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SIMULATIONS OF AN ITERATIVE MISSION PLANNING PROCEDURE FOR FLYING GLIDERS INTO STRONG OCEAN CURRENTS

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Abstract

This paper presents a framework for simulation software which was developed as a tool for mission planning for ocean gliders and other AUVs. The software takes into account the dynamic effects of the ocean currents on the motions of the AUV and aims to make glider operations be more safe, more predictable, and more efficient.

1 Introduction

The ocean glider is designed as a tool for ocean observation and marine monitoring. It is intended to be of low cost to build and inexpensive to operate. These advantages encourage more and more scientists and researchers to continuously improve the design of ocean gliders and to extend the applications. The absence of an onboard, battery powered navigation system, i.e. an Inertial Navigation System (INS), and the low flying speed contribute to the properties of low power consumption and long endurance. The on-board deduced-reckoning process can provide the glider with acceptable position estimation when the accumulated error is reset by a GPS fix after the glider comes to the ocean surface, and, when the current is not too strong.

For missions requiring more accurate waypoint achievement, or, to cross a strong current zone to get to the next intended waypoint, we need either to upgrade the glider navigation hardware (sensors) or to optimize our operations of the glider. Upgrading the glider hardware may improve the accuracy with which the glider can estimate its present position; the latter can also be improved by upgrading the information concerning the hydrodynamic behaviour of the glider which is used within the ded-reckoning algorithm i.e. angle of attack, glide speed, glide angle [1]. Adding a propulsion system may allow the glider to make progress against an ocean current which otherwise would exceed the forward speed of which the glider is capable, on an as-needed basis and in keeping the overall aim of minimizing the glider's energy consumption per unit of distance travelled [2]. Another approach is to order the sequence of waypoints in a favourable way so as to be able to pass through sufficiently close to all the waypoints without going upstream against strong currents more often than necessary.

A glider without an onboard INS, in the presence of ocean currents, is likely to drift away from the target path defined by the waypoints in its mission file. In practice, after the glider surfaces and obtains a GPS fix, and compares with the target waypoint, it can then correct its heading and fly toward the target waypoint. If the ocean current information is available, this heading correction can be performed during the mission (using an on-board process), or, during mission planning. Since the ocean current information file is too large to store in the memory of the present generation of gliders, trying to perform a real-time on-board heading correction is not feasible. A process for heading correction which makes use of available information about the ocean currents at the time at which the mission is being planned, is a more practical approach.

This paper presents an iterative mission planning procedure and a glider tracking simulation used to evaluate the procedure. The goal of the development of the procedure and the simulation program is to improve waypoint achievability and energy-efficient glider operations.

2 Framework of the Simulation

The simulation software uses an iterative procedure which is based on a glider motion model [1] and a 3-dimensional drogue tracking program, DROG3D [5]. Figure 1 shows the overall framework for the iterative procedures. A central component is the Tracking Simulation which models the motions of the glider. The program assumed that the motion of the glider with respect to the Earth can be expressed as sums of the velocity components of the ocean currents and the motions of the glider with respect to calm water. The glider motions are controlled dynamically by controlling the status of the buoyancy engine and the pitch angle of the glider. Within each step of the iteration procedure, there is a complete tracking simulation from the mission start point to the final waypoint.

