Slocum Glider
Extending the Endurance

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Abstract

“We have found, over the years, that the payoff in increase of knowledge often is greatest the more unconventional the idea, especially when it conflicts with collective wisdom.” (Stommel, 1989)

Slocum battery-powered ocean gliders have become an integral part of the oceanographer’s toolbox with surprising rapidity over the last decade. Teledyne Webb Research (TWR) has been involved with autonomous underwater glider design since its inception and continues to push the technology to further the distance travelled, sensors integrated, and mission endurance.

In collaboration with the Rutgers University Coastal Ocean Observation Lab (RU-COOL), we will review recent endurance flights of battery powered Slocum Gliders including a New Jersey to Halifax, Nova Scotia run and a New Jersey to the Azores mission - adding to Rutgers’ impressive tally of 62,000 km flown. Given the low speed of gliders, it is important to use ocean currents to advantage, and the vision that the act of flying a glider across an ocean would challenge and teach students – has commenced again in April 2009 with another Trans-Atlantic crossing attempt flown by Rutgers undergraduates.

We also review the Slocum Thermal Glider, a long-range endurance glider that harvests its energy from the world ocean’s thermal gradients. By exploiting our existing battery-powered glider technology, using the existing control, navigation, communication, sensor, and steering hardware and software, we have logged successful engineering trials for thermal-powered prototypes (Fig 1). The constructs of each and advances made with engine heat transfer and electrical generation potential are detailed. We believe that the daring objective of deploying fleets of capable, sensor-laden gliders for multi-year transoceanic operation is an achievable goal.

Figure 1 Slocum Thermal Glider.
Introduction

Rutgers University Coastal Ocean Observation Lab (RU-COOL) and Teledyne Webb Research (TWR) continue, with a growing family of others, to push the envelope of addressing the integration of new and novel sensors, increased stored energy, and manipulating reduced energy usage.

Applying the UUST conference as a milestone marker, the past two years have been busy with integrating new sensors, addressing extending the endurance of the Slocum glider platform, and bringing the Thermal glider from prototype to production.

We share some historical perspective, discussion of energy choices, details of endurance flights, and an overview of harvesting propulsion energy from the ocean itself.

Historical Background

Doug Webb founded Webb Research in 1982 (recently acquired by Teledyne) after retiring from 20 years at Woods Hole Oceanographic Institution (WHOI). His goal: to develop and manufacture floats and low frequency sound sources. His dream: to design an AUV capable of circumnavigating the world.

It was 1986 when Doug first detailed in one of his notebooks a thermal engine able to harvest energy from the thermal stratification of the ocean. And importantly, one that it has the capability to store the resulting energy as a pressurized volume of fluid to be used when desired. The following page in the notebook includes the first sketch of an ocean glider, envisioned as a vehicle that could advantageously use this energy store as buoyancy drive propulsion.

The concept for the glider, however, had been brewing for quite awhile as captured by a 20 Apr 1978 WHOI memo written by Henry Stommel and Lloyd Regier. "Doug Webb made some engineering computations of the power required to move steered SOFAR floats at small speeds such as 10 km/day for periods of up to several months. The power requirements are so small that the idea is a practical one. What advantages might they have? Various ideas like shooting them across acoustic tomographic ranges, or at intervals northward from Bermuda to map the recirculation, come to mind"

Henry Stommel, the world-renowned oceanographer, neighbor, and friend of Doug Webb’s was at first not particularly interested in gliders. That is, not until he conceived of an AUV race around the world and envisioned what such an event could potentially teach people about the oceans; then he became enthusiastically involved. It was Hank who christened the gliders after Joshua Slocum, the first man to sail singlehandedly around the world.

Hank thus wrote the oft referenced futuristic article The Slocum Mission in Oceanography breathing life into a roving fleet of Slocum gliders controlled via a central command center collecting data from the interior of the world’s oceans.

Doug, the “pioneering ocean engineer” of the story, split the effort into two parts: the vehicle and the thermal engine. With the support of the Office
of Naval Technology (ONT) the first glider flight trials began in 1991 first in Wakulla Springs, FL and then in Lake Seneca, NY. They were successful, however, funding ceased due in part to the Navy shift of interest from blue or deep-water to shallow-water oceanography after the collapse of the Soviet Union and advent of the Persian Gulf War. The glider, envisioned with a thermal engine, typically needs deep water for the thermocline and thus was put on hold for a time. The thermal engine itself was tested in Lake Seneca, NY mated to a profiling float that Doug had already pioneered. Internal funding at Webb Research with a small grant from the National Oceanic and Atmospheric Administration (NOAA) allowed a deployment of the thermal float in 1995 in the waters off of Bermuda.

