Slocum Glider

Persistent Oceanography

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"The projects that I have always liked best are the ones conceived on the spur of the moment by an inquisitive individual. We try to reserve twenty percent of our Slocums to pursue such sudden inspirations. They are generally the most exciting; they evolve in unexpected ways and reveal new dimensions of the unknown about the ocean."
Henry Stommel, *The SLOCUM Mission*, 1989.

Abstract—Two decades have passed since Stommel's futuristic article popularized Doug Webb's underwater glider concept. Stommel's imagination was sparked by the opportunity gliders provided to broaden our understanding of the oceans and perhaps even more important to him, by the potential it had to draw peoples interest and excitement for ocean dynamics.

Slocum Gliders have helped to redefine range and endurance in the world of AUVs, and as mobile sensor platforms have made a significant impact on our ability to better see into the world's oceans.

Teledyne Webb Research (TWR) provide an overview of the latest Slocum G2 design, the hybrid glider with thruster, latest sensor suites, and an update on the energy harvesting Slocum Thermal E Twin. Three main mission objectives will be reviewed: polar regions, urban shelves, and long duration transects approximating the course of the Challenger expedition of 1872-76.

Having made the first ever oceanic crossing by an AUV, Slocum glider RU27 is presently on display at the Smithsonian Ocean Hall and another Slocum G2 flight, having just completed an Iceland - Azores - Canary Islands leg is now on its way to Brazil and continues to draw together the International Consortium of Ocean Observing Labs (I-COOL) focusing on international and educational outreach.

With the advent of procurements of Slocum gliders in large numbers by both the US Navy and the Ocean Observation Initiative (OOI) Coastal and Open Ocean we are on the cusp to realizing Stommel's vision of fleets roaming the oceans.

Keywords; Autonomous Underwater Gliders; Persistent Ocean Observation; Hybrid Glider;

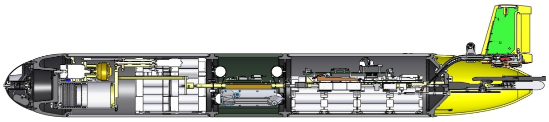
I. INTRODUCTION

Slocum gliders have become an integral part of the early adopter's oceanographic toolbox. A rapidly expanding family of users continue to build on innovative ways to better view the ocean interior by using gliders combined with their sensor suite complements. While Teledyne Webb Research (TWR) has delivered over 250 systems to date, until recently the technology acceptance had not yet reached a scale of large numbers of continuously operating fleets. Recent glider programs for the Navy Littoral Battlespace Sensing - Gliders (LBS-G) program and the Open Ocean Initiative (OOI) Coastal and Open Ocean bring a production level that allows an expansion of vehicle capability - both individually and in fleet use.

Our vision, working with the oceanographic community, is to provide a platform that can be adapted and expanded to meet the needs of an evolving requirement for discovery.

II. G2 - THE NEXT GENERATION GLIDER

Fully realized, the LBS-G and OOI programs combined will require an additional 200 gliders. In anticipation of the potential glider increases and demanding requirements, TWR set about to create the Slocum G2 - the next generation glider.

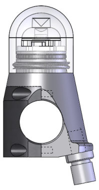


A significant change in design architecture resulted. Instead of providing shallow and deep glider variants as in the past, the G2 is pressure tolerant to the full 1000 meters depth operation and building on the modular concept, can be outfitted with interchangeable front pump sections that are optimized for desired operational depths. Pump combinations include 30, 100, 200, 350, and 1000 meters.

Carrying the additional structure to handle a greater pressure tolerance and still have acceptable payload performance in the shallow water regime is made possible by utilizing patented composite hulls sections that are significantly lighter than comparably pressure rated aluminum hulls. Additionally these hulls are tuned to closely match the compressibility of water providing buoyancy drive energy savings during ascent and descent. For a standard length G2 this results in an additional 300 cc of drive volume.