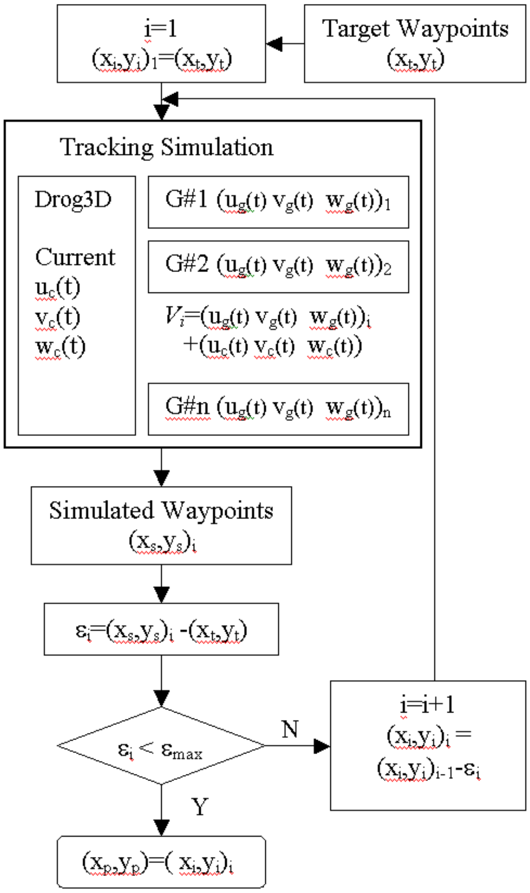

Figure 1. Framework of the Iterative Procedures

In the iterative portion of the mission planning procedure, the algorithm utilizes the differential horizontal distance between the target waypoint (x_t, y_t) and the achieved waypoint (x_s, y_s); this differential (error) is used to update the heading setting for the next iteration. The iterative process continues until the differences (at all waypoints) between the target and the achieved positions fall within the predefined tolerance ε_{max}.

The glider tracking program is the centre part of the iterative procedure that tracks the glider movement. At each time step the forward speed of the glider is the vector sum of the local current speed and the glider behaviour speed; the latter is determined from the measured hydrodynamic behaviour of the glider in calm water [1]. The local ocean current is represented by flow vectors at a number of nodes distributed within the simulated ocean domain; these flow vectors are computed using a finite element method [3]. The local current speed at each point where the glider passes is interpolated from the flow vectors at the nodes surrounding the local point. The glider behaviour speed and direction are simulated using a rigid-body and hydrodynamics module. In the dynamics module the horizontal and vertical components of the glide speed and the glide path angle are determined by using a set of parameters which were obtained from previous sea trials with the same glider. The upward and downward glide characteristics are often not symmetrical as s a result of the pre-trial ballasting procedure [4] and local variations of the density of the seawater [1]. Thus the required parameters must include both the upward and downward gliding behaviours. The overall vertical profile of the saw-tooth glide path is constrained by several parameters, such as the maximum flying depth, the minimum flying depth, the local sea depth and the distance to the next waypoint. When the glider is flying between two adjacent waypoints the glider heading is determined by the vector from the previous waypoint to the next waypoint, plus an angle of correction; the angle of correction is calculated by the simulation in the previous iterative cycle.

2.1 Ocean Currents

During the simulation of gliders flying in the ocean, the ocean current and bathymetry are reproduced in the background by the program DROG3D. The bathymetry and currents are read in as inputs and the ocean currents are calculated from a finite element model [3]. The ocean currents are presented by time-varying velocity vectors at tens of thousands of nodes distributed throughout the simulation domain. At each node the velocity vector is represented in terms of three components (u_c, v_c, w_c) in the form:

$$\begin{aligned} u_c(t) &= \mathrm{Re}[A_u e^{i(\omega t-\phi_u)}] \\ v_c(t) &= \mathrm{Re}[A_v e^{i(\omega t-\phi_v)}] \\ w_c(t) &= \mathrm{Re}[A_w e^{i(\omega t-\phi_w)}] \end{aligned} \tag{1}$$

Since a long glider mission may span a period of four months, the simulator will require ocean current information for the whole of that period. Some of the monthly-averaged ocean currents, from June to September, around Newfoundland at the depth of 30 m