On the glider front, interest from the Navy, now the Office of Naval Research (ONR), returned and battery powered gliders were developed first as test beds for navigation, software, and flight control. An early prototype Slocum glider was delivered to Scripps in 1996 as a technology transfer from industry to academia.

The first glider sea trials were conducted with a Slocum at the Rutgers’ LEO-15 New Jersey site in July 1998. This spurred a collaborative relationship with academia, as these unique platforms quickly garnered interest for different sensor integrations and a natural complement to other technologies such as satellite imagery.

With the advent of global communications, gliders are today a successful research platform capable of worldwide operations with an array of different sensor suites for both military and scientific applications. A family of Slocum gliders exists today including: 200m, 1000m, and 1200m Thermal variants. To date over 150 systems have been delivered to 43 different groups in 14 countries – each group contributing in realizing a new method of observing the oceans.

Pairing the thermal engine with the Slocum Glider has steadily made progress in the background with significant advances in the past two years.

New Sensors

Sensor suites are typically integrated into the modular payload bay of the glider. Some sensors, however, are simply too large or have special requirements and are affixed to the exterior of the vehicle. The Rockland Scientific microRider (Fig 2) is an example of a piggy backed sensor that requires a clean water view in front of the glider to measure turbulence.

Figure 2  microRider turbulence sensor piggybacked on a Slocum Glider.

Another recent sensor addition is the Rutgers’ Fluorescence, Induction and Relaxation (FIRe) that provides an
extremely sensitive proxy for phytoplankton physiological status. In other words, are the forests of the sea healthy? Light sources, however, used by the Satlantic FIRe (Fig 3) require a lot more power than many sensors integrated presently, and started us focusing on higher density energy sources.

Figure 3  FIRe and PAR sensors integrated into a modular payload bay.

Another potential higher energy use sensor, the TRDI 600 KHz ADCP is presently undergoing integration into a Slocum with an 11 degree canted hole ported into the side of a payload bay.

These power intensive sensors, combining a number of sensor suites, and the desire for greater distance and longer endurance have led us to be smarter with our sampling strategies and to look at available energy sources. For instance, recent updates to the control code allow altering individual sensor sampling based on depth ranges and sensors can be turned on for certain events as the “storm gliders” are used.

Battery Chemistries

Alkaline

As first conceived, the early legacy gliders, share the common traits of being relatively portable, adaptable, and affordable. These features allowed groups to add sensors, not need extensive handling gear, and take deployment risks to further science – all things made more difficult with a larger and more costly AUV platform.

What has set gliders apart from propeller driven AUVs is their slow speed and inherent water column transition as they make their way along in a sawtooth flight pattern.

As with all AUV’s there is ever the balance of sensor load, communications, hotel load, speed, and endurance.

The Slocum Glider family began with a shallow water version rated for 200m with optimized pump motor gearboxes for 100m and 30m depth operations. Alkaline batteries were used as the primary power source based on cost, ease of handling and transport. These fit well in the littoral environment particularly where bio-fouling could be high. Deployments range from 20 to 50 days depending on sensor payloads, sampling regimes and communication and gliders with optics would typically need to be cleaned at the length of this duration – so alkalines while a good fit. Alkalines, however, have the disadvantage of requiring replacement and careful ballasting management.

Lithium Ion

To assist in making the glider field turnaround easier, we have recently integrated and shipped Lithium-ion Samsung ICR18650_22 battery sets to NAVO and Rutgers (Fig 4). These secondary (rechargeable) battery replacements give approximately 10% better energy density performance than
alkaline chemistry, with the obvious benefit of allowing recharging without opening the glider.

Figure 4 Lithium Ion Slocum batteries.

Lithium

Given the increased power demand from sensors and the desire to go longer and further, one inevitably turns to Lithium primary batteries, which provide a significant increase in energy density as compared to other chemistries.

Slocum drop in lithium packs have been developed by end users with the C size Saft 26500 lithium-thionyl chloride, the C size Tadiran cells, and the C size Electrochem CSC-93 lithium-sulfuryl chloride.

TWR is presently working on an Electrochem DD size CSC-93 battery set to reduce cell cost (Fig 5).

Given the characteristic voltage drop on a discharge curve over time for alkaline chemistry it is easier to predict end of life as there is a slope to match against. The lithium discharge profile is much flatter, therefore it is more difficult to determine remaining energy from a voltage. However, with a known heavy load such as the pumping time at depth one can monitor the voltage drop giving an indication for remaining energy.

