Cooperative Multi-AUV Tracking of Phytoplankton Blooms based on Ocean Model Predictions

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Abstract— **In recent years, ocean scientists have started to employ many new forms of technology as integral pieces in oceanographic data collection for the study and prediction of complex and dynamic ocean phenomena. One area of technological advancement in ocean sampling if the use of Autonomous Underwater Vehicles (AUVs) as mobile sensor platforms. Currently, most AUV deployments execute a lawnmower-type pattern or repeated transects for surveys and sampling missions. An advantage of these missions is that the regularity of the trajectory design generally makes it easier to extract the exact path of the vehicle via post-processing. However, if the deployment region for the pattern is poorly selected, the AUV can entirely miss collecting data during an event of specific interest. Here, we consider an innovative technology toolchain to assist in determining the deployment location and executed paths for AUVs to maximize scientific information gain about dynamically evolving ocean phenomena. In particular, we provide an assessment of computed paths based on ocean model predictions designed to put AUVs in the *right place at the right time* to gather data related to the understanding of algal and phytoplankton blooms.**

I. INTRODUCTION

The coastal ocean is a complex system that is composed of the merging dynamics and interactions between atmospheric, oceanographic, estuarine/riverine, and land-sea processes. Impacts from ever increasing urbanization, alteration in land use and land cover, and ongoing climate change alter the physical and biogeochemical state of our coastal ecosystems with unknown consequences [1]. Based on the high ecological and socio-economic importance of coastal regions [2], it is important to be able to accurately assess, and predict, human impact upon, and the processes that drive this system.

Historically, infrequent measurements from ships, buoys and drifters have accounted for the majority of oceanographic observations. However, effective observation of the dynamic ocean at the multiple spatiotemporal scales can neither be done infrequently nor with one instrument in a fixed location. Multiple and adaptable sensors facilitate simultaneous and rapid measurements that can capture the variability of processes such as ocean upwelling and tidal mixing. Recently, remote sensing satellites have been employed to obtain high-resolution, synoptic views of the ocean, aquatic robots, i.e., Autonomous Underwater Vehicles (AUVs), are becoming an integral participant in oceanographic data collection, and physical and biological ocean models are playing a larger role in understanding and predicting ocean behavior. Each of these tools provides a piece of the bridge that narrows the gap between observation, understanding, and prediction of the ocean. Even with the available technology and data collection capabilities, we still face great challenges to gain of comprehensive knowledge of the ocean. Here, we contribute to expanding our ocean science knowledge through a strategic combination of existing technologies and tools to determine sampling locations and strategies that return information of high scientific merit.

The Ocean Plume Tracking Algorithm BuiLt on Ocean Model Predictions (OPTA-BLOOM-Pred) is a mission planning algorithm that utilizes ocean model predictions to determine locations to be visited by an AUV, plan a trajectory for the vehicle to execute, and improve navigational accuracy. The design of OPTA-BLOOM-Pred includes an innovative toolchain satisfying two objectives: 1) to utilize ocean model predictions as a component in an end-to-end autonomous prediction and tasking system for tracking dynamic ocean features, 2) to provide near-real time, in situ measurements to an ocean model to increase the skill of future predictions. We utilize the capabilities of the model to predict the evolution of an evolving feature, and use this information to determine a path along which to sample. The model is also used to assist in solving the four-dimensional (three spatial plus time) motion planning problem of steering an AUV between sampling locations in the presence of environmental disturbances, i.e., arrive at the appropriate time and location to sample. The data assimilation component promotes better field representation in the model by supplementing existing sparse datasets.

Simulation results and proof-of-concept experiments have validated practical implementation of OPTA-BLOOM-Pred, and motivate its application during a full-scale, long-duration deployment to track evolving phytoplankton blooms, see e.g., [3], [4] and [5]. However, to date, environmental conditions and vehicle availability have not coincided for the study of the formation and development of an algal bloom in Southern California coastal waters.

Despite significant research efforts worldwide, a current understanding of overall phytoplankton bloom dynamics is poor to non-existent. Hence, our ability to predict scenarios resulting from ocean temperature, acidification, and/or nutrient fluctuation is severely limited. In this paper, we address the challenge of determining where and when sampling assets, i.e., AUVs, should be deployed to observe and monitor events related to HAB research. This paper presents path planning and asset allocation results for the OPTA-BLOOM-Pred Algorithm, which designs missions for collaborative, multi-vehicle feature tracking of evolving features over many days. We begin with a brief background and motivation, followed by a description of the tools and technologies utilized in this study. Section III presents the broad scope and impact of the problem we consider. In Sect. III-A, we provide specific details for the path planning problem considered in this paper. A review of the OPTA-BLOOM-Pred Algorithm and our path planning technique is addressed in Sect. IV. Results from the three day experiment are presented in Sect. V-B, with a quantitative assessment of the effectiveness of the computed paths. We conclude with general comments, further assessments and future work in Sect. VI.

II. BACKGROUND AND MOTIVATION

In recent years, there has been a documented increase worldwide in the occurrence and intensity of algal and phytoplankton blooms. These biological phenomena are a primary research interest of the authors, and in particular, the assessment, evolution and potential prediction of algal blooms that have the potential to include harmful algal species (i.e., Harmful Algal Blooms (HABs)). To study HABs and assess the reasons for the observed increase in their occurrence in southern California, the University of Southern California (USC) Center for Integrated and Networked Aquatic PlatformS (CINAPS) (`http://cinaps.usc.edu/`) has designed and implemented an embedded sensor network, consisting of static and mobile nodes [6].

Harmful algae can wreak havoc on an aquatic ecosystem via toxin production, or by their accumulated biomass adversely affecting dissolved oxygen levels. Impacts to humans include, but are not limited to, severe illness and potential death following consumption of, or indirect exposure to HAB toxins. In addition, coastal communities and commercial fisheries can suffer severe economic losses due to fish, bird and mammal mortalities, and decreases in tourism due to beach closures. Thus, it is of interest to predict when and where HABs may form and which coastal areas they could affect. For more general information about HABs, see [7]. Specific information related to algal bloom formation, evolution, composition and biology can be found in [8], [9], [10], [11] and [12]. Further motivation for the study of HABs by use of the path planning techniques presented here can be found in [3], [6] and [13].

