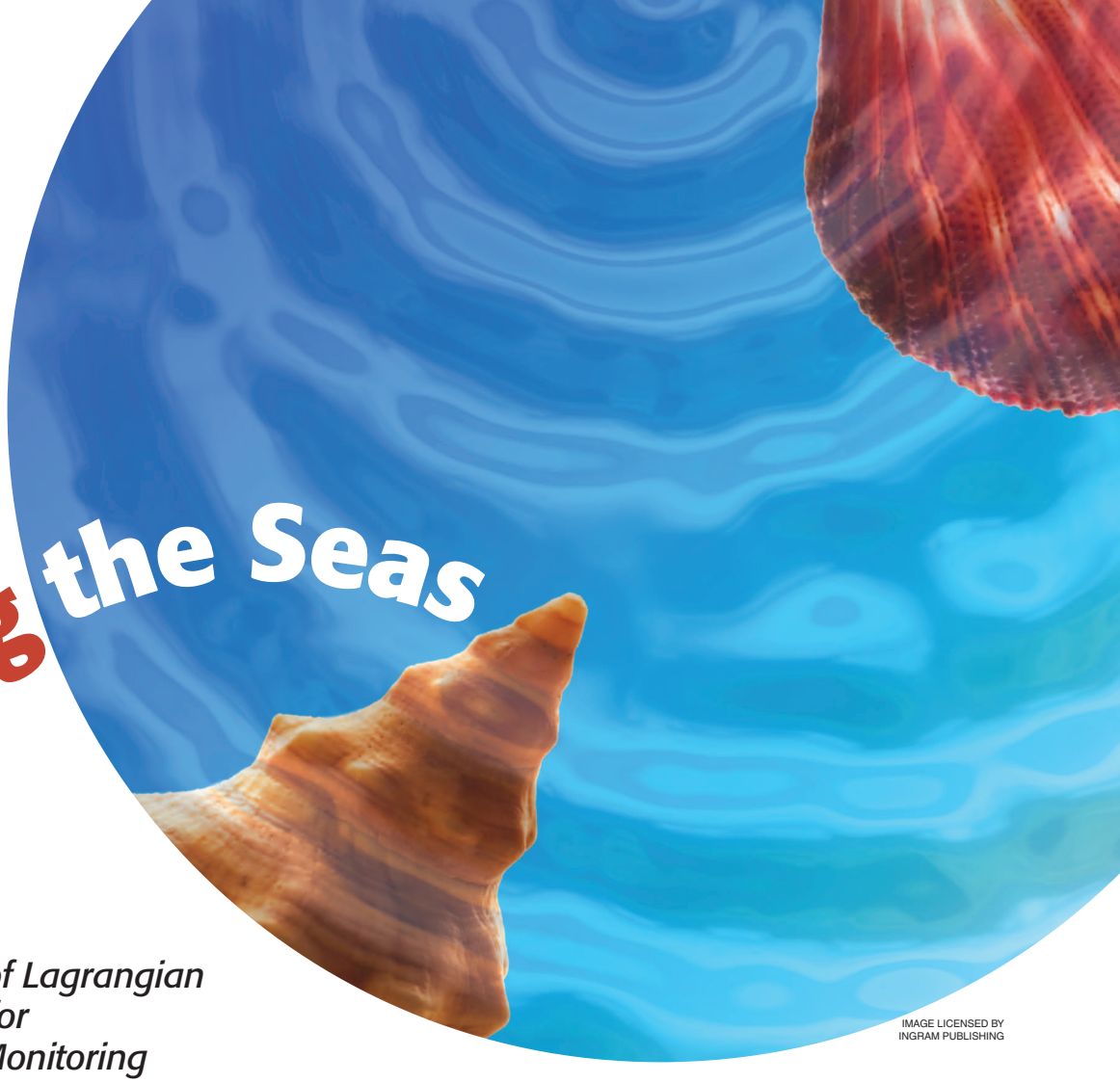

Circling the Seas

Design of Lagrangian Drifters for Ocean Monitoring

IMAGE LICENSED BY INGRAM PUBLISHING

By Supreeth Subbaraya, Andreas Breitenmoser, Artem Molchanov, Jörg Müller, Carl Oberg, David A. Caron, and Gaurav S. Sukhatme

Lagrangian drifters are oceanographic devices used to study circulation patterns in the ocean. The devices are typically passive, which means that they have no actuators to initiate motion. They are mainly driven by the ocean currents. A drifter, as depicted in Figure 1, in principle, consists of a surface float and a drogue connected via a tether. The surface float provides the necessary buoyancy to hold the drogue at a certain depth, whereas the drogue (and, thus, the whole drifter) is carried by the currents prevailing at that depth of the ocean. A main focus of oceanographers' and marine biologists' research is the complex dynamics of the ocean, the circulation patterns of water, and the induced movements of effluents, larvae, and other microorganisms [1]. Drifters are used to tag and track the ocean currents and can help to better explain both oceanographic as well as biological phenomena. Our particular interest is the monitoring task of tracking wastewater plumes in the coastal ocean. In this article, we describe the design of low-power, low-cost Lagrangian drifters for ocean monitoring, developed at the Robotic Embedded Systems Laboratory (RESL) at the University of Southern California (USC). We discuss the design challenges and present the overall system characteristics of the RESL drifters. The drifters are augmented by radio communication, which simplifies the task of drifter recovery by a research vessel and enables setting up a bidirectional wireless sensor network between drifters,

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autonomous underwater vehicles (AUVs), vessels, and base stations.

The Monitoring Task at the Hyperion Treatment Plant

Our motivation for the design of customized Lagrangian drifters for ocean monitoring originates from the requirement to inspect and maintain the 5-mi wastewater outfall of the Hyperion Treatment Plant (HTP) in Los Angeles (for background information related to HTP and the monitoring task, see http://www.lacitysan.org). The HTP has a 5-mi primary pipe (i.e., a pipe that is more than 8 km long) with a discharge of approximately 1 billion L/d of treated wastewater plumes. During inspection or repair of the 5-mi pipe, the wastewater has to be diverted to a secondary 1-mi pipe (i.e., a pipe that is only 1.6 km long), an activity called the "1-mi diversion plan" (see Figure 2). Because the outfall during diversion is much closer to the shoreline, the risk of the wastewater plume reaching the beaches is much higher and can substantially impact the public health at recreational beaches and, beyond that, affect the entire marine ecosystem in the area.

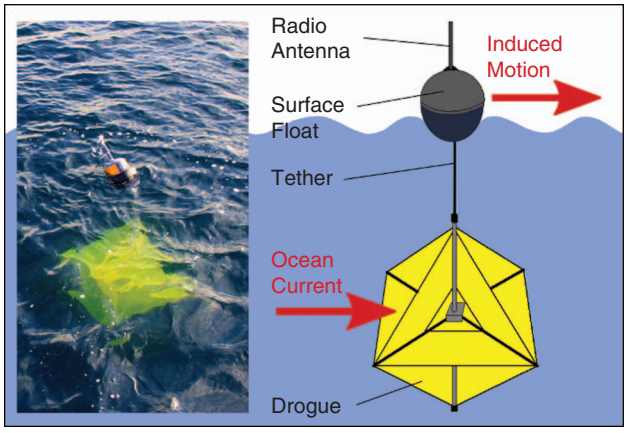


Figure 1. The typical drifter design. The surface float houses the electronics with the subsystems for localization and communication, and provides the buoyancy. The drogue provides the drag required to move along with the ocean currents.

