Slocum Glider
Expanding the Capabilities
UUST 2013

Clayton Jones, Ben Allsup, Doug Webb
Teledyne Webb Research
Falmouth, MA
cjones@teledyne.com

"...I walk into our control room, with its panoply of views of the sea. There are the updated global pictures from the remote sensors on satellites, there the evolving maps of subsurface variables, there the charts that show the positions and status of all our Slocum scientific platforms, and I am satisfied that we are looking at the ocean more intensely and more deeply than anyone anywhere else."
Henry Stommel, *The SLOCUM Mission*, 1989.

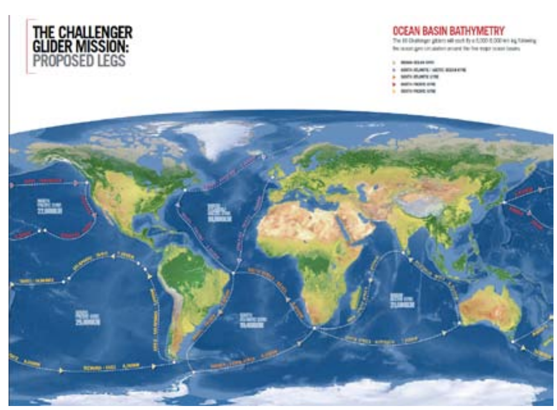
Introduction

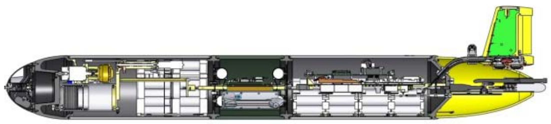
Henry Stommel's imagination was sparked by the opportunity gliders provided to broaden our understanding of the oceans and perhaps even more important to him, by the potential it had to draw peoples interest and excitement for ocean dynamics.

Teledyne Webb Research (TWR) provides here an overview of the latest Slocum G2 features including the hybrid thruster, increased buoyancy pump displacement, new sensor suites, and an update on the energy harvesting Slocum Thermal E Twin. Three main mission objectives will be reviewed: polar regions, acoustic data telemetry, and long duration transects approximating the course of the Challenger expedition of 1872-76.

On the Challenger front, a Slocum G2 named Silbo has completed the Iceland - Azores - Canary Islands legs, and is now on its way across the Southern Atlantic. The Rutgers University RU 29 has left South Africa and is presently transiting to Brazil. With these endeavors, we continue to draw together the International Consortium of Ocean Observing Labs (I-COOL) focusing on international and educational outreach.

Procurements of Slocum gliders in large numbers by both the US Navy and the Ocean Observation Initiative (OOI) Coastal and Open Ocean bring us closer to realizing Stommel's vision of glider fleets roaming the oceans.



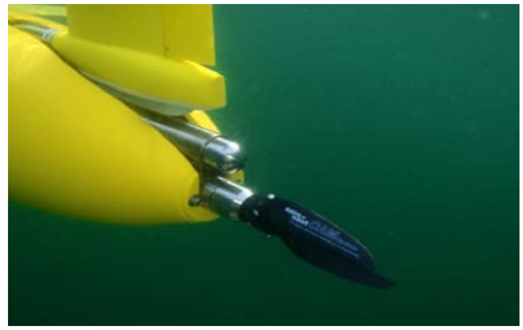


Slocum G2 Glider

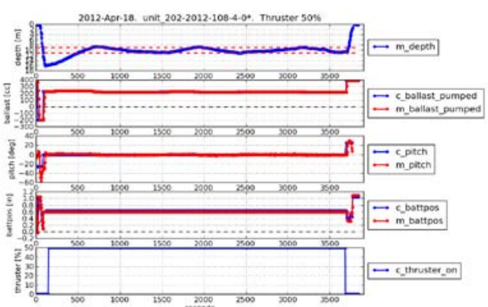
Underwater gliders have become an accepted oceanographic platform which, through international education outreach programs, certainly are fulfilling Stommel's vision of creating interest and curiosity about our oceans. To date over 350 Slocum Gliders have been delivered to 64 user groups world-wide with uses and new applications expanding. Teledyne Webb Research (TWR), in collaboration with our users, continues to increase system flexibility and ease of use. From coastal surveys to global crossings, gliders are advancing our understanding of ocean dynamics.