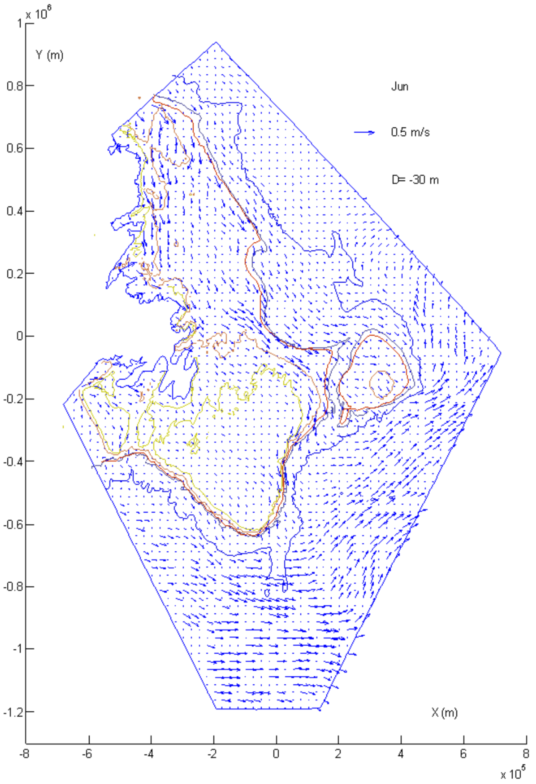

Figure 2a. Model currents at 30 m depth for June

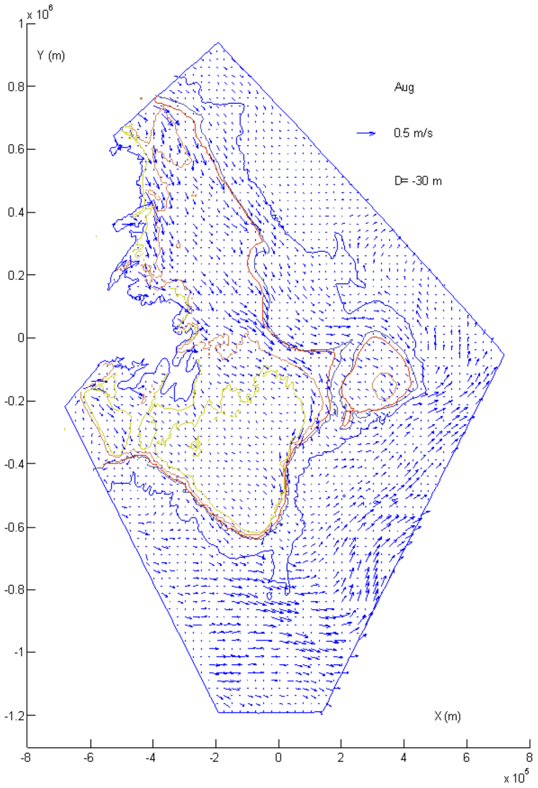

Figure 2c. Model currents at 30 m depth for August

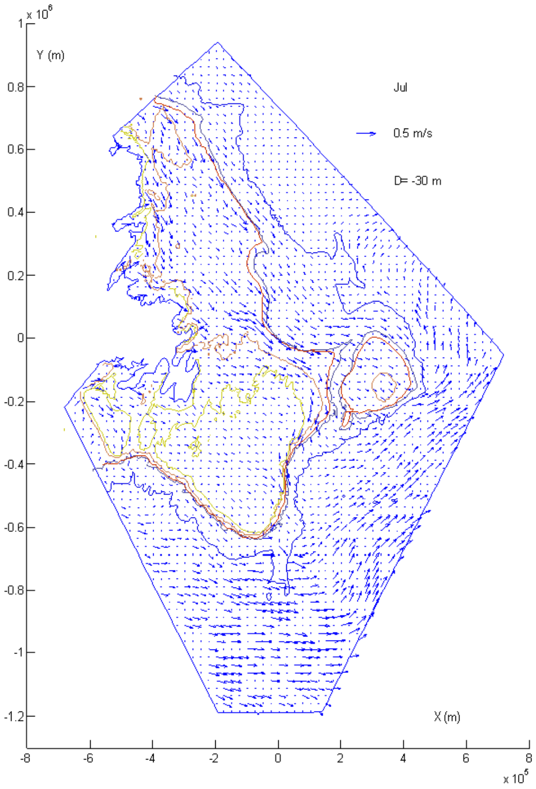

Figure 2b. Model currents at 30 m depth for July

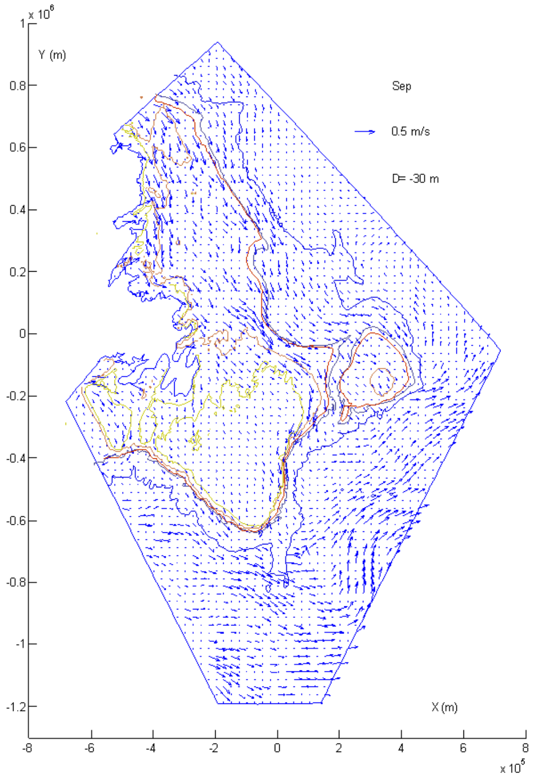

Figure 2d. Model currents at 30 m depth for September

are shown in Figure 2. The plots show that currents in most regions are less than 50 cm/s while the current at many locations is up to 30 cm/s. Considering that the actual horizontal speed for most gliders is around 40 cm/s, in order to fly gliders to these regions the mission routing should be well planned. It has been found that the currents deeper than 30 metres are much less affected by the surface conditions, and, most of the currents below 30 metres are weaker than the currents close to the surface.

2.2 Glider Motion Modeling

Analysis of the glider motion data from sea trials [6] showed that the glider motion is sensitive to both the glider parameters and the environmental conditions. This was indicated by the full-scale glider motion response initiated by movements of the piston (in the buoyancy engine) and the pitch control battery. These results show that the dynamic model for glider simulations should be quite different from that for propeller-driven AUVs or submarines. The fidelity of the simulated motion of an AUV is mainly dependent on the values of its hydrodynamic coefficients. However, glider motion simulations depend not only on the vehicle's hydrodynamic coefficients but also on the ballasting condition and water density. Depending on the ballasting a glider may dive much faster than it can climb, or vice-versa. If the glider is incorrectly ballasted, it will either remain at the surface unable to dive, or, it will sink to the seabed. Thus ballasting a glider appropriately for seawater in which it will operate is imperative, and will affect the glider dynamics dramatically.

As another example, when a glider is approaching a fresh water river mouth from seawater where it has been properly ballasted and has been flying well, it is going to sink to the bottom of the river, thus the water density has a large effect on the glider motion as well. A good glider motion simulator should include appropriate values of all three of these factors (ballast condition, water density and vehicle hydrodynamic coefficients) since the glider motion depends on all of them. In a sense each of these three factors contributes equally to the performance of a glider.

With these considerations in mind, the model for the glider motion simulation in this paper is simply based on the statistical results of the glider motion data collected from sea trials.

The glider motion simulation is based on two major components, steady flying behaviour and the behaviour during three types of transitions. Steady flying includes steady dives and steady climbs, and, the three types of transitions include dive-to-climb, climb-to-dive, and turning from side-to-side.