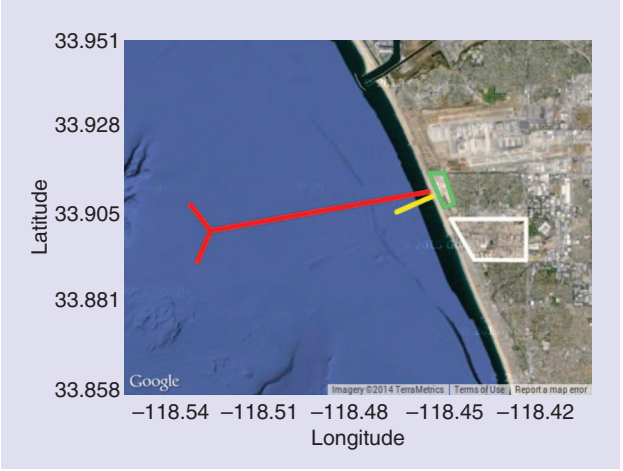


Figure 2. The HTP outfall map. During inspection or repair, approximately 1 billion liters per day of treated effluent from the HTP (green) need to be diverted from the 5-mi pipe (red) to the shorter 1-mi pipe (yellow). The 1-mi diversion plan activity requires monitoring of the HTP outfall. The Chevron Refinery (white) and some power generation stations also have outfalls to the same area, which complicates the monitoring task.

To study the effect of the diversion activity, the plume has to be tracked for a period of one to one and a half months as per the plans from HTP. The studies require data samples to detect changes in the water on chemical or biological (mainly bacteria) levels and analyze the impact of the plume on the coastal ecosystem for the duration of days to weeks. In particular, marine biologists are interested in researching whether or not the nutrient-rich plume would trigger algal bloom.

By tracking a patch of water, the number of required measurement platforms can be greatly reduced.

The monitoring task at the HTP is complex. It is complicated by the outfalls from neighboring industries, electricity-generating stations, and freshwater discharges, creating ambiguity in determining the exact cause of an occurring environmental problem. The movement of the plume is further affected by the diurnal wind patterns, tidal motions, and upwelling. The main challenge in sampling is to achieve sufficient temporal and spatial resolutions. Due to the dynamic motion of water in the ocean and the resulting variability in the movement of advected plumes, a large number of measurement platforms would need to be deployed at fixed locations on a fine-meshed grid, which is practically impossible given the vastness of the region of interest.

One way to predict the location of a plume is to use an ocean model, such as the Regional Ocean Modeling System (ROMS), which is a predictive ocean model for the Southern California Bight (see http://ourocean.jpl.nasa.gov) [2]. The model builds on a grid with spatial resolution in the order of kilometers. Thus, the outfalls of the HTP and nearby stations all fall into a single grid cell of ROMS. Given such sparse data, it becomes difficult to predict and track the plume discharged from the HTP based on ROMS only [3]. On the other hand, constantly tracking the plume by profiling ships and AUVs could be costly, because the vehicles have high operation costs and are energy constrained.

The monitoring task benefits from a system like a drifter. By tracking a patch of water, the number of required measurement platforms can be greatly reduced. A drifter is able to follow and permanently indicate the current location of a wastewater plume (tagging). It stays with the plume and sends periodic location updates over the duration of the monitoring task. This way, scientists can go out in a monitoring boat or send AUVs to obtain periodic measurements

from the region of interest around the drifter [4]. Then, having multiple drifters available will allow scientists to monitor an ongoing phenomenon like the wastewater discharge at the HTP outfall much more persistently over time.

Related Work on Dzzv Systems

The concept of a drifter is not new. Drifters have been developed, studied, and improved upon during various research programs, such as the North Pacific Experiment [5], the World Climate Research Program [6], the Global Atmosphere Research Program [7], and the Coastal Dynamics Experiment [8], since 1975. One of the major projects on drifters was the National Oceanic and Atmospheric Administration's Global Drifter Program (see http://www.aoml.noaa.gov/phod/dac/index.php) [9]. During this program, the mechanical and electrical parts were consistently upgraded by state-of-the-art technologies available at that time. This led to the foundation of different drifter-making companies like Pacific Gyre, MetOcean, Clearwater Instrumentation, and many more. For example, the Microstar drifters from Pacific Gyre (see http://www.pacificgyre.com/files/microstar.pdf) were developed as part of the research work on ocean technology [10]. A brief history of drifters is summarized in [11]. An overview of surface velocity program drifters and experiments using them is presented in [6]. Furthermore, a low-cost global positioning system (GPS)-based drifter was developed in [12].

Most of the AUVs today are equipped with radio modems for local radio communication.

Our drifter system is inspired by the Microstar drifters. The drogue design is similar; however, the design of the mechanical and electronic parts and the operation of the RESL drifters are different.

Design Challenges

The RESL drifters have specifically been designed to meet the application requirements that arise from monitoring a discharged plume at a near-shore outfall. The requirements of the HTP monitoring task pose several challenges in the drifter design. The main design challenges are summarized in Table 1.

The 1-mi diversion plan requires more than a month of inspection and repair activities, for which multiple drifters are supposed to track the wastewater plume. The drifters need to be repeatedly dropped at different time points during a day. Periodic measurements by multiple drifters enable monitoring in a persistent fashion but require that the drifters function efficiently and robustly and can be built at a low unit cost of US$700–US$1,000 (the price range has been decided based on the request of HTP; we believe that this price range is reasonable and representative for low unit cost in the scientific domain. In comparison, the sale price of a Microstar drifter unit is around US$2,150). So that HTP workers and scientists can handle deployments of many drifters a day, the drifters must have manageable size and weight and must be reusable. Moreover, built-in modularity would allow for further adjustments on site, e.g., adjusting the drogue in depth to study variations of depth-dependent measures like currents and temperature across the wastewater plume. The main function of a drifter is to track the plume and provide periodic location updates. Thus, each drifter needs to be equipped with accurate global positioning and telemetry systems to communicate its position to the user. Thereby, localization and communication update frequencies must be adjusted to achieve acceptable power consumption.

The GPS is widely used in robotics to obtain outdoor location data. In early drifter designs, Argos satellites were used for both localization and communication [13]. Globalstar and Iridium satellites are common for telemetry in marine systems (e.g., on the Microstar drifters). Data communication via satellites is rather costly [11]; however,

Table 1. Design challenges for drifter systems.