Hybrid

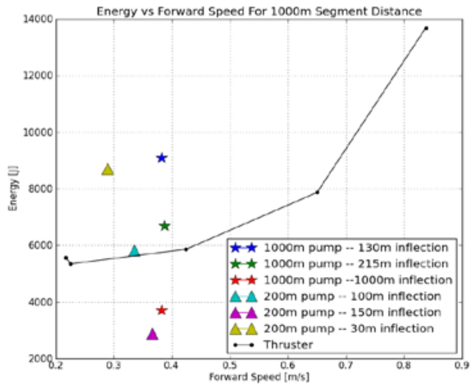
Begin with efforts from our colleagues at Memorial University, an add on thruster has gone through commercialization at TWR. This resulting hybrid vehicle has been created by integrating an efficient thruster in the aft end of the Slocum.



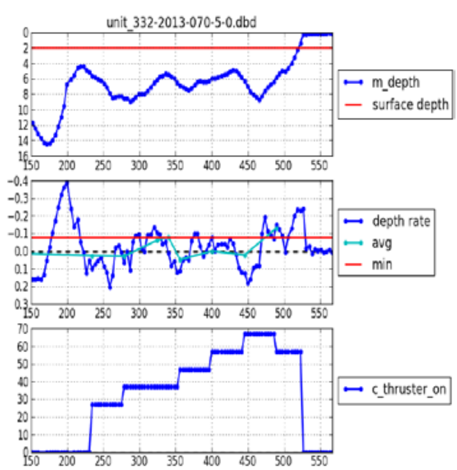
The propellers fold when not engaged to reduce drag during buoyancy only mode and snap open when in thrust mode. Blending both buoyancy control and thruster propulsion allows for expanded mission capability and greater flight efficiencies.



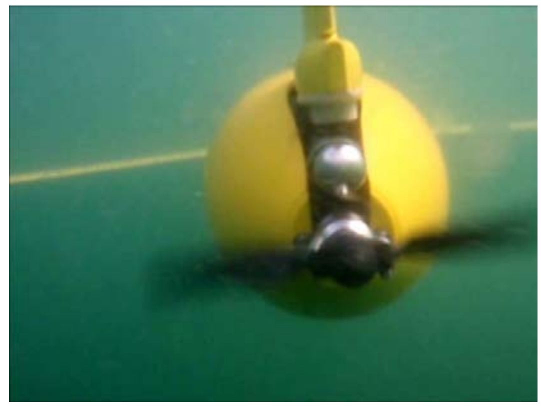
In a bathtub flight mode, the glider adjusts its volume to achieve a target depth or altitude off of the bottom at neutral buoyancy and then the thruster is engaged for horizontal flight. This, unlike traditional propeller driven AUVs which have a slight positive buoyancy and must constantly work to stay at desired depth, allows a better flight efficiency. In fact, at the nominal flight speeds that the glider achieves in buoyancy driven flight (0.35 m/s), the thruster's efficiency is slightly worse, but close to that of the buoyancy pump when operating at its optimal depth range.



If the pump, however, is operating out of its optimal depth range, the thruster is more efficient per distance transited at the same nominal speed. Therefore, one mission advantage example 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 can achieve over 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 provide a greater average efficiency than spending days trying to break through at slower speeds.



The thruster can also be used to break through lower density surface waters, ascending the glider to a shallow enough depth that the air bladder can inflate for communications. Above is an example of a glider intentionally ballasted heavy and the thruster step increasing in power to propel the glider to the surface.



The hybrid glider simply stated, allows a pilot greater flexibility in mission construct within a variable set of environmental parameters.

