Slocum Gliders – A Component of Operational Oceanography

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Abstract

As defined by sustained data collection and real-time data distribution, Slocum Gliders are progressing into a component of operational oceanography. The long established collaboration between Webb Research Corporation (WRC) and the Rutgers University Coastal Ocean Observation Lab (RU COOL) provides an overview of the current capabilities of gliders, field data collected, and description of an adaptive command/control center allowing remote world-wide operation.

From the humble beginning of the first sea trials of the Slocum Electric Glider at Rutgers LEO-15 New Jersey site in July 1998 to the present day Endurance Line at the same location, with gliders running repeated 250 km round trips to the shelf break each month for the past year and a half and carried forward to operations around the world, gliders have evolved into an operational oceanographic tool. Rutgers data sampling has moved from intensive shipboard sampling 12 hours/day during the month of July into a new era of continuous, year-round adaptive sampling. Highlighted are a number of physical and optical sensor suites that have been integrated into the modular payload bay of the vehicle and the data sets that have resulted.

To facilitate vehicle operations, Rutgers and WRC, sponsored by the Office of Naval Research (ONR), have developed a command/control center entitled Dockserver that allows users to fly fleets of gliders simultaneously in multiple places around the world via the Internet. WRC continues to work on the backbone of this system while Rutgers is enhancing the agent oriented software to make Gliders fly adaptively, responding to a goal set. Details are presented on the architecture of this system and how the recognition text based system can be applied to other controllable components in the network.

Webb Research Corporation’s Slocum Gliders have been successfully integrated by Rutgers into their Operations Center. They are the backbone to the 24/7/365 sampling program that Rutgers has established. Gliders have proven to be not only robust but also able to collect high quality data during adverse weather conditions that would not allow normal shipboard sampling to occur, flying successfully during a number of

N’oreasters, and Hurricanes Ivan and Jeanne. To date, Rutgers and WRC have flown Gliders off of Martha’s Vineyard, just outside of NY Harbor, off of NJ, off of Norfolk, VA, on the West Florida Shelf near Sarasota, the Sargasso Sea and in the northwestern Mediterranean. Rutgers’ use of gliders is an example of an innovative instrument finding its path into operational oceanography.

Introduction

Gliders, as currently configured, were first detailed in Doug Webb’s lab book on 2/8/86 [1] as a novel instrument approach and publicized in 1989 by Henry Stommel’s view of a roving fleet of instruments [2]. It has taken some time to bring these concepts to reality, yet gliders are steadily making there place in the world as a high endurance sensor platform. More importantly, this class of long range and relatively low cost autonomous underwater vehicle (AUV) is opening capabilities of an affordable adaptive sampling network that has the potential of substantially increasing our knowledge of the world’s oceans.

A number of gliders of different forms, used by several organizations, are currently in existence. This paper will touch on the field trials that have been conducted by Rutgers University (RU) and Webb Resesearch Corporation (WRC) to depict examples of where the technology is today. The underlying goal is to develop and engage a broader use community.

The group of glider users and beneficiaries is growing and we believe that it can be confidently stated that this community aspires to reach the goal as set on paper by Henry Stommel as he described the Mission Control center overlooking Buzzards Bay, “*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 position 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.*” [1]

Vehicle Description

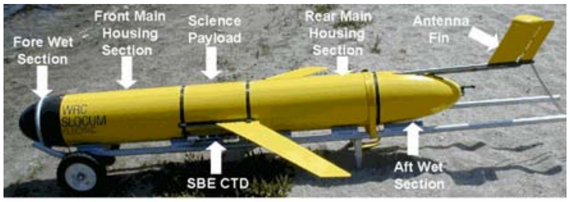


Figure 1 – Overview of Slocum sectional architecture.