Basic functionality	The surface float and drogue need to be designed to lower the effect of winds and surface waves, whereas the currents at the selected depth of the drogue must have maximum impact. Capabilities for extensions on the drifter functionality should be provided, including interfaces for additional sensors and actuators.
Form factor and modularity	Drifters should be small and modular for ease of use. Small size and weight facilitate a drifter's storage, transportation, and deployment. A modular drifter design eases the process of assembly and repair (e.g., swapping batteries or electronic subsystems).
Operation time and power consumption	Drifters should be power efficient to operate over more than one month and keep the onboard electronics for localization and communication operable during this time. This allows for long-term studies of algal bloom or circulation patterns in the ocean.
Localization and communication	Drifters should communicate periodic location updates from anywhere in the ocean to report on a tracked phenomenon. Location accuracies of a few meters are reasonable.
Robustness and unit cost	The performance of drifters should not be affected significantly by the rough conditions of the ocean. However, low unit cost is key to manufacture and deploy multiple drifters. Multiple drifters allow for increased resolution by sampling data points in parallel. Drifters can be lost in the ocean; they can be hit by a boat or ship or picked up by people. So they had better be affordable also for this reason.

satellites provide broad coverage. Communication at radio frequency (RF) is much faster but is limited in range [14], [15]. Most of the AUVs today are equipped with radio modems for local radio communication. In contrast, most of the commercial drifters use only satellite communication and do not include radio modems. Hence, using them with AUVs or establishing an entire network of drifters, robots, and base stations may not be possible. There are several advantages in having a radio modem as a secondary means of communication on a drifter: 1) it allows for direct two-way communication between drifters and AUVs, which increases the autonomy in monitoring because drifters and AUVs can coordinate without human intervention; 2) it provides a second set of location data along with satellite telemetry when the drifters come closer to the shoreline, within radio communication range of base stations on shore; 3) it supports drifter recovery by utilizing connectivity and signal strength of the radio for the search (drifter recovery is important, e.g., for reusing the drifters and retrieving additional data that has been stored on board). Custom-made drifters allow for specific optimizations in the system design (e.g., reduced power consumption) and functionality (e.g., added radio communication). Further design challenges, such as lowering the unit cost or building in the flexibility to change electronic subsystems, sensors, and actuators, can be addressed. Given these and the aforementioned considerations, we decided to build our own drifter system based on present-day drifter technology.

System Design

In this section, we describe the design of the RESL drifters and suggest a supporting near-shore ocean-monitoring network that embeds the drifters. The workflow of the ocean-monitoring network, including the drifter system, is outlined in Figure 3.

Mechanical Design of the Drifters

The main mechanical components of the drifters are a surface float, a tether, and a drogue, as shown in the schematic of Figure 1. During the mechanical design, we paid special attention to the design challenges that affect a drifter's modularity, its form factor and basic functionality (i.e., the capability of following a current).

Figure 4 shows one of our drifters when it is completely assembled. The body of the surface float is cylindrical in shape with a length of 0.63 m. It is made of a polyvinyl chloride (PVC) pipe 0.16 m in diameter, which is enclosed at each end by PVC caps. The surface float is made watertight by having an O-ring and an enclosing mechanism. Inside the float, there are separate sections to mount the electronics, battery pack, and ballast material for proper buoyancy. The radio antenna is mounted in PVC housing on the topside of the float to position it above surface level for good radio communication. Oscillations of the float due to wave action can lead to disturbances in radio communication; the buoyancy of the system and the shape of the float were designed to help overcome such issues. A 3-mm stainless steel fibrous cable is used as the tether connecting the float and the drogue.

We designed a corner-radar-reflector-type drogue that is 1.47 m long and 1.2 m wide. The drogue is made from ripstop nylon fabric that is sewn to form an octahedron, which is spanned by fiberglass spars. The drag area ratio, i.e, the ratio of the drag area of the drogue in relation to the drag area of the tether and surface float, was designed to be larger than 40 (following [16]). This ratio determines the drifter slip, which is a measurement of the accuracy with which the drifter follows the currents.

Electrical Design of the Drifters

The surface float houses the drifter electronics, which consist of several electronic subsystems. Two important subsystems of the drifter are the localization and the communication modules. The localization module acquires the drifter position via GPS (GPS receiver), and the communication module sends off data via satellite communication (satellite transmitter). Apart from the localization and communication modules, the drifter is equipped with a radio modem and a microcontroller board. The microcontroller is responsible for the control-and-correct interaction between all the electronic subsystems. Figure 5 shows the block diagram of the drifter electronics.

Microcontroller Board

Keeping in mind constraints, such as low power, low cost, and modularity for future enhancements, we designed a general purpose microcontroller board, 9.9 cm × 5.1 cm in size, with a low-power MSP 430 microcontroller from Texas Instruments and standard SPI, I2C, UART, USB, GPIO, and ADC interfaces. The board has the capability to log data onto a secure digital (SD) memory card, which can be used as an alternative data source to data communicated via satellite and radio. The current consumption of the controller board is 2 mA in active state and in the order of microamperes in sleep state. Optocouplers are used for signal and power-switching operations to save power. Digital isolators separate the noise from the radio modem.

Nearby monitoring stations and robots can send commands via radio to the drifters, as well.

Localization and Communication Modules

We found GPS and satellite communication to be today's most suitable technology for localizing and communicating with a drifter system. The search for GPS receivers as localization modules and satellite transmitters as communication modules led us to the SPOT Satellite GPS Messenger (SPOT tracker). The SPOT tracker is a compact, integrated module, with a form factor of 9.4 cm × 6.6 cm × 2.5 cm.