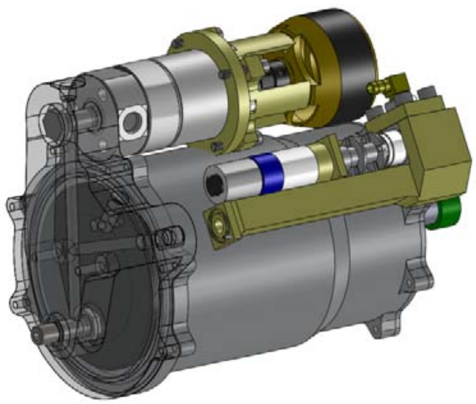
Buoyancy Pump Displacement

Increasing the vehicle lung capacity, or dynamic volume, allows the glider to have a larger delta density capability and/or greater speed. TWR has commercially released a shallow 800cc pump and is presently working on a deep 1000cc pump. Complementing the hybrid glider, these increased displacements are particularly useful in coastal areas where there may be a freshwater influence, or global gliders that may cross through a range of densities.

These modular pump families are still optimized for a variety of depth operations:

- Shallow family: 30, 50, 100, 200 meters (as shallow as 4 meters minimum water depth)
- Deep family: 350, 1000 meters

For the shallow system, the piston diameter has been increased with all other sizing remaining the same, allowing it to be Slocum G2 compatible.



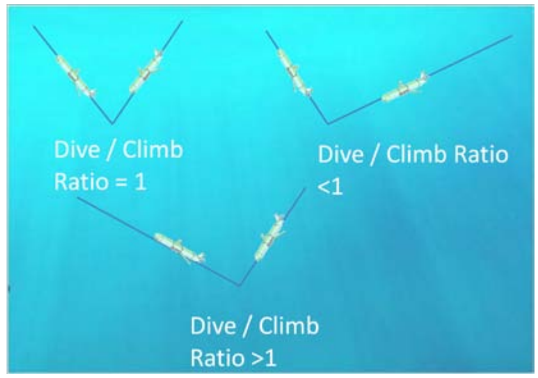
The deep pump gains a larger reservoir and utilizes the newer stainless steel metal bellows that has been recently shipping with Slocum G2 systems. The cycle life of these bellows has increased from 10K to 400K prior to needing refurbishment.

The density range that the glider is able to overcome is increased. Also included is the 335 cc derived from TWR's patented composite hull when operating to 1000 meters:

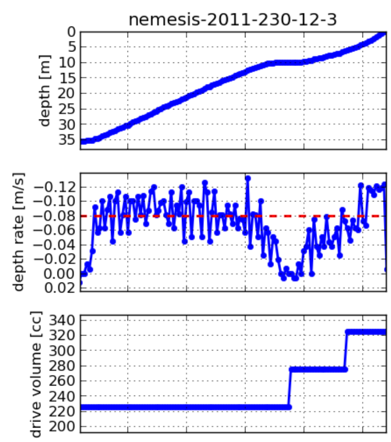
- 800 cc buoyancy: 12 kg/m^3 (reduced by 100 cc drive allocation).
- Thruster: 17 kg/m^3
- Combined: 29 kg/m^3

Speed:

- From buoyancy: up to 1 knot, dependent upon density and depth, a function of pump speed and total displacement.
- From thruster: up to 2 knots (can be combined with buoyancy).
- Speed kills: your battery, that is.



In order to take advantage of this increased drive in an automated fashion, glider autoballast software was created to allow the pilot to simply define the total volume desired for speed and the glider then adjusts the center point of the drive to provide a dive/climb ratio of one.



Running on top of autoballast is speed control, which ensures that a set minimum desired vertical velocity is met. If the glider slows, the buoyancy drive is then modulated in a step wise fashion to increase to an acceptable speed.

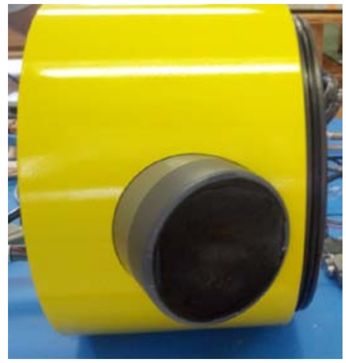
Reducing drive to a total of 300 cc, plus the 335 cc from the compressible composite hull, and placing the glider in low power mode, users have been able to achieve an energy consumption rate of less than 2 Ah/day. The standard lithium primary battery is nominally de-rated to 700 Ah and the extended battery to 1030 Ah - providing well over a year endurance with careful management.