Steady dive

From one set of data collected from a sea trial by a SLOCUM Electric^{TM} glider it is summarized that the vertical speed ranges from 15 to 20 cm/s. The flying path angle ranges between -29 and -35 degrees while the glider pitch angle ranges from -30 to -20 degrees. Thus the angle of the attack ranges from 5 to 9 degrees. The rate of descent depends on the ballast condition, and , the flight path angle depends on the lift-to-drag ratio of the whole glider; these values will change when a glider is prepared for operation in seawater of a specified density but these are typical values obtained from sea trials [6]. The parameters governing steady dives in these simulations are therefore

(i) a vertical velocity of -18 cm/s, and
(ii) a flight path angle of -32°

Steady climb

From the same set of data collected it has been found the glider climb speed is a little higher than the speed during a dive. The vertical speed of climb ranges from 15 to 23 cm/s. The flying path angle and the glider pitch angle during climbing remain similar to those during diving. They range from 29 to 35 degrees and from 20 to 30 degrees respectively. Again the angle of attack ranges from 5 to 9 degrees. The parameters governing steady climbs in these simulations are therefore

(i) a vertical velocity of 18 cm/s, and,
(ii) a flight path angle of +32°

Transition from dive to climb

Whenever the glide path changes from a steady-state dive to a steady-state climb, the present simulation makes the flight path angle change instantaneously. Future versions will include a time delay which takes into account the pitch moment of inertia of the glider, and, the variation of glide speed during the transition. A similar instantaneous behaviour is presently used for transitions from climb to dive; future behaviours will include both of the above-mentioned dynamic effects.

Transition of turning

Whenever the glider turns from one heading to another, the present simulation makes the change in heading take place instantaneously. Future versions will include a time delay which takes into account the control law for the rudder deflection, the yaw moment of inertia of the glider, and, the variation of glide speed during the turn. The importance of these dynamic effects will be shown in future versions of the simulation software.

3 Examples of Simulation

Two examples which have been used to test the simulation program. One is the simulation of a 7-point-mission for which sea trials data are available. The second example is a long voyage which is being planned for the DFO survey line on the Southeast Grand Bank on the Newfoundland Shelf. Both simulations set the minimum gliding depth at 10 m. The altimeter was set to 10 m which triggers the glider transition from dive to climb when the glider is a distance of 10 m above the seabed.

3.1 The Sea Trial of 7 Waypoints

As the first test, the convergence of the iterative procedure was the most important concern. Another concern was the comparability of the simulated results and the data from the sea trial. It is shown in Figure 3 that the flight path gets closer and closer to the target trajectory with each iteration. The target trajectory is shown in black and is defined by the 7 waypoints. The trajectory of the glider during the first attempt, iteration 1, is represented in red by 6 straight line segments. The waypoints achieved are far away from the target waypoints. The maximum differential between targets and achieved during the first iteration occurs at the last waypoint and is almost 1000 metres. The second iteration reduced the maximum differential down to less than 600 m. Then the third iteration further reduced the maximum differential to less than 400 m. A portion of the vertical glider trajectory traversed during the third iteration is shown in Figure 4, along with the seabed profile. The plot indicates that the glider is flying within the prescribed vertical envelope, between 10 m under the sea surface and 10 m above the seabed. Although the maximum gliding depth was set to 200 m, the glider never reached that depth since the mission was in a region of shallow water.

3.2 Southeast Grand Bank Line

Since there are plenty of available oceanographic data collected by ships and buoys along the Southeast Grand Bank Line, Newfoundland, it is intended to collect comparison data by flying a glider along that line. The reasons are not only to provide comparisons of data collected from a different platform but also to provide data of higher density in both spatial and time-wise senses. The southeast line of Grand Bank is defined by a straight line from (W53.00 N46.50) to (W49.00 N41.50). Ten waypoints are distributed in a sequence along the line from the NW to the SE, and are shown in Figure 5. The distance between two adjacent waypoints is 71 km and the planned straight-line route covers 778 km in total. Several attempts were made with the ten-waypoints mission before realizing that the setting of the glider vertical speed was too slow to overcome the strong currents near waypoint 8. A set of simulations with different glider speed settings, from 18 to 34 cm/s with an increment of 2 cm/s, and, with the flight path angle remaining at 28 deg, have been performed. However, all attempts resulted with a simulation time-out while the glider was struggling to reach waypoint 8.