Studying HABs in southern California is unique compared to other coastal communities around the globe. In this region, the dynamics are primarily driven by large-scale regional processes as southern California experiences significant decadal and interannual variability associated with the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) [14] and [15]. Specifically, in recent months we have been experiencing El Niño conditions, as equatorial Pacific, sea-surface temperatures remained above average through August 2009. These conditions strengthened through winter 2009-2010 in the Northern hemisphere [16], and have impacted southern California with more frequent and intense storm events in the early months of 2010. These storm events freshen sea-surface waters through direct rainfall into the ocean and from freshwater inflow at the coastal boundary from streams and rivers. This river runoff supplies nutrient-rich waters to the ocean surface, which promotes conditions that have the potential to produce a *bloom* of photosynthetic organisms (i.e., algal bloom).

A. Regional Ocean Modeling System - ROMS

The predictive ocean model incorporated into the algorithms presented in this paper is the Regional Ocean Model System (ROMS) - a split-explicit, free-surface, topography-following-coordinate oceanic model. ROMS is an open-source, ocean model that is widely accepted and supported throughout the oceanographic and modeling communities. Information on ROMS can be found in [17] and [18].

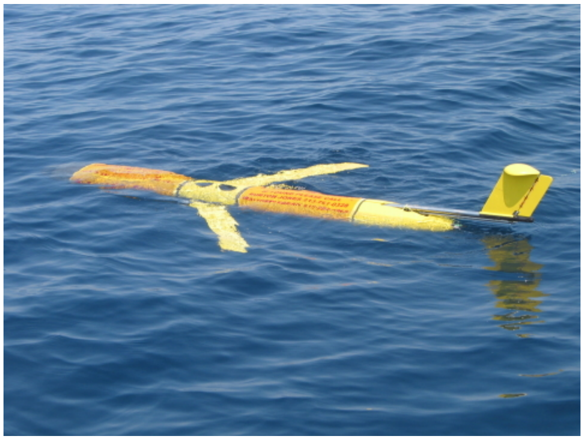

Fig. 1. One of the two Slocum gliders owned and operated by the CINAPS team at USC. This photo was taken just before beginning a mission off the Northeast coast of Santa Catalina Island, CA.

The version of ROMS used in this study is compiled and run by the Jet Propulsion Laboratory (JPL), California Institute of Technology, and provides hindcasts, nowcasts and hourly forecasts (up to 36 hours) for southern California coastal waters through a website interface, [19] or raw data access via a THREDDS Data Server [20]. Details on the JPL version of ROMS are in [21], [22] and [23].

B. AUV: Slocum Glider

The AUVs considered for this study are Webb Slocum autonomous underwater gliders [24], see Fig. 1. A glider is a passively actuated AUV, designed for long-term ocean sampling and monitoring [25]. General information regarding standard operating procedure for autonomous gliders can be found in [4] and [26], with details on the communication protocols for USC's gliders in [27] and [28].

III. PROBLEM OUTLINE

An open question in coastal ocean science is to disseminate whether or not we can distinguish anthropogenically affected processes from natural variations and effects. Since the primary triggers that drive algal blooms are not well understood, and depend greatly on the complex interaction between the microbes and their surrounding environment, we are interested in the ability to track and monitor ocean features resulting from anthropogenic inputs. This can help answer questions related to increased urbanization of coastal regions. In addition to predicting, tracking and studying algal blooms, it is also of interest to consider features or phenomena that have the potential to lead to the production of an algal bloom. Hence, hereafter we will refer to any feature of interest to be tracked as simply a *plume*.

Depending upon the type of plume considered, and the instrumentation suite available on the vehicle, different locations within a plume may be of interest, e.g., its boundary or extent, subsurface chlorophyll maximum, salinity minimum, its centroid, etc. Continuing with the development of this work presented in [3], [4], [5] and [13], we opt to track the centroid and the boundary of the extent of a plume. We assume that we have at least two vehicles to perform the missions, e.g., one centroid tracker and one boundary tracker. On-board the glider, chlorophyll and optical sensors, among others, collect data throughout the mission relating to specific properties of the water within the plume.

The basic mission plan to track and monitor dynamically evolving ocean plumes is iteratively generated as follows. First, we identify a plume via remotely sensed data from the Moderate Resolution Imaging Spectroradiometer (MODIS) by utilizing the selection algorithm presented in [29]. We then use ROMS to predict the behavior of the plume for a short time period, e.g., 16 hours. This prediction is used to generate a sampling plan for the gliders that steers them to regions of scientific interest within the plume, e.g., centroid and boundary locations. Throughout execution of the sampling plan, collected data are transmitted via an embedded wireless network, cf., [27] and [28], and assimilated into the ocean model. After assimilation, ROMS generates a new prediction. This entire process is repeated until the feature dissipates or is no longer of interest. For this study, we assume that the plume is a single, connected region, although a plume does have the potential to evolve into multiple disconnected regions. In the event of separation, we choose a single region of interest based on parameters of interest. Choosing a particular plume, or portion thereof, to track is ongoing work presented in [29].

A plume will propagate and evolve with ocean currents and internal microbial interactions. Here, we assume that ocean currents dominate the propagation of the plume. Since our initial detection of a plume is based on remotely sensed data from MODIS, the plume is represented as a 2-D feature on the ocean surface. Thus, we assume that the evolution of the plume is driven primarily by ocean surface currents. The waypoint-selection algorithms that determine the path for the glider are based on the planar propagation predictions of ROMS. By implementing these paths on gliders, which traverse the ocean following a saw-tooth trajectory, we hope to gain more information about the three-dimensional structure and evolution of algal blooms.