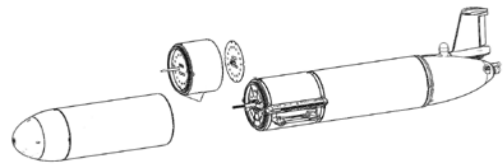
Sensor Suites

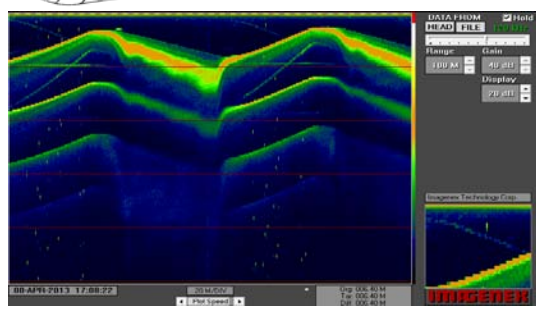
The Slocum G2 is designed foremost as a senor truck, lending its adaptability to both internally and externally mounted sensor suites. A dedicated science bay processor manages when sensors are in operation by flight mode selection and depth range.

Photo: Algot Kristoffer Peterson

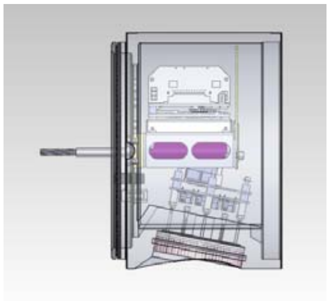
An example of an externally mounted sensor is the Rockland Scientific microRider with its shear probes extending in front of the glider.



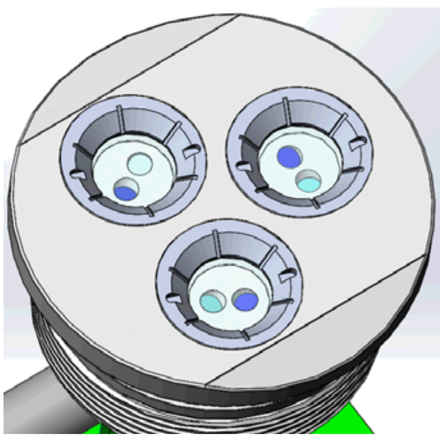




The integrated Imagenex 853 contains both a wiring harness and tie-rod extension allowing it to be used on any G2 glider with minimal modifications. Here referred to as a half-stack payload bay.



Similarly the RDI Explorer ADCP has been reconfigured in a half length, or half-stack payload bay, that can be readily swapped in or out of a vehicle based on mission requirements.

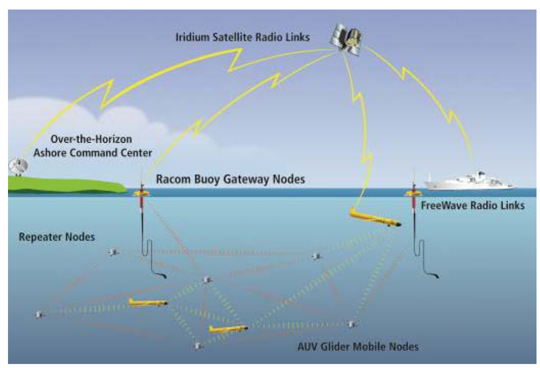


Optic elements of the Turner Cyclops have been inserted into a standard glider window port to create a three channel suite rated for 1000 m operation.

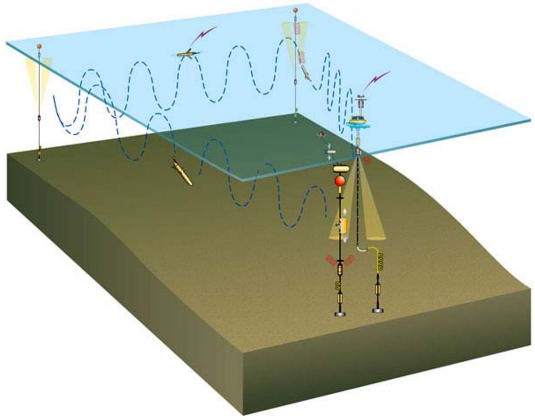
The Vemco fish tracker has been added into a payload bay, allowing the gliders to be a receive node in the Ocean Tracking Network (OTN) to help increase our knowledge of fisheries and habitat.