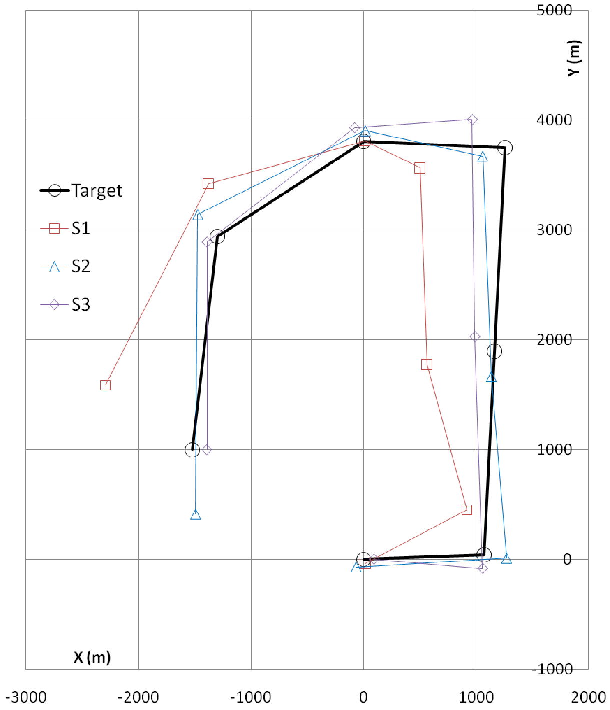

Figure 3. Waypoint achievement of 7-waypoint-mission

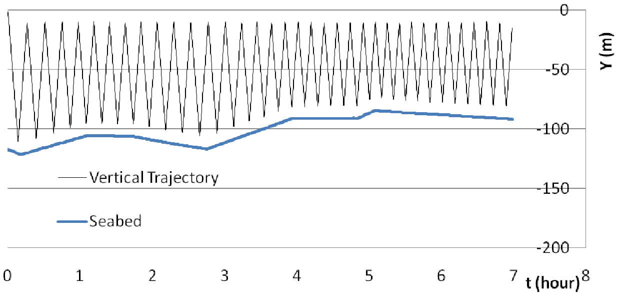

Figure 4. Vertical trajectory of the third iteration and the seabed of the 7-waypoint-mission

Once the region of strong current has been identified, one strategy is to identify an intermediate waypoint which is upstream of the line prior to reaching that region, and, then to let the favourable current carry the glider downstream to finish near the final waypoint. This strategy has been used successfully and one of these simulations is shown in Figure 6. It corresponds to a vertical speed of 22 cm/s and a flight path angle of 28°.

During the first iteration the glider drifted 32 km away from waypoint 2, and 14 km away from waypoint 3. The glider then passed the next four waypoints very closely. The simulated mission timed-out when the glider was 9 km away from waypoint 7 and was flying against the current toward waypoint 8. In the second iteration, the glider passed waypoints 2 and 3 closer than it did during the first iteration. The distances between the achieved and target values for these two waypoints were reduced from 32 to 12 km and from 14 to 2 km respectively. After three iterations, the maximum discrepancy for the first 7 waypoints was continuously reduced down to 10 km.

After the investigation of the ocean current along the southeast line it was realized that the ocean current between waypoint 7 and waypoint 8 was too strong to be overcome by the glider. The ocean current along the southeast line is shown in Figure 7. It displays the movements over a period of 15 days of drifters which were initially placed and released along this line. There are two regions where strong ocean currents go to the southwest and one region where they go to the northeast along the line. The first strong current region is located between waypoints 1 and 3, and the average current is around 15 cm/s and is directed slightly to the SW of the planned route. The second strong current region is located between waypoints 7 and 8 and the current varies over a wide range, from 1 to 40 cm/s. The direction of the strongest current is about 45 degrees to the left of the route and this explains why the glider can never get to waypoint 8 in a straightforward approach. The third strong current region is between waypoints 9 and 10. There the current goes to the southeast and then east, gradually increasing in speed up to 35 cm/s. However, the glider has never penetrated that region in our simulations since the simulated missions always time-out while the glider is on its way from waypoint 7 to waypoint 8.

