# Sensor Networks of Freely Drifting Autonomous Underwater Explorers

Jules Jaffe
Marine Physical Laboratory
Scripps Institution of Oceanography
jules@mpl.ucsd.edu

Curt Schurgers
Electrical and Computer Engineering Dept.
University of California, San Diego
curts@ece.ucsd.edu

## ABSTRACT
With the increasing sophistication of both manned and unmanned systems for remote ocean exploration, a wealth of knowledge about heretofore-unknown oceanic processes has become available. However, no technologies currently exist to observe organisms and processes without disturbing them, as they move with the natural motion of the oceans. We propose a new class of ocean sensing, whereby free-floating underwater devices operate autonomously and collaborate through an acoustic underwater network between them. This new class of sensing will provide a window into understanding the multifaceted interactions between the ocean's currents, underwater ecosystems and our impact on them. In this paper, we will present the design of our underwater vehicle, which drifts freely with the ocean currents and is equipped with a buoyancy control piston. Results from sea tests illustrate the feasibility of our design, including its depth tracking abilities.

### Categories and Subject Descriptors
J.2 Computing in the physical sciences: Earth and Atmospheric Sciences

**General Terms:** Experimentation

**Keywords:** Underwater sensor networking, autonomous vehicles. Underwater acoustic communication

## 1. INTRODUCTION
### 1.1 The need for a different kind of ocean sensing:
Fundamental to the progress of science is the collection of relevant and accurate data. Arrays of telescopes peer into the vastness of space, while satellites show us details of rain forests far below. Oceans, while covering a large part of the earth, are much harder to investigate. Over the past few years, researchers have started developing appropriate ocean sensing technologies, relying on a combination of bottom mounted sensors, guided underwater vehicles and surface instruments to acquire information [4]-[10]. A common trait of these technologies is that the sensors are either quasi-stationary (anchored) or exhibit active motion control (guided).

However, the pelagic ocean environment is characterized by intrinsic natural dynamics such as waves, tides and currents, which play a major part in oceanic interactions. Although the existing sensing technologies, as above, are well suited for the tasks they were designed for, they are limited in their capability to provide information in the frame of reference of the phenomena and organisms themselves. Coastal circulation patterns, for example, greatly impact the spread of patches such as oil spills and other pollutants. They also play a large role in how planktonic communities evolve over time and are impacted by climatic changes.

### 1.2 Applications:
We envision swarms of such freely drifting drogues following the effluents from sewers, measuring three-dimensional features of coastal circulation, and partaking in week- or month-long missions of data collection. Physical and biological data gathering would now become available to oceanographic scientists at space-time scales that were heretofore unattainable. Such free-floating explorers would, for example, open the door to studying the intricate links between coastal circulation and important ecological processes, such as larval dispersal and settlement. Here, observations of sub-surface trajectories at high spatial and temporal resolution will provide new insights into dynamical processes that deliver biogenic particles and nutrients to near shore ecosystems.

Another important application is that of coastal pollutant tracking, illustrated in Figure 1. Drogues are deployed at storm drains, follow the coastal currents and help map which regions will be most impacted and steer appropriate response efforts. The societal and environmental impact of these applications can be profound, especially in density populated coastal communities.

### 1.3 Contributions:
Our goal is to create this new class of sensor and vehicle technologies, enabling the deployment of swarms of free-floating drogue instruments. As a first step towards this goal, we have developed a single actively ballasted prototype that has been


*WUWNet'06,* September 25, 2006, Los Angeles, California, USA.

tracked in three dimensions. Equipped with a temperature and depth (pressure) sensor, the drogue can be actively ballasted in order to maintain depth, "ride" an isotherm, or vertically migrate through the use of a buoyancy control actuator. In this paper, we present the design of this standalone drogue vehicle and illustrate its feasibility and basic abilities with data from preliminary sea trials.

