Using Webb gliders to maintain a sustained ocean presence

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***Abstract-* Buoyancy driven Slocum gliders were a vision of Douglas Webb, which Henry Stommel championed in a vision published in 1989. Slocum gliders have transitioned from a concept to a technology serving research and environmental stewardship. The long duration and low costs of gliders allow them to anchor spatial time series. Large distances, over 600 km, can be covered using a set of alkaline batteries. Lithium batteries can anchor missions that are thousands of kilometers in length. Since the initial tests, a wide range of physical and optical sensors have been integrated into the glider allowing measurements of temperature, salinity, depth averaged currents, surface currents, fluorescence, apparent/inherent optical properties active and passive acoustics. A command/control center, entitled Dockserver, has been developed that allows users to fly fleets of gliders simultaneously in multiple places around the world via the Internet. Since October 2003, Rutgers gliders have conducted 157 missions, traversed >55,000 kilometers, logged >2600 days at sea, and logged ~350,000 vertical profiles. The capabilities of the glider make them an indispensable tool for the growing global effort to build integrated ocean observatories. For example, gliders are now a central tool within the National Science Foundation Ocean Observatory Initiative (OOI) and the National Oceanic and Atmospheric Administration's Integrated Ocean Observing System (IOOS). Gliders provide a new magnet in which to attract young people into the ocean science and engineering. For example Rutgers undergraduates now anchor long duration flights of gliders world-wide beginning their freshmen year. This is critical to training the next generation.**

I. INTRODUCTION

For centuries, oceanographers have relied on observations gathered from ships during cruises of limited duration. This expeditionary research approach has resulted in major advances in understanding the global ocean. These and many other successes have expanded our view of Earth and ocean processes, and have demonstrated a need for sampling strategies spanning temporal and spatial scales that are not effectively carried out using ships. To address this observational gap, the scientific community has consistently called for the development of the capability to maintain a continuous sampling and monitoring presence in the ocean [1].

Mobile platforms are undergoing exponential development and are transitioning into observational tools. One such autonomous platform that is rapidly becoming indispensable are gliders. Gliders, as currently configured, were first detailed in Doug Webb's lab book on 2/8/86 as a novel instrument approach and was subsequently publicized in 1989 by Henry Stommel's view of a futuristic smart fleet of instruments [3]. It has taken some time to bring these concepts to reality, yet gliders are steadily earning their reputation as a high-endurance sensor platform. More importantly, this class of long-range and relatively low-cost autonomous underwater vehicle (AUV) is making affordable adaptive sampling networks a reality.

Fig. 1. A Webb glider at the surface offshore Hawaii attracting fish.

We will review our experience with Slocum gliders (Figure 1) and will demonstrate how they offer the potential improvement in our capability to observe the oceans. A number of different gliders have been developed and are being used by many organizations; however, for this paper we will only discuss the field efforts conducted by Rutgers University (RU) and Webb Research Corporation (WRC). We emphasize that the successes of this group are matched by other groups at other institutions. Our "take home" message is that Gliders are a robust technology capable of anchoring large field campaigns. Additionally, we will also highlight how Gliders will benefit many different users and serve as a magnet for the next generation of scientist and engineer.

II. OUR GLIDER EXPERIENCE AS OF WINTER 2009

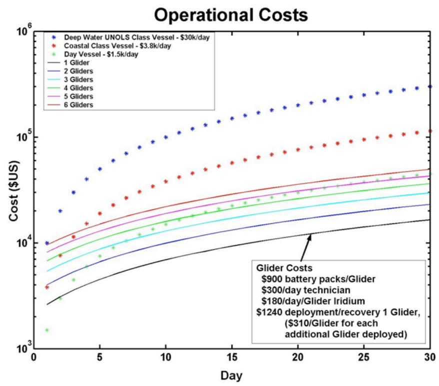

Figure 2. The costs in United States dollars for maintaining ships and gliders at sea. Ship costs represent the average daily charge that varies with ship class based on averages in the year 2005. The glider costs include the expenses of deploying, maintaining, and recovering a glider.