The Slocum Glider is a 1.8 m long torpedo-shaped, winged AUV (Figure 1). It maneuvers through the ocean at a forward speed of 30-40 cm/s in a sawtooth-shaped gliding trajectory, deriving its forward propulsion by means of buoyancy change and steering by means of a tail fin rudder. The vehicle is currently capable of carrying a range of high-quality scientific payloads, including physical (CTD), optical (fluorometer, PAR, spectrophotometer, backscatter, transmissometer), and acoustic sensors. The primary vehicle navigation system uses an on-board GPS receiver coupled with an attitude sensor, depth sensor, and altimeter to provide ded-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 commended to surface. Operational endurance, utilizing alkaline batteries, is 25 to 50 days, depending on sensor payload carried and sampling regimes. Horizontal distance traveled averages 24 km per day. The vehicle is operational in 4 to 200 meters of water depth and can be optimized for 30, 100, and 200 meters operation with select gearboxes. Newly developed is the Slocum 1km (1000 meter depth rated) vehicle. A more complete description of this vehicle class, including other forms, can be found in [3].

Deployments

Rutgers presently operates a fleet of four gliders (Figure 2) and has deployed them singly and collectively in various parts of the world. To date these vehicles have completed over 12,000 km in transect (Figure 3).

Figure 2 – Four Slocum Electric 200m gliders readied for deployment.

The vehicles, once ballasted for the deployment site, can be deployed and operated remotely from any location with internet access. Communication is carried out by the satellite service Iridium calling into a modem bank located at Rutgers.

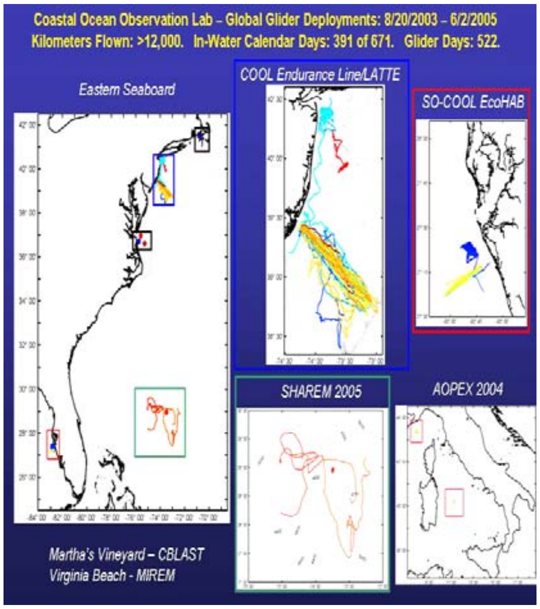


Figure 3 – Rutgers University transects depicting glider operations to date. Over 12,000 km traveled.

Gliders are typically deployed and recovered out of small vessels by one or two people. A large ship deployment is shown in Figure 4 with an optional pickup point on the top of the vehicle (Figure 5).

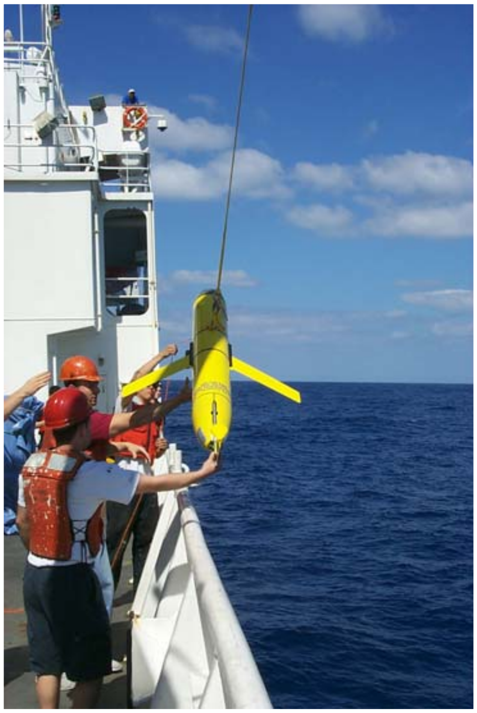


Figure 4 – Slocum Glider deployed and recovered off of RV Pathfinder 2005.

