Using a Fleet of Slocum Battery Gliders in a Regional Scale Coastal Ocean Observatory

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Abstract: Rutgers University is constructing the New Jersey Shelf Observing System (NJSOS), a regional-scale (300 km x 300 km) observatory for the coastal ocean which includes the LEO15 site. Spatially extensive surface remote sensing systems (CODAR, satellites) are continuously collecting data in this region. However, only during the month of July in 1998, 1999, 2000 and 2001 were extensive subsurface physical and optical data collected and only in the LEO15 vicinity. The July samplings were labor and boat intensive. Obtaining the subsurface data in the LEO15 area required the use of up to seven boats and manpower to collect, process and analyze the information. To make the collection of subsurface data in the NJSOS more efficient, less expensive and more complete both spatially and temporally, Rutgers University has worked with Webb Research Corporation on their development of the Slocum Glider autonomous underwater vehicles. Currently Rutgers owns a fleet of four Gliders that can be used individually or as a group to collect subsurface data in the observatory region.

The Slocum Glider is a 1.5 meter long, torpedo shaped, winged vehicle that flies through the water column in a saw-tooth-sampling pattern by changing its buoyancy. The vehicle is steered to a particular location by a rudder. It can carry a range of scientific payloads including physical (CTD), optical (fluorometer, transmissometer, PAR) and acoustic sensors. Using alkaline batteries, the Glider has an endurance of 30 days and a range of 1500 km. At regular intervals the Glider surfaces to obtain a GPS fix, transmit sensor, vehicle status and position data to the Control Center and download, if necessary, a new mission from the Control Center.

The Control Center has been designed to coordinate a fleet of gliders based on data transmitted to it from the fleet and from other scientific systems. The design utilizes Agent Oriented programming, a concept from Artificial Intelligence. Software agents are computational entities that can work autonomously in environments inhabited by other agents. The Mission Control Center is a multi-agent decision making system consisting of: Glider Data Agents (one per Glider), a Mission Control Agent and Data Agents from other systems (CODAR, satellite SST's). The Mission Control Agent receives status reports and data products from the other agents, updates the status board, sends e-mail warnings of potential problems to controllers and then evaluates the information it has to decide whether to continue the current mission or design and start a new mission.

The fleet of Slocum Gliders flying beneath the satellite and CODAR derived surface fields will provide 3-D information for assimilation in forecast models. Full water column undulations will provide data on the temperature and salinity structure below the satellite SST's. Undulations above or below the thermocline will provide depth average current estimates to improve the assimilation of CODAR surface current maps. The glider fleet will collect this subsurface data continuously, more efficiently and over a much wider area than we have been able to do previously.

I. INTRODUCTION

Rutgers University is constructing the New Jersey Shelf Observing System (NJSOS), a regional-scale (300 km x 300 km) observatory for the coastal ocean to study the physical forcing of continental shelf primary productivity in the New York Bight (NYB). Fig. 1. Spatially extensive surface remote sensing systems (CODAR and an international constellation of satellites) are continuously collecting data in this region. However, only during the month of July in 1998, 1999, 2000 and 2001 were extensive subsurface physical and optical data collected and only in the LEO15 [1] vicinity, a 30 km x 30 km subset of the NJSOS. The subsurface sampling in July was labor and boat intensive and weather dependent. Up to seven research vessels were used during this time with corresponding manpower to collect, process and analyze the data. If seas reached a height of greater than four feet some research vessels had to remain at the dock. While invaluable datasets were collected

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during these cruises, scientists wanted to make the collection method more efficient, less expensive and cover a larger area both spatially and temporally.

As a result of this desire for improvement in the data collection methodology, Rutgers University has been working with Webb Research Corporation on their development of the Slocum Glider Autonomous Underwater Vehicle (AUVG). Currently Rutgers owns a fleet of four Gliders that can be used individually or as a group to collect subsurface data in the observatory area around the clock and calendar.