The Slocum glider is a 1.8 m long torpedo-shaped, winged AUV. It maneuvers through the ocean at a forward speed of 20–30 cm/s in a sawtooth-shaped gliding trajectory, deriving its forward propulsion by means of a buoyancy change and steering by means of a tail fin rudder. The altimeter and depth sensor enable preprogrammed sampling of the full water column. The primary vehicle navigation system uses an on-board GPS receiver coupled with an attitude sensor, depth sensor, and altimeter to provide dead-reckoned navigation, with backup positioning and communications provided by an Argos transmitter. Two-way communication with the vehicle is maintained by RF modem or the global satellite phone service Iridium. All antennas are carried within the tail fin that is raised out of the water when the vehicle is commanded to surface at some predetermined interval. Operational endurance, utilizing alkaline batteries, is 25 to 60 days, depending on sensor payload and sampling regimes. Horizontal distance traveled averages 24 km per day. The vehicle is operational in 5 to 200 m of water depth and can be optimized for 30, 100, 200 and 1000 m operation with select gearboxes.

The mission duration of a glider is largely a function of the number of sensors and the water depth. The largest power drain in the glider involves the operation of the pump and, therefore, the battery life is shortest in shallow seas. Despite the shortened battery life, deployments last over three weeks, providing the scientist usually several thousand vertical casts. The increase in data quickly justifies the costs of maintaining Gliders for sustained observations (Figure 2). The operational costs for Gliders include technician time, costs for deployment/recovery, batteries, and Iridium phone charges. Based on standard daily costs for a range of research vessels (deep water, medium, small coastal vessel), the operational costs of Gliders are economical (Figure 2). The typical costs of operating the deep-ocean and coastal class research vessels exceed the cost of operating single glider deployed for a full multi-week mission. The costs of smaller research vessels exceed a glider after three days. One technician can operate several gliders so the increased costs associated with operating multiple gliders reflect increased deployment/recovery costs, batteries, and Iridium charges. Given this the costs of medium research vessel will exceed operating a fleet of six gliders in about four days. Gliders will never replace ships, but populating the oceans with Gliders will allow ships to use their time wisely as they will

Figure 3. RU gliders ready for deployment.

know when and where to sample the ocean. This will allow the ship time to be used to spend its time at sea testing/deploying new instruments and conducting experiments.

Rutgers currently maintains a fleet of over 20 gliders (Figure 3). The glider built through competitive grants have to date conducted 157 missions, traversed >55,000 kilometers, logged >2600 days at sea, and logged ~350,000 vertical profiles. These gliders missions have been conducted world-wide and are coordinated at Rutgers main campus (Figure 4). The missions have spanned efforts from the polar to temperate and tropical seas. The data has been highly valuable and has been central to 13 peer reviewed manuscripts in 6 years with 9 more papers in press or in review. The manuscripts have a mean number of 7 authors and thus the gliders are central to interdisciplinary ocean science.

Operating a fleet of gliders necessitates an automated command and control (C2) system in order to optimize glider missions to resolve the temporal and spatial patterns of the process of interest. This requires the C2 to be flexible and adaptable as the environment is constantly evolving. We have been constructing a C2 system for a fleet of Webb Gliders; however, the system is scalable to allow the incorporation of a number of data inputs, allowing the fleet to make intelligent goal oriented decisions that feeds back into dynamic adaptive resource allocation. The software package allows information from a scientist, the glider itself, other sensing systems such as high frequency radar, satellites, or additional gliders, to optimize a particular glider's flight characteristics or waypoints. New mission directives are automatically uploaded to the glider during surfacing and the glider begins its new sampling regime or waypoint bearing. Optimization can be done for features like, but not limited to, currents, tides, thermoclines, and haloclines.

