Evaluation of the Coordinated Sampling Performance of Underwater Gliders in Strong and Variable Currents: A Simulated Case Study in the Chesapeake Bay

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***Abstract*—An underwater glider is a high-endurance unmanned vehicle capable of autonomous data collection with minimal operator intervention. Coordinated control of a fleet of underwater gliders enables efficient monitoring of dynamic spatiotemporal ocean processes by regulating the space-time separation of measurements. However, coordinated glider behavior degrades in the presence of strong and variable ocean currents. The Glider Coordinated Control System (GCCS) is a simulation and control tool that models the coordinated behavior of gliders in real-time. In this paper we describe a simulated glider deployment adapted for the Chesapeake Bay by the Regional Ocean Modeling System. We also describe experiments with the GCCS using simple tidal flow models. These simulations evaluate the viability of existing cooperative control strategies for glider deployments in operational areas with strong and variable currents.**

I. Introduction

The variety of ocean monitoring systems available today helps us create a more complete and effective ocean model for use in prediction and analysis of marine environments. Recent technological developments have led to increased use of autonomous sampling platforms that have been adapted to incorporate real-time control methods for sustained use in a dynamic environment. Autonomous underwater gliders allow for unmanned sampling missions that require endurance and independence of the sampling platform. These vehicles can be guided either individually or as a coordinated fleet using the Glider Coordinated Control System (GCCS) software to allow for efficiency in the fleet's sampling pattern. Recently, field tests of GCCS-controlled gliders have taken place offshore in fairly deep and open water. The next step in the improvement of the GCCS is to determine its limits in glider coordination control. The functionality limits of the GCCS are dictated by the autonomous coordination of the gliders over a range of currents. As water currents increase, it becomes increasingly difficult to keep glider motion coordinated. With the GCCS, a range of currents can be simulated with a continuous flow, which models the ebb and flow of the tides as a sinusoidal or square wave. Further adaptation of this system for specific locations, such as the Chesapeake Bay, allows us to simulate glider fleet behavior in an actual varying flow field. Since the Chesapeake Bay is a very shallow and narrow body of water, it creates a unique environment in which the tides are not fully predictable and the flow velocities can range from 0 knots to around 1.5 knots (77 cm/s). Not only is such a site important to test flow velocity effects on long-term glider coordination, but it may also help scientists develop techniques to better understand and model the physical Bay environment [1].

These electric gliders are propelled through the water in a vertical zigzag motion. As they traverse the water column, gliders become pushed off their desired courses over time due to changing tides and encountered surface and deepwater currents. The flow through the Chesapeake Bay control volume, however, is more varied in strength due to its shallow depth (the maximum depth of the Bay is in a narrow ravine that extends about 50 meters below the water's surface) and relatively narrow mouth into the Atlantic Ocean. The autonomous operation of underwater gliders is greatly affected by varying water currents due to their lack of thrusters to control their relative speed through the water. The currents within the Bay will cause the gliders to be pushed off course by impeding or accelerating their absolute speed over the Bay floor, thus affecting the positions at which they will surface to obtain a bearing. Even when compensating for currents, the spatiotemporal coordinated control algorithm of the GCCS will eventually be rendered ineffective due to the gliders being pushed off course to the point that they will no longer reach the desired configuration over the course of a few days.

II. Glider Operation and Deployment

An underwater glider is a high-endurance unmanned vehicle capable of autonomous data collection with minimal operator intervention. These electric gliders, as shown in Figure 1, are operated in wide range of marine environments, from shallow enclosed bays to the open ocean, though they are most frequently deployed within a few kilometers of the shoreline. With a maximum operating depth of 200 meters, these gliders must monitor and adjust their depths without any outside control input in order to avoid damage to the gliders' internal systems that may result from high water pressures at depth. Another important factor that affects glider operation specifically near the shore is encountering areas of shallower water in which a diving glider could impact the seafloor. This is avoided by setting the GCCS to determine the water bathymetry at a given position and updating the maximum dive depth simultaneously so that a glider will not contact the seafloor.

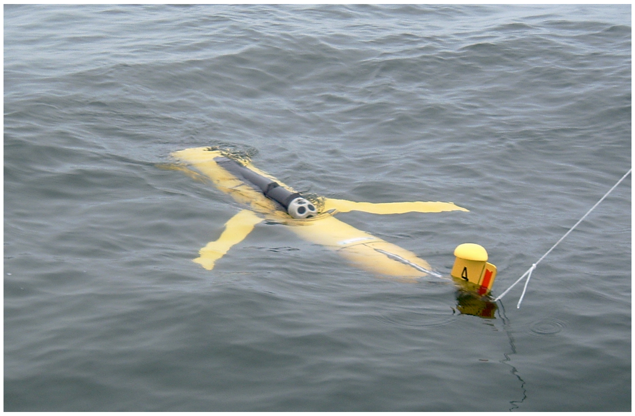

Figure 1. Slocum Electric Glider deployment. *Photo credit: Stephanie Petillo.*

As is the nature of all gliders, these autonomous underwater vehicles are not actively propelled through the water by thrusters. Instead, these gliders contain a more energy-efficient buoyancy pump in the nose cone that changes the internal volume, and therefore the overall density, of the vehicle. This change in internal volume will cause the glider to dive or surface, and the presence of planar swept wings will result in forward directional motion. Combining the vertical and horizontal translational motion of a glider results in a vertically zigzagging dive pattern through the water, as depicted in Figure 2. The yaw of a glider is controlled by the port-starboard rotational motion of a vertical tail fin, allowing the glider steer left and right. The user can program each glider to individually follow a given course of waypoints, or the gliders' motions can be coordinated for optimized sampling of a region by linking their waypoint tracks through the GCCS.