We assume the starting location L of each vehicle is known, and the ROMS prediction of the plume evolution is accurate. The initial delineation of the plume is a set of geographic locations ($\mathcal{D}$) that encompass the plume's extent. The discrete locations in $\mathcal{D}$ are forecasted as if they were Lagrangian drifters in the ROMS surface current prediction. Additionally, we assume that the glider travels at a constant horizontal speed. During the waypoint selection and path generation, vehicle separation is not considered. The gliders do not have on-board sensory capabilities to actively assess vehicle separation while underwater, thus there is no way to enforce a separation constraint on a deployed glider. There is no adaptive behavior incorporated during the execution of the planned trajectory. In particular, we do not provide an adaptive approach in our algorithm to overcome model or navigational error when tracking a plume. It is well known that an autonomous glider is a slow moving vehicle with limited control capabilities. With this in mind, during deployments if a vehicle surfaces in a location that is extremely off course, or conditions change dramatically, our remediation approach is to generate a new plan.

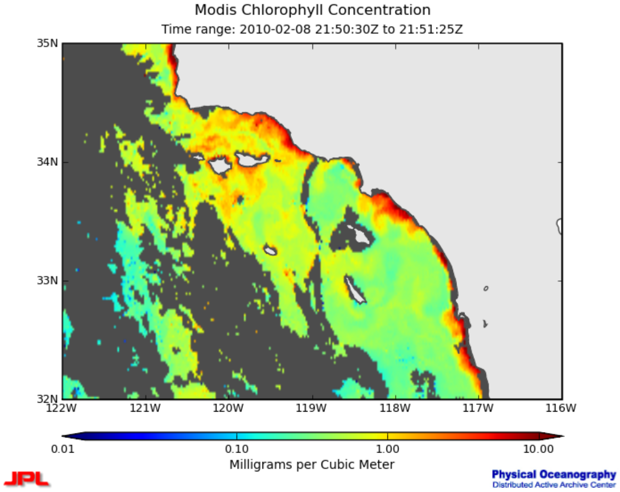

Fig. 2. Chlorophyll concentration measured by the MODIS satellite off the coast of Los Angeles, CA on February 8, 2010. Photo courtesy of the Physical Oceanography Distributed Active Archive Center at JPL.

A. *Problem Statement*

The goal of this paper is to provide an assessment of a path planning technique to track evolving ocean plumes based on ocean model predictions. It had been previously noted in [3], [5] and [13], that previous field deployments of our computed paths had no metric for assessment. This is primarily due to the fact that the tracked plumes were proxy delineations or pseudo-features. The results presented in the aforementioned publications served as a proof-of-concept validation for the technology toolchain, as well as to assess the ability of the gliders to accurately navigate to prescribed waypoints that define its mission. The navigational accuracy is studied in [4]. Here, we present a comparison that provides an initial assessment of the planned paths by comparing it to the plume advection technique presented in [29]. A detailed assessment during an actual deployment is still pending, as weather, vehicle availability and remote sensing devices have not yet combined to present an opportunity to detect and track an actual plume in southern California coastal waters.

To conduct this preliminary assessment, we examine historical data from the days following a major rain event that occurred on February 6 and 7, 2010; southern California accumulated just over 3" of rain during this period. As a result from this accumulation of precipitation, the San Gabriel and Los Angeles Rivers deposited large amounts of fresh water runoff into the ocean. The anthropogenic effect of this storm can be seen in Fig. 2, which shows the chlorophyll concentration measured from MODIS on February 8, 2010. Plumes containing high concentrations of chlorophyll, resulting from river runoff, are depicted in red.

The areas of high chlorophyll concentration mark potential regions of interest to study due to a higher likelihood of development of an algal bloom. Practically speaking, we cannot select every small region of high chlorophyll concentration to track, nor would we gain much information by selecting a large encompassing region. Thus, we focus on *hot spots*, or areas of significant concentration of chlorophyll greater than a chosen threshold, as the plumes to study. Detection of the hot spots is done by use of the algorithm presented in Sect. IIB of [29], which presents a method for thresholding Fluorescense Line Height (FLH) values from

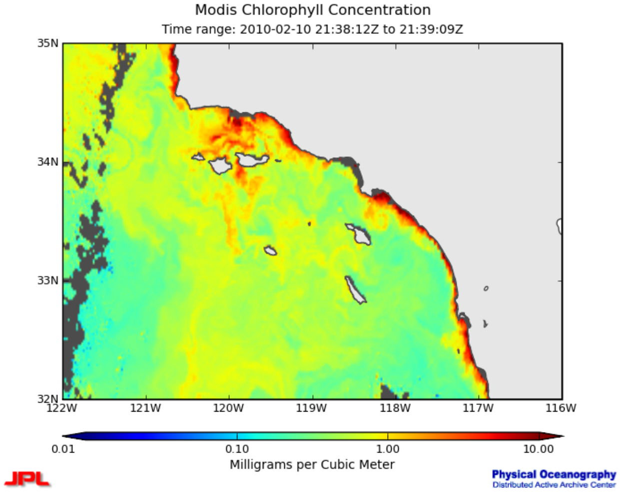

Fig. 3. Chlorophyll concentration measured by the MODIS satellite off the coast of Los Angeles, CA on February 10, 2010. Photo courtesy of the Physical Oceanography Distributed Active Archive Center at JPL.

MODIS satellite data. The algorithm in [29] was modified for use here to threshold chlorophyll values rather than FLH values from the MODIS data.

Examining MODIS data for subsequent days, we observe that on February 10, 2010, there is still a strong presence of surface chlorophyll, although the areas of concentration have shifted and changed, see Fig. 3.