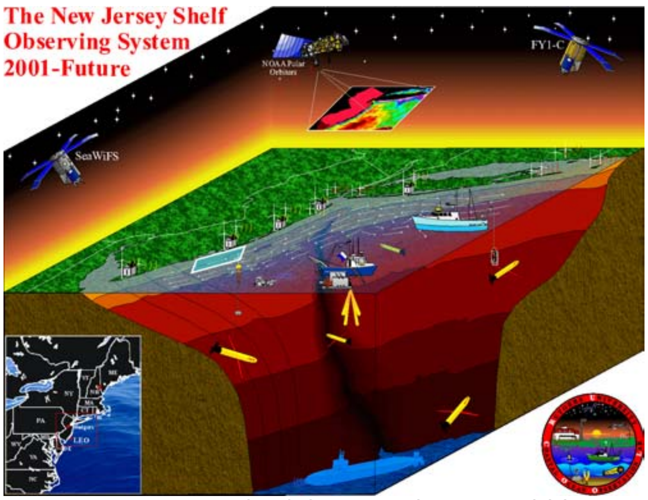


Fig.1 The New Jersey Shelf Observing System (NJSOS). The white square delineates the 30 km x 30 km LEO15 research space.

II. GLIDER PHYSICAL DESCRIPTION

The Slocum Battery Glider, named after Joshua Slocum, the first person to solo circumnavigate the world, is a torpedo shaped, winged vehicle that is 1.5 meters long, weighs 52 kilograms and has a hull diameter of 21.3 cm. The wings, made of composite material are mounted just aft of the center of buoyancy. There are three main hull sections plus wet fore and aft sections. The front wet section or nose dome houses a 9-14 kHz transducer for a Pinger to locate the Glider underwater or Telesonar Modem for acoustic communication and a 200 kHz transducer for altimeter use. The nose dome also has a hole on the centerline for large bore movement of water as is created by the displacement piston pump. External weights can be added inside the nose dome for ballast trimming. The first main hull section houses the displacement piston pump, pitch vernier mechanism, altimeter electronics, ballast weights and a large alkaline battery pack that supplies power and serves as the mass moved by the pitch control during ascent and descent. The middle hull section houses the science payload, additional energy and ballast weights. This section is removable to facilitate an easy exchange of sensors for different missions, calibration or maintenance. The third main hull section houses the back chassis that ties the glider together, the ARGOS PTT, the Iridium and FreeWave modem communication engines, the catalyst, the air pump system, battery power, vehicle controller, hardware interface board and attitude sensor. A pressure transducer is ported through the aft endcap. The aft battery pack can be manually rotated for static roll offsets. The air bladder, steering assembly, burn wire, jettison weight and power umbilical are housed in the wet tail section. This section also has provisions for external trim weights and wet sensors. Protruding through the aft end cap and through the tail cone is the antenna fin support. This boom is a pressure proof conduit for the antenna leads and low noise amplifier for the GPS. Below the boom is a protected conduit for the steering motor linkage. Attached to the boom is the antenna fin. The rear portion of the antenna fin acts as a rudder. Fig. 2.

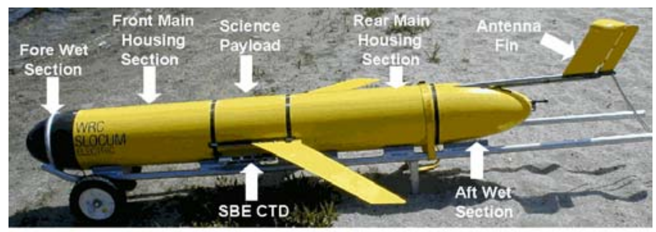


Fig. 2. Slocum Battery Glider.

III. GLIDER OPERATION

The Glider is neutrally buoyant. To dive, the displacement piston pump moves water into the nose making the vehicle's nose heavy. To ascend, water is pushed out of the nose by the piston pump making the Glider buoyant. The air bladder in the aft section provides buoyancy and stability while the Glider is surfaced. The inflated air bladder also lifts the tail fin out of the water to facilitate communication of the Glider with its Command Center. To trim to the desired dive and climb angles a lead screw drives the forward battery pack fore or aft as a vernier. To steer the glider the back portion of the tail fin is moved as a controlled plane that acts as a rudder. The wings provide pitch stability for the glider and translate vertical velocity into horizontal velocity so that the vehicle glides downward when denser than the surrounding water and glides upward when buoyant. The glider requires no propeller.