Figure 5 – Optional Hydrodynamic Pick Point.

As shown in a recent anti-submarine warfare (ASW) exercise involving Slocum Gliders from a number of groups, it is possible to deploy the vehicles from over the horizon and have them transit into the area of interest (Figure 6). These four gliders led to a cumulative 4782 profiles over 22 days - as compared to 19 shipboard CTD casts, and 367 air deployed XBT casts. Overall, the gliders greatly enhanced the NAVO feature modeling in the Smart-Search 05 with the data assimilated (Figure 7) by cooperatively filling in areas of environmental uncertainty.

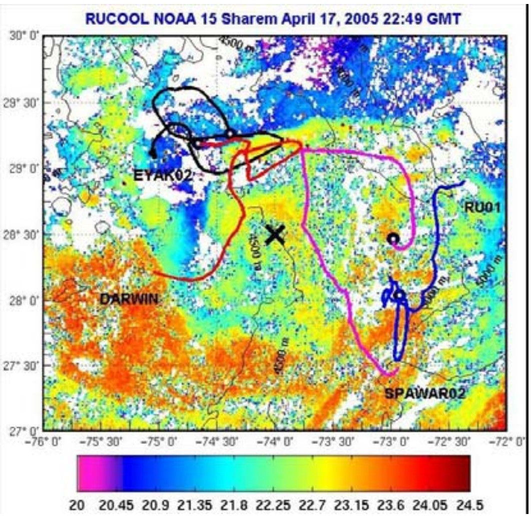


Figure 6 – Gliders deployed at four corner points transit their way to the targeted eddy feature.

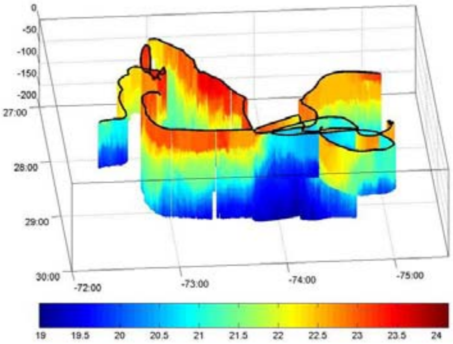


Figure 7 – Temperature sections of converging gliders.

Sensor Suites

It is the resulting data that are the driving components of this technology. The glider is simply the truck that carries the sensors through the areas of interest and provides storage and communication of data sets. To that effect, Slocum is equipped with a modular payload bay that is capable of carrying a number of sensor suites. Included is a science processor that is interfaced to the flight controller and can be programmed with proglets to operate additional sensors that have a RS-232 or TTL output. To date there have been physical, optical [4], and acoustic packages integrated into the payload bay and interfaced with the science controller for data collection. Rutgers has concentrated primarily on physical and optical parameters including a conductivity, temperature, depth (CTD) sensor, a variety of optical sensors from Wet Labs, and in conjunction with MOTE Marine a spectrophotometer for detection of harmful algal blooms.

Due to the buoyancy driven operational mode, gliders naturally undulate through the water column to provide forward motion. This makes them ideal platforms when one is interested in water column profiles. Over a year and a half worth of temperature sections on an endurance line off of NJ can be seen in Figure 8.

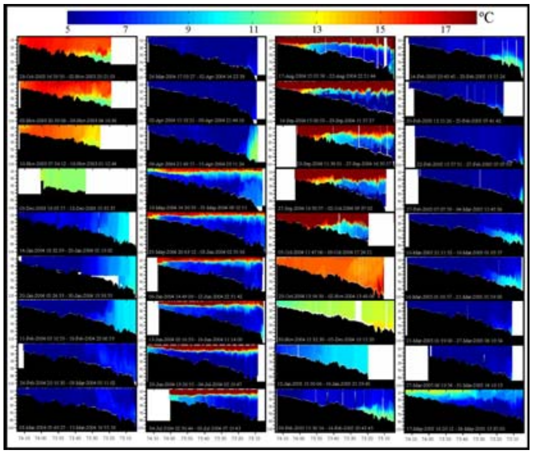


Figure 8 – Endurance Line temperature sections Oct 2003 – May 2005.