With no significant additional input of fresh water or nutrients, this implies that the plumes created from the river runoff caused by the rain events on February 6 and 7 propagated through the ocean, and remained detectable for multiple days. It is important to track and monitor these types of features to broaden our understanding of the 3-D dispersion of evolution of plumes in this coastal region. Although this event did not result in one, this is the type of scenario with a high probability of developing into an algal bloom. Comparing Figs. 2 and 3, we see that the general regions of high chlorophyll concentration remain the same, however the extent of high concentration dispersion has moved coast-ward in Fig. 3. From a preliminary examination of the data during the proposed time period, we found relatively moderate current velocities, suggesting that a plume in this area would move relatively slow, allowing for adequate sampling to be performed by an autonomous glider.

Once we have determined the initial delineation of the plume extent from thresholding chlorophyll values in the MODIS dataset, we apply OPTA-BLOOM-Pred to design a path to track the predicted movements of the plume based on ROMS predictions. Due to cloud cover and data gaps, we do not have remotely sensed data to ground truth daily predictions of the plume evolution. Since we cannot precisely determine the actual plume evolution, we advect the plume by use of recorded surface current measurements made by multiple CODAR Ocean Sensors, high-frequency (HF) radars[1]. These HF radar sites are located at multiple locations along the southern California coast, and record data used for ocean current and wave monitoring. The data collected by the radars are gathered at ~ 15 minute intervals and are averaged to provide surface current velocity measurements for each hour. Utilizing these historical measurements for local surface currents, we can provide a realistic propagation of the plume. The method for plume propagation by use of HF radar data is presented in [29]. Here, the authors demonstrated that their probabilistic approach showed promising results for propagating large, coherent plumes through the analysis of historical data for the Monterey Bay region.

In the next section, we present the algorithm that generates the paths allowing the AUV to follow the general movements of a plume and gather data.

IV. PATH PLANNING ALGORITHM

The path planning algorithm utilized in this study is OPTA-BLOOM-Pred, which was developed in a series of publications culminating with [5]. In the path generation presented here, OPTA-BLOOM-Pred utilizes two waypoint-selection algorithms to define paths that track the boundary and centroid of a plume. These algorithms utilize the ROMS hourly predictions of a delineated plume to generate a waypoint list that guides the AUV to predicted locations of the selected areas of interest within the given feature, e.g., centroid and boundary. For details regarding the development of the centroid and boundary tracking, waypoint-selection algorithms, see the series of articles [3], [5], [13] and [28].

A. *Ocean Plume Tracking Algorithm BuiLt On Ocean Model Predictions (OPTA-BLOOM-Pred)*

The basic idea of OPTA-BLOOM-Pred is to track and collect daily information about dynamically evolving ocean features by using autonomous gliders as sampling platforms. As a brief description, the OPTA-BLOOM-Pred initially generates a waypoint-based path for the glider from the ROMS prediction of the surface evolution of the plume. The waypoints that define this path are chosen to be the surfacing locations for the glider. Thus, the path steers the glider to surface at chosen locations of interest within the plume, i.e., centroid and boundary. Since the glider travels below the sea surface, and executes a sawtooth-shaped trajectory between depths of $10-100$ m, we cannot assume that it is subjected to the same current regime as the plume, which is assumed driven by surface currents. Since Slocum gliders are dead-reckoning vehicles, OPTA-BLOOM-Pred alters the surfacing intervals (waypoint distances) of the glider along the path in an attempt to match the spatiotemporal location of a surfacing with the intended location of interest. Additionally, for each selected waypoint, the algorithm computes an aiming location to assist the glider in surfacing at the prescribed waypoints along the path. The aiming locations are iteratively computed by perturbing a parameterized glider trajectory between the two considered surfacing locations such that, by incorporating the four-dimensional ROMS predicted currents, the glider will surface within a desired distance from the prescribed location. A description and example of the iterative trajectory planning that incorporates ROMS 4-D velocity predictions can be found in [5].

Note that since the boundary is not a single point location like the centroid, it is not as critical to match its precise spatiotemporal location. Thus, for these waypoints we do not attempt to alter the surfacing intervals, but keep the regular four hour intervals as originally chosen. This is also done since we expect the prediction of the boundary of the plume

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[1] An interactive map containing detailed information about each radar station, as well as downloadable data can be accessed at: `http://www.sccoos.org/data/hfnet/?r=3`.

to be less accurate, since three-dimensional plume evolution and dispersion is not well understood.

OPTA-BLOOM-Pred outputs 4 boundary waypoints, and at most 4 centroid waypoints that define a 16 hour mission for tracking a plume. We present OPTA-BLOOM-Pred in Algorithm 1, and refer the reader to [5] or [6] for full descriptions of the centroid and boundary tracking waypoint-selection algorithms.