Subsea Data Telemetry From Gliders

Of the first Slocum gliders delivered in 2002, four were equipped with integrated Teledyne Benthos acoustic modems.



These “Gateway” gliders have the capability of collecting data from seafloor mounted nodes by acoustic transfer, storing, and then forwarding the files via radio line-of-sight or Iridium satellite communications. Further, if the water acoustic properties are favorable, the glider is also able to stay at the ocean surface and become a direct conduit to the nodes.

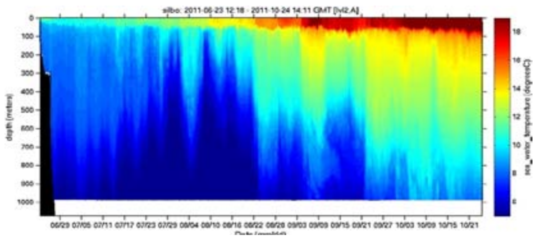


The basis of this technology is being used in the NSF OOI Open Ocean program. Each site consists of three deep ocean moorings where one will have a surface expression and two will not. The Slocum G2 gliders complement the moorings by collecting physical oceanographic data during transit between the moorings. When in range, the gliders will poll the acoustic modem up to 2.5 km deep on the sub-surface moorings to collect the stored data set and then subsequently transfer this back to the operations center via Iridium telemetry. Additionally, an acoustic command/control link to the mooring is provided to change sampling schema. During this remote operation, the gliders are planned to be on location for a year between servicing events. Operational deployments have just begun at Station Papa in the north Pacific.

Global Gliders

Building on the success of the first ever AUV trans-oceanic crossing, an growing effort has been focused on re-fulfilling 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 2015 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. Deployed again on July 24, 2012 we were planning to see Silbo next in Brazil. In coordination with Rutgers students, a decision was made to change course to the Caribbean based on more favorable currents.



In the last weeks, Silbo had an abort whereby the ejection weight was properly released. Presently surface drifting, we expect to be soon close enough to shore for a reasonable recovery. The intention is to refurbish and re-deploy. A second track is also visible in red depicting Rutgers RU29. This glider left South Africa and is en-route to either St. Helena or Ascension Island. To follow along go to http://www.i-cool.org/?cat=77

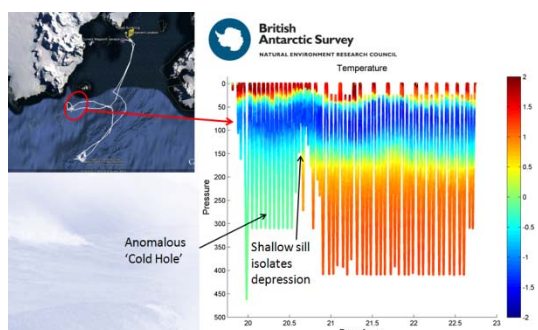
Thermal to Electric Generation

Truly a global-class glider, the Slocum Thermal glider promises many years of endurance. With Office of Naval Research (ONR) support and in cooperation with the Jet Propulsion Lab (JPL), TWR has prepared two vehicles that not only use the thermocline to produce the buoyancy drive but also convert hydraulic energy to a electrical energy. JPL's charge board and batteries utilize excess volume drive run through a generator to recharge the electrical system. The hydraulic genset can also be run in reverse, allowing the glider to pump without a thermal charge if required by using the charged or primary batteries.

The Slocum Thermal E-Twin is equipped with two external engines to create over 1000 cc of pressurized liquid that can be directed for electrical generation or buoyancy drive. These gliders will be deployed from Hawaii in August.

Antarctica

Having supported the first ever use of gliders in Antarctica in 2007, TWR continues to work with both Rutgers and the British Antarctic Survey (BAS) in these remote harsh areas where gliders have been used every austral summer since to capture phenomena that otherwise might be missed.