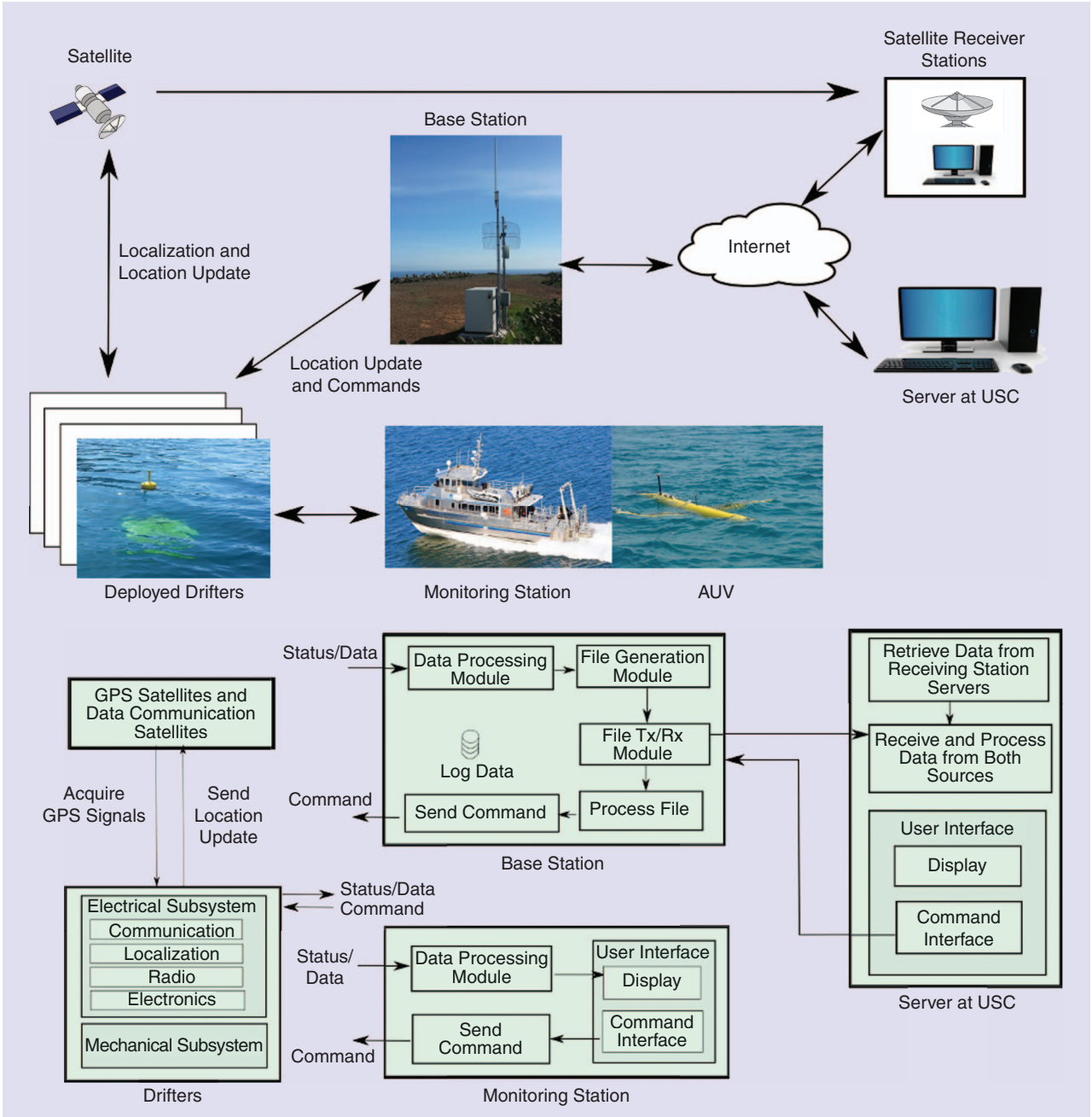


Figure 3. An overview of the drifters and the near-shore ocean-monitoring network. The ocean-monitoring network forms the supporting framework of the drifter system: The radio communication allows for bidirectional communication with the drifters, whereas the satellite communication to servers and base stations is unidirectional. (Photograph of the R/V MANTA research vessel by All American Marine.) (Drawing of the PC setup by the Maryland Department of Health and Mental Hygiene.)

It combines a Ublox AMY-5M GPS receiver (which is the world's smallest GPS receiver today) and a Globalstar STX-2 simplex modem, requires a 5-V power supply, and is power efficient. The SPOT tracker has a duty cycle of 20 min, wherein, when turned on for location update, it first acquires a GPS fix and then transmits the location three times to ensure delivery (because it is a simplex device). Hence, one location update takes 20 min. The GPS receiver and control points (on/off) have 3.3 V levels and can directly be interfaced by the microcontroller.

Radio Modem

For the radio subsystem, we selected an XBee 900-MHz radio modem, which is a common choice among embedded system designers and electronics hobbyists. These radio modems are small duplex devices that work on different networking protocols and can have RF data rates up to 200 Kbps. The dimensions of our radio subsystem are 2.2 cm × 3.3 cm × 0.4 cm. The range of the radio modem depends on many different factors, such as the line of sight, the gain of the antenna, the power available, or environmental factors like rain and

humidity. As the radio subsystem is used only as a secondary telemetry system on the drifters (besides the satellite communication module), the range is not critical. A range of 1.5–3 km is sufficient, which can be reached by the XBee 900-MHz radio modem with a 2.5-dB gain whip antenna placed on the top of the drifter.

Design of the Overall Ocean-Monitoring Network

The workflow of the near-shore ocean-monitoring network, including multiple drifter systems and other networked components, is shown in Figure 3. Each drifter deployed in the ocean uses the SPOT tracker to acquire its position from GPS satellites and transmits location updates over satellite and the Internet. The SPOT tracker sends e-mails to an assigned account. In our case, the servers at USC obtain the position information by parsing these e-mails at periodic time intervals.

In addition, a drifter can use the radio modem to transmit its current status and position (along with potential sensor data) every minute to a base station ashore, a monitoring station on a research vessel, or a marine robot (e.g., an AUV) within communication range. The servers at USC store the data received via satellite and radio communication. A webpage with a user interface visualizes the data; a command interface allows control commands to be sent back via the base stations to the drifters using radio communication. Nearby monitoring stations and robots can send commands via radio to the drifters, as well. Each drifter stores its status and received data on the onboard SD card. This additional set of data, in turn, can be obtained by querying the drifter or at the end of a mission after drifter recovery. Continuous messaging, especially enabled by radio devices in reach, helps provide a better localized network, consisting of drifters, robots, and research platforms, including monitoring stations and web interfaces.

Figure 4. The RESL drifter. One of our three drifters when it is completely assembled. Each drifter system is composed of a drogue, a tether, and a surface float with a radio antenna.

System Characteristics

Once the drifters were built, we evaluated their characteristics. We present our findings and discuss to which extent aforementioned design challenges and application-specific requirements have been met.

Basic Functionality, Form Factor, and Modularity

The basic functionality of tagging ocean currents reliably for several days has successfully been established with our design. The field experiments, presented in the subsequent section, demonstrate the achieved performance of the RESL drifters when deployed in the coastal ocean. All the drifter parts are easy to handle; they can be carried and assembled by a single person at deployment time. The lightweight and small form factor is beneficial for easy recovery of the drifters. For example, when recovering a drifter using a boat, the drifter can be pulled manually on board. Moreover, the radio on the drifters helps in finding a drifter in the ocean during recovery; it communicates location updates more frequently and with little delay compared to satellite communication. Finally, this allows scientists to localize a drifter in the vicinity of the assumed—outdated and thus imprecise—search location transmitted by satellite.