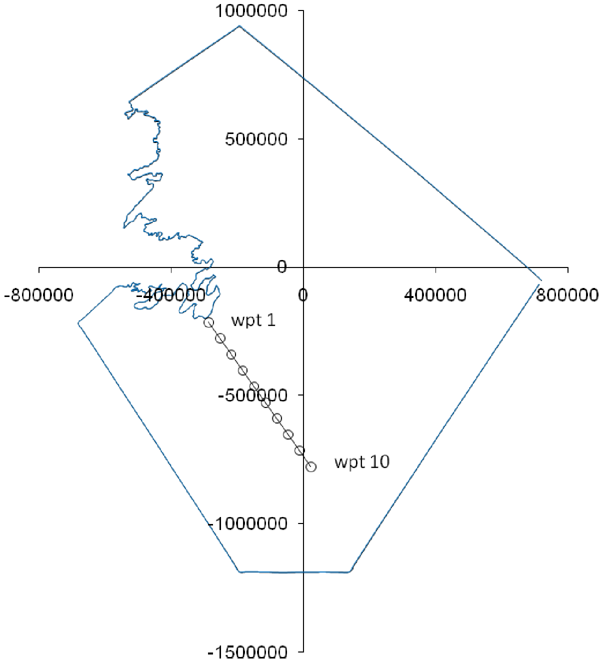

Figure 5. Designated waypoints along the Southeast Line of Grand Bank, Newfoundland

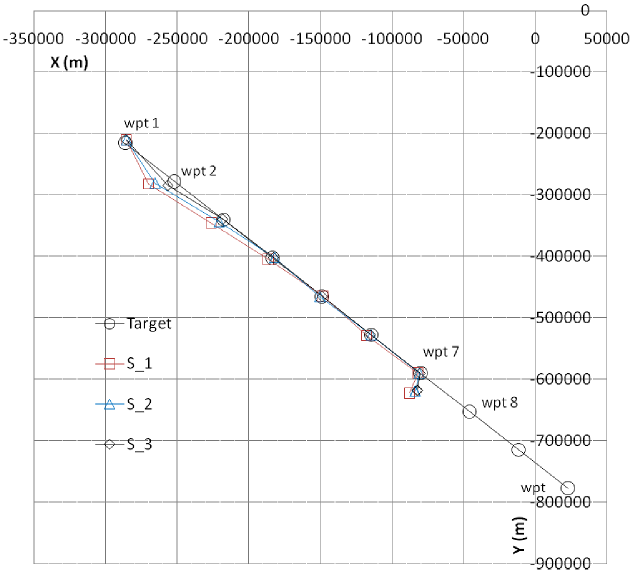

Figure 6. Waypoints achieved along the Southeast Line of Grand Bank, Newfoundland

