Abstract

Rutgers University Coastal Ocean Observation Lab (RU-COOL) and Webb Research Corporation (WRC) continue to apply the autonomous underwater Slocum gliders in field operations spanning the globe. Our goal is to share the operational experience that we have had with this class of vehicle in the past years and to show the unique data sets acquired.

The continued strong collaboration between WRC and Rutgers has led to advances in glider operations and applications. Discussed are deployment and recovery techniques, reliability, lessons learned, integrated sensors suites, and adaptive controls utilized to optimize mission goals and data return. Shared are numerous data sets including salt intrusions as seen off of New Jersey, plume tracking, and biological water sample matching.

Recent accomplishments include adaptive fleet control during the ONR sponsored Shallow Water ’06 (SW06), RIMPAC, LATTE, ASAP, CBLAST, Perth, a submarine launch, the continuation of LEO-15 New Jersey site Endurance Line, and an LTER Antarctic deployment. As of July 2007, Rutgers has flown more than to 100 missions with over 31,000 km flown giving an impressive 875 calendar days in the water as seen in Figure 1. Deployments and operations are orchestrated from the COOL Room at Rutgers.

Figure 1. Rutgers University world map of deployments.
Introduction

UUST conferences provide wonderful milestones to review the progress and technical achievements that have occurred over the past two years. On the technical forefront, Webb Research Corporation (WRC) has continued to improve the capabilities of the Slocum Gliders with the introduction of greater depth capability, additional payloads, and deployment advances. Regarding fieldwork, Rutgers University (RU) has pushed the envelope for deployments both with coordinated fleets and in extreme locations.

Gliders

With the support of a number of Institutions and Universities throughout the world, WRC has continued with software and hardware improvements to the Slocum glider. Presently, over 90 systems have been delivered to 27 institutions in 10 countries. This paper concentrates on the teaming relationship between Rutgers and WRC, however, we must stress that there are a number of providers and user groups, without whom, this technology would not have advanced to the present state. In short, gliders have truly transitioned from a novelty to an accepted oceanographic sensor platform.

Thermal Glider, an update:
A bit of history of how we got to this point. The genesis of all present ocean gliders began with an entry in Doug Webb’s lab book on 2/8/86. On page 254 is detailed a thermal engine that harvests propulsion energy from thermocline of the ocean by means of a material state change and on page 255 a description of a gliding vehicle that could utilize this buoyancy drive. In order to prove the concept of the gliding vehicle itself, battery powered hydro-mechanical versions were first constructed as test beds. It was quickly realized that these “electric gliders” had substantial merit of their own and were capable of extended durations with a variety of sensor suites. As with the nature of bringing new technology to life, resources are limited and due to demand the 200m and 1km gliders have prevailed, with less attention available to push the Thermal glider forward. In the background, however, incremental progress is being made and for those who have followed the history of glider technology, an update is in order. During March and April of 2005 and again in February 2006 successful sea trials of the Slocum Thermal glider utilizing state change propulsion were conducted (Figure 2). Further efforts are presently underway to continue refining the design and to engage in long distance deployments to fulfill the original concept.

Glider advances:
Where much of our attention is being focused, is in advancing the capabilities of the present battery driven gliders.
The depth capability of the Slocum glider has now been extended to 1000 meters (1km Slocum glider) with most deployment activity centered in the Mediterranean Sea and off of Norway. Mechanically, with the exception of the pressure housing thickness and the hydraulic pump system, the components and architecture of the system are the same as the 200 meter variant. The same code base is maintained to support all vehicle types.

As part of increasing the depth capability, WRC’s engineering of composite carbon fiber fore and aft hulls for the Slocum 1km gliders is a significant technical advance. These provide a reduction of hull weight and allow one to build in a desired compressibility. A patent has been awarded to WRC for this composite work as it applies to buoyancy control in profiling floats.

All systems retain an aluminum modular payload bay to allow machining of ported windows and sensor feeds.

Sensor suite capabilities are routinely being added including a number of optical sensor packages, multispectral radiometers, oxygen, and hydrophones. Figure 3 shows a 1km Slocum glider with 2 Wetlabs ECO pucks, an upward and downward looking Satlantic radiometer package, Aanderaa optode, and Seabird CTD. A number of groups have also been flying Slocum gliders with towed arrays up to 30 meters in length.

Overall, the value of gliders is as a sensor platform and their usefulness expands as compact low power sensors become available for integration. We can easily envision where coordinated fleets of gliders will help to provide a complete biogeochemical view of the ocean.