Sensor sampling occurs typically every 2 seconds during the downcast profile. The data are dense, recorded around the clock, reported in near-real time, and frequently during time periods when a ship would not be available due to weather constraints. The gliders have been able to collect data and report in during several storm sessions including hurricane Ivan (Figure 9) and a North Easter with reported 10 meter wave heights.

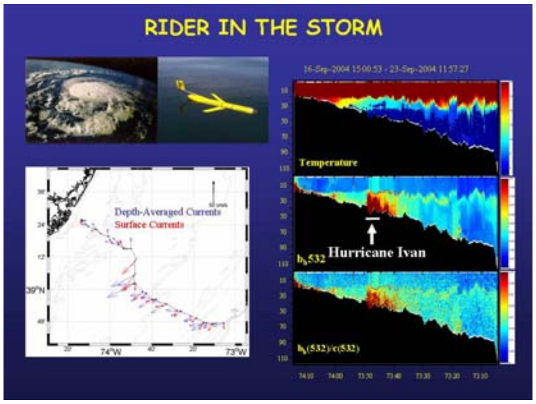
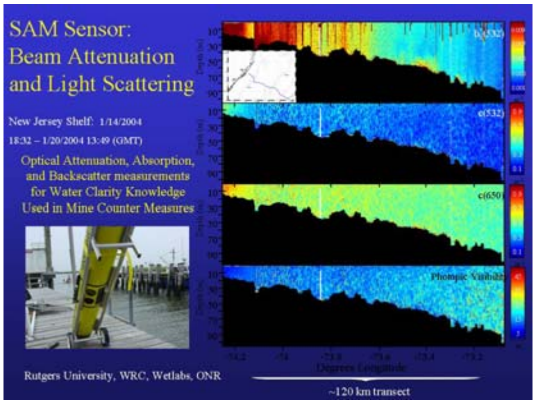

RIDER IN THE STORM

Figure 9 – Glider pushed off track by Hurricane Ivan, yet continues to record data and report in.

Two of the RU gliders are equipped with a sensor package developed in cooperation with Wet Labs called the SAM sensor suite. Mounted into windows in the payload bay this package determines the optical properties of the water and, as developed for mine counter measures (MCM), can determine the water visibility along with the optical and bio-optical features of the water column (Figure 10). Rutgers demonstrated this capability in a Navy exercise CJTFEX 2004 and in addition has flown the package to look at bio-productivity.


SAM Sensor:
Beam Attenuation
and Light Scattering

New Jersey Shelf: 1/14/2004
18:32 – 1/20/2004 13:49 (GMT)

Optical Attenuation, Absorption,
and Backscatter measurements
for Water Clarity Knowledge
Used in Mine Counter Measures

Rutgers University, WRC, Wetlabs, ONR

Figure 10 – Wet Labs SAM sensor and ECO puck suite integrated into a Slocum payload bay.

In collaboration with Mote Marine Lab, a modular payload bay section containing a Hyper-spectral Spectrometer is used to determine the similarity index of Karenia brevis (Brev Buster) in search of harmful algal blooms (red tide) off of Sarasota, FL A. (Figure 11).

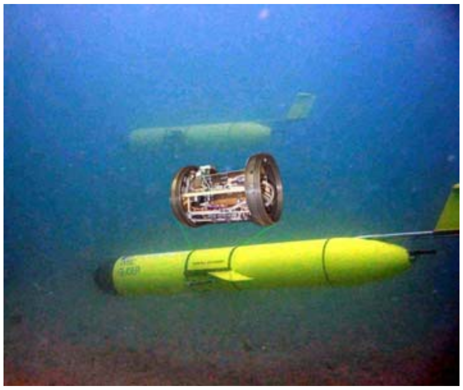


Figure 11 – Brev Buster, a harmful algal bloom detection package as a modular Slocum payload bay.