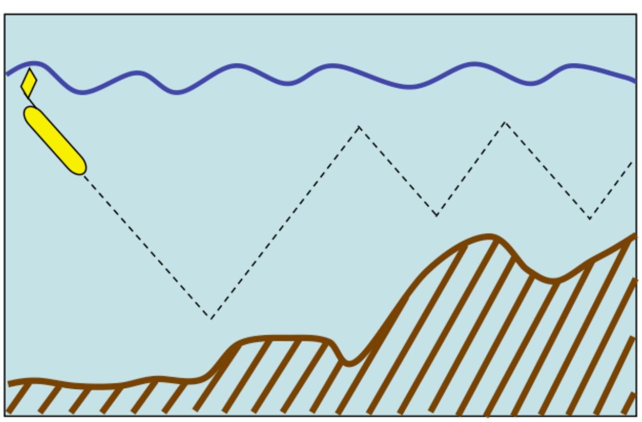

Figure 2. Verticle profile of glider zigzag motion with varying seafloor bathymetry.

Deployment locations are chosen based upon the scientific potential of a site. These gliders are equipped with an array of scientific instruments that allow for the determination of the temperature, salinity, density, light attenuation, and chlorophyll-a and oxygen content of the water at depth. Other important factors to consider at a given deployment location are the physical geography of the water boundaries, water depth and the range of current velocities. We have chosen the Chesapeake Bay as the simulated deployment site for updating the GCCS to incorporate actual flow data, as described below. This site is of interest due to the tidal and current velocity effects of the Bay's shallow depth and relatively narrow mouth to the ocean. The currents within the Chesapeake are known to reach speeds of up to 2 knots in certain areas, with the average maximum speed on a daily basis being around 1.5 knots (77 cm/s). In relation to the gliders' maximum and nominal horizontal speeds through the water of 40 cm/s and 25 cm/s, respectively, the currents in the Chesapeake may cause a significant disturbance in the gliders' coordination in the water when the gliders are linked and controlled by the GCCS. Not only is it important to determine if the gliders will be able to coordinate their sampling patterns in the Chesapeake, but it is also important to adapt the control algorithm of the GCCS for a more general tidal flow simulation of stronger currents up to 1 m/s to determine the spatiotemporal effect of the various flow speeds on the glider coordination time [2].

III. GCCS Adaptation

The GCCS is a robust glider simulation and control model that autonomously controls a fleet of underwater gliders in an array pre-dictated by the user. This system incorporates a planner and simulator for optimal sampling pattern determination and mission prediction for a fleet of coordinated gliders before actual deployment of a glider in the water. Motion of the gliders, both in simulation and in the water, is synchronized by the GCCS planner along specified tracks in order to decrease the overlap in data collected by the glider fleet. Essentially, if any two or more gliders are within a couple kilometers' radius of each other at any given time, those gliders will likely be collecting very similar hydrographic data. The GCCS aims to reduce the amount of data overlap and increase sampling efficiency by guiding the gliders into a synchronized sampling pattern such as that seen in Figure 3 [3].

Initially, the glider simulation software simulates the sampling pattern of a fleet of gliders following set tracks in still water. Adaptation of the GCCS for varying flow fields can be incorporated as constant-amplitude tidal flow or real current flow data from a specified location, as seen in Figure 4. We updated the most current GCCS model to run glider mission simulations and predictions for the Chesapeake Bay using bathymetric data (plotted in Figure 5) from the Regional Ocean Modeling System. Once this was completed, we began to integrate water current data from the Chesapeake Bay into the GCCS flow model, as shown in Figure 6. These data were taken every 2 hours over the course of June and July of 1996 and will be used to obtain a more realistic simulation of how a fleet of three coordinated gliders is affected by the ebb and flow of the Atlantic Ocean's summer tides in the Chesapeake. This system is also used to collect "real-time" hydrographic data, such as salinity and temperature, through simulations and field testing.

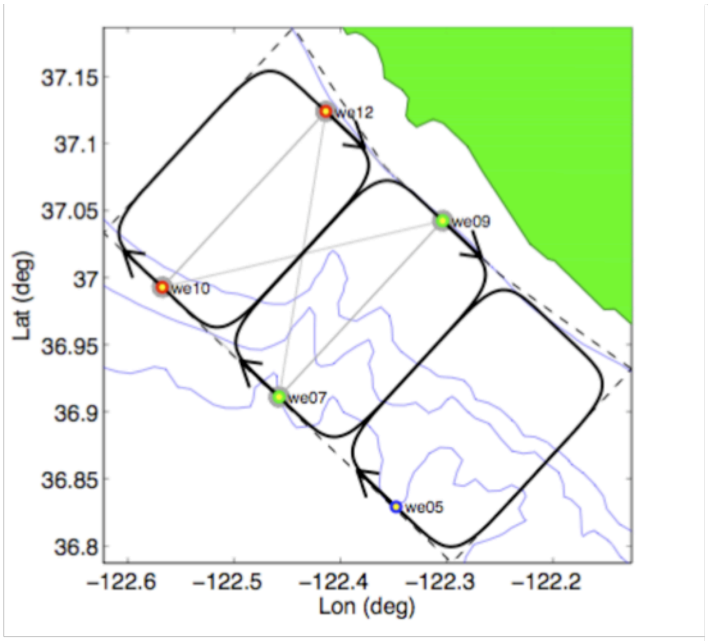

Figure 3. Fully coordinated glider motion along sampling tracks in benign flow (Derek Paley).

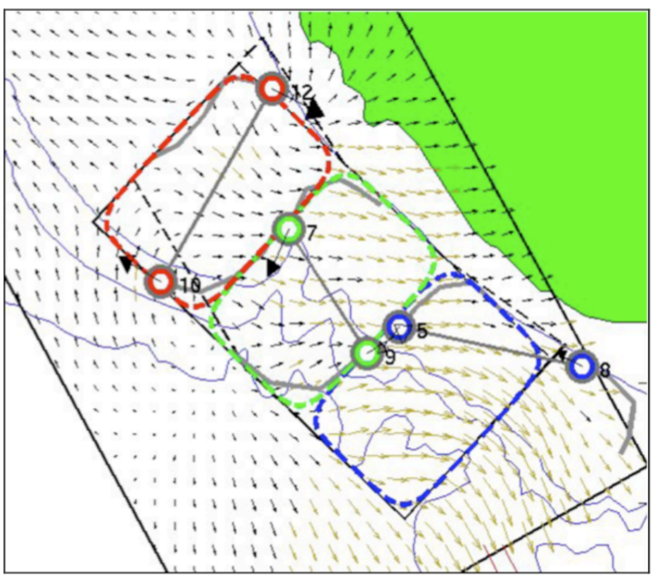

Figure 4. Degradation of glider synchronization in the presence of water currents (Derek Paley).