A novel addition to the modular payload bay system has been a Bottom Lander (Figure 4). Traditionally, Autonomous Underwater Vehicles (AUVs) are always in motion while operating. An additional buoyancy control system allows a glider to achieve greater negative buoyancy and thus the ability to stop, while deployed, and rest on the sea floor. In this fashion, a whole new paradigm of mission function, and control can be explored. Some of these options include, but are not limited to; the ability to navigate to a certain location by “leapfrogging” against tides, sensing some sporadic activity, and seeding an area for advanced deployment operations. Given the potential hazards of bottom survivability, the wingspan has been reduced with increased chord. Additionally, the tail fin boom has been shortened and over-molded with a ruggedized antenna tail fin and an integral direct drive fin motor (Figure 5).
Unique glider deployments include a 2005 underwater launch from a submarine Dry Deck Shelter (DDS). This necessitated the design of no-tools-required snap-in wings (Figure 6). The glider then performed its survey mission and was subsequently recovered days later by surface vessel. This wing style is now incorporated in all vehicles. Work to accomplish a submarine tube launch package is in progress.

**Command and Control (C2)**

Dockserver, the land or ship-based communications auto-attendant for the gliders is the backbone for automated command and control. The self-deployed, Java based, Glider Terminal permits simultaneous multiple terminal connectivity to remotely view Dockservers from anywhere in the world. With layered windows, a single operator can readily monitor a fleet of gliders. Further, Dockserver is architected to perform any number of XML scripts that are queued by means of text-based recognition on the glider surface dialog. In this manner, instructions can be left in advance of a glider surfacing to collect data, re-direct waypoints, or change flight parameters. This underlying structure facilitates an adaptive capability by means of various inputs such as the scientist, satellite imagery, other gliders, etc to create goals that are translated into glider mission construct. Overlays exist to map the glider field, keep track of engineering items such as battery voltage, vacuum, etc. and to display data sets.
**Field Results**

**Going where no glider has gone before:**
The Antarctic Peninsula is undergoing, arguably, the most dramatic climate change on Earth. The Western Antarctic Peninsula (WAP) region has experienced a significant winter warming trend during the past half century (~5.4 times the global average, *Vaughan et al.*, 2003). Consistent with this warming, the sea ice season is shorter with perennial sea ice no longer present, *Stammerjohn et al.*, 2006) and the maritime system of the northern WAP is expanding southward, displacing the continental, polar system of the southern WAP while 87% of the glaciers are in retreat (*Cook et al.*, 2005). Ecosystem response to these changes is evident at all levels in the marine food chain. Mounting evidence (*McCarthy et al.*, 2001) suggests that sea ice-related ecosystems of the polar regions may be especially sensitive to global climate change. Thus, the WAP region is proving to be an exceptional area to study ecological (*Smith et al. 2003*) and physical (*Martinson et al.*, 2006) response to climate variability, to study the complex feedback mechanisms associated with this variability and to better understand the chemical and physical processes associated with climate change.

One particular aspect of the WAP marine system lends itself to immediate testing of the near continuous sampling of an ocean glider: the question of the ocean heat flux and its role in WAP climate change. Clearly ocean heat, available in the Upper Circumpolar Deep Water (UCDW), delivered to the WAP continental shelf by the Antarctic Circumpolar Current (ACC) is a critical component of the warming, being the only local source of heat in winter. This WAP region has been the location of the long-term Palmer LTER project and the Southern Ocean GLOBEC project, so considerable shipborne (snapshot) information has been collected, providing a foundation against which to plan the glider flight and establish hypotheses not otherwise testable from shipboard data, and to leverage logistics via partnering with the PAL–LTER annual cruise for deployment and recovery.

Rutgers and Webb Research have demonstrated the ability to operate Slocum gliders world-wide by means of Iridium (global communication satellites) and have demonstrated adaptive command and control from laboratories in New Jersey, Massachusetts and from portable computers in remote locations. This group flew the very first Slocum glider and since then has accumulated over 31,000 kilometers underwater in the tropics and temperate waters. The distance equates to 1,577 glider days at sea since October 2003. With a sufficiently robust technology, the opportunity for a deployment in a polar environment was envisaged. The gliders have worked in winter waters below 2°C offshore New Jersey and have operated in severe storms bolstering our level of confidence. However, despite the success in non-polar waters, the extreme polar environment, even in the polar summer, offers some particular risks. Specifically: (1) the battery power de-rating associated with cold temperatures; (2) the possibility of communication interference and ballasting with freezing of wind blown ocean spray; and (3)
flying in regions containing a completely different megafauna, whose response to a glider is yet to be discovered (e.g., leopard and elephant seals); (4) encounters with icebergs of huge spatial extent relative to glider size and flight path course; and (5) response to episodic polar lows (reduced in strength and frequency in summer, but still capable of bringing in severe polar conditions). These summer polar conditions must be fully tested before a more elaborate large scale winter test can be undertaken, the latter will advance the state of our understanding of the regional change through unprecedented resolution in spatial/temporal sampling (e.g., whereas typical shipborne CTD stations are located km apart, requiring nearly 3 hours per station on the shelf, the glider will provide 10 profiles/km, covering 1 kilometer of lateral travel distance in about 1 hour).