To facilitate the predictions of endurance TWR has developed a highly detailed energy analysis spread sheet energy spreadsheet backed by discrete and total consumption measurements as well as pulse discharge testing of batteries. This tool takes into account flight parameters, number of cells, chemistry type, communication intervals, and operating temperatures. A recently designed coulomb meter in the glider has significantly aided in the monitoring of energy consumption during flight.

Figure 5 78 Electrochem DD CSC-93 cell Slocum Glider Battery Packs.
Endurance Flights

RU15 Flight NJ – Halifax, Nova Scotia

The launch of RU15 on March 7, 2008 began a shakedown cruise from the New Jersey Coast to Halifax, Nova Scotia for a distance of 2600 kilometers (Fig 6).

Students used the Gulf Stream to advantage, although had to be vigilant about getting caught in eddies. So Stommel’s vision that the act of flying a glider across vast stretches would challenge and teach students more about the ocean was being fulfilled.

“This is the future of oceanography,” Marlon Lewis, Dalhousie oceanography professor and founder of Satlantic, Inc., commented. “These gliders can take measurements with higher resolution and can travel in far worse conditions than we can with ships—and they cost the equivalent of approximately 3 days of operating costs for our large sea-going vessels.”

This flight marked the first use of Electrochem C cells in a Slocum in preparation for a more ambitious run.

RU17 Flight NJ – Azores

Figure 7 RU17 Deployed on May 21, 2008.

RU17 was deployed on May 21, 2008 (Fig 7) with a newly extended payload bay designed for additional energy storage. (This design is also being considered for use in the Antarctic region for alkaline cells to circumvent transportation issues.) In total, 435C size Electrochem CSC-93 cells were fit into the vehicle.

A success on many fronts, RU17 was within 20 km of the Azores EEZ line when we lost communications on October 28, 2008. The Rutgers students, technical staff and scientists flew RU17 a record breaking distance of 5,700.59 km spending 160 days at sea (Fig 8).

The flight of RU17 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. Path planning for RU17 required data and forecasts, and operational centers with existing products were eager to contribute to the success of the mission.

The University of Maine provided a link to their satellite data when the Rutgers acquisition system went down and required repairs. A similar satellite receiving station in the Canaries
provided local coverage on the European side. The NASA Ocean Color Web provided access to the global MODIS dataset for SST and Chlorophyll that filled the gap between the higher resolution direct broadcast data acquired on either side of the Atlantic. The Altimetry products generated by the University of Colorado, especially the geostrophic currents, were in constant use. Ocean model forecasts were provided by the Naval Oceanographic Command and by our partners in Spain. The NOAA National Hurricane Center and Oceanweather websites provided wind and wave forecasts. The international Argo program provided subsurface temperature and salinity profiles for ballasting and flight planning.

RU27 Flight Across the Atlantic

Applying lessons learned, particularly with regards to bio-fouling, RU27 was prepared with a 200m pump, an anti-fouling coating, coulomb counter and launched on April 27, 2009.

Presently RU27, christened The Scarlet Knight, is over half way across the Atlantic (Fig 9) flying with a consumption rate of 33 watts per day and is scheduled for an in-water inspection when it nears the Azores in September.

Progress and blogs can be followed at http://rucool.marine.rutgers.edu/atlantic/

“...This was a risky mission. Everyone knew that. We also knew that we would learn a lot more by trying than by staying at home.” Scott Glenn, Rutgers University oceanography professor. “We tried once. We learned a lot. We’ll try again in the Spring.”

Thus, setting the stage for the next attempt to cross the pond, we were all ready and determined to try again.

Figure 8 RU17 flight NJ to the Azores.

Figure 9 RU27 halfway in the Transatlantic Crossing.

Figure 10 RU27 Flight Status Indicators http://rucool.marine.rutgers.edu/atlantic/.
Educational Outreach

Proving the glider to be a useful tool in science is one of the reasons for such endeavors. The other is that we were challenged by NOAA to fly a glider across the Atlantic on an inspirational flight that entrained students. Stimulate the next generation of oceanographers and excite the public around the world about what is happening in our oceans.

"For the good of your country, you need to fly a glider across the Atlantic." Dr. Richard Spinrad NOAA.

When you go on an adventurous mission, if you succeed, everyone will have wanted to follow along with you. And if by chance you happen to fail, those who follow along will understand more fully the challenge at hand.

Science is not about the pretty result at the end; rather, it's about the arduous process researchers often have to take to get there. Our task is to help the public understand the true nature of science, and the best way to do that is to let them follow on a voyage of adventure.

Crossing the Atlantic with an autonomous robot would be Oceanography's new Sputnik. And the Internet will allow anyone and everyone to swim with the glider as it makes its way across.