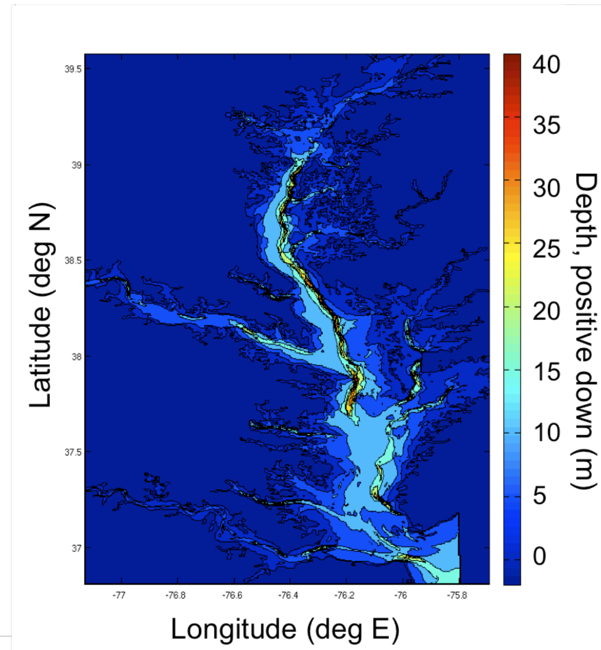

Figure 5. Chesapeake Bay bathymetry map.

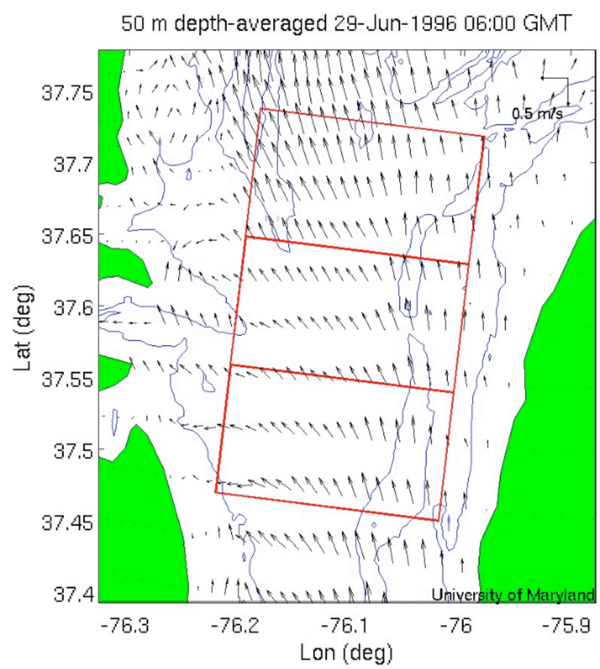

Figure 6. Actual flow field in the Chesapeake Bay.

Accounting for the variable water flow through the Chesapeake Bay, or in any other body of water, can be simulated through the GCCS. Initially run with no flow through the Chesapeake, the GCCS is able to guide each glider towards its track and quickly coordinate the fleet as a whole for sampling efficiency. By setting a constant-amplitude tidal flow variable, we are able to generate either a sinusoidal or square wave in- and out-flow of water in the Bay. This semidiurnal tidal flow model (having a period of about 12 hours and 25 minutes) accounts for the magnitude and direction of the periodic rise and fall of tides twice over the course of a day, but is not an accurate model of how actual tides affect individual locations, or in this particular case, how larger oceanic tides will affect the relatively enclosed Chesapeake Bay. To account for this, we integrate Chesapeake Bay flow data into the GCCS to simulate actual tides and overall water motion that a fleet of gliders may encounter while attempting to coordinate their sampling patterns. By running this simulation before an actual glider deployment in the Chesapeake, we can determine if coordination of glider sampling in this location is feasible. From a more quantitative standpoint, the limits of the GCCS's control algorithm to actively coordinate glider motion can be determined through observing the long-term effects of a range of tidal flow strengths (simulated sinusoidally) on glider coordination. This is modeled and tested by intensification and de-intensification of the peak speeds (the amplitude) of the simulated flow field.

IV. GCCS Testing

In conducting tests using the GCCS, we aim to determine whether existing glider coordination strategies are sufficient for operations in tidally driven currents. This requires that we evaluate both the glider tracking (how closely the gliders follow their set paths) and coordination (how well the gliders are synchronized with each other).

To deduce an answer to this question, we first employ the GCCS to conduct a virtual experiment simulating a glider deployment in the southern region of the Chesapeake Bay using hydrographic data modeling the Chesapeake (provided by the University of Maryland Center for Environmental Science). This allows us to determine if the control algorithm of the GCCS will be able to keep the gliders' paths coordinated as periodic peak flows of about 77 cm/s occur approximately every 6 hours. Second, we test the GCCS control with a semidiurnal sinusoidal tidal flow simulation that incorporates a range of flow speeds and determine the approximate flow speed at which the GCCS's control algorithm can no longer coordinate the gliders' sampling patterns within the course of a mission.

In the pursuit of each of these goals, the GCCS was used in a configuration adapted for water sampling along tracks in the southern region of the Chesapeake Bay. As is consistent with the map in Figure 7, all simulations include a fleet of three gliders that aim to coordinate their motion in parallel along the rounded rectangular sampling tracks shown.