Figure 7. Slocum glider deployed near Palmer Station, Antarctica.

On January 2007 the first Slocum glider was deployed in the WAP as a pilot for future missions (Figure 7) This deployment required some technical efforts focused on optimizing the Glider for the long duration flight under extreme conditions.

Flying smart on the WAP: The glider was deployed on January 9th, 2007 off Palmer Station (Figure 8.) The glider then started an offshore transect of about 40 kilometers before turning sharp left and heading south down the coast. This along-shore transect was 400 km long. Then the glider was instructed (not shown) to fly a leg back towards the coast near Rothera Station. Throughout the 23-day mission, the glider sent real-time data back to the operations center at Rutgers University. These data were published on a public website. Additional daily glider reports were sent directly to ships conducting complimentary science in the area. This is the strategy that has allowed scientists in New Jersey to optimize the glider through difficult conditions which included typhoons in Asia, rip currents and wave surge offshore Hawaii and mesoscale eddies offshore Australia. The glider was equipped with a CTD (Temperature, salinity and density) along with an optics payload measuring particle load and Chla concentrations. These data showed significant interaction between the ocean physics and biology (Figure 9). The high density of data is able to resolve the daily signal in the Chla concentrations and the alongshore variability of the surface freshwater flux.

Figure 8. Along shore track of Slocum Antarctica deployment.
**Figure 9.** Alongshore glider sections in the WAP showing a) temperature, b) sound velocity, c) salinity, d) Chlorophyll A concentration, e) density, and f) optical backscatter at 470nm.

**Coordinated glider flights:**
As a component of an ONR effort, the group maintained a sustained Glider fleet within the SW06 experimental area offshore New Jersey using Gliders being constructed and delivered as part of the Rutgers Glider Technical Center. The glider team successfully dealt with the compact delivery schedule that resulted in the majority of the gliders running their first check out mission during the experiment. Glider operations totaled 17 deployments sampling over 6,400 km and acquiring over 50,000 CTD casts (Figure 10). The data analysis team produced a real-time quality controlled glider CTD dataset that was made available to modelers for assimilation.

**Results:** Persistent southerly winds through June, July and August resulted in persistent upwelling along the inner NJ shelf and along the southern coast of Long Island. Albany’s wettest June in over 200 years of record keeping produced the fifth largest Hudson River discharge in nearly 90 years of record keeping. The result was a persistent offshore surface flow from the NY Bight Apex along the Hudson Shelf Valley that then turned southward, flowing through the SW06 area. This produced a pool of fresher than normal water on the outer shelf during the initial months of SW06. The pooling of water on the outer shelf was aided by the eastward flows from the Delaware interrupting the southward
flows from the Hudson Shelf Valley. September brought hurricanes and northeasters, resulting in a significant change in the surface currents to a more uniform shelf-wide flow to the southwest. Offshore in the Slope Sea, a large warm core ring formed in the spring, sweeping the region clear of the typical size warm core rings before being reabsorbed itself by the Gulf Stream, resulting in an offshore influence dominated by the smaller shelf break eddies.

Lessons learned:

Certainly the advances in oceanography that gliders are providing are significant. As with any new instrumentation, there are the expected trials and tribulations, however, keeping an open interface and communication loop between design, manufacturing, and end users is a key element to truly making in impact with regards to looking into the ocean better than we have previously. This partnership provides an iterative feedback that drives the evolutionary changes for system enhancements, reliability, and sensor integration.

Throughout the learning curve we have found that mission simulation, checkout sheets, and careful vehicle preparation are the key to a successful deployment.
Of the total 90 delivered systems, 7 vehicles have been lost due to situations most likely beyond glider software or hardware control: known mechanical issue (1), ship collisions (2), striking landmass (1), science package pressure failure (1), severe weather recovery (1), unknown (1). An additional three WRC owned test vehicles have been lost during preliminary trials.

This has led to careful review of deployment location prior to deployment, particularly in coastal areas. Attention is paid to surface and submerged hazards, shipping lanes, and strong tidal bores. During more recent missions, careful utilization of these environmental information have allowed the gliders to fly in difficult regimes such as Liverpool Bay, New York Harbor, Antarctica, and into storms Ernesto and Beryl that have resulted in unprecedented oceanographic data sets with no loss of equipment.

Other typical hazards include pickup by tour boat operators and fishermen. Clearly marked contact information and “Scientific Instrument - Please leave in the water prior to this date” have helped reduce pickups.

Parting Shot (Figure 12): An unexpected bio-fouling issue that we have experienced a few times in the Gulf of Mexico is the attachment of Remora (Remora Echeneidae) to the hull of the gliders. Unfortunately these fish, which can be up to half the length of the glider body, are negatively buoyant and can hold a glider down until they decide to free themselves.

Figure 12. Remora attaching to a Slocum glider.

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