It is certainly envisioned that gliders do not replace current data collecting technology, they augment it by providing a rich data stream that allows better use of resources such as ships or other AUVs to target specific areas of interest that have been in part identified by these roving sensor grids.

Command and Control (C2)

It quickly becomes apparent that in order to operate the fleet of gliders necessary to resolve the temporal and special grid being discussed [5], there is a necessity for an automated command and control system. Further, if one can take this system and apply adaptive control based on targeted goals, we venture into the realm of an autonomous ocean sampling network [6].

WRC and Rutgers, aided by ONR funding, collaborated in an effort to produce components of a C2 system that are robust and versatile, so that they can handle a fleet of glider platforms. We, however, envisioned a system not limited to gliders, rather one that would be capable of incorporating a number of sensor inputs and make intelligent goal orientated decisions that then feed back into dynamic adaptive resource allocation.

In this fashion, hooks have been put in place to create a backbone that will enable tying together multiple inputs to create a much larger and more powerful adaptive network. The software package that has been developed takes information from a scientist, the glider itself, other sensing systems such as CODAR (COastal radar), satellites or additional gliders and optimizes 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 (Figure 12). Optimization can be done for features like, but not limited to, currents, tides, thermoclines and haloclines and can allow for ground-truthing of satellite imagery. Data are automatically pulled from the vehicle and made available for web based presentation.

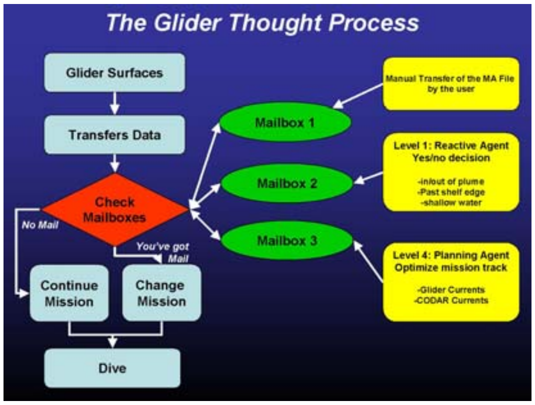
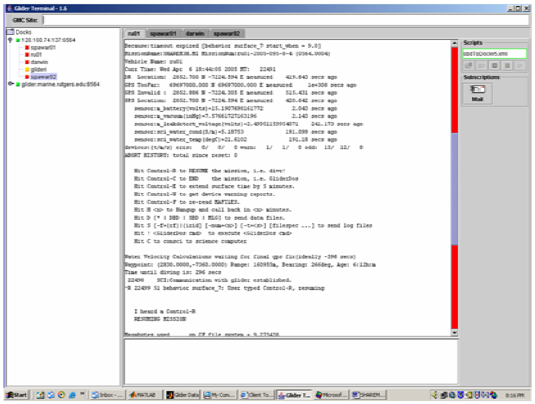


Figure 12 – Glider Mailbox flowchart.

As part of this process, a Slocum Glider Simulator was developed to help facilitate the testing of the mission control center, provide a training tool, and prove out glider software changes. The simulator features are derived from the low-level device drivers that control the actuators on a glider. The simulator can range from stand alone electronics only to a complete glider that can be put into simulation mode and fly on the bench with all actuators working (fin, pump, pitch, etc.). Adding real world fidelity of the external environment, the simulator contains variables allowing the change of water currents and wind speed, so that the glider and command/control center may be exercised prior to deployment.