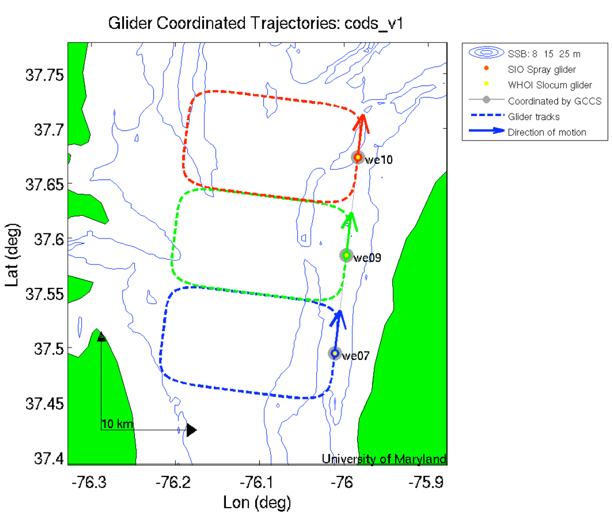

Figure 7. Target sampling tracks for the coordinated motion of gliders in the southern region of the Chesapeake Bay.

A. Integration of Chesapeake Bay Flow Field Environment

The GCCS has been adapted to incorporate the effects of actual flow fields in the Chesapeake Bay by writing a script that describes the hydrographic environment and flow dynamics based on actual oceanographic data collected in the Bay in 1996. Once we fully integrated this script into the GCCS flow environment script, we ran the glider simulator and planner for the duration of time covered by the Chesapeake flow data (about 10 days). It was hypothesized that the gliders would be unable to coordinate their motion in this time, or would be somewhat coordinated but consistently significantly pushed off course by water currents to the point that they end up regularly crossing paths with one another. Thus the use of the current control algorithm with the GCCS would be determined insufficient to control gliders in the Chesapeake without active human intervention.

B. Variation of Theoretical Sinusoidal Tidal Flow

Stemming from testing of the GCCS with the Bay environment, we subsequently ran the glider simulator for mission durations of 10 days and varied the peak water flow speed from 0 to 0.5 m/s to test the limits of the GCCS control algorithm with a theoretical sinusoidal tidal flow. We chose to evaluate the GCCS at flow amplitudes of 0, 10, 25, and 50 cm/s based on the nominal glider speed of about 25 cm/s horizontally through the water. It was expected that a flow of 0 or 10 cm/s would have very good tracking and coordination, 25 cm/s flow would significantly perturb the glider coordination and tracking due to instances of gliders traveling head-on against a flow of the same nominal speed, rendering the gliders unable to progress in a timely manner, and 50 cm/s flow (twice the glider speed) would be closest in effect to the Bay environment, pushing the gliders farthest off track and preventing them from coordinating with each other. Once this data was analyzed, we could more accurately determine the approximate limits of the coordinated control of the gliders over the duration of such a mission.

V. Results and Analysis

The Chesapeake Bay hydrographic model is successfully integrated into the GCCS and has been run with the glider simulator and planner in order to optimize the tracking and coordination of three Slocum Electric Gliders (labeled we07, we09 and we10) running parallel tracks in the Chesapeake Bay. One feature that is interesting to note is the random initial placement of the gliders in the center of their tracks, shown in Figure 8, and how that affects the subsequent glider coordination as they are pushed off track (especially by strong and variable currents). As it turns out, each run of the GCCS shows a relatively lower spacing error (meaning higher coordination) between we07 and we09 (the two more southerly gliders) than between we07 and we10 or we09 and we10. This is a result of the initial positions of the gliders, since they first must each head towards a point on the track as they start tracking and coordinating. Gliders we07 and we09 consistently head for parallel points on their tracks, but we10 does not, making it difficult to coordinate in strong currents without the initial advantage of traveling in the same direction to reach the track.

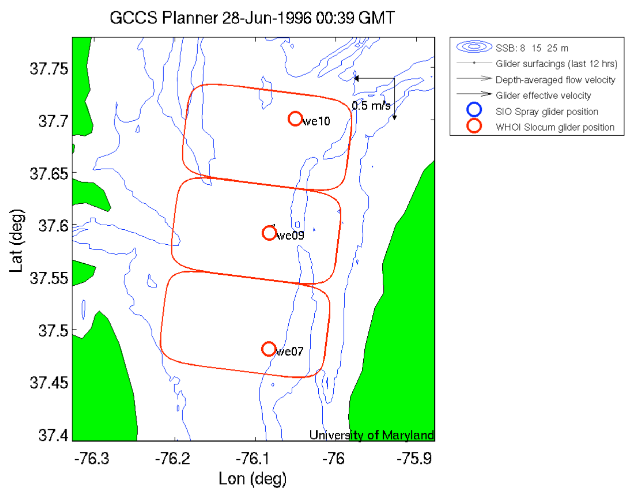

Figure 8. Inital glider deployment locations.

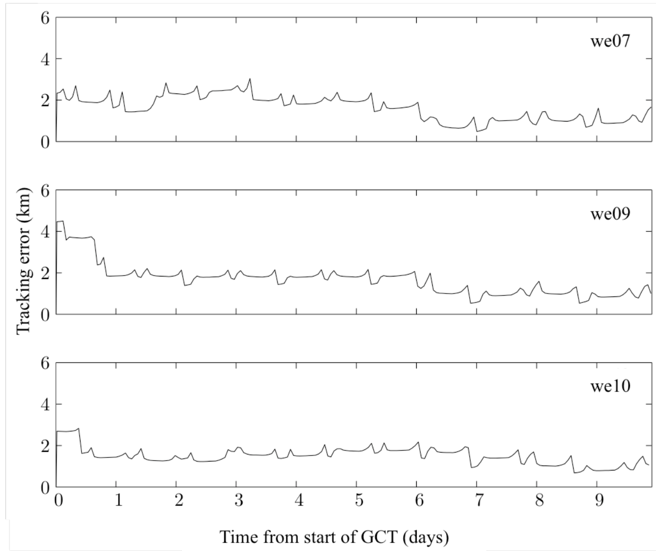

Figure 9. Glider tracking error in a zero-flow environment.