The three mechanical parts (surface float, tether, and drogue) are separate and thus modular. The drogue can be folded across its width. The electronics themselves are modular and can be extended by additional components, such as sensors and actuators. The surface float provides extra space for extensions. To maintain the mechanical properties of the drifter, we assume that the extensions are mainly made inside the drifter body. Thus, a natural limitation is given by the inner size of the surface float

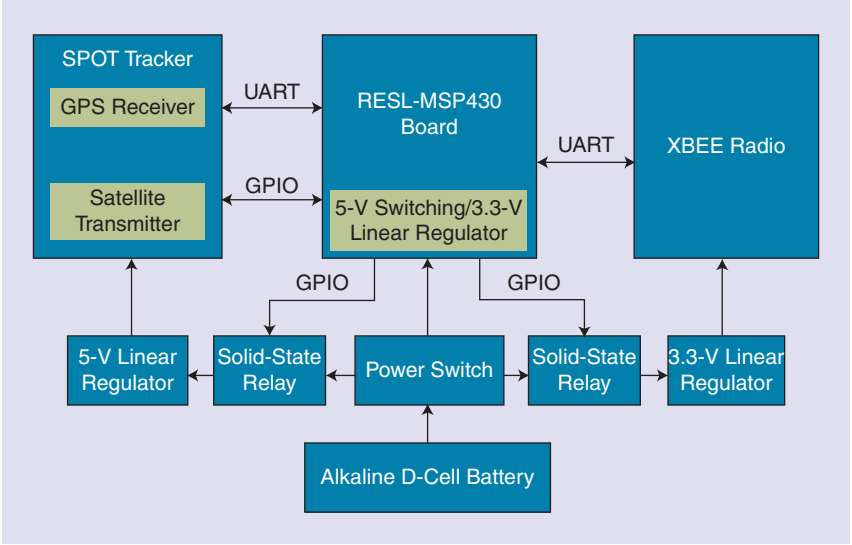


Figure 5. A block diagram of the drifter electronics. The UART lines are for data communication, whereas the GPIO lines control the power switching. The system is powered by five D-cell alkaline batteries with a supply voltage of 7.5 V. Switching circuits are available for conserving power.

and the amount of ballast material that can be added or removed to guarantee buoyancy stabilization. Small and lightweight sensors (e.g., temperature sensors) can also be attached to the drogue; however, the placement of bigger and heavier sensors outside the surface float may require some adjustments in the drifter design. Although compact, the cylindrical shape of the surface float is suboptimal. The ideal shape would be spherical to reduce the impact of surface waves and winds to a minimum. A spherical float requires a spherical mold to realize the required shape and size; the molding process using glass fiber material is more elaborate than the construction from PVC but will be considered for the next improved version of the initial prototype.

The basic functionality of tagging ocean currents reliably for several days has successfully been established with our design.

Operation Time and Power Consumption

Several tests were conducted to analyze the power consumption, battery lifetime, and update rates of the drifter system. The tests were performed by placing the drifters on the rooftop of a building with clear view of the sky. When a drifter is out in the ocean, it may experience lossy radio links with the base station (e.g., messages do not arrive due to heavy waves blocking the transmitted signals [17]), which increases the number of queries and responses sent by the base station and the drifters, i.e., the drifters communicate more frequently. The condition of the ocean can also affect the time to acquire a GPS fix. Consequently, compared to our laboratory tests, a real mission in the ocean may result in higher power consumptions and time delays.

The power consumption test was run once for each update rate of the SPOT tracker of one message per 20, 30, 40, and 60 min, each for a duration of 6 h. The radio modem was enabled and transmitted a message every minute. Average power consumptions of 40.17, 33.10, 26.24, and 20.49 mA/h were measured. For five D-cell alkaline batteries with a total charge of 20,000 mAh, calculations result in expected battery lifetimes of a drifter of 15, 18, 22, and 28 days.

The battery lifetime test was then run on two drifters. Both satellite and radio communication were enabled. The update rates of the SPOT trackers were set to one message per 20 min for the first drifter and to one message per 30 min for the second drifter. The first drifter ran for 14 days and the second drifter for 23 days. These values agree with the previously calculated battery lifetimes. There is enough space in the drifters to connect more batteries in parallel, which can increase the battery lifetime to approximately one month for the tested update rates in the best case. For characterization of the worst-case behavior, further field testing would be required.

The battery-lifetime test additionally gives insight into the data delivery and position accuracy of the SPOT tracker. The first drifter delivered 798 out of a total of 894 messages successfully over 14 days. The second drifter delivered 883 out of 994 messages over 23 days. The rate of successful transmissions is nearly 90%. The position accuracies of the SPOT trackers, measured as distance root-mean-square errors over the total operation time, were 21 m and 7.7 m for the two drifters.

Localization and Communication

The above tests confirm that the accuracy of the SPOT tracker localization module lies in the range of meters to tens of meters. Even though the error can go beyond the intended error of a few meters (as specified in Table 1), this is mostly caused by outliers. Overall, the error is small compared to the scale of the ocean and, thus, should not have negative affects on the basic functionality of the drifter system. Our field experiments further support these findings.

The drifters must provide periodic location updates independent from their current position in the ocean to track a plume successfully. The desired broad coverage is inherently fulfilled by our design choice of utilizing GPS and satellite communication for the drifter's localization and communication modules. The SPOT trackers on our drifters are made user programmable and can be configured to receive periodic location updates at intervals of seconds. The average speeds of the ocean currents near the HTP pipes are in the range of 0.2–0.4 m/s (see http://www.sccoos.org/data/roms-3km/). Taking into account these speeds and the given GPS accuracy, a SPOT tracker update rate in the range of one message sent per 1–10 min would be reasonable. On the other hand, the update rates influence the power consumption and the operation time of the drifter system. We finally decided on an update rate of one message per 20 min being a good trade-off—not only sufficient to keep track of the drifters but also more practical because the power consumption is kept within the limits that are supported by the drifter system.

In comparing the time stamps of GPS fixes logged on the drifter's SD card with the time when data was received from the SPOT tracker, the delay between a fix and transmission is found to be 1–10 min. This means location data may be 10 min old in the worst case. The delay mainly causes problems during drifter recovery, where a drifter has moved away by the time the recovery boat reaches the communicated location. Here, the radio communication helps to get more recent data during recovery.

Using the radio modem as a secondary communication module does not induce hard constraints on the range; a short-range radio with a range of 1.5–3 km is sufficient for drifter recovery and for establishing a near-shore network among drifters, AUVs, monitoring, and base stations, which can facilitate the operations of ocean-monitoring missions.

Like the SPOT tracker, the radio modem is fully configurable by the user; transmission rates have been adjusted to receive one message per minute, given the relatively low

speeds of the ocean currents. We tested the radio communication between a drifter and a base station at Santa Catalina Island, California, where we have access to a Freewave radio base station as part of the RESL underwater glider network [18]. A Gumstix single board computer with an XBee radio and a 6-dB gain antenna was set up at a site 75 m above sea level. The 2.5-dB antenna on the drifter is placed 0.1–0.15 m above water surface. The drifters were deployed for approximately 10 min at locations 2.4, 3.2, 4.8, and 6.4 km away from the base station at Catalina. The drifters transmitted every 5 s. The percentage of packets received uncorrupted at the base station from each location was 76.64, 72.36, 66.10, and 57.03%, respectively. The loss in transmission is caused by the low height of the antenna above the water surface. The waves are good absorbers of radio waves and affect the radio communication negatively. As benchmark, we reached a success rate of 97% and a communication range of over 9.5 km between the base station and a boat. The settings of the boat are similar to the settings of the drifters in terms of GPS receiver and XBee radio, but the 2.5dB gain antenna is placed higher up in the open air at 1 m above the water's surface. Finally, a communication range of approximately 700 m was achieved between the boat and a drifter. Considering that a low-cost radio was used, overall, the measured ranges substantiated our design choice of the XBee radio modem and suggest its usability for our application.