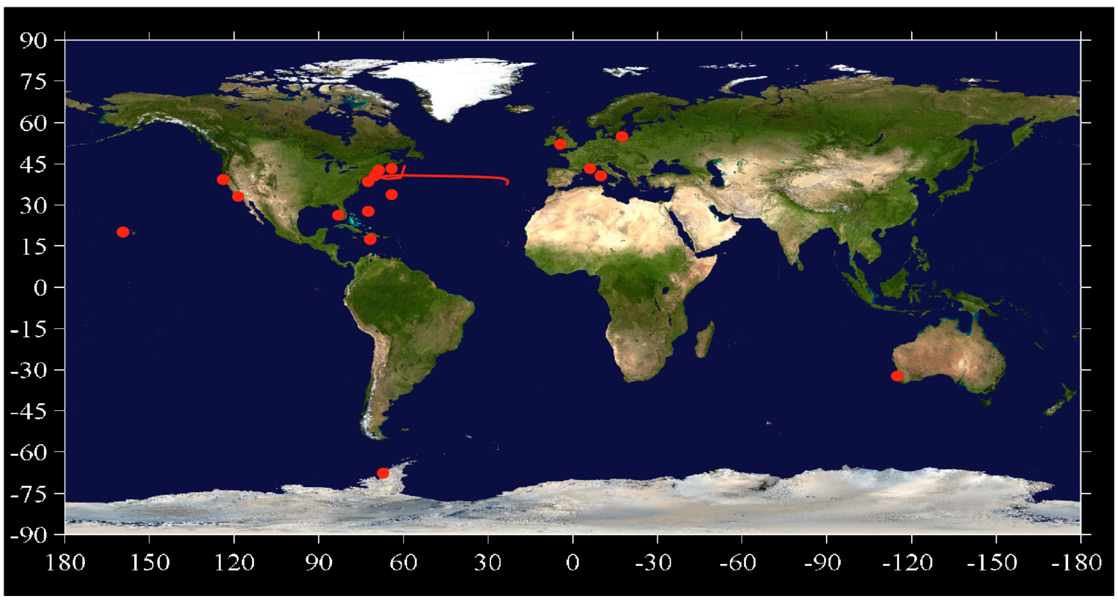

Figure 4. The global deployments for the RU gliders. The coming months in summer 2009 has missions planned for a second attempt to cross the Atlantic, along with science missions offshore Norway, Alaska, and Northeast seaboard of the United States.

Deployments can also allow ground-truthing of satellite imagery. Data are automatically pulled from the vehicle and made available for web based presentation.

III. GLIDER SENSORS

The value of the Glider surveys will increase as the sensors available for Webb Gliders expands (Figure 5). The main bottleneck for integrating sensors is minimizing their size and power consumption. In experience this has been a three-step process. The first is the efforts by the manufacturers to minimize the sensors for the gliders. Most often, the second phase involves mounting a self-recording sensor on a glider to collect data, which is often needed to secure funding from federal agencies for full sensor integration. The full integration and field demonstration is the final and third phase. Based on history working with WetLabs, Mote Marine Laboratory, Satlantic, and Webb Research this end-to-end process takes close to two to three years depending on the sensor complexity. This process has successfully integrated many diverse sensors into a Webb glider. Measurements presently being made by gliders include physical (temperature, salinity, turbulence), acoustic (active and passive), optical (spectral radiometry, backscatter, attenuation scattering, absorption, digital imagery), fluorescence (chlorophyll a, colored dissolved organic fluorescence, fast repetition rate fluorometry), and dissolved gas (oxygen)

Figure 5. The sensors that have been carried on Webb gliders. They include (starting at the top left panel) oxygen, passive acoustic, attenuation, chlorophyll/colored dissolved organic flourometers, turbulence, fish finders, scattering and backscattering packages, spectral backscatter, radiometer, digital cameras, acoustic doppler measurements, fast repetition rate flourometry, and absorption.

With so many sensors now available, the power required often outstrips the capabilities of a standard glider configuration. To address three strategies have been pursued. The first strategy is to increase the number of batteries that the glider can carry. This has resulted in the development of the "stretch" glider. The stretch glider's longer body allows for more battery packs and/or larger sensors. The second strategy has been to develop lithium battery packs for the Webb gliders. Working with Electrochem, a fully outfitted lithium glider was operated for several months and Coulomb meter measurements suggest glider lifetimes of 300-360 days is now available. The final strategy is to fly the gliders as swarms. The swarms represent packs of gliders carrying distributed sensors, allowing a full complement of data to be collected. These swarms we have termed "Darwin clusters" as the adaptive capabilities of gliders are operated as evolving network that allows data to be merged between the platforms while also providing a mesoscale network to map features in the ocean.

IV. Near Term Challenges

Gliders are key technologies to exploring extreme environments and episodic events, which are disproportionately important to many ocean processes. Targeted extreme environments include the poles, severe storms, urbanized ports and developed coastlines, which are often avoided by scientists because of the hazardous operating conditions.