Algorithm 1: Ocean Plume Tracking Algorithm BuiLt On Ocean Model Predictions (OPTA-BLOOM-Pred)

```
Require: A significant fresh water plume is detected via direct observation or remotely sensed data.
    repeat
        A set of points ($\mathcal{D}$) is chosen which determine the current extent of the plume.
        Input $\mathcal{D}$ to ROMS.
        ROMS produces an hourly forecast for all points in $\mathcal{D}$.
        Input hourly forecast for $\mathcal{D}$ into Centroid and Boundary waypoint-selection algorithms, see [5].
        Execute waypoint generation for centroid and boundary tracking.
        Execute optimization algorithm on centroid waypoints to coordinate spatial and temporal movement of the feature, see [5].
        Compute the alternate waypoints at which the vehicle aims, to arrive at the prescribed goal location.
        Uploaded computed alternate waypoints to the AUV.
        AUV executes mission.
        The AUV sends collected data to ROMS for assimilation into the model.
    until Plume dissipates, travels out of range or is no longer of interest.
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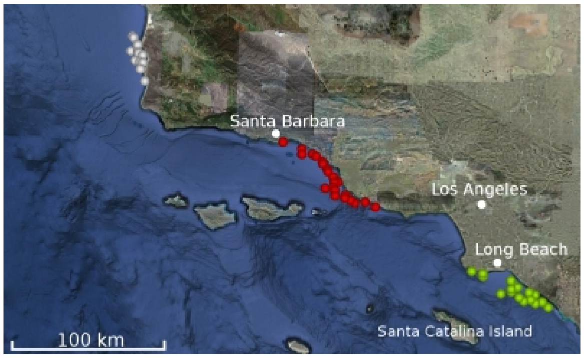


Fig. 4. The colored dots represent the center pixel of hot spot areas that have a chlorophyll concentration greater than 3 mg/m^3. Image created by use of Google Earth.

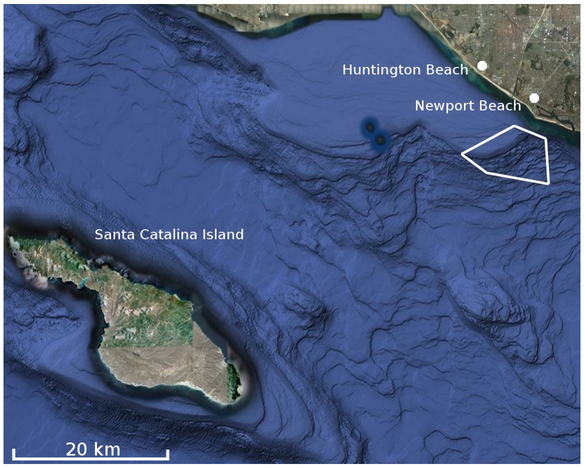


Fig. 5. A general overview of the initial delineation of the plume as chosen by thresholding chlorophyll values from MODIS data. Image created by use of Google Earth.

V. RESULTS

A. Problem Set-up

Intentions for this study were to assess OPTA-BLOOM-Pred using criteria obtained from a field deployment tracking a plume. As this deployment did not materialize, we consider an assessment based on the following criteria. First, we demonstrate the practical applicability of our technology toolchain through successive iterative path planning over the course of three days. Secondly, we compare the evolution of the plume based on ROMS predictions to the evolution produced by advecting the plume by use of hourly HF radar measurements. And thirdly, we comment on the validity of the computed paths to position the vehicle in the *right place at the right time* for collection of data in a moving feature.

B. Path Planning

The MODIS data used to create Fig. 2 were run through the hot spot detection algorithm presented in [29]. In the threshold filter a pixel is selected as a hot spot if that pixel and all eight adjacent pixels have chlorophyll concentrations greater than 3 mg/m^3. The selected areas are shown by the red, green and white dots in Fig. 4. These selected *hot spots* are used to define the initial plume conditions for tracking. In the event of an algal bloom, these regions are the actual algal bloom. For the case of river discharge after a rain event, the measured chlorophyll in the water is primarily Chromophoric Dissolved Organic Matter (CDOM), and is of interest to investigate because this type of plume may promote the onset and development of an algal bloom.

From the identified hot spots, we delineated a plume area on which to apply OPTA-BLOOM-Pred. The plume was chosen in the area of the green dots in Fig. 4, since this is a primary area of study and location of repeated glider deployments for the authors. Also, the hot spots marked by the red and white dots in Fig. 4 are initially located too close to the coast. This is an issue for practical deployment concerns and propagation over multiple days, as local currents were observed to be directed onshore. The initial delineation of the plume examined here is given in Fig. 5. The data from the MODIS satellite are timestamped