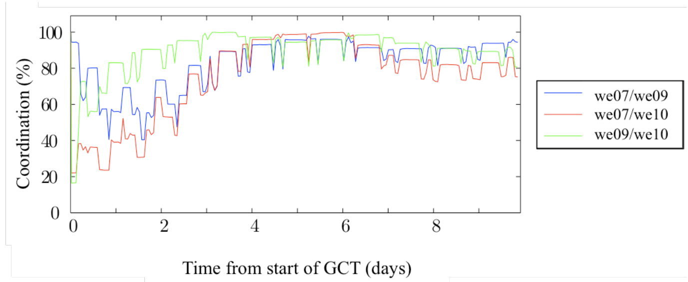

Figure 10. Glider coordination in a zero-flow environment.

One important feature of the GCCS is the ability to create movies of the spatiotemporal motion of the gliders around their tracks in both the presence and absence of a Bay flow environment. This facilitates the comparative analysis of active tracking and coordination between various multi-day glider missions. The generation a spacing error plot for each missions allows for the quantitative comparison of glider coordination over the duration of a mission. The tracking error tells us how closely the gliders followed the tracks over the course of a mission. The movies that we generated mark the interdependence of tracking and coordination, showing an increase in overall tracking error as coordination degrades.

A. Zero-Flow Environment

Figures 9 and 10 show the tracking and spacing errors, respectively, of the gliders for a 10-day mission in the Chesapeake with no flow (constant 0 cm/s water speed). Ideally, these plots are expected to show almost zero tracking and spacing error (100% coordination) throughout the course of a mission, however, this is evidently not the case. We see in Figure 9 that there is consistently just under 2 km of tracking error even in a zero-flow environment, suggesting that there is a problem within the control system such that we can not use tracking error to quantitatively evaluate the effects of simulated or actual flows in the Bay. The very high coordination is as expected from a zero-flow environment, however we see a slight decrease in coordination even when one glider starts to turn a corner later than the others. This is likely a result of the varying bathymetry around each track, causing a slight variation in surfacing times and waypoint locations. The accuracy of the planned surfacing positions, though not exactly on the desired tracks, is very high. This is shown in Figure 11, where the green stars are actual glider surfacing positions and the black points are desired surfacing positions (covered by the green stars in this case due to perfectly predicted surfacing positions in zero-flow conditions).

B. 10 cm/s Sinusoidal Tidal Flow

Figures 12 and 13 show the tracking and spacing errors, respectively, of the gliders for a 10-day mission in the Chesapeake with a sinusoidally-simulated semidiurnal north-south tidal flow of 10 cm/s amplitude. A tracking error of about 2 km remains throughout this mission, whereas the presence of a low tidal flow appears to increase the duration of 100% coordination between gliders over that of the coordination in the zero-flow environment. This may be a result of the gliders getting pushed by the flow just enough and at just the right time to help them remain so closely coordinated. The slight waviness of the paths the gliders trace through the water is seen in the pattern of the green stars (glider surfacing positions) in Figure 14, showing slight instability in the glider's motion due to the simulated flow.

C. 25 cm/s Sinusoidal Tidal Flow

Figures 15 and 16 show the tracking and spacing errors, respectively, of the gliders for a 10-day mission in the Chesapeake with a sinusoidally-simulated semidiurnal north-south tidal flow of 25 cm/s amplitude. A tracking error averaging about 2 km remains throughout this mission, though the tracking error range increases, ranging from 0.5 km to 3.5 km due to the flow amplitude matching the nominal glider speed. The spacing error between gliders in 25 cm/s flow continues

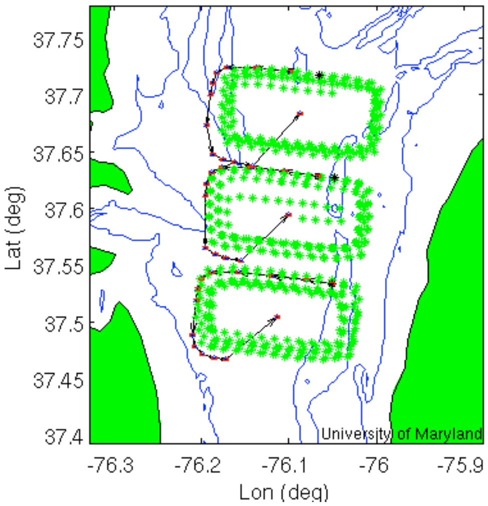

Figure 11. Glider surfacings resulting from zero-flow conditions.

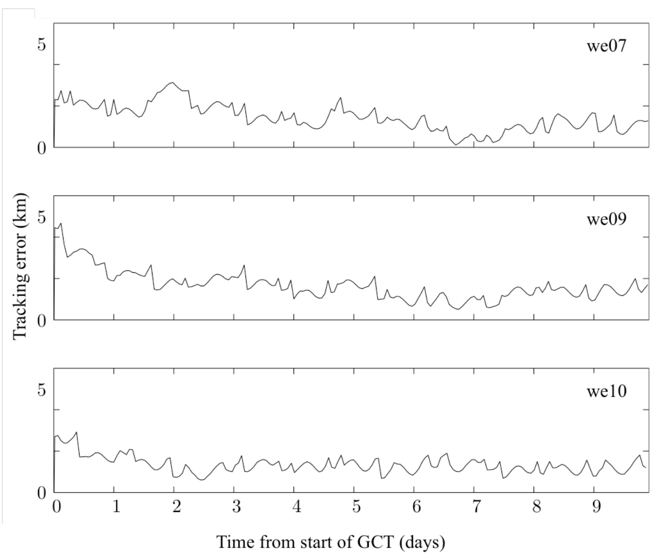

Figure 12. Glider tracking error in 10 cm/s flow.

to remain very low for a slightly shorter duration than that resulting from the 10 cm/s flow. As such, the control system is sufficient to consistently coordinate the gliders around their tracks and surface them within a few kilometers' radius of the predicted surfacing positions shown in Figure 17. It is also evident from these results that there is significantly more instability in tracking and coordination with a 25 cm/s flow environment than with one of 10 cm/s, however, it is possible that these instabilities could be resolved if the gliders are deployed for a longer-duration mission of weeks or months in an attempt to achieve more accurate and precise steady-state results.