Over the course of building RU17, RU27, the test Flight to Halifax, and the Across the Pond experience, undergraduate involvement in the Coastal Ocean Observation Lab has increased by an order of magnitude. Typically there were 1 or 2 undergraduates in the Lab on a regular basis, including a record setting 3 undergraduates in 1994. Now, depending on how you count, there are between 10 and 20 undergraduates working in the Lab.

Undergraduate students are seeking new opportunities earlier in their careers. In the past the majority of students came to the Lab during their Junior year. Occasionally we would entrain the rare Sophomore, a lucky break because we would both benefit from the opportunity to spend two summers together. Now, attracted by the grand scale of international glider missions, we are even pulling in Freshmen through the various Intro to Oceanography courses and Freshman seminars that we use as feeders. Work-study students are seeking us out during the school year. Traditional summer internships are being used to attract students from outside Rutgers, and to send Rutgers students abroad. Some Seniors are staying with us through the summer after graduation before they move on. Some of the new Freshman will have spent 4 years working with us in the Lab over the course of their undergraduate careers.

The students are seeking both the hands-on research opportunities and the camaraderie of group projects that RU17 and RU27 have provided. They are prompting us to teach more mid-level undergraduate courses. Our traditional capstone courses, for example, the first year graduate course in Physical Oceanography, are still being taken, but the capstone course now recommended for their final semester is Communicating Ocean Science, an NSF sponsored class developed by Lawrence Hall of Science. The course introduces students to modern educational theory, it provides hand-on opportunities to
practice what they learn at Liberty Science Center, and they use that experience as a basis for mentoring the younger multi-disciplinary students in the lab. Even after graduation, we see that the students use the new tools available to them, like video IM and Skype to stay in touch, and to field questions from younger students that are just starting out.

What did the students do during this project? We had several small teams or sometimes individuals contributing to a common goal. Two students helped with the physical glider build. Two worked on determining and improving the flight characteristics of RU17, including work on the flight characteristics of the extended payload bay, energy savings on communications and trim battery movements, and optimizing the gains on the Digifin for improved steering. Two worked on the CODAR network in the U.S. as the takeoff point, one went to Spain to work on their CODAR network as a potential landing point. One worked on path planning and the new Google Earth and Google Maps interfaces. Another worked on the webpage interface describing what we are doing. During the summer, the more senior level students took full control of the flight planning and waypoint changes. During the fall semester, the younger students came in and filled their shoes.

Given the rapid expansion of glider operations in the U.S., and world-wide, the community is going to need more people training in the operation, maintenance and use of gliders for ocean research and operations.

**Thermal Glider**

Electric gliders change their buoyancy by means of converting stored battery energy into a pressure volume change with a hydraulic pump. If we can arrange to harvest this energy needed for the buoyancy change from the thermocline of the ocean – there is a substantial energy savings that can be applied to greater endurance. Further, given the greater depths that the Slocum Thermal must fly to in order to induce the phase change (1200m), it is possible to allow the flight controller to sleep for periods of time reducing power even more.

The present Thermal glider deployed, Drake, is exhibiting an average energy consumption of 242 mW/per day. Although Drake has an alkaline battery set, the next Thermal being constructed will have a 90 DD cell Electrochem CSC-93 pack translating into a 3.6 year endurance.

In construct (Fig 11), the patented thermal engine consists of a heat exchange tube, accumulator, valve manifold, and both external and internal (to the pressure hull) bladders. The heat exchange tube is comprised of an outer aluminum pressure vessel that is filled with a wax chemistry tuned to undergo a phase change at 10°C. In the center of the wax is a flexible hose which can be filled with mineral oil. In operation, the glider leaves the surface by rotating the valve and allowing oil from an external bladder to enter into the pressure hull to an internal bladder, decreasing vehicle volume, causing the vehicle to descend. Prior to leaving the ocean surface, the accumulator, backed by 3000 PSI Nitrogen, must be charged with oil while
the wax in the thermal heat exchange tube is in a liquid state. As the glider dives it passes through the 10 C thermocline into colder waters and the wax begins to freeze, contracting and allowing oil to be drawn into the flexible center hose in the heat exchanger from an internal bladder. Inflecting at the bottom of its 1200 m deep dive, the valve turns again and the accumulator pushes oil to the external bladder overcoming the hydrostatic pressure, increasing vehicle volume, causing the vehicle to rise. Again, traversing the 10 C thermocline into the warmer surface waters of the ocean, the wax melts, expanding and forcing the oil in the middle hose out at high pressure into the accumulator thus re-charging the system for the next dive (Fig 12). The harvesting cycle continues over and over (Fig 13) as the glider makes its way along collecting and periodically transmitting water column information back to the ground control station.