Dockserver, written in Java, is a self deployed Linux based communications center that runs application code entitled Glider Terminal. This handles all vehicle traffic and acts as a data repository (Figure 13). When a glider surfaces, it calls in via RF modem or Iridium, is answered by the Dockserver that is in charge of logging the surface dialog of the instrument, and can perform any number of scripts that may be waiting in prioritized mailboxes. The glider itself is menu driven in its surface dialog. These scripts, written in one's language of choice, are typically text recognition drivers that engage the glider to perform particular functions, such as requesting a data transfer, uploading new mission parameters, or hold the glider at the surface for direct user interaction. Inherent is the ability to send email notification of actions taken or specific text strings read, such as ABORT. The system can handle multiple vehicles in separate windows that one can toggle between. Given the appropriate level of access one can engage the Dockserver from any internet hub in the world and multiple terminals can view the process simultaneously.



```
Because:timeout expired [behavior surface_7 start_when = 9.0]
MissionName:SHAREM38.MI MissionNum:ru01-2005-095-8-4 (0364.0004)
Vehicle Name: ru01
Curr Time: Wed Apr  6 18:44:05 2005 MT:   22491
DR  Location:  2852.700 N -7224.594 E measured     419.640 secs ago
GPS TooFar:   69697000.000 N 69697000.000 E measured      1e+308 secs ago
GPS Invalid :  2852.886 N -7224.305 E measured     515.431 secs ago
GPS Location:  2852.700 N -7224.594 E measured     420.642 secs ago
   sensor:m_battery(volts)=15.1907698162772          2.043 secs ago
   sensor:m_vacuum(inHg)=7.57661727163196            2.143 secs ago
   sensor:m_leakdetect_voltage(volts)=2.48995115995 4071    241.173 secs ago
   sensor:sci_water_cond(S/m)=5.18753              191.099 secs ago
   sensor:sci_water_temp(degC)=21.6202              191.18 secs ago
devices:(t/m/s) errs:   0/   0/   0 warn:   1/   1/   0 odd:  13/  12/   0
ABORT HISTORY: total since reset: 0

   Hit Control-R to RESUME the mission, i.e. dive!
   Hit Control-C to END     the mission, i.e. GliderDos
   Hit Control-E to extend surface time by 5 minutes.
   Hit Control-W to get device warning reports.
   Hit Control-F to re-read MAFILES.
   Hit H <n> to Hangup and call back in <n> minutes.
   Hit D [* | DBD | SBD | MLG] to send data files.
   Hit S [-f=(rf)|(irid)] [-num=<n>] [-t=<n>] [filespec ...] to send log files
   Hit ! <GliderDos cmd>  to execute <GliderDos cmd>
   Hit C to consci to science computer

Water Velocity Calculations waiting for final gps fix(ideally ~396 secs)
Waypoint: (2830.0000,-7360.0000) Range: 160955m, Bearing: 266deg, Age: 6:12hrm
Time until diving is: 296 secs
 22498     SCI:Communication with glider established.
^R 22499 51 behavior surface_7: User typed Control-R, resuming


   I heard a Control-R
   RESUMING MISSION

Megabytes used      on CF file system = 9.273438
```

Figure 13 – Glider Terminal component of the Dockserver.

The data that are pulled from the glider, as well as the surface dialog is available for file transfer protocol (ftp) for data visualization.

A health monitor parses engineering data from the surface dialog text that a glider sends and publishes a web based interface, providing the first layer of data visualization. Shown are such items as battery voltage, vehicle map position, internal vacuum, and depth-averaged currents (Figure 14).