D. 50 cm/s Sinusoidal Tidal Flow

Figures 18 and 19 show the tracking and spacing errors, respectively, of the gliders for a 10-day mission in the Chesapeake with a sinusoidally-simulated semidiurnal north-south

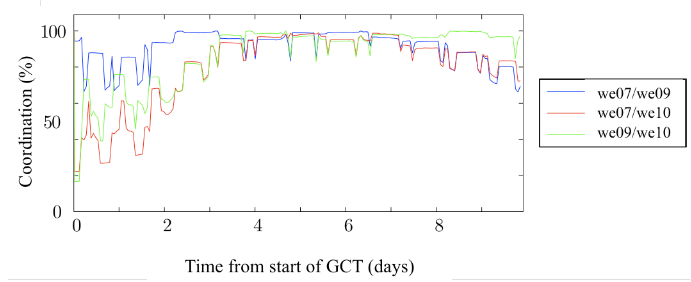

Figure 13. Glider coordination in 10 cm/s flow.

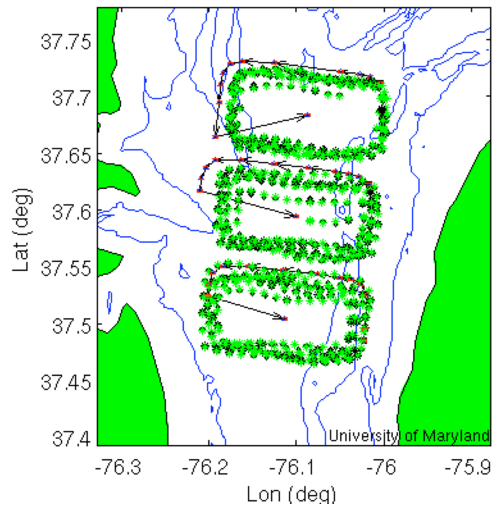

Figure 14. Glider surfacings resulting from 10 cm/s flow.

tidal flow of 50 cm/s amplitude. In this high-speed flow, which is twice the nominal glider speed horizontally through the water, the gliders are pushed around significantly by the currents. This results in tracking errors ranging from 0 to 5 km – a 67% greater range than that of gliders in 25 cm/s flow. In examining the spacing error between gliders, it is interesting to note that there is no spacing error decay at the end of the mission and the coordination shows a clear increase in precision after the first 2.5 days, and again after 5.5 days have gone by since the deployment, despite the distances that the gliders get pushed by the currents, as shown in Figure20. This is likely due to the domination of the strong currents over the gliders' nominal speed through the water in influencing the gliders' surfacing positions. However, the very low eventual we07/we09 spacing error juxtaposed with the consistently high final spacing errors of we07/we10 and we09/we10 also demonstrate that the strong currents themselves can somewhat maintain glider coordination or dis-coordination over a period of time even though the control algorithms used to coordinate the glider have failed.

E. Chesapeake Bay Model Flow Environment

Figures 21 and 22 show the tracking and spacing errors, respectively, of the gliders for a 10-day mission (midnight, June 28th, 1996, to 10 p.m., July 7th, 1996) in the Chesapeake, incorporating the Chesapeake Bay model flow environment.

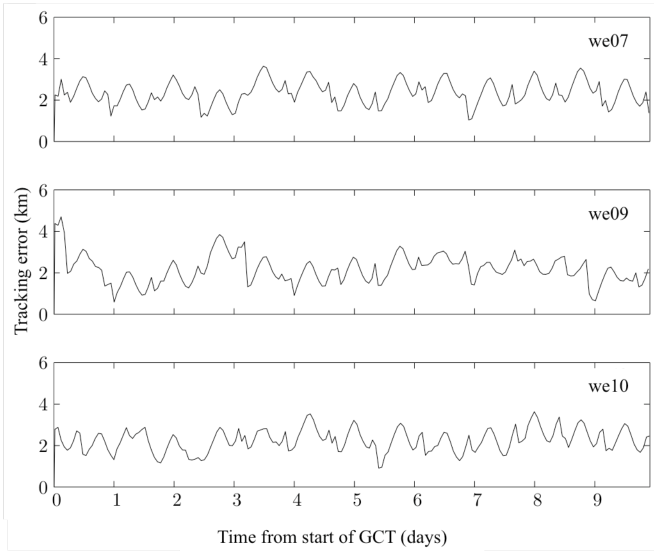

Figure 15. Glider tracking error in 25 cm/s flow.

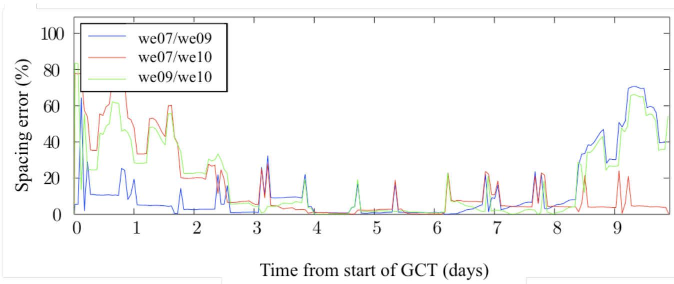

Figure 16. Glider spacing error in 25 cm/s flow.