Optional recovery features have been added to the system to aid in re-location and large ship operations. The nose recovery system houses a 10 meter retrieval line that is released upon command. The floating nose cone and the glider separate and a grapnel line can be passed over the retrieval line to then lift the glider up by its front end with either a davit or A-frame. A strobe light is also available to help with night recovery.

A choice of interchangeable energy systems exist including alkaline chemistry and lithium primary. The lithium option consists of 78 Electrochem DD CSC-93 cells, and up to 114 cells with an extended energy payload bay.



The electronics boards have transitioned to surface mount components where possible and much of the wiring has been reduced by use of plug in modules and a communication interface board. The connectors are all of a positive lock variety.

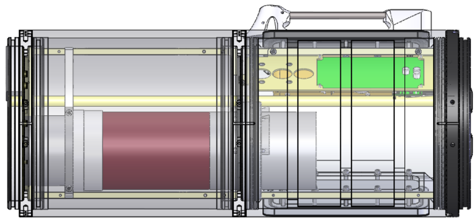
The modular payload bay is still of 6061-T6 aluminum construction to allow the porting of sensor windows. The internal end plates shields have been now designed to accept stainless steel pie shaped weights to aid in ballasting. Bays can be stacked to create a stretched glider.

One of the latest sensors is the TRDI 600 Explorer ADCP phased array in a modular half-length payload bay with integral tie rod and wiring harness to truly be plug and play..

The Satlantic SUNA nitrate sensor is mounted external to the glider and electrically fed through the aft payload bay ring.

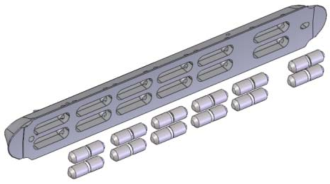
Optic elements of the Turner Cyclops has been inserted into a standard glider window port to create a four channel suite.

A Gamma-Rad NaI Scintillation Probe has been integrated into a dual science payload bay.



A dedicated science processor handles all of the incoming sensor data and creates its own file structure for offloading - significantly increasing the data collection rate available.

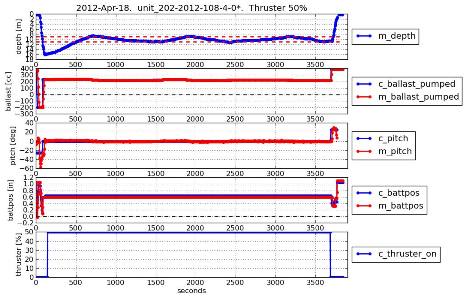
Snap in wings have been upgraded to a custom orientated weave of carbon fiber material for greater robustness. Wing rails now feature a pocketed back that accepts slugs of stainless steel weights to help facilitate external ballasting. They also include a locking set screw in addition to the spring catch.



Overall, the G2 has been upgraded for greater reliability and ruggedness. The gliders have been subjected to and passed a number of environmental tests including shock, vibration, drop, and thermal extremes.

Hybrid Glider

Memorial University and TWR have mated an efficient folding propellers thruster in the aft end of the Slocum to create a hybrid glider and are presently conducting a number of flight trials. The propellers fold when not engaged to reduce drag during buoyancy only mode and snap open when in thrust mode. Blending both buoyancy control and thruster propulsion allows for expanded mission capability and greater flight efficiencies. In a bathtub flight mode, the glider adjusts its volume to achieve a depth at neutral buoyancy and then the thruster is engaged for horizontal flight, unlike traditional propeller driven AUVs which have a slight positive buoyancy and must constantly work to stay at desired depth. At the nominal flight speeds that the glider achieves in buoyancy controlled flight (0.35 m/s), the thruster's efficiency is very close to that of the buoyancy pump when operating at its optimal depth range. If the pump is out of its optimal depth range, the thruster can be more efficient per distance transited. Therefore, one mission advantage is to fly a deep glider over a coastal shelf area with the thruster until in suitably deep waters to begin undulations and water column measurements. Although at a significantly higher energy hit, the present thruster configuration being tested can achieve 0.8 m/s alone and 1.15 m/s combined with the buoyancy drive allowing the vehicle to overcome stronger current regimes. A burst of speed to get on the other side of a strong eddy boundary may be more efficient than spending days trying to break through at slower speeds. Also the thruster can be used to break through lower density surface waters getting the glider to a depth that the air bladder can inflate for communications. The hybrid glider simply allows for greater flexibility in the ocean environment.