![Figure 11 Thermal glider cutaway view.](image1)

![Figure 12 Depth pressure in bar, Temperature C](image2)

![Figure 13 Glider sawtooth flight in dbar, accumulator pressure in bar drop at inflection and increase during ascent.](image3)

Earlier generation Thermal gliders were constructed with two heat exchange tubes while the next generation thermal moved to a single tube due to a faster heat transfer design. This pressure tolerant aluminum engine tube is external to the vehicle pressure vessel hull. If we peer into the end of the thermal engine tube one would see in cross section the outer aluminum shell and a flexible rubber tube running down the center (Fig 14). This is held in place with some thin metal discs that are press fit into the aluminum shell to aid in heat transfer (Fig 15).
Figure 15 Wax in solid and liquid states, opening and squeezing oil in a center rubber tube.

Figure 16 Accumulator in center, thermal engine heat exchange tube on bottom.

The first accumulator type was with an internal piston separating 3000PSI nitrogen, the spring force, and on the other side mineral oil when charged. Recently, due to a concern with long-term leakage of gas past the sliding piston, a zero-leakage welded metal bellows has been incorporated to separate the gas and oil.

In flight it is not necessary to fully surface provided the accumulator has a measured full charge – and the glider is on its way again for the next dive cycle elegantly repeating “yos” it navigates through the interior of the ocean. A typical flight is 5 yo’s, or 17.5 hours submerged before surfacing and calling home.

Thermal Flights

On December 12, 2007 with Dr. David Frantonti’s Autonomous Systems Laboratory (ASL) at WHOI, Slocum WT01 was launched in the Caribbean. WT01 flew a course from St. Thomas to St. Croix in repeated sections for 4 months helping to observe the geostrophic flow of water between the islands, traversing over 3000 km in the process. In April 2008 WT01 was recovered for inspection and readied for a longer trip planned from the Caribbean to Bermuda. WT01 worked its way out and around the islands to stall in its northward flight due to a strong warm core eddy. Waypoints were changed to
fly west to swing around the eddy. When the glider entered the corner of the Bermuda Triangle in June 2008, it failed to call in again (Fig 17).

Undaunted, we then began preparing a pair of next generation Slocum Thermals with the single faster response thermal engine heat exchange tube as described. One utilizes an alkaline battery set and a second unit is being outfitted with Lithium batteries. All use the patented composite hull for lightness and water compressibility matching.

The first of the two, christened Drake, has been constructed and successfully trialed in July 2008 at Lake Seneca, a 200m deep cold water lake in upper-state New York where there is a very thin warm water layer at the surface of the lake just allowing for thermal flight. This unit also makes use of a TWR designed buoyancy “amplifier”, providing a generous boost in buoyancy during ascent through the warm-low density thermocline. Drake was deployed on June 22, 2009 from St. Thomas (Fig 18) and sent out via the Anegada Passage. If the test run goes well, destination Cape Verde.

The second is scheduled to be in the water this September. Modifications include the metal bellows accumulator and “liquid pitch”. Instead of moving a mass for the vernier pitch adjust, a small volume of dense fluid will move from end-to-end in the glider.

Electric Generation

Once one considers the energy savings achieved by the use of harvesting energy from the thermocline, it is tempting to use this same method to generate electricity giving theoretically indefinite endurance. This design has proceeded surprisingly well and has been bread boarded (Fig 19). We are able to convert hydraulic energy drawn from the accumulator to a constant voltage electrical energy using straight-forward commercial components with 60% efficiency. If we drop efficiency to 45% to account for storage loss, given 500cc displacement at 1600dbar with a 4 hour cycle period the glider is capable of generating 250 mW – on par with our present usage.
Acknowledgments

The involvement over the years in bringing a number of technologies to life; has highlighted a fundamental recipe to success. Success, as defined in our case, is having the privilege of being instrumental in enabling people to better understand the interiors of oceans around us. The key ingredient, if distilled to one word, is collaboration. Collaboration between technology providers, academia, and governmental funding sources, carefully cultivated and leveraged with other technologies, is capable of changing our fundamental understanding of world ocean dynamics. Coupling this with an affordable research platform and recent paradigm shift of making the resulting abundant and rich data sets publically accessible has helped to change the face of and faces in oceanography.

The community of vehicle builders, worldwide funding agencies and users are the force in bringing glider technology to fruition.

Programmatically, in the US, The Office of Naval Research (ONR), National Oceanic & Atmospheric Administration (NOAA), and the National Science Foundation (NSF) are thanked for supporting much of this work.

Figure 20  Slocum glider.
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