Due to peak tidal flow amplitudes of up to 77 cm/s in the Chesapeake Bay, the tracking error of the gliders ranges from 0 to over 6 km for we07 and we09, and from 0 to 5 km for we10. Although the spacing error precision resulting from the simulated 50 cm/s is not present in the results from the bay flow environment, we still see a clear decrease in random spacing error after about 5 days. Similar to glider motion in 50 cm/s flow, the strong Bay tidal currents cause a failure of the GCCS's control algorithm and the gliders' motions are dominated by the currents of the Bay. As seen in Figure 23, the predicted glider surfacing positions (black) were frequently kilometers off the actual surfacing predictions, making it not only difficult to compensate for the currents, but also to plan and reach waypoints around the tracks while coordinating motion between gliders. It is also evident that the gliders were unable to even maintain motion near the general loop configuration of their individual tracks for much of the mission. There are multiple instances in which two gliders either crossed paths, seen in Figure 24, or a glider looped back over its achieved waypoints, seen in Figure 25, after being pushed off course by the Bay flow. This behavior of looping back on waypoints was also seen in the glider paths in 50 cm/s flow.

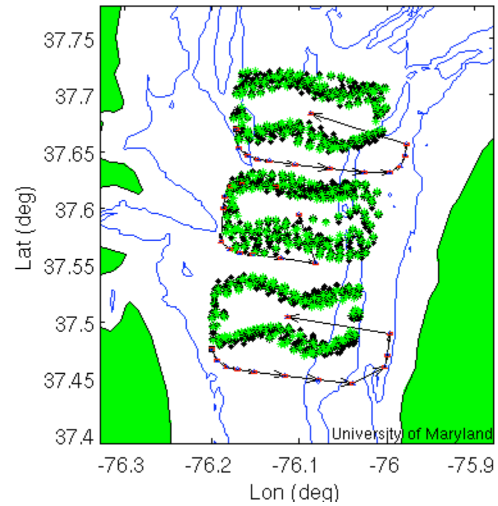

Figure 17. Glider surfacings resulting from 25 cm/s flow.

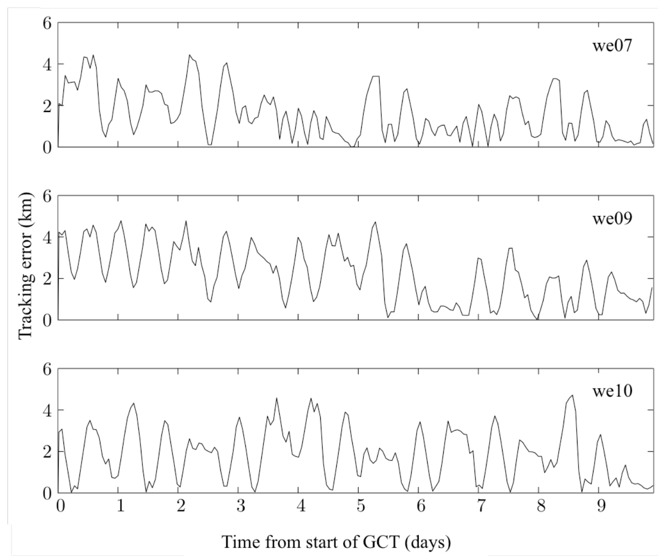

Figure 18. Glider tracking error in 50 cm/s flow.

VI. Future Work

It is important to continue research with the GCCS in exploring ways to prevent glider coordination failure by improving the control algorithm within the GCCS to function successfully in areas harboring strong and variable currents. Other results that will give further insight to the basic effects of the Bay currents and the robustness of current and future glider coordination strategies will be obtained through running glider mission simulations with the same three tracks in the Chesapeake Bay, but without having the gliders trying to coordinate with each other. Glider coordination time may also be improved using the GCCS by determining optimal deployment times, sampling track dimensions, and initial deployment locations for each glider in the Chesapeake Bay based upon tide predictions and the dynamics of glider motion in tidal flows.

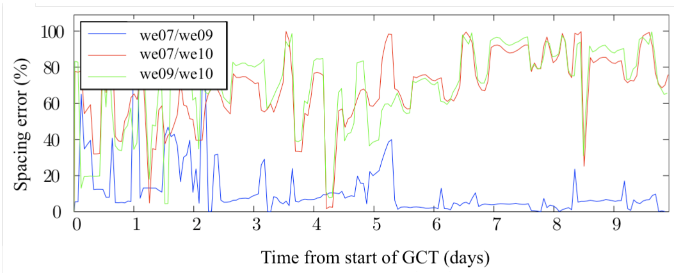

Figure 19. Glider spacing error in 50 cm/s flow.

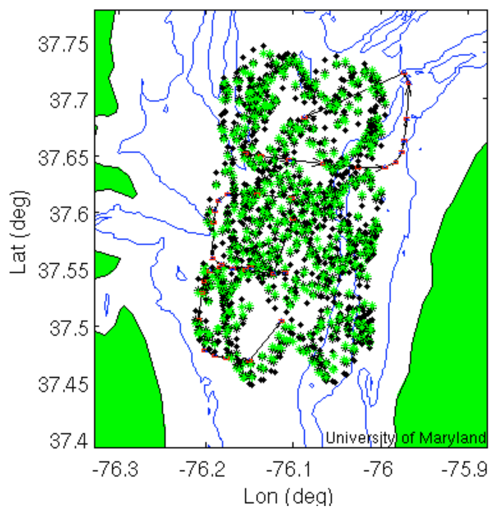

Figure 20. Glider surfacings resulting from 50 cm/s flow.

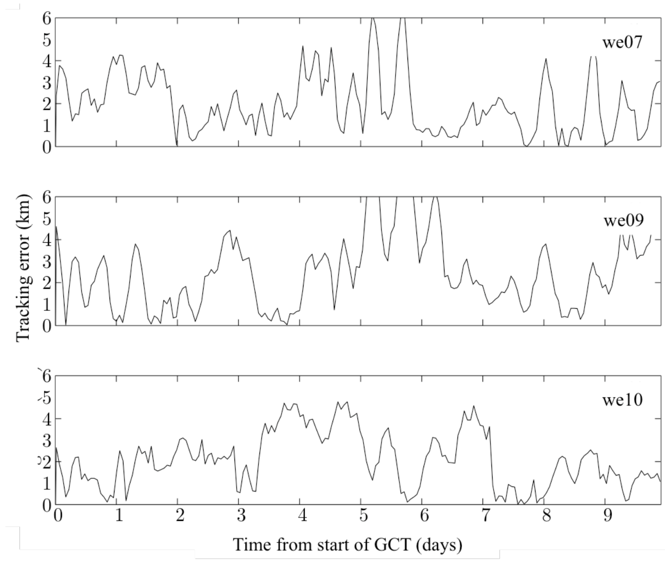

Figure 21. Glider tracking error in Chesapeake Bay flow.