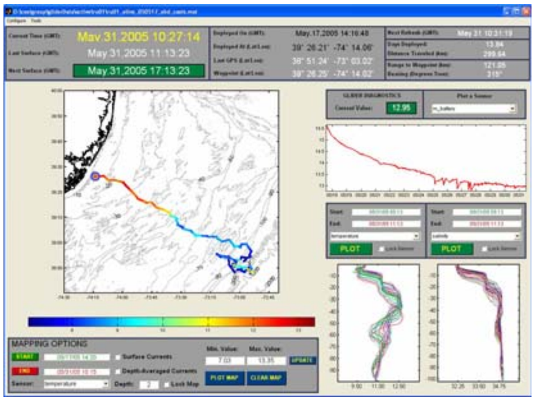
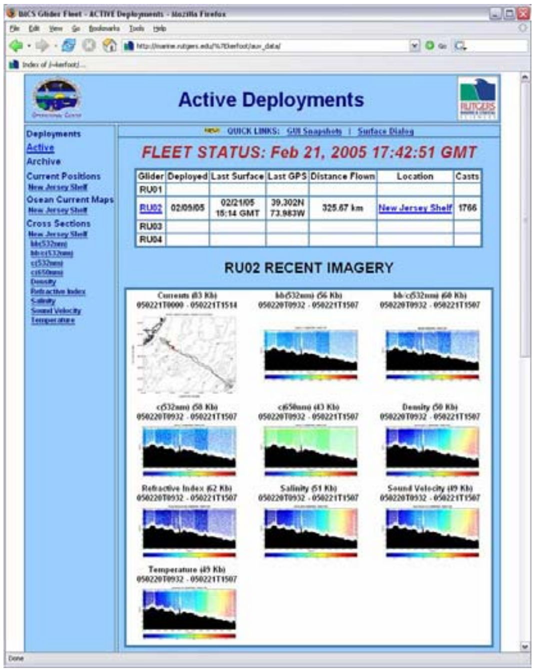


Figure 14 – Health monitoring of the Glider Performance.

The data files themselves are transferred in binary format converted and renamed by the Dockserver and are then available by ftp to a data product handler (Figure 15). Here the data may be quality controlled and are served to the web in various forms. In addition, the data may be re-written into additional forms for specific assimilation into models. This module also provides an archive link to recall previous data.

Rutgers co-developed the glider C2 (Command and Control) and use it as an integral component of the RU COOL command center. All of the data collected are presented and freely available to the public via web access.



Active Deployments

FLEET STATUS: Feb 21, 2005 17:42:51 GMT

Glider	Deployed	Last Surface	Last GPS	Distance Flown	Location	Casts
RU01						
RU02	02/09/05	02/21/05 15:14 GMT	39.302N 73.983W	325.67 km	New Jersey Shelf	1766
RU03						
RU04						

RU02 RECENT IMAGERY

Figure 15 – Data products from the glider and tags to archived data.

Adaptive Behavior

Given the basics of C2 provided, Rutgers has applied tools to enable several forms of adaptive sampling and dynamic control.

This has been shown using set points for adaptive sampling, such as determining temperature or salinity points which change the vertical control of the glider based on profile information. The glider is then automatically instructed, by the generation of a new depth parameter text file, sent via the Dockserver mailbox, to change its undulation depth points to fly either above or below a stratified density layer. Bio-optical properties are a direct extension to this type of control.

Horizontal control in the form of transmitting a new waypoint text file has been utilized to follow a fresh water outflow (Figure 16) and to turn the glider around for instance when it reaches a specified water depth (Figure 17).

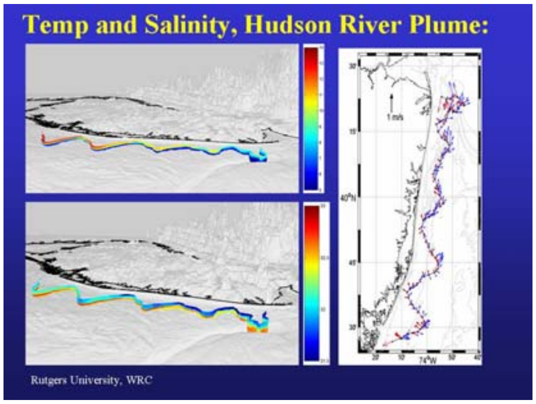


Figure 16 – Zig Zag to trace a cold water river plume.