Gliders are now a central technology that will anchor climate change research being conducted in the Antarctic and Arctic. One effort will use gliders along the West Antarctic Peninsula as part of the NSF's Long term Ecosystem Research program in collaboration with British scientists. Here the efforts will be to provide a sustained regional presence when the research vessel is not available. This requires scientists to utilize the Antarctic field stations as a staging facility. This strategy was demonstrated successfully in 2007 and 2009 (Figure 6). Additionally, gliders will help scientists to understand why deep canyons are associated with large penguin breeding colonies. Radio-tagged penguins will be used to adjust the sampling areas of a Darwin cluster of gliders capable of mapping the physics, chemistry, phytoplankton, currents and higher trophic levels, in order to understand if canyons are associated with sustained upwelling that provide a predictable food resource near the breeding colonies. The second polar effort will be conducted in the Arctic in collaboration with Norwegian researchers. Here the goal will be to develop a time series site between the Svalbard and Norway to understand regional circulation impacting ice flows and regional warming trends.

Science efforts are usually curtailed during severe storms; however observing networks are robust and allow scientists to safely study these processes in real-time. One nice example was from a storm event encountered in October of 2003 [2]. The gliders are equipped with a conductivity–temperature–depth sensor, and an ECO-sensor pucks. October is the transition between summer and winter seasons, which starts with surface cooling that preconditions the shelf for rapid mixing during fall storms. The mixing storm of October 2003 was a classic northeaster. Early in the storm when waves were high, sediment resuspension was limited to below the pycnocline. After the pycnocline eroded through growth of the bottom boundary layer, particles immediately filled the full water column. The spectral ratio of backscatter indicated that the particles were likely similar materials both before and after the stratification was eroded. The backscatter profiles in the bottom boundary layer decay with distance from the bed at rates consistent with theory but with variable slopes. The reduced slope of the backscatter profiles increased after stratification was lost, which is consistent with an increase in vertical transport or turbulent mixing. Wave bottom orbital velocities during this time were decreasing, and the glider vertical velocities showed no enhancement consistent with Langmuir cells. Enhanced mixing was related to the interaction of the surface and bottom boundary layers while the stratification was eroded, and the observed variability in the resuspension during the event was also due to the tide.

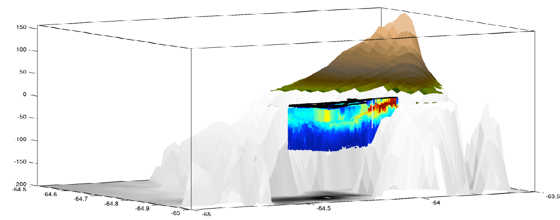

Figure 6. A 3-D section of chorophyll fluorescence measured offshore Palmer Station in December 2008. The high chlorophyll values are associated with upwelled water. The next phase of the research is to understand if this upwelled water is associated with the Antarctic Circumpolar Deep Water.

Urbanized ports are often process-rich environments with strong signals to study, but the difficulties of working in a heavily used environment often preclude scientific study. These areas are often regions of high current. Therefore it is critical to develop the new automated flight behaviors that allow the glider to sense its environment and make smart decisions to enact the best behavior to sample the local environment while avoiding contact with humans. This challenge is perhaps the most difficult to tackle.

A final theme is to extend the limits of long-duration underwater glider flights. These efforts have focused on developing new power and control systems. The long duration studies are powerful magnets to entrain undergraduate students. These flights have the potential to increase the visibility of ocean exploration to the general public. The Coastal Ocean Observation Lab is developing new undergraduate initiatives as part of a University-wide effort to transform undergraduate education at Rutgers. Enabled by an ocean observatory operations center purposely located on the main campus of a major research university, the lab has established a program featuring hands-on team-based research projects that compliment course-work and are specifically designed to entrain undergraduates. The program encourages students to become involved as early as their freshman year, remaining in contact with many of the same students and professors for their full 4 years at Rutgers. A series of Introduction to Oceanography courses with significant freshman participation, and a variety of small seminar courses given to first-semester freshman, serve as the feeder courses. Interested students join us in the lab in their second semester, either through 1-credit research courses or work-study programs.