Transoceanic Flights

RU27: New Jersey to Spain

The underwater flight of RU27 was conducted in the enduring spirit of the National Ocean Partnership Program. In effect, it launched an unfunded International Ocean Partnership Program that united a community within the U.S. and across the Atlantic. Having a glider deployed at sea motivated collaborations that may otherwise have taken years to develop. Although the transatlantic crossing was certainly a technical achievement, the historical success of this event may one day be better measured by the tremendous educational and international outreach that this collaborative effort spawned. As a result, Rutgers University (RU) and TWR grew contacts and friends worldwide, increased foreign exchange student opportunities, began a RU class *Atlantic Crossing* that drew a diverse range of students, and increased the undergraduate participation in the lab by an order of magnitude.

Scarlet's 7-month Pathfinding Mission Across the Atlantic

Dubbed Scarlet Knight by the *Atlantic Crossing* students, RU27 had undulated through the top 200 meters of water, *flying* over 7,400 km in 221 days using 2.79E+07 Joules, approximately 76% of the available energy. With a nominal speed of 30 km/day, the students had to astutely use the ocean currents to their best advantage using satellite imagery, ocean circulation models, and data the glider provided itself.

Scarlet Knight or "Escarlata Caballero" in Spanish, was brought ashore in Baiona, Spain, famous for being the landing site of one of Christopher Columbus' ships, the *Pinta*, when it arrived in March 1493 to be the first to announce the discovery of the New World.

Scarlet Knight's crossing sparked the imagination of a younger generation who were learning the rewards of being daring, to embrace the chance of failure, yet persevere and try again. It is this message that accompanied the original Slocum RU27 Glider as it went on display in the Ocean Hall Exhibit at the Smithsonian Museum.

Much like what Charles Lindbergh's 1927 first solo flight across the Atlantic did for air travel, soon it will be commonplace to have gliders crossing ocean basins. We also expect that records of duration and distance will be broken again and again, as the community of vehicle builders and users continue to push the envelope of performance.

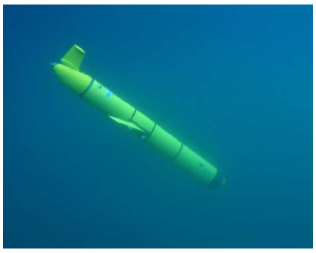
Interviewed for the documentary in Baiona, the Rutgers students asked Doug Webb a last wrap-up question, "Do you have any advice for us?"

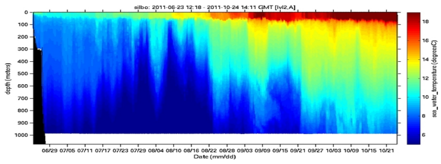
Doug had three things to say;
Work hard
Have fun, and
Change the World.

Silbo - Iceland to Canary Islands

Next? Our focus is to fulfill the "Challenger Mission" by flying gliders along the approximate tracks of the Challenger expedition of 1872-76. While we continue for the time being with single glider legs, by 2014 the International Consortium of Ocean Observing Labs (I-COOL) hopes to be in the position to launch up to 16 gliders to fill in the tracks and accelerate coverage.

On July 23, 2011 a Slocum G2 1000m glider, Silbo, was deployed off of the coast of Iceland and set a course to the Canary Islands. With a stopover in the Azores, Silbo arrived in Gran Canaria on May 22, 2012.