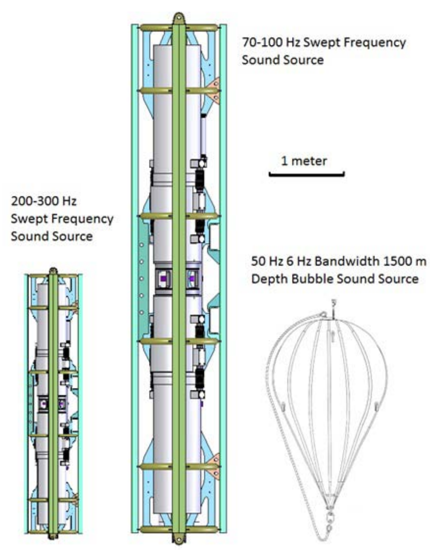


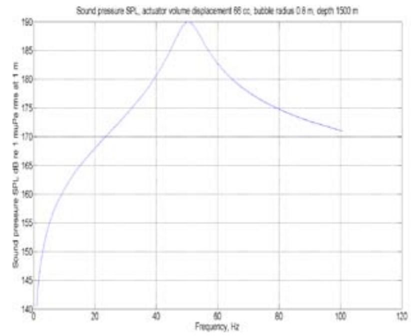
For example, on site in Rothera with BAS this past year, TWR helped to capture a data set of an anomalous "cold hole" where water had been trapped by a shallow sill. Plans are already in place for TWR to return this coming year and test software changes with enhanced autonomy robustness to help with situations such as getting lodged under ice bergs.

Under Ice Navigation/Communication

When we look at both the Arctic and Antarctic it is inevitable that we will want the gliders to foray under the ice.

Long-range tomography and acoustic communications and navigation all share the same need for efficient and manageable sources. In the Arctic the need for low frequencies is made more acute by the loss that occurs when signals reflect from the ice. While no single source technology can fulfil all needs, the tuneable and non-tuneable tube sources are shown to be remarkably efficient down to approximately 100 Hz for both navigation and tomography. At lower frequencies than this, the sources become very large and unwieldy. Other options, for example the gas bubble source that TWR is developing, are possibilities for much frequencies down to 50 Hz





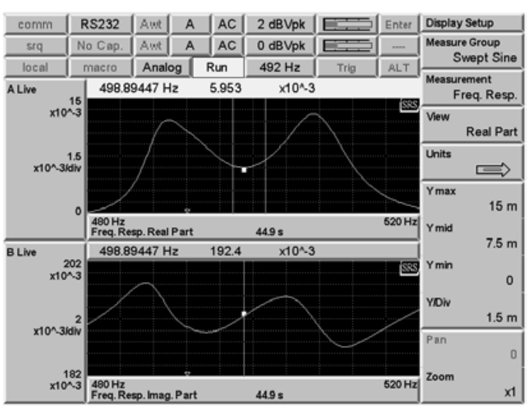
With this low broadband, it has been modelled that three bubble sources could insonify the entire Arctic providing navigation as a form of underwater GPS. The low power signal could even be coded to naturally sound like an ice structure breaking.

For this form of navigation, the glider simply needs an acoustic receiver coupled to an accurate time base such as a chip scale atomic clock.

Communication requires that the gliders also carry a source - with the usual caveats regarding size, weight, and power constraints on this size vehicle.

Initial experiments with coherent signalling under the ice has shown that a nominal 700 Hz single hull source is feasible to approximately 100 km range.

TWR has been experimenting with doubly resonant sound sources that are essentially a resonant tube within another resonant tube and driven by a transducer. This broadening of the band allows for greater robustness in selective fading and better overall communication rates. A family of these sources has been built over a range of frequencies.



A TWR composite 500 Hz source has been recently built with an in water weight of six kg, an efficiency of over 50%, and an open ocean range of greater than 500 km. Such a source could be used to seed the ice field with little special handling equipment for navigation purposes. And a variant is viable to be carried by a glider for low data rate communications from the vehicle itself.

Acknowledgments

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

Programmatically thanks go to: The Office of Naval Research (ONR), National Oceanic & Atmospheric Administration (NOAA) and its Integrated Ocean Observing System (IOOS) component, Naval Oceanographic Office (NAVO), Space and Naval Warfare Systems Commmand (SPAWAR) and the National Science Foundation (NSF).

Bibliography

Morozov, A.. K., C. Jones, J. Manley, Unmanned Vehicles and Acoustics for Underice Environmental Monitoring, Offshore Technology Conference 2012.