Robustness and Unit Cost

The drifters must be low cost. The total unit cost of our drifter system is about US$1,000: roughly US$500 for the drifter body design and US$500 for drifter electronics, including material cost, manufacturing process, and SPOT tracker service charges (the cost excludes man hours for manual processing and assembly, as they can vary considerably for early prototype development).

The mechanical parts were manufactured from materials that are likely to survive the rough ocean conditions. The surface float is made from PVC material, which is affordable and easy to machine. Note that we did not specifically test the robustness of our drifters to storms; particularly, the drifters have not been deployed in stormy sea.

The first experiences from testing our drifters in field experiments, however, led us to conclude that both cost and robustness of the designed drifter system are sufficient for the realization of multiple reusable drifters for nearshore operation.

Field Experiments

We conducted field experiments with one, two, and three RESL drifters to test different aspects of the drifter system.

Effects of Winds, Waves, and Ocean Currents

A first set of field experiments was run at Santa Catalina Island to evaluate the effects of surface winds, waves, and ocean currents on the drifters. Ideally, the effects of winds and waves on a drifter's motion are minimal, whereas the ocean currents at a particular depth form the main driving force of the drifter.

First, we tested the impact of winds and waves by deploying one of our drifters close to a dock in Fishermans Cove, Santa Catalina, where the ocean currents are fairly weak, but the wind and wave action was significant that day. The drogue was placed at a depth of 1 m. The drifter moved not more than about 2 m over 40 min. This indicates that our drifter design, although cylindrical in shape, is indeed only slightly affected by local prevailing winds and waves. The drifter stays with the weak current, as shown by Figure 6(a).

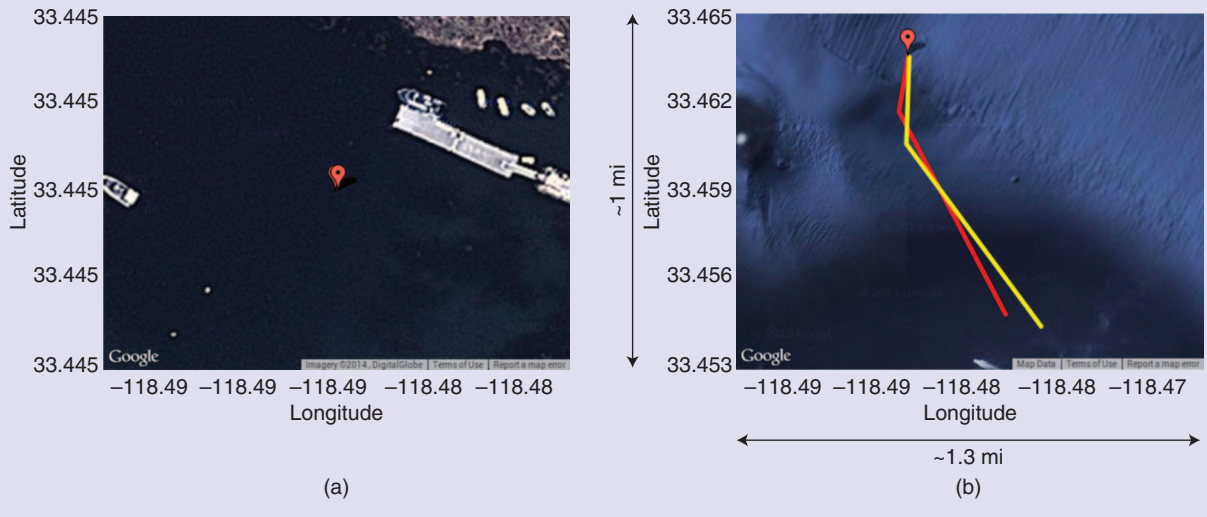


Figure 6. The effects of winds, waves, and ocean currents. (a) A drifter with drogue at 1 m was deployed near a dock at Santa Catalina Island, where ocean currents are fairly weak. Despite of surface winds and waves, the drifter (red marker) stayed within the range of 2 m. (b) Two RESL drifters (red and yellow) with the same drogue depths of 1 m equally follow the ocean currents.

In a second test, we checked the basic capability of the drifters to follow an ocean current. Two drifters were deployed off the coast of Santa Catalina at the location marked in Figure 6(b). The depths of the drogues of the two drifters were adjusted to 1 m. The duration of the test was approximately 2 h. The trajectories of the drifters are shown in Figure 6(b). Both drifters moved in the same direction and stayed together as they were following the current at 1-m depth.

A third experiment tested the full drifter deployment. An RESL drifter was deployed in the ocean near Santa Catalina for the duration of 17 h. The drogue of the drifter was again set to 1 m in depth. The drifter updated its position every 30 min via satellite using the SPOT tracker. The resulting trajectory of the drifter is shown in Figure 7. Twenty-seven messages were delivered successfully via satellite out of the total of 34 messages for 17 h. The drifter moved at an average speed of 0.14 m/s. The data logged on the SD card matched the communicated trajectory, which proves the basic functionality of the drifter design: The drifter is capable of tracking a tagged current, logging its positions, and sending continuous position updates from a distance via satellite communication.

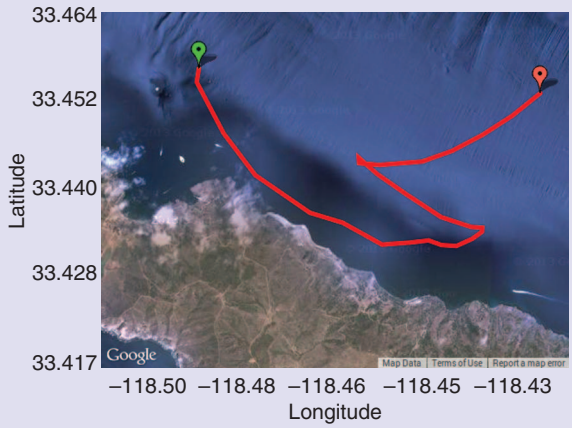


Figure 7. A test of basic functionality. A drifter was deployed at the start point (green marker) and drifted over the duration of 17 h along the displayed trajectory to the end point (red marker).

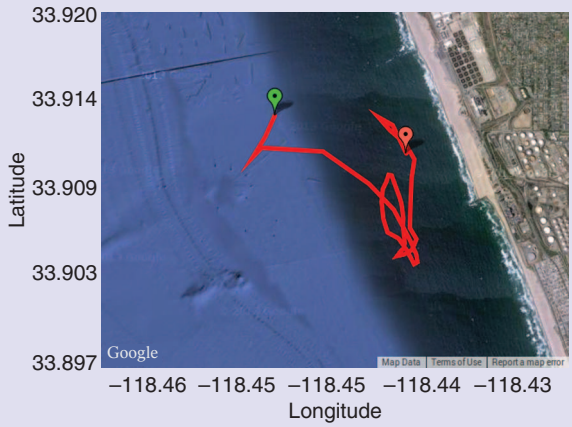


Figure 8. The trajectory of a drifter deployed at HTP. The drifter was dropped at the location of the green marker and finally drifted to the location of the red marker over the duration of two days.