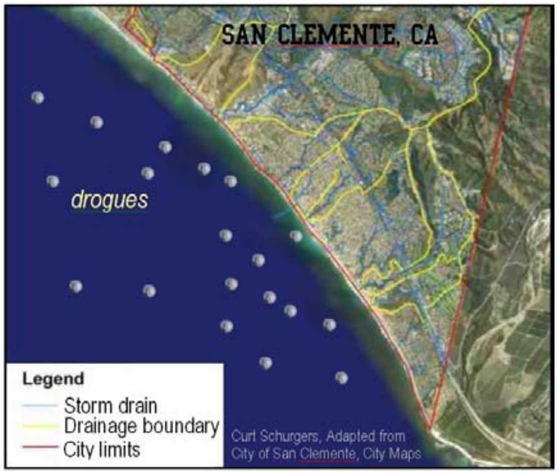


Figure 1. Coastal pollutant tracking

## 2. DROGUE DESIGN

In this section the current design of the drogue is described, in addition to the results of sea trials that permitted an evaluation of the system's capability to maintain depth.

**Hardware:** The prototype system, developed over the last several years is shown in Figure 2. One of the design goals for the system was to create a drogue that would be as small as possible. This is because there is significant spatial vertical structure in the ocean that can be "averaged out" by a vehicle that is too large. After trying various designs, a pragmatic solution was constructed and is shown in Figure 2. Here, one can see a 25 cm diameter sphere consisting of two halves that can be disassembled for access into its interior.

The internal components of the system are a small microcomputer controller; a stepper motor coupled to a retractable piston, a depth and temperature sensor, and a set of batteries. In its current form, the system is depth rated to 100 meters. This permits exploration of the upper part of the ocean ordinarily referred to as the euphotic zone.

## 3.SEA TRIALS

### 3.1 Vehicle tests

Since an important aspect of the system's performance is the ability to hold station at either fixed depth, temperature or salinity we decided to test this capability. After neutrally ballasting the drogue (by adding a brass ring, shown on the left side of Figure 2) it was submerged in a 10 m deep tank in order to verify the integrity of both the hardware and the software that provides the depth control. After these tests indicated that the system was working adequately, we moved onto actual sea trials, approximately 2 miles offshore of the Scripps Institution of Oceanography in San Diego.

The drogue vehicle was taken out to approximately 80 m depth where it was deployed from a 16-foot boat in calm seas. Tests were conducted which consisted of commanding the vehicle to descend to various depths and to maintain those depths for a given amount of time (approximately 6 or 10 minutes). The achieved depth record from the vehicle was internally recorded by the computer and then retrieved after the drogue resurfaced. Figures 3 and 4 illustrate the depth record versus time. Figure 3 shows that the vehicle, commanded to go to a depth of 50 meters,

**Figure 2. The Drogue prototype: 25 cm diameter**

was successful in finding and maintaining this depth. It ascended back to the surface after "timing out" at 20 minutes after deployment. Similarly, Figure 4 displays the vehicle's performance after being commanded to go to a depth of 30 meters with a time out after 800 seconds. These results indicated that the vehicle was capable of executing these tasks in a reproducible and reliable manner.

### 3.2 Acoustic tests

Although the above tests verified that control of the vehicle was possible, additional sea trials were undertaken to test the potential of both tracking and communicating with the vehicle acoustically. This is an important aspect of our program. Additional sea trials were therefore undertaken in order to characterize the acoustic transmission path between the vehicle and either a ship (in our case) or another vehicle. For these generic tests, a set of 5 Vemco VR22 transmitters were utilized with frequencies from 34 kHz to 42 kHz. The transmitters' output power level was approximate 165 dB re 1 μPa. Although these transmitters were designed to track large animals, we chose to suspend them at candidate depths on a small mooring in order to determine their suitability for our tracking and to also investigate the features of the acoustic channel. The Vemco transmitters simply emit a "ping" at a fixed frequency (narrow band) at an inter-ping interval that is proportional to their depth.

Results were inspected in order to judge both the signal level/quality and usefulness for range/angle estimates needed for localization purposes. Results indicated that the range sensing capability was highly dependent on the temperature structure of the water with the longest range of 2 km achieved in well-mixed conditions. Apparently, in other scenarios, the temperature structure of the water resulted in a downward refraction of the sound rays which decreased the receive level by a large amount compared to well mixed conditions. This limited detection in highly temperature dependant environments to ranges of 0.5 km.