These courses are focused on specific long duration glider missions to teach to students oceanography while simultaneously gaining hands-on experience. The initial task supported by the undergraduate student team - to be the first to fly an autonomous underwater glider from Tuckerton, New Jersey to Halifax, Nova Scotia - was accomplished in the spring of 2008. Their second task, still ongoing, is to be the first to fly a glider across the Atlantic from New Jersey to Spain. Rutgers alumni donated a glider for use as the primary platform to engage undergraduates in projects related to ocean observatories. The National Science Foundation provided a RIOS summer intern, in this case an aeronautical engineer from the University of Maryland. Qualitas, a Spanish company installing and operating the national HF Radar network for Spain, contributed an internship for a student with a dual major in Marine Science and Spanish. Glider training courses, developed and delivered for NOAA-sponsored IOOS projects, used extensively by the operational Navy, NATO and the European Glider Association were used to spin students up over the winter break in every aspect of glider operations. Each student on the team was responsible for a specific aspect of the long-duration flights. Two freshman worked alongside the three glider technicians to help with the construction and testing of the actual glider. At the end of their spring semester, they returned to their high school, giving talks to their science teacher's class and the high school robotics team on what they accomplished at Rutgers in their freshman year. Two juniors worked on the flight characteristics of RU17, optimizing the flight controls and providing feedback to the manufacturer. Two freshmen worked on the NOAA-sponsored IOOS Mid-Atlantic HF Radar network as the launch zone for these two flights, while a junior worked on HF Radar in Spain to help prepare the landing zone. Two seniors worked on path planning, website development, and the Google Earth interface that has been used in three Navy exercises, is part of our Middle Atlantic control center. The first attempt in 2008 failed, as the glider encountered problems close to 200 kilometers from the Azores. The students despite the set back set the world's record for distance covered by an AUV (Figure 7). A second attempt begins in Spring 2009.

V. SUMMARY

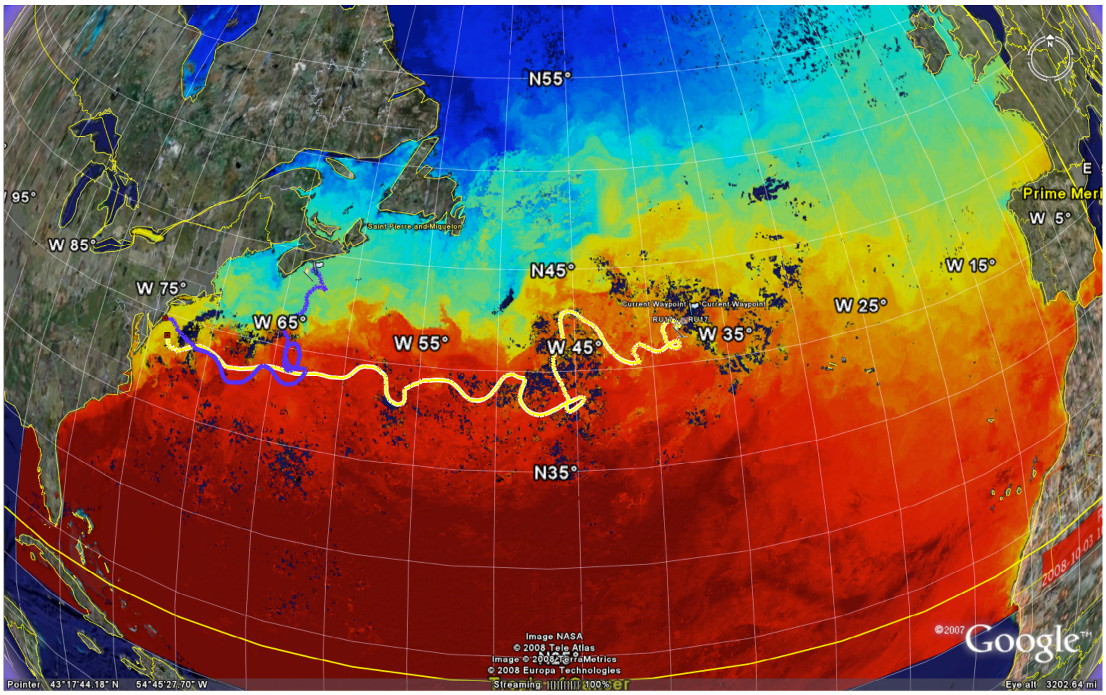

Figure 7. The path of undergraduate glider missions focused on long duration missions. The blue line shows the successful flight from New Jersey to Halifax. The yellow line shows the student's first attempt to cross the Atlantic.

Gliders are a robust technology that allows scientists to maintain a sustained presence in the ocean and this will enable oceanographic to tackle critical issues facing the community. The gliders will also provide a unique technology that will entrain the next generation ocean scientists and engineers. These two factors make it a very exciting time to be an oceanographer.

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