February 8, 2010 at 2150 GMT, so we initialize the path planning to begin on February 8, 2010 at 2200 GMT. We assume that the vehicles will be freshly deployed to begin this mission, thus we can choose their initial locations. We present path planning strategies for multiple gliders to cooperatively track an evolving plume over the course of three days and compare this to the movement of the plume computed by advection with recorded HF radar measurements. Since the gliders were not physically deployed to execute this mission, we can only provide the planned path output by OPTA-BLOOM-Pred. We make the assumption that the glider will navigate to the prescribed waypoints along the path. An investigation into the navigational accuracy of the gliders implementing techniques used in OPTA-BLOOM-Pred during previous deployments can be found in [4].

The predicted evolution of the plume, HF radar advection of the plume and the computed paths to track the centroid and boundary of the plume are presented in Figs. 6 - 8 for day one through three, respectively, of the simulation. The paths displayed for the vehicles are the expected paths that the gliders follow projected to the ocean surface. Each vehicle begins its trajectory at the location marked with the yellow glider icon. The selected waypoints that define the path are given by the stars along the trajectory. When visible, the predicted centroid of the plume is given by the orange dot. The delineation of the plume advected by HF radar measurements is given by the red polygon. The centroid of this plume is given by the yellow push-pin. The centroid tracking vehicle follows the cyan-colored, solid line path and the boundary tracking vehicle follows the cyan-colored, dashed line path. Since the data determine a relatively slow evolution of the plume, once the glider is able to reach the predicted centroid, it is easily able to stay in contact with it. Since the distance between predicted centroids is less than the distance that the glider can travel in four hours, the centroid tracking, waypoint-selection algorithm chooses an extra location for the glider to visit, see [3], which are depicted by the squares in Figs. 6 - 8.

Fresh water river outfall plumes are buoyant, and float a high in the water. In general, these plumes have a stronger leading edge, i.e., sharper gradient, and a more diluted trailing edge. Thus, deploying gliders at the front of the plume may provide more valuable information, and allow the vehicle a better chance to remain in contact with the feature. To satisfy this constraint, and based on the ROMS predicted evolution of the plume, we choose (33.5389° N, −117.9647° E) as the initial deployment location for both vehicles. This location is denoted by the glider icon in Fig. 6.

As mentioned earlier, the surface current velocities in the region chosen are relatively small. This is an interesting artifact since typical conditions following a storm event generally involve high winds. This wind forcing increases the velocity of surface currents and will propagate a plume much more rapidly. However, ROMS predictions and HF radar measurements show low magnitude cyclical velocities rather than larger magnitude, single-direction currents. This current pattern can be observed in Figs. 6 - 8.

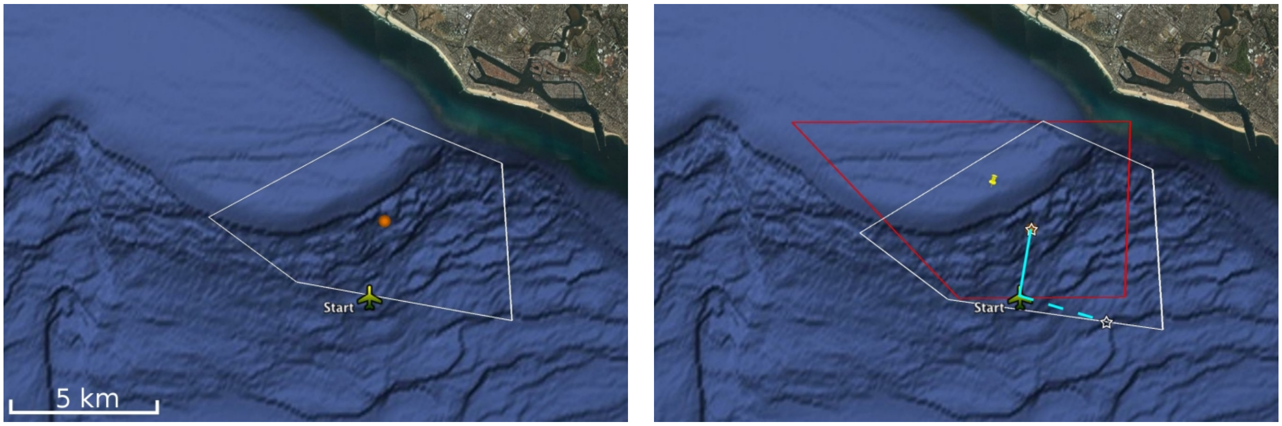