The Glider, moves through the water in a saw-toothed shaped trajectory at a forward speed of 30-40 cm/s. The saw-tooth pattern is optimal for both vertical and horizontal observations in the water column. It has a depth range of 4-200 meters. Glider navigation is done using GPS, internal dead reckoning and the altimeter. Communication between the Glider and the Glider Command Center is done using line of sight radio frequency (RF) modem (FreeWave) for local high speed communications, ARGOS for a recovery beacon and Iridium for bi-directional satellite communications. Deployment duration, dependent upon what scientific measurements are being taken and what type of communication is being used, averages 30 days with a range of 1500 km.

An emergency abort procedure has been built into the Glider in the event that a system on the Glider fails and it cannot surface on its own. The abort system consists of a replaceable/rebuildable battery activated corrosive link that after a period of time in either fresh or salt water will release the spring ejected jettison weight located in the aft wet housing. The Glider will then rise to the surface within the limits of the mass lost. [2]

IV. SCIENTIFIC PAYLOAD

The first sensor package integrated into the Glider was a Sea-Bird Electronics non-pumped, low drag conductivity, temperature and depth package specifically designed for this project. The conductivity and temperature sensors are attached to the outside of the scientific payload bay. Fig. 2. The pressure sensor is ported out the front of the science payload hull section. A HOBI Labs Hydroscat-2 backscatter and fluorescence sensor has also been included in the scientific measurement package. This sensor measures optical backscatter at two wavelengths, B_b676 (red) and B_b470 (blue) and chlorophyll fluorescence at B_b676. The optics on this package are downward looking. Fig. 3.

Fig. 3. Hydroscat-2 mounted in the science payload section of the Glider.

An optically based sensor under development to study marine phytoplankton communities, specifically red tides will be integrated into the Glider in 2003.

V. GLIDER CONTROL SOFTWARE

A Mission Control Center is under construction to guide the fleet of Gliders in their data collection. The goal of this Center is to develop a flexible autonomous and responsive tool to coordinate the Glider Fleet Mission using data transmitted to it from the Glider fleet and from other scientific systems such as CODAR and satellite SST's. A mission is a set of scientific instructions that tell the Glider(s) where and how to sample. For example, a mission can be written to track vertical features such as thermoclines or horizontal features such as fronts. Fig. 4.

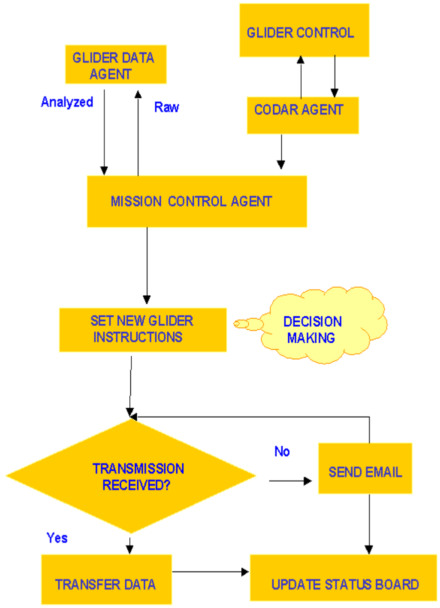


Fig. 4. Agent Flow-Chart.

The implementation of the Mission Control Center is based on Agent Oriented Programming, a concept from Artificial Intelligence. Agent oriented programming deals with the construction of software agents which are entities that behave rationally, have decision making capabilities and act on behalf of the user. Decision-making will be done using an influence diagram. Influence diagrams take into account the utility theory concept and probability theory to arrive at the best decision. The Mission Control Center consists of two modules, one for decision-making and another for visualization of data and tracking of the Gliders. Each source of information will have an agent (i.e. each Glider, CODAR, satellite SST's). JAT Lite (Java Agent Toolkit) from Stanford University provides the basis for communication between the agents using KQML (knowledge query manipulation language).