Experiment at the Hyperion Treatment Plant

The initial motivation for our work originates from the 1-mi diversion plan activity at HTP. During the diversion activity, we expected a total area of about 10 km × 18 km along the coast around the HTP to be monitored. We conducted a preliminary test with one of our drifters at HTP. A RESL drifter was deployed at the outlet of the 1-mi pipe (indicated in yellow in Figure 2), at the location shown as a green marker in Figure 8. The drifter was deployed for two days, as discussed with the authorities. The drogue was set to a depth of 3 m, which would be within the expected depth range of a discharged wastewater plume.

Figure 8 shows the resulting trajectory of the drifter for the two-day period. The update rate of the SPOT tracker was configured to send one message every 20 min. The near-shore ocean-monitoring system with base stations for radio communication could not be set up for this preliminary test because it requires permissions and further logistic support from HTP.

As previously mentioned, an ocean model like ROMS provides an alternative source of localized data of the ocean. If we compare simulated ROMS data with the velocities of the ocean currents calculated from the drifter trajectory, we notice that the data can be substantially different. Figure 9 visualizes two drifter trajectories generated by ROMS for currents at depths of 1 m and 10 m under conditions similar to the conditions of the actual experiment at HTP (i.e., the same start positions near the 1-mi pipe, same day, and same duration). ROMS provides only sparse data at such local scales. As we can clearly see, the currents and thus the trajectories generated by ROMS (Figure 9) deviate from the trajectory of the real drifter with drogue at 3-m depth (Figure 8). We find that drifters provide a very practical tool for monitoring ocean currents at a local scale.

Experiments with Multiple Drifters

Ocean currents can change significantly over time and have different directions at different depth layers. Generally speaking, due to the complex dynamics of the ocean, multiple drifters must be deployed at different points in time and at different locations, with their drogues adjusted to different depths, to collect data at proper temporal and spatial resolutions.

A monitoring task like the one at HTP ideally requires multiple drifters deployed each day for over one month to tag and track the currents carrying a plume in a reliable way. Similar to [4], we assume that each deployed drifter tags a water patch with an area of roughly 1 km^2. Hence, if we were to cover the total area that has to be monitored during the diversion activity by deploying drifters on a regular grid in parallel, we would require about 180 drifters at a time.

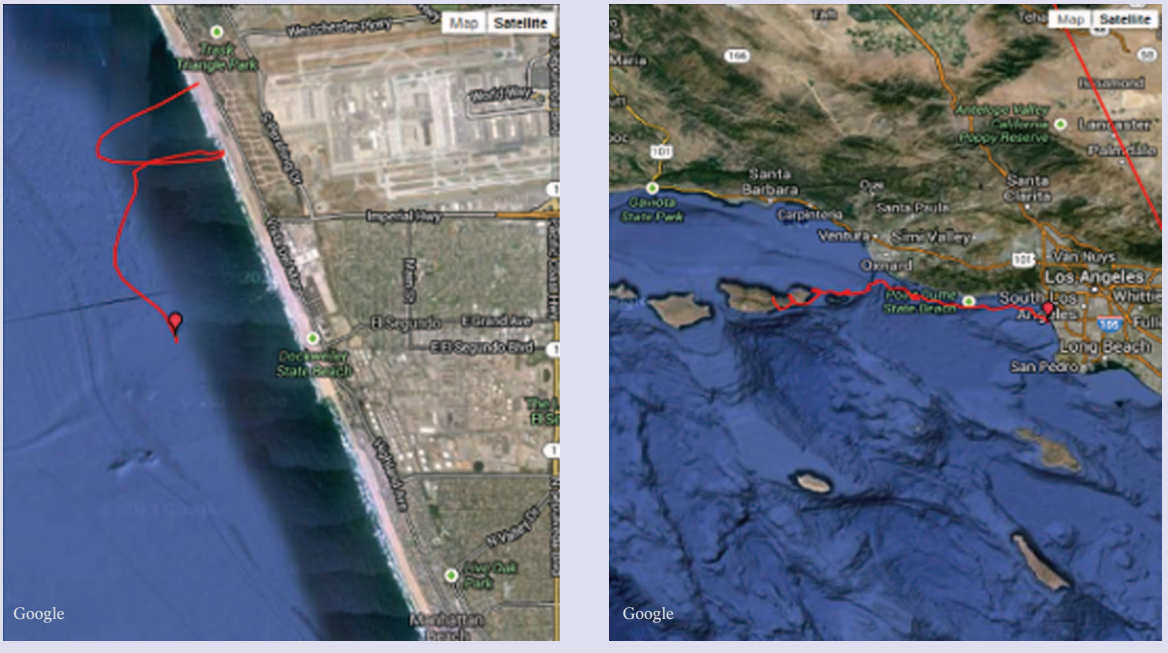
Instead, let us now consider the sequential deployment of drifters. Assuming that we drop one drifter at the HTP outfall once an hour and that a drifter travels with an average speed of about 0.3 m/s and reaches the boundary of the monitoring area after one day on average, then we require around 30–60 drifters for continuous operation. The exact number of drifters depends on various factors; e.g., it depends on the number of ships in service for timely drifter recovery, once the drifters reach the boundary or get stuck at a certain location. Also, the required number of drifters would multiply if more than one drifter, potentially with different drogue depths, was deployed at a time. In practice, with regard to the concrete HTP monitoring task, a reasonable monitoring plan could make use of about 10 drifters, where a single drifter with drogue at depth of 3 m (i.e., the depth of the outfall pipe) is dropped four times a day.

The above numbers motivate our overall drifter design, which aims at an ocean-monitoring network of multiple low-cost drifters that are easy to recover. For now, we tested the monitoring task under the multidrifter scenario in field experiments with up to three RESL drifters deployed in the ocean [Figure 10(d)]. In the experiment, a HOBO Pendant temperature sensor was attached to the center of the drogue of each drifter. The sensors are 5.8 cm × 3.3 cm × 2.3 cm in size and allowed to measure temperature at varying depth. The experiment confirms that it is feasible to add small sensors to a drogue without sensibly affecting the drogue's mechanism.

Figure 10(a) shows the trajectories of two drifters with drogue depths of 1 m and 5 m. Once deployed, they started separating from each other over time. The radio communication was enabled for the experiment. The data received from the SPOT tracker only included 10 GPS coordinate points for the experiment duration of 2.5 h. The combined location data from both SPOT tracker and radio modem consists of 86 coordinate points, resulting in more accurate tracking of the drifters' trajectories. Figure 10(b) visualizes these differences in accuracy.