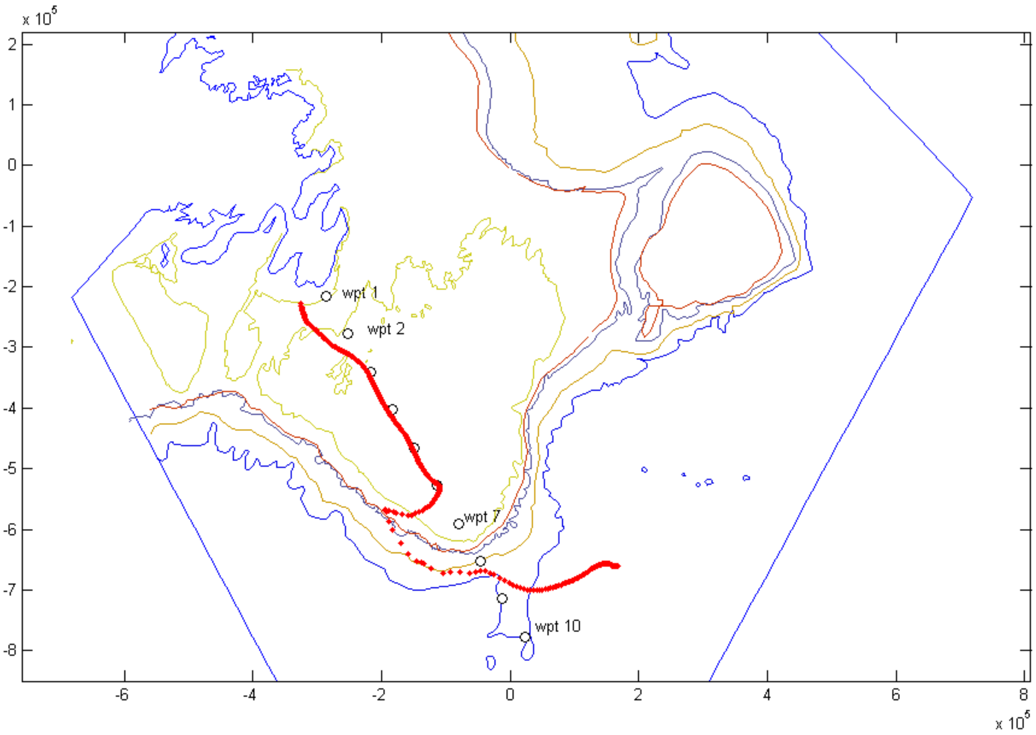

Figure 7. Ocean current along Southeast Line represented by the drifted distance of 15 days

4 Results and Discussion

Comparative studies for two geographic locations have been conducted through simulations. The simulations include different configurations of waypoints (e.g. straight lines, triangles, rectangles, circles) in Newfoundland where maps of the fullscale ocean currents are available, in particular in Conception Bay, Placentia Bay and over the Grand Banks In these regions the numerical models for the prediction of the ocean current have been validated. The comparison shows that for some cases a mission plan which has been optimized using the above criteria, does make a significant improvement to the efficiency of operation of an ocean glider and the waypoint achievability. In the first case, Figure 3, the simulation traces the glider flying under the influence of the ocean currents with the result that the glider drifts away from its target waypoints. The discrepancies between the target and achieved waypoints can be reduced through a process of iteration. In the second case, Figure 6, the simulation results indicate that the glider could not reach waypoint 8 and beyond, due to the strong currents in that region, without appropriate mission planning which is difficult to implement in an automated procedure. To fly a glider in moderate currents, of speed less than 20 cm/s, the iterative procedure does improve the waypoint achievements, as at waypoint 2 and 3 in this case. Although mission revisions can usually be performed via the Iridium communications link when the glider is on the surface of the sea, it is useful to know, from this type of simulation what could happen to the glider before it begins the intended mission.

5 Conclusions and Future Efforts

A simulation software for glider mission planning with consideration of the effects of ocean currents has been developed. The software reproduces the predefined ocean current in the background calculations and tracks the glider motions with a simple glider dynamic model. Based on the investigations of two simulated cases it has been found the simulation method provides reasonable results although there are plenty of improvements which can be made in the future. For example, the modeling of the glider transitions, from dive to climb and from climb to dive could be improved, and the effects of surface GPS corrections and the dynamics of heading changes (turning) could be incorporated. On the other hand, additional outputs and details could be generated by the simulation once the required information is available and added as input. For example, the glider endurance could be estimated from the on-board battery capacity if the power consumption of all onboard sensors and actuators is known.

6 Acknowledgments

The authors thank Dr Guoqi Han of Fisheries and Oceans Canada, for making the ocean current information around Newfoundland available. We would like to express our gratitude to Professor Brian O. Blanton of the University of North Carolina for his generosity in releasing the program DROG3D for public use.

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