Creed, E.L., C. Mudgal, S.M. Glenn, O.M. Schofield, C.P. Jones, and D.C. Webb, Using A Fleet of Slocum Battery Gliders in a Regional Scale Coastal Ocean Observatory, Oceans 2002 pp 1234-1238.

Davis, R.E., C.E. Eriksen, and C.P. Jones, Technology and Applications of Autonomous Underwater Vehicles, Autonomous Buoyancy-Driven Underwater Gliders, Edited by Gwyn Griffiths, Taylor & Francis, 2003.

Duda T.F., Morozov A.K., Howe B.M., Brown M.G., Speer K., Lazarevich P., Worcester P.F., Cornuelle B.D. Evaluation of a Long-Range Joint Acoustic Navigation / Thermometry System, *Proceedings of Oceans 2006.*

Glenn, S., Kohut, J., McDonnell, J., Seidel, D., Aragon, D., Haskins, T., Handel, E., Haldeman, C., Heifetz, I., Kerfoot, J., Lemus, E., Lictenwalder, S., Ojanen, L., Roarty, H., Atlantic Crossing Students, Jones, C., Webb, D., Schofield, O. 2011. The Trans-Atlantic Slocum glider expeditions: A catalyst for undergraduate participation in ocean science and technology. Marine Technology Society 45: 75-90.

Glenn, S.M., et al. The Expanding Role of Ocean Color and Optics, *Oceanography* 17(2): 86-95, 2004.

Griffiths, G., Jones, C., Ferguson, J., Bose, N., Undersea Gliders, Journal of Ocean Technology, 2007, Volume II, number II, pp 65-75.

Jones, C.P., Webb, D., Kohut, J., Glenn, S., Kerfoot, J., Schofield, O., Roarty, H., Aragon, D., Haldeman, C., Graver, J., Yan, A., Slocum Gliders – Advancing Oceanography, Proceedings of UUST Conference, New Hampshire, August 2007.

Jones, C., Creed, E., Glenn, S., Kerfoot, J., Schofield, O., Slocum Gliders – A Component of Operational Oceanography, Proceedings of the UUST Conference, New Hampshire, 20-25 August 2005.

Jones, C.P., Slocum Gliders as Coastal Observation Remote Sensing Platforms, Oceanology International, March 2002.

SLOCUM: A Long Endurance Ocean Profiler powered by Thermocline Driven Engine. Sea Technology, February 1998.

Simonetti, Paul, SLOCUM GLIDER: Design and 1991 Field Trials, WHOI, ONT contract N00014-90C-0098

Schofield, O., Kohut, J., Aragon, D.,, Creed, L., Graver, Haldeman, C., Kerfoot, J., Roarty, H., Jones, C., Webb, D. C., Glenn, S.. Slocum Gliders: Robust and Ready, Journal of Field Robotics 24(6): 474-585, 2007.

Schofield, O., Glenn, S. Kirkpatrick, G., Jones, C., and Twardowski, M. (2004) Measuring Mesoscale in-situ Optics of the Continental Shelves with Autonomous Webb Gliders. Oceans 2004.

Stommel, H., The Slocum Mission. Oceanography, 22-25, April 1989.

Stommel, H., A. Voorhis, and D. Webb. Submarine Clouds in the Deep Ocean. *American Scientist*, 59(6):716-722, 1971

Webb, D.C., P.J. Simonetti, and C.P. Jones (2001). SLOCUM, An Underwater Glider Propelled by Environmental Energy, IEEE Journal of Oceanic Engineering, 26, 447-452.

Webb, D.C., and P.J. Simonetti (1999). The SLOCUM AUV: An Environmentally Propelled Underwater Glider. Proceedings of the 11th International Symposium on Unmanned Untethered Submersible Technology, August 23-25, 1999. Published by the Autonomous Undersea Systems Institute, pp 75-85.

Webb, D.C., and P.J. Simonetti (1997). A Simplified Approach to the Prediction and Optimization of Performance of Underwater Gliders. Proceedings of the 10th International Symposium on Unmanned Untethered Submersible Technology, Sept. 1997. Published by the Autonomous Undersea Systems Institute, pp 60-68.

Webb, D.C., Thermal Engine and Glider entries, Notebook No. 2, pg. 254 - 255, 2/8/86.