The Mission Control Agent is the central agent in this design. The glider surfaces at regular intervals and transmits the data it has collected to the Glider Data Agent. The Glider Data Agent processes, analyzes and plots the data. Plotting is done using NOAA's Java based Scientific Graphics Toolkit (SGT) and

BBN Technologies software OpenMap. The data results are then communicated to the Mission Control Agent who uses them to decide what the new instruction set for the Glider Fleet will be.

The Mission Control Agent also checks the status of the Gliders. It periodically contacts the Glider Agent for a new data set. If new data is not received, the Mission Control Agent sends an e-mail status report to the scientist using the system stating there is a problem. In the future this notification system will be modified to also send out pager messages. Finally, scientists can take control of the software at any time.

VI. SEA TRIALS

In July 2000 the Glider was deployed offshore Tuckerton, NJ for its first unteathered open ocean flight. The Glider's nominal mission profile consisted of a series of 2.5 minute undulations with a surfacing interval every 45 minutes. During each surfacing interval, the Glider obtained a new GPS position and data was transferred to the Shore Command Center via FreeWave modem. The Glider remained deployed for 10 days, collecting 5,190 CTD casts. Based upon the expected and actual location of the Glider both along- and cross-shore currents were derived. During this deployment a storm passed through the area allowing for a Free Wave communication test during non-ideal sea conditions. Communications were maintained in 4-5 foot seas, 10 miles from shore. Fig. 5 shows the movement of the Glider during its ten-day deployment in July 2000 (solid white line).

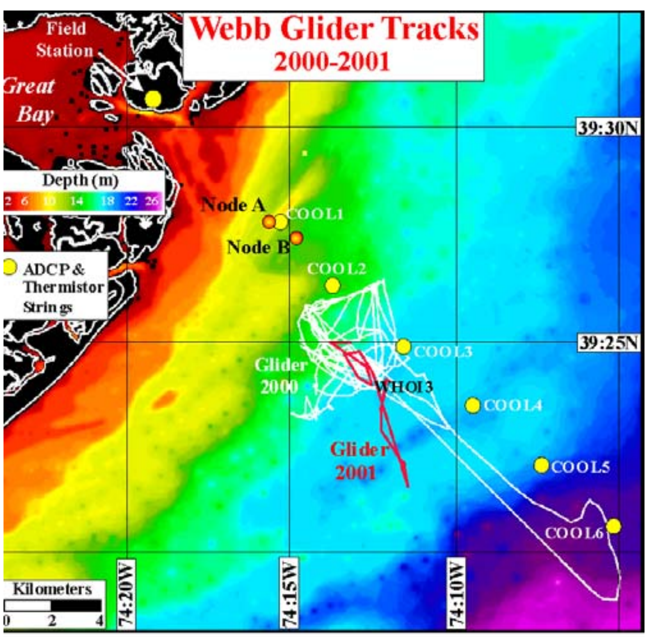


Fig. 5. Mission track for July 13-22, 2000 Glider deployment shown by solid white line.

A contour plot of the temperature data the CTD mounted in the science payload bay collected along the cross-shelf test segment of this mission is shown in Fig. 6.

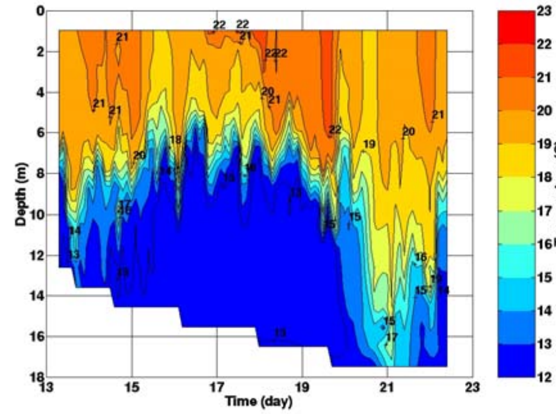


Fig. 6. Temperature data collected during the July 13-22, 2000 Glider deployment.