A much more powerful layer of dynamic adaptation, based on Agent Oriented Programming "KQML" (knowledge query manipulation language) is used as a software agent communication language. This allows other inputs such as satellite imagery, other gliders, or CODAR fields to aid in the decision making process determining the flight control of a single glider. For instance, satellite imagery may show an area of interest that is set as an agent goal to be ground truthed. Based on this, utilizing the data from other gliders in the fleet and the current vectors from CODAR, it may be that the glider closest to the area of interest will not be the optimal unit to send. It may be determined that the depth averaged currents (gliders) and surface currents (CODAR) will actually enable a vehicle that is further away to arrive more expeditiously. Or, there may be different sensor suites on particular gliders that would eliminate one vehicle or promote another for the task. Much of this work was proven using manual manipulation, utilizing these functions in the Smart Search SHAREM exercise (Figures 5 and 6), with the goal of seeking eddy formations and filling in environmental data blanks for the model to assimilate.

While the satellite imagery example has not yet been field tested, Figure 17 depicts adding the knowledge of the CODAR surface currents to calculate and drive the optimal track for the glider to follow.

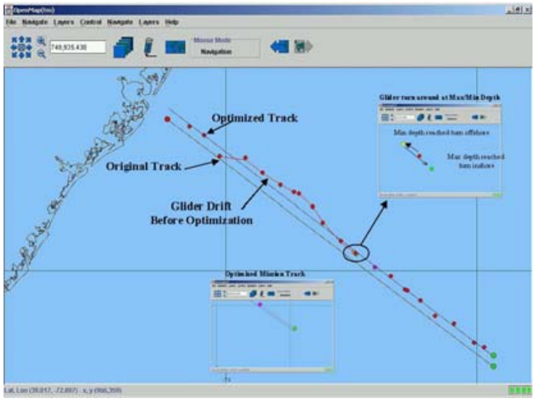


Figure 17 – Optimization of glider flight path taking in CODAR information. Also depicted, is a turn around event based on water depth.

With these tools in place, one can envision an adaptive network, progressively learning from a variety of sensor inputs, which drive an adaptive dynamic array of gliders to seek out targeted structures.

Further, given the text based recognition construct, it is certainly possible to facilitate other vehicles and sensor platforms with the same tool set.

Slocum gliders respond to small text based mission files. These can be generated as described above for external adaptive control. In addition, glider code architecture is in place to create control functions coming from the on-board science processor. This permits internal adaptive control, where the vehicle may respond to set points on collected data, such as ambient noise collected by hydrophone to engage in a behavioral change.

There will always be a balance between having a self-aware vehicle with internal adaptive capabilities and one that is externally controlled regarding the predicted outcome of the behavioral drivers. It is our job, however, to provide both capabilities and allow the growing field of end users to determine the best applications.

Future Work

The anticipated efforts are to increase the functionality of Dockserver and its data visualization tools, adding in a database search engine and GUI mission writing tools. Overall, the glider must still undergo a number of enhancements to increase robustness, ease of use, and endurance. In particular, divided internal hardware architecture is being designed to reduce vehicle interconnects and wiring, robust wings that require no tools for installation, easier ballasting methods, external weight adjust points, greater lung capacity to handle a greater range of water densities, composite hull structures, large ship deployment and recovery aids and glider structures, re-chargeable batteries, lithium batteries, air deployment capabilities, and continued software enhancements and payload integration.

Acknowledgments

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We would also like to acknowledge the growing community of vehicle builders and users, as it is these groups that are bringing the glider technology to life:

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Massachusetts Institute of Technology
MOTE Marine
IFREMER
Institut für Meereswissenschaften
Obervatoire Oceanologique de Villefranche
Princeton University
Scientific Fisheries
Scripps Institute of Oceanography
Southampton Oceanographic Centre
SPAWAR
University of NC - Wilmington
University of NC - Chapel Hill
University of South Florida
University of Washington
Woods Hole Oceanographic Institution

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