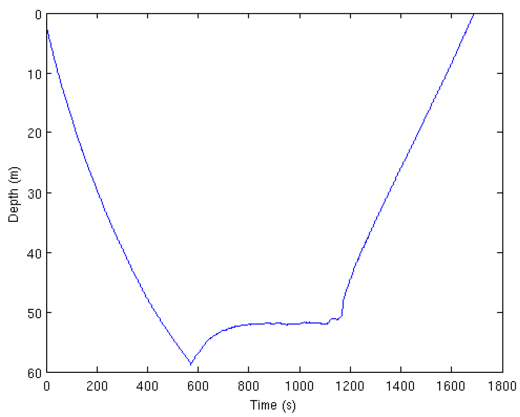


**Figure 3. A plot of depth vs. time for the at-sea deployment of the vehicle when the vehicle was commanded to go to a depth of 50 meters and maintain it.**

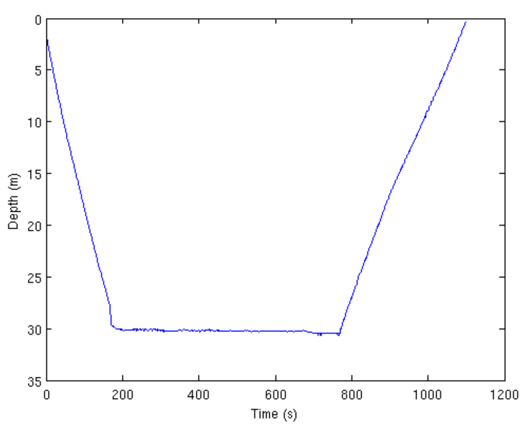


**Figure 4. A plot of depth vs. time for the at-sea deployment of the vehicle when the vehicle was commanded to go to a depth of 30 meters and maintain it.**

Signals were also analyzed in order to judge the quality of the received sound in faithfully reproducing the transmit signal. Results indicated that the received pulses were substantially longer than transmit, presumably due to reverberation from the sea surface at these shallow depths. As such, coherent processing of the signal was limited to the initial arrival that occurred in the first millisecond. Nevertheless, phase extraction methods, for these narrow band signals were successful in yielding a good estimate for angle of arrival, as judged on a set of four receiving hydrophones. Ultimate range bearing resolution was judged to be approximately +/- 5 meters over a range of one km.

Owing the relatively short range capability of the acoustics (.5 km – 2 km) and the seeming disparity between the interest of the oceanographers to study features on the scale of 5 – 10 km, we have been pursuing the idea of networking the drogues so that information can be passed from a ship or shore station to them and retrieved from them.

## 4.FUTURE WORK: NETWORKING CHALLENGES

As mentioned earlier, we envision future data gathering missions of swarms of such drogues. In principle, each individual drogue could collect data independently and store it in its memory banks for post-mission retrieval. However, this would preclude any interactive applications. On the other hand, if data measurements are extracted in real-time through underwater communications, they can guide the deployment of extra resources such as more elaborate sensors, guided vehicles or research vessels. This becomes especially crucial as future missions of drogue swarms may last for weeks or months. In addition, communication lets users inject commands to reactively adjust the mission profile. It is also essential in supporting cooperative tasks such as coordinated depth control and sampling strategies, and in enabling location estimation and tracking.

However, direct communication between each individual drogue and surface elements, such as buoys or vessels, is not always possible. Our drogues are by design free-floating and are at the mercy of the uncontrollable motion of the oceans. As a result, they unavoidably move beyond the direct communication range of surface elements, as the range of underwater modems is limited to a few miles [3] (ocean currents range up to 2.5 m/s on the surface and 0.1 m/s in the deep ocean [11]). Instead, a multi-hop ad-hoc acoustic network is needed to interconnect the drogues, as shown in Figure 5. Surface buoys and vessels link to the underwater drogue network and relay data to land-based laboratories and users via traditional RF wireless technologies.

Compared to existing work on underwater networking, our setup presents a set of unique challenges. Existing underwater networking testbeds include Lotus [4], ASSEM [5] and the current U.S. Navy's experimental Telesonar Program, called Seaweb [6]. More recently, projects such as SNUSE [7], UW-ASN [8], AMOUR [9] and the SPAWAR DSSN program [10] have started looking specifically into underwater sensor network issues. However, all these projects focus on a mix of semistationary anchored sensors and propelled underwater robots. What sets our network apart is the presence of uncontrollable, passive mobility.

