may derive many useful relationships from Eqn. 6; among them are:

$$r_o(95\%) \approx 2.08 r_o(50\%); \quad (7)$$

$$r_o(50\%) \approx 1.18 \sigma. \quad (8)$$

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

This section derives formulas for relative water motion, and misalignment of the INS/DVL 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

$${}^I\vec{v}^B = {}^I\vec{v}^W + {}^W\vec{v}^B. \quad (9)$$

The velocity measured by the DVL is then

$${}^I\vec{v}_{DVL}^B = T_{DVL/B} T_{B/I} {}^I\vec{v}_I^B \quad (10)$$

$$= T_{DVL/B} T_{B/I} ({}^I\vec{v}^W + {}^W\vec{v}^B)_I. \quad (11)$$

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,

$$T_{DVL/B} \approx \begin{bmatrix} 1 & \psi_m \\ -\psi_m & 1 \end{bmatrix}, \quad (12)$$

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

$${}^W\vec{v}_I^B = \begin{bmatrix} v \\ 0 \end{bmatrix}. \quad (13)$$

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

$${}^I\vec{v}_I^W = \begin{bmatrix} v_x \\ v_y \end{bmatrix}, \quad (14)$$

and for the outbound leg, let

$${}^I\vec{v}_{DVL}^B = \begin{bmatrix} v_{ox} \\ v_{oy} \end{bmatrix}. \quad (15)$$

Substituting Eqn. 12 through Eqn. 15 into Eqn. 11 gives

$$\begin{bmatrix} v_{ox} \\ v_{oy} \end{bmatrix} = \begin{bmatrix} 1 & \psi_m \\ -\psi_m & 1 \end{bmatrix} \begin{bmatrix} v_{ox} + v \\ v_{oy} \end{bmatrix} \quad (16)$$

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,

$$\begin{bmatrix} v_{ix} \\ v_{iy} \end{bmatrix} = \begin{bmatrix} 1 & \psi_m \\ -\psi_m & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} v_{ox} - v \\ v_{oy} \end{bmatrix} \quad (17)$$

Equations 16 and 17 contain four scalar equations with the four unknowns v , ψ_m , v_x , and v_y , and may be solved:

$$v = \frac{v_{ox} + v_{ix}}{2}; \quad (18)$$

$$\psi_m = -\frac{v_{oy} + v_{iy}}{v_{ox} + v_{ix}}; \quad (19)$$

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} \approx \begin{bmatrix} 1 & -\psi_m \\ \psi_m & 1 \end{bmatrix} \begin{bmatrix} \frac{v_{ox} - v_{ix}}{2} \\ \frac{v_{oy} - v_{iy}}{2} \end{bmatrix}. \quad (20)$$

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

$$v_{ox} = 1.617; \quad (21)$$

$$v_{oy} = 0.01248; \quad (22)$$

$$v_{ix} = 1.199; \quad (23)$$

$$v_{iy} = -0.1045. \quad (24)$$

These are in meters/second. Substituting the values in Eqns. 21 through 24 into Eqns. 18 through 20 gives the values stated in Section V-D. Also, the lateral water current in the ice-fixed frame is

$$v_y = 0.065 \text{ meters/second.} \quad (25)$$

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