Comparing the evolution of the plume based on ROMS to that based on HF radar data, we observe slight discrepancies. The ROMS predictions shows a steady trend to the southeast, whereas the HF radar data gives a more northerly advection. We remark that the order of magnitude of the velocities is similar for both cases, but the direction differs. The difference in direction of the current velocities may be a result of the interpolation of each of the data sets. Since ROMS predictions and HF radar measurements are provided as a discrete grid, and not a continuous vector field, error is induced in the estimation of the field between grid points. As an overall path plan for sampling the centroid and boundary of the HF radar data (assumed to be ground truth), the proposed method does a reasonable job here. The boundary tracker ends up on the trailing edge since the plume moved in a different direction than the ROMS prediction. The centroid tracker comes close to the HF radar centroid in hour 12 with one of the additional sampling points, and overall provides good, albeit skewed, coverage of the interior of the plume. The centroid of the plume is computed as the centroid of the minimum bounding ellipse of the convex hull of the plume delineation. Thus, if the plume does not expand equally, the centroid is pulled in toward the direction of maximum expansion. Since the centroid of the plume here is simply a proxy area of interest, we need not concern ourselves with a more rigorous definition. Since this is a slow moving feature, including additional waypoints for the centroid tracking vehicle greatly helped in providing coverage of the plume.

The vehicles each execute a 16 hour mission. After completion of this mission, both vehicles steer toward a predicted location of the plume given by ROMS for 2200 GMT the following day. The centroid tracker heads toward the predicted centroid, while the boundary tracker heads towards a location on the boundary of the current leading edge of the plume. This is included to simulate a real deployment scenario when the glider will have some down time waiting for the data assimilation and ROMS update for the following day. Here, the gliders have eight hours to navigate from the location where they ended their mission to the location where they will begin the mission for the next day; this translates to approximately 6 km. During the time frame studied, the final locations of one mission were always less than 6 km from the predicted starting location for the next mission. The initial plume for the start of day two is the location of the advected plume given by the HF radar data for 2200 GMT on February 9, 2010. Results for day two of the mission are presented in Fig. 8.

For day two of the mission, we see similar trends to those seen for day one. The magnitude of the velocity is the same order of magnitude for ROMS and HF radar, however the plume propagation is in different directions. For this mission, the boundary tracker again ends up on the trailing edge and rapidly loses contact with the evolving extent. During an actual deployment, this behavior may not be considered bad, as data could be collected regarding the dissipation on the trailing edge. Earlier, we eluded to the fact that plumes do have a 3-D structure that is poorly understood, and any examination in and around these plumes can play a valuable role in increasing our understanding. The centroid tracker actually acts as more of a boundary tracking vehicle, as again the coverage inside the plume is good, but skewed in the direction of the ROMS predicted evolution.

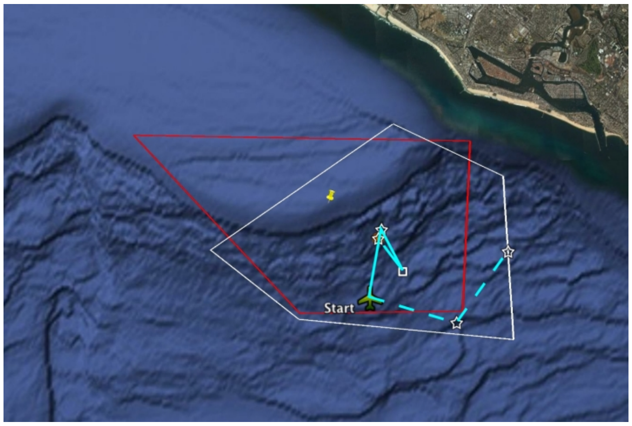
The initialization for the start of day three is the location of the advected plume given by the HF radar data for 2200 GMT on February 10, 2010. The results for day three of the mission are presented in Fig. 8. Again, we see similar trends to those seen in days one and two, although the magnitude of the currents has decreased. For this mission, the path plan for both vehicles actually does an excellent job of tracking the respective locations of interest. This is primarily due to the fact that the movement of the plume is relatively slow. We remark that the location of the ROMS predicted centroids and the HF radar centroids are within 2 km of each other, and thus it is not difficult for the glider to sample and observe the desired area.