With a new set of lithium batteries installed, Silbo carries a de-rated 1030 Amp hours of available energy - projected to supply over a year endurance. Deployed again on July 24, 2012 we expect to see Silbo next in Brazil. To follow along go to http://www.i-cool.org/?cat=77

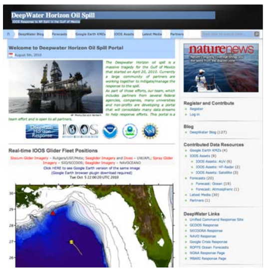
TWR is actively testing a number of low surface energy coatings, film adhesives, and biomimetic film adhesives to combat biofouling for these long journeys. The predominate biofouling concern is barnacles, and if the glider can avoid staying in bio-productive waters above 15 C for more than a few hours before returning to deep and cold then the larvae settling appears to be mitigated. Once settled, however, the barnacles will remain attached and while growth is retarded at colder than 15 C, any time spent above this temperature will re-accelerate the growth rate.

Urban Coastal Areas

There is a continued focus on understanding the dynamics and forecasting of coastal urban areas. Gliders have and are continuing to play an important role in collecting data in these environments. Rutgers alone has flown over 93,000 km with many of these as part of endurance lines which are repeated throughout the year. The OOI Coastal initiative is to keep gliders continuously flying on rotations on both the West and East coasts of the US.

Deep Water Horizon

In response to the oil spill in the Gulf of Mexico, a number of groups volunteered their expertise in water mass tracking and, using optical sensors, detection of hydrocarbons. A true grass effort response took place on the glider front with Rutgers, University of Southern Florida, University of Delaware, and MOTE Marine all contributing Slocum Gliders. Collected were over 6000 km of data lines with 317 glider days flown.

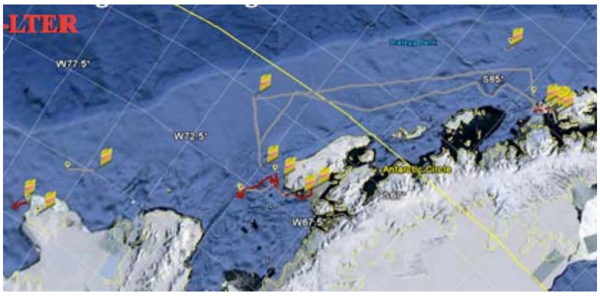



The Integrated Ocean Observing System (IOOS) coordinated the data stream and Rutgers hosted the website for the visualization tools and the blogging.

Polar Regions

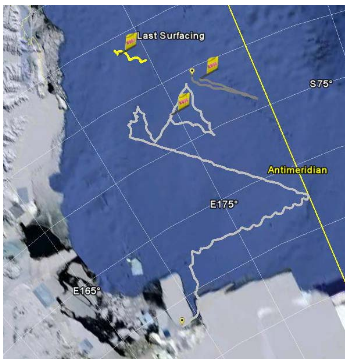
Antarctica

In this past austral summer eight gliders run by Rutgers and the University of Delaware were deployed in the seas surrounding Antarctica, six shallow and two deep vehicles. Each glider was equipped with a science payload appropriate for its intended mission. Sensors deployed include CTD, Optode, Eco-puck, FiRE, and ADCP. The roles of these gliders in the science plan included missions to 1) identify specific water masses and high priority regions for ship sampling, 2) map spatial extent of features within the context of concurrent ship-board measurements, and 3) demonstrate the long-term capability to connect research facilities around the continent as a means to extend data coverage in time and space.



On December 11, 2010 the Slocum G2 RU26 was deployed from the Ross Sea ice edge and flown out under an ice bridge of pack sea ice.

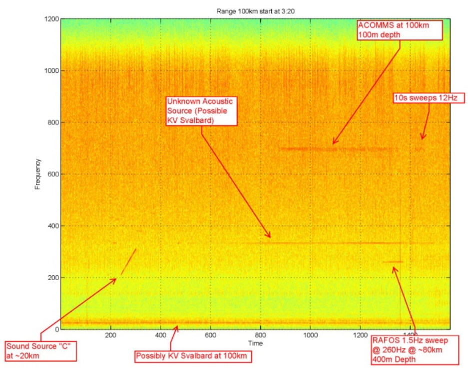
RU26's task was to map Antarctic Modified Circumpolar Deep Water which was expected to be characterized by warmer up-welling deep water that contains trace metals and micro-nutrients that drive phytoplankton blooms. Having an advanced knowledge of the water distribution allowed the R/V Palmer to bypass the time usually used to survey and move directly to sampling during the cruise beginning in January. In addition, the glider data collected helped resolve variability seen in the point shipboard casts by capturing how the tidal structure affected the up-welling events.