At the end of the ten-day mission the Glider rendezvoused with the R/V Caleta and CTD data from the Glider was compared to CTD data collected by two CTD systems aboard the research vessel. The data collected by all CTD systems compared favorably. Fig. 7.

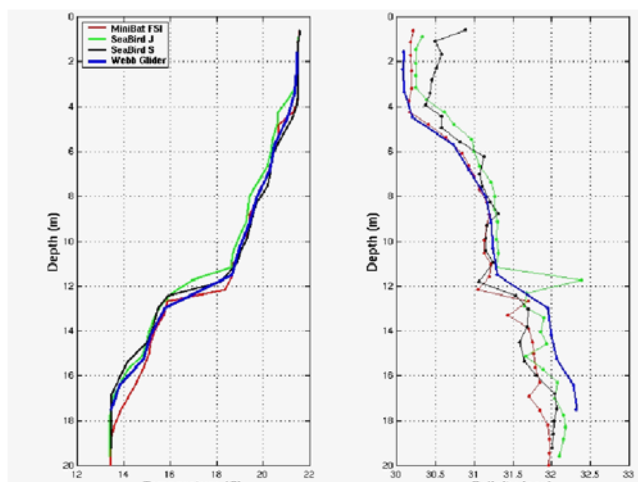
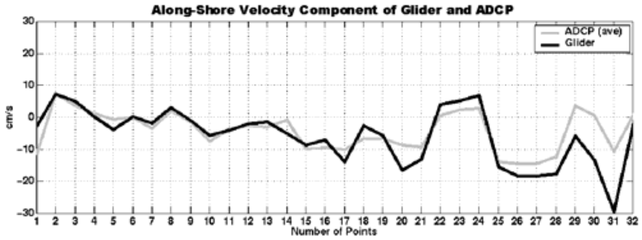


Fig. 7. Comparison of conductivity and temperature data from the Glider and shipboard CTDs.

Whenever the Glider was within 2 km of a LEO-15 ADCP during the July 2000 deployment, the Glider's depth time series was used to average the corresponding ADCP velocities. When compared, the depth-averaged currents derived from the Glider data were similar to the depth averaged ADCP data. Fig. 8.



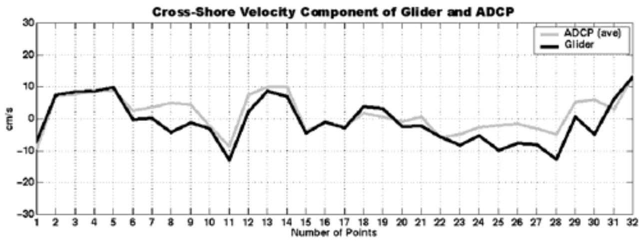


Fig 8. Along- and cross-shore currents derived from the expected and actual location of the Glider during its July 13-22, 2000 mission compared with moored ADCP data.

VII. FUTURE PLANS

A. Software:

The agent software will become part of the glider's onboard science computer. This will allow each glider to think independently and work cooperatively with other gliders in the society of agents.

B. Field Work:

1) Long-term Glider tests are planned for the New York Bight Apex to observe the interaction of the Hudson River plume with the stratified continental shelf waters. These deployments will allow scientists to test many of the tracking and control algorithms based on fronts and vertical gradients observed in the physical data.

2) As was mentioned in the scientific payload section, miniaturization and installation of a spectrophotometer into the Glider science payload is planned for 2003. This optically based instrument is being developed in conjunction with Mote Marine Lab. The device will measure particulate and dissolved absorption signatures that delineate phytoplankton load and composition. This sensor will be used off of the Florida coast to detect and track red tides.

3) A hockey puck sized absorption and attenuation meter is being developed by WetLabs for integration into the Glider's science payload.

Acknowledgments

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