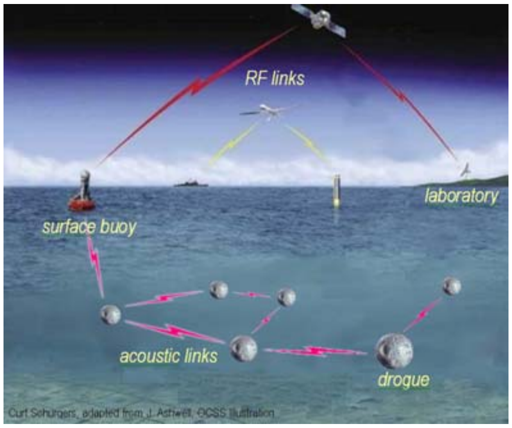


**Figure 5. Network of free-floating drogues**

Our challenge is to enable drogues to network efficiently while subject to the ocean's currents and constrained by a limited supply of energy. This goes beyond the issues present in networks with fixed bottom instruments (in which case mobility is not an issue) or propelled underwater vehicles (where energy costs of networked communication are insignificant compared to those of propulsion). More specifically, we have to develop topology control mechanisms, routing strategies and methods for tracking drogues' locations. These have to be extremely energy-efficient, while also incorporating adaptive mechanisms to deal with the uncontrollable drogue mobility behavior. All of these present challenging new problems to the underwater networking community. Our eventual goal is the evolution of underwater networked and self-localizing sets of freely floating instruments into usable oceanographic instruments.

As man ever more on encroaches upon the environment, the need for information-based ecosystem management has increased drastically. However, information about the multifaceted interactions between the ocean's circulation, underwater ecosystems and our impact on them is still extremely limited. In order to address the problem, we are developing a new class of ocean sensing, whereby free-floating underwater vehicles operate autonomously and cooperate through an acoustic underwater network. Our working prototype design illustrates the feasibility of a system that contains all necessary components and currently is able to support stand-alone autonomous operation including depth control. Uncontrollable mobility combined with the need for extremely energy-efficient operation make network design filled with new open research problems.

## 5. ACKNOWLEDGEMENTS

The authors would like thank the National Science Foundation for support.

## 6. REFERENCES

[1] Colgan, C., "Underwater Laser Show," Explorations, Scripps Institution of Oceanograhpy, Vol.12, No.4, pp.20-27, Spring 2006.

[2] Woods Hole Oceanographic Institution, Acoustics Communications group, "WHOI Micro-Modem," http://acomms.whoi.edu/micromodem/.

[3] Landau, L. D. and E. M. Lifshitz , "Fluid Mechanics," Pergamon Press, 1939.

[4] Adams, A., Hinton, O., Sharif, B., Salles, G., Orr, N., Tsiminedes, C., "An Experiment in sub-sea networks – The LOTUS Sea Trials," ECUA'00, Lyon, France, 2000.

[5] Blandin, J., Person, R., Strout J., Briole, P., Etiope, G., Masson, M., Golightly, C., Lykousis, V., Ferentinos, G., "ASSEM: array of sensors for long term seabed monitoring of geohazards," International Symposium on Underwater Technology, pp.111-115, 2002.

[6] Rice, J., et al, "Evolution of Seaweb Underwater Acoustic Networking," Oceans Conf., Providence, RI, pp. 2007-2017, 2000.

[7] SNUSE: Sensor Networks for Undersea Seismic Experimentation, ISI, http://www.isi.edu/ilense/snuse/index.html, last accessed June 2006.

[8] Underwater Acoustic Sensor Networks (UW-ASN), Georgia Institute of Technology, http://www.ece.gatech.edu/research/labs/bwn/UWASN/, last accessed June 2006.

[9] AMOUR (Autonomous Modular Optical Underwater Robot), http://groups.csail.mit.edu/drl/underwater_robotics/amour/amour.html, Rus Robotics Laboratory, last accessed June 2006.

[10] Distributed Surveillance Sensor Network (DSSN), SPAWAR Systems Center, San Diego, http://www.nosc.mil/robots/undersea/dssn/dssn.html, last accessed June 2006.

[11] Statnikov, E., "Speed of Ocean Currents," The Physics Factbook, http://hypertextbook.com/facts/2002/EugeneStatnikov.shtml.