Under Ice Navigation/Communication

Low frequency sound sources are one of TWR's core capabilities and we have demonstrated years of deployments including under the ice in the Fram Strait used both for navigation and tomography. An acoustic receiver integrated into glider make it possible to facilitate long range navigation under ice - supplanting the unavailable GPS signal. An advance on just the acoustic navigation is to also provide a communication channel to get some limited information and heartbeat back from the vehicle (6 bpd).

We have constructed and trialed a flooded glider hull section with a 694 Hz transducer. The results during an Arctic test indicate that we would have at least a 100 km range. On the same recording from a support ship, it is possible to see our swept frequency sound source 200 - 300 Hz, our RAFOS fixed source 260 Hz and the glider ACOMMS source 694 Hz at various ranges from the vessel.

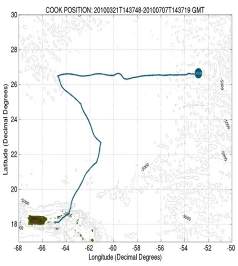


Thermal Glider

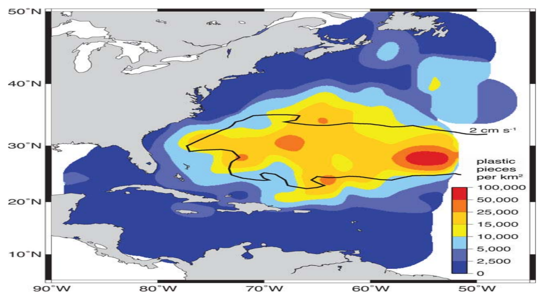
Electric gliders change their buoyancy by means of converting stored battery energy into a volume change with a hydraulic pump at pressure. The original concept for autonomous underwater gliders was to harvest the energy needed for the buoyancy change from the thermocline of the ocean giving a substantial energy savings that can be applied to greater endurance.

Drake was deployed in 2009 from St. Thomas and travelled 3,000 km while at sea for 160 days and then stopped reporting in.

Cook was deployed on March 11, 2010 from St. Thomas and was flown by Rutgers students until it failed to call in 106 days out for yet unknown reasons. During its travel 60 Ah were used out of a 750 Ah battery pack, extrapolating to a potential endurance of 3.4 years.



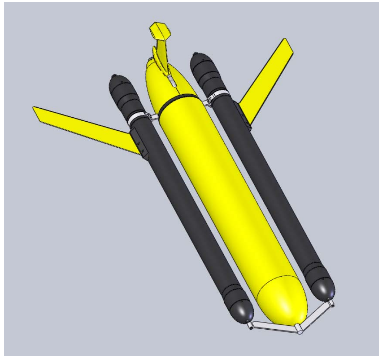
A possible hypothesis for these losses is that in both instances the gliders were flown into the center of a gyre that



contains up to 100,000 plastic pieces per square kilometer. Looking forward, we will certainly avoid flying in this area of the ocean.

Thermal to Electric Generation

With Office of Naval Research (ONR) support and in cooperation with the Jet Propulsion Lab (JPL), TWR is preparing two vehicles that not only use the thermocline to produce the buoyancy but also convert hydraulic energy to a electrical energy. The Slocum Thermal Twin E, with two phase change engines, is able to recharge a set of lithium-ion batteries while underway by running excess hydraulic drive through a generator on board. Successfully bench tested at TWR, and field proven on the JPL version of a thermal float, we expect to have these in the water in the beginning of 2013 in collaboration with Rutgers for student piloting participation.



Acknowledgments

Thanks goes to the existing and increasing number of new users who continues to drive the expanding capabilities of the gliders.

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