Ocean currents can change significantly over time and have different directions at different depth layers.

Figure 10(c) shows the trajectories of all three drifters, with their drogues adjusted to 1 m, 3 m, and 5 m in depth for a deployment over 3 h. The drifter with the drogue depth of 1 m (yellow trajectory) deviates slightly from the initial deployment location. This, together with the measured final separation between the three drifters, confirms that the resulting movement vectors (and thus the ocean currents) at different depth layers can be significantly different. The multidrifter experiments were conducted six days apart, at the same location and time of day. The movement of the drifters, however, pointed into opposite



(a) (b)

Figure 9. Drifter trajectories based on ROMS data. Trajectories resulting from ROMS for a simulated drifter with (a) drogue at 1-m depth and (b) drogue at 10-m depth. The trajectories generated by ROMS are clearly different from the data obtained by a deployed real drifter (as shown in Figure 8).

The drifters contribute to a more pervasive ocean-monitoring system that can provide increased resolution and accuracy, compared to methods that use data from ocean models or AUVs solely.

directions for the two tests. This further proves that the directions of ocean currents change considerably for different points in time, even at the same location.

The experiments with multiple drifters can also be seen in a broader context as precursor studies to the idea of designing active drifter systems. Some of our recent research efforts [3], [19] address the design and control of drifters with one additional degree of freedom, i.e., an additional actuator to autonomously adjust the drogue along the depth direction. This way, a single drifter can gain limited control over its moving direction by changing the depth of its drogue to select which current to tag during runtime. The experiment with three drifters in Figure 10, each with its drogue at a different depth, represents a successful preliminary test toward an active drifter that would select a moving direction from three distinct depth layers.

Conclusions

This article presented our work on designing, building, and testing customized Lagrangian drifters for ocean monitoring. The general design challenges as well as specific requirements for a real-world monitoring task were outlined and subsequently incorporated throughout the system design of the drifters.

We tested the RESL drifters by analyzing their system characteristics in laboratory tests and took three drifters out to the ocean for tests under realistic conditions. The drifters are designed for use in a near-shore ocean-monitoring

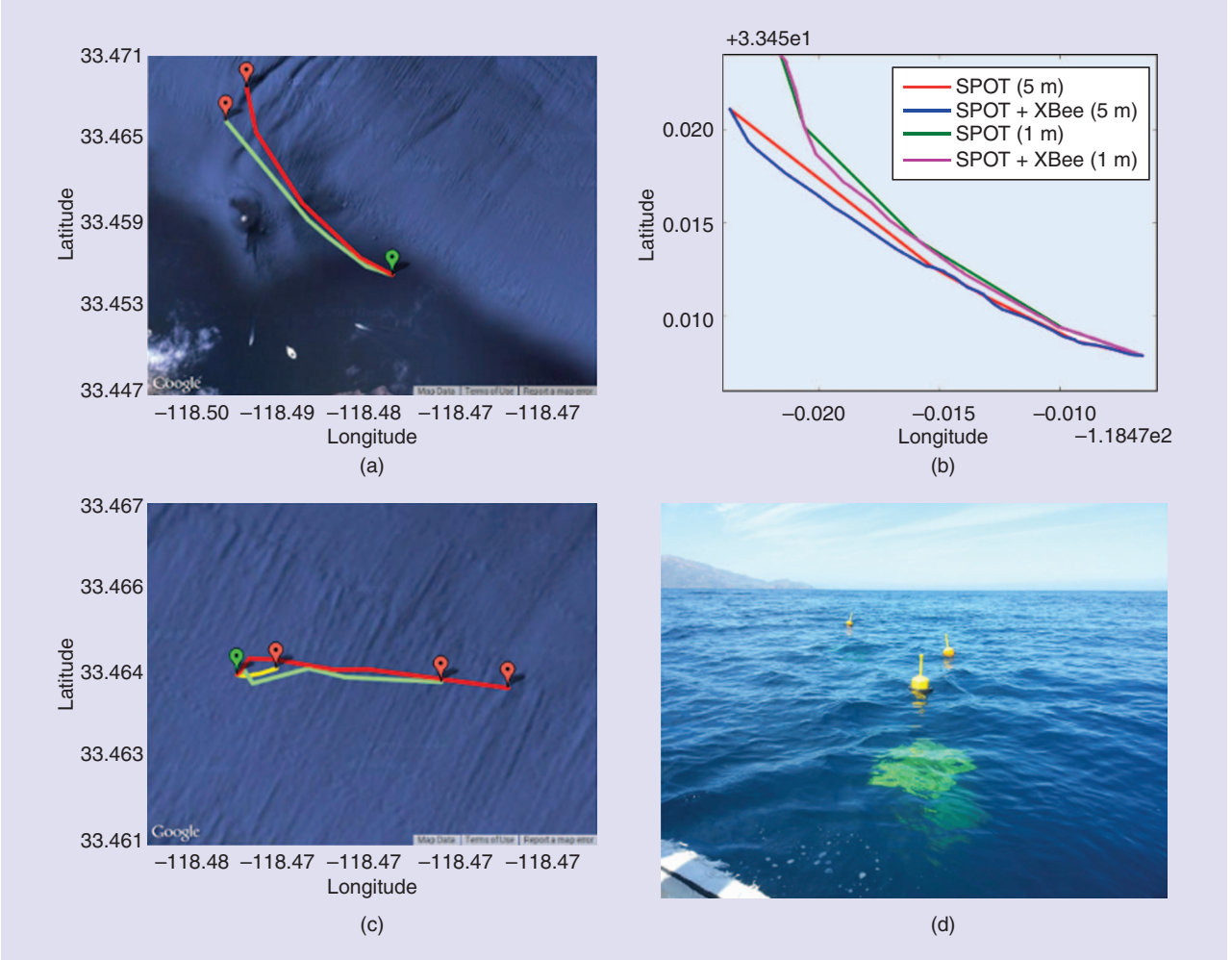


Figure 10. Multiple drifters. (a) Trajectories of two drifters (red markers) with drogues at depths of 1 m (red trajectory) and 5 m (green trajectory), both starting from a common deployment location (green marker). (b) Trajectories of the two drifters, once obtained from SPOT tracker only and once when SPOT tracker and XBee data are combined. (c) Trajectories of three drifters (red markers) with drogues at depths of 1 m (yellow trajectory), 3 m (green trajectory), and 5 m (red trajectory), starting from the same common deployment location (green marker). (d) The three RESL drifters right after they were deployed.

network, which connects drifters, AUVs, research vessels, and base stations on shore. The drifters contribute to a more pervasive ocean-monitoring system that can provide increased resolution and accuracy, compared to methods that use data from ocean models or AUVs solely.

There are two future directions considered in the article. The first is to improve on the system design to establish a modular low-power, low-cost multidrifter system with applications in oceanographic research. The second is to develop active drifter systems with actively controlled drogues and additional anchors or sails, which could add beneficial mobility to the drifters when monitoring ocean phenomena within a locally bounded area of interest.

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