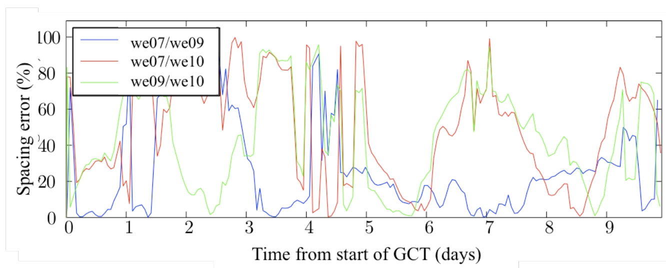

Figure 22. Glider spacing error in Chesapeake Bay flow.

VII. Conclusions

The scope of this project incorporated five 10-day simulated glider deployments in the Chesapeake Bay, each demonstrating the performance of the GCCS's control strategy for underwater gliders through four simulated tidal flows and a modeled Chesapeake Bay flow environment. In evaluating the results from the glider missions in the flow fields of amplitudes 0, 10, 25, and 50 cm/s, it is determined that we cannot accurately simulate Chesapeake Bay flow with a constant amplitude semidiurnal tidal flow due to wide variations in actual Chesapeake Bay tide amplitudes. However, the Chesapeake Bay flow model did produce results similar to that of the 50 cm/s sinusoidal flow.

The robustness of the coordination strategy to compensate for flow perturbations in the Chesapeake is highly dependent on flow speed. The coordination strategy is able to sufficiently account for perturbations up through 25 cm/s flows, because this matches the nominal glider speed horizontally through the water. Tidal flows matching or exceeding 50 cm/s, however, push the gliders significantly off course and out of synchronization. This is again reinforced by the results from the glider deployment using the modeled Bay flow environment, where the tidal flows reach speeds of up to 77 cm/s.

This project illustrates a limitation of the glider coordination strategy, and thus motivates the design of new control strategies to handle strong and variable currents. The identification of this need is important to the scientific and engineering community due to the impact of glider coordination on the efficiency of hydrographic data collection. Once a reliable glider coordination strategy is developed to effectively deal with strong and variable currents, these power-efficient underwater gliders will no longer be limited to low-speed flow regions for deployment and data collection, widely expanding their potential for use throughout the scientific and engineering community.

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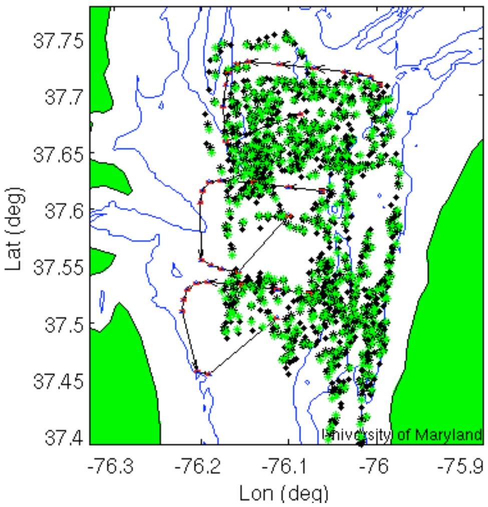

Figure 23. Glider surfacings resulting from Chesapeake Bay flow.

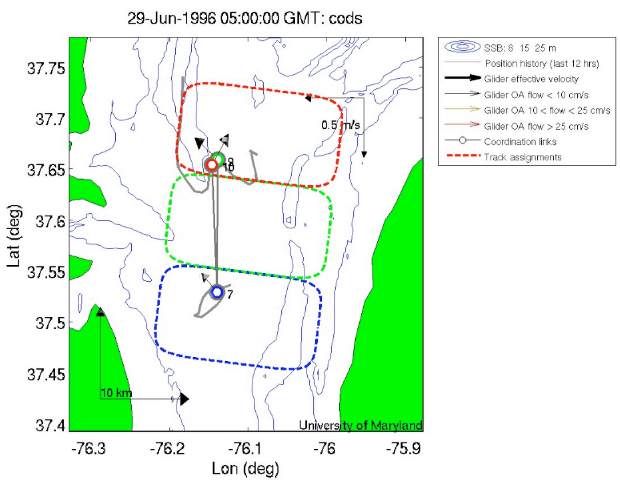

Figure 24. Gliders we09 and we10 crossing paths in Chesapeake Bay flow.

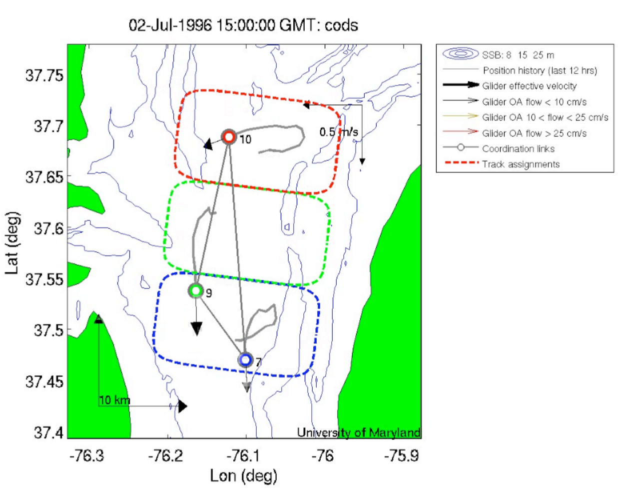

Figure 25. Glider we07 looping back on waypoints in Chesapeake Bay flow.