Overall, for the three day mission, we have demonstrated the iterative applicability of our method to generate paths to track evolving ocean plumes. The next stage of this research

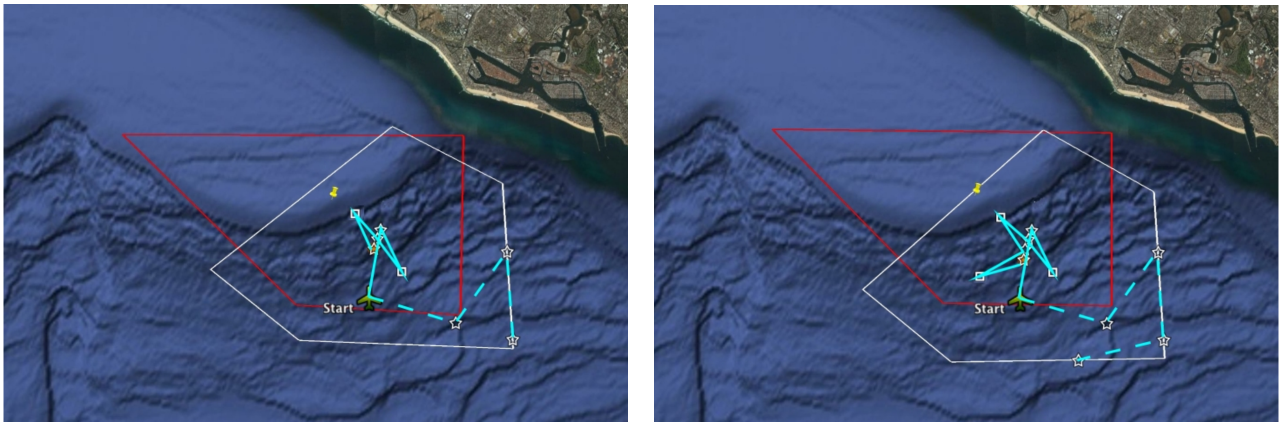


(a) Day 1, $T = 0$ hrs

(b) Day 1, $T = 4$ hrs



(c) Day 1, $T = 8$ hrs



(d) Day 1, $T = 12$ hrs

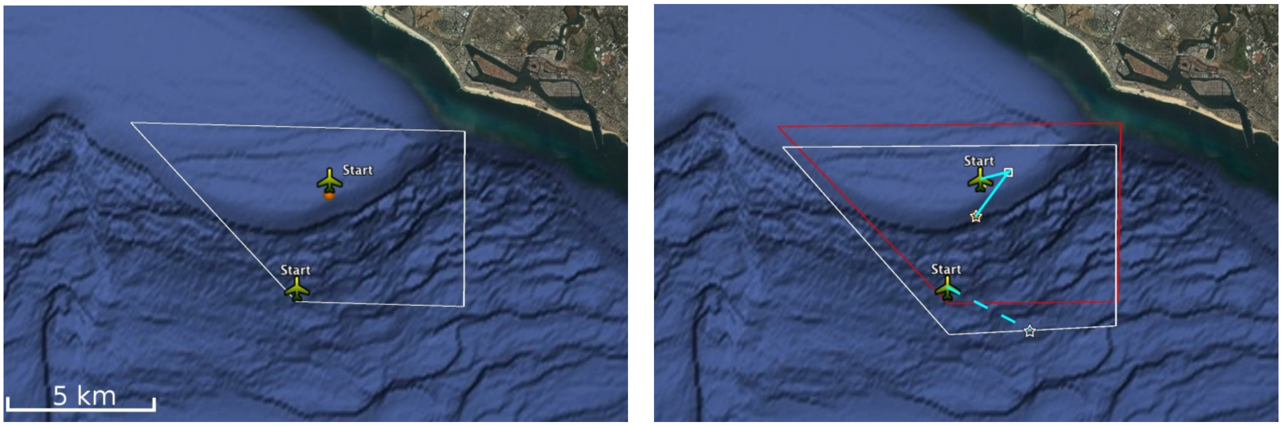
(e) Day 1, $T = 16$ hrs

Fig. 6. Panels 6(a) - 6(e) show the results of the path planning for $0, 4, 8, 12$ and 16 hours, respectively, of day one of the plume tracking mission. The ROMS predicted evolution is given by the white polygon. The HF radar predicted evolution is given by the red polygon. The selected waypoints that define the path are given by the stars. When visible, the predicted centroid of the plume is given by the orange dot. Additional waypoints to be visited by the centroid tracking vehicle are depicted by the squares. The centroid tracking vehicle follows the solid line path and the boundary tracking vehicle follows the dashed line path. Image created by use of Google Earth.

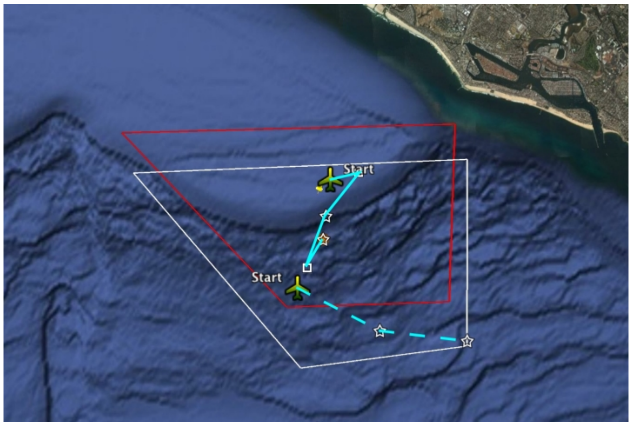
is to demonstrate the full-scale implementation by tracking an actual plume. During early 2010, we are participating in the Southern California Bight Regional Marine Monitoring Program; a regional (Santa Barbara to the U.S.-Mexico border) study conducted once every five years focused on analyzing the importance of natural and anthropogenic nutrient sources to the promotion of HABs. For this study, we will keep gliders on deployment in the waters off the southern California coast performing routine sampling missions to develop a long time-series of data. These gliders will also be lying in wait for the opportunity to be retasked to track an observable plume.

VI. CONCLUSION

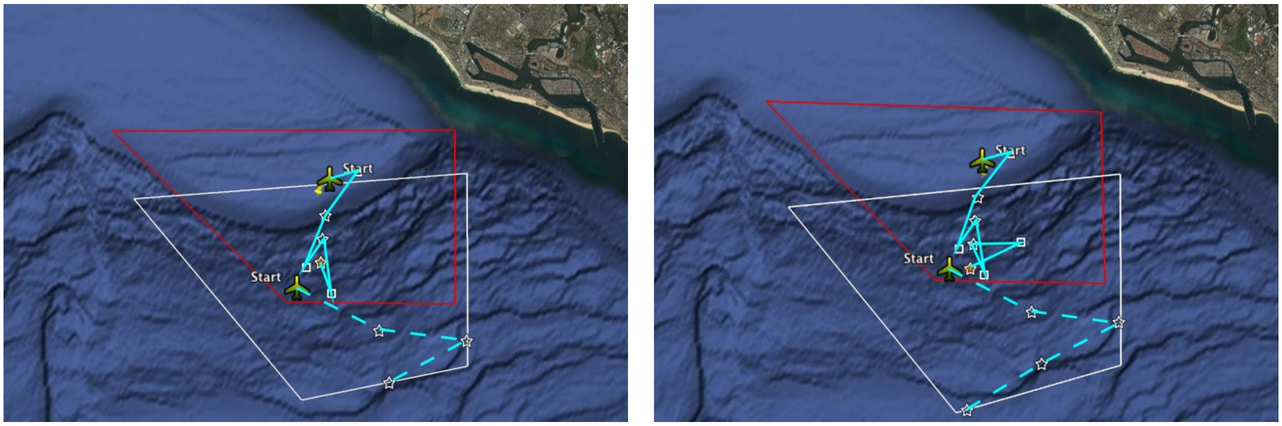
In this paper, we presented path planning results from OPTA-BLOOM-Pred for tracking the centroid and boundary of an evolving plume in the coastal ocean near Los Angeles, CA. We utilized the a plume detection algorithm from [29] for selecting a region of interest for the experiment. The path plan was based on the predicted evolution of the



(a) Day 2, $T = 0$ hrs (b) Day 2, $T = 4$ hrs



(c) Day 2, $T = 8$ hrs

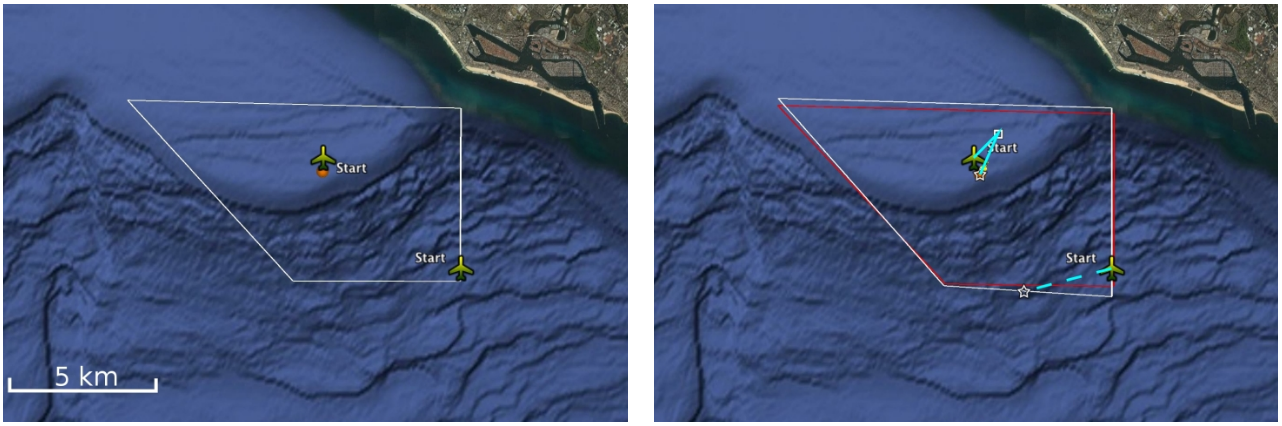


(d) Day 2, $T = 12$ hrs (e) Day 2, $T = 16$ hrs

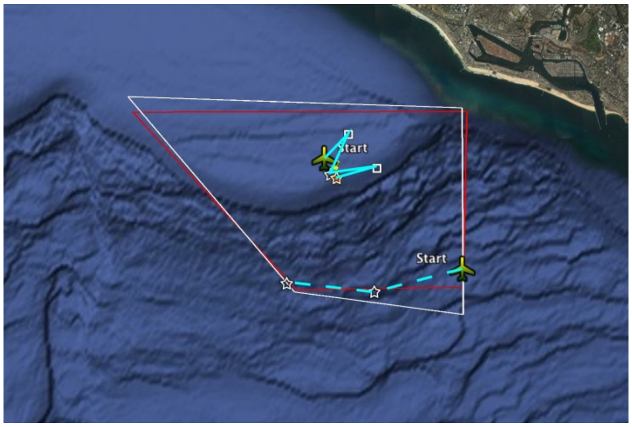
Fig. 7. Results of the path planning for the second day of the plume tracking mission. The ROMS predicted evolution is given by the white polygon. The HF radar predicted evolution is given by the red polygon. The selected waypoints that define the path are given by the stars. When visible, the predicted centroid of the plume is given by the orange dot. Additional waypoints to be visited by the centroid tracking vehicle are depicted by the squares. The centroid tracking vehicle follows the solid line path and the boundary tracking vehicle follows the dashed line path. Image created by use of Google Earth.

plume generated by ROMS. We also implemented the plume advection technique presented in [29] to predict the evolution of the selected plume based on HF radar measurements of surface currents. Results of both prediction techniques and the computed paths were plotted together for assessment of the planning and as a qualitative comparison between the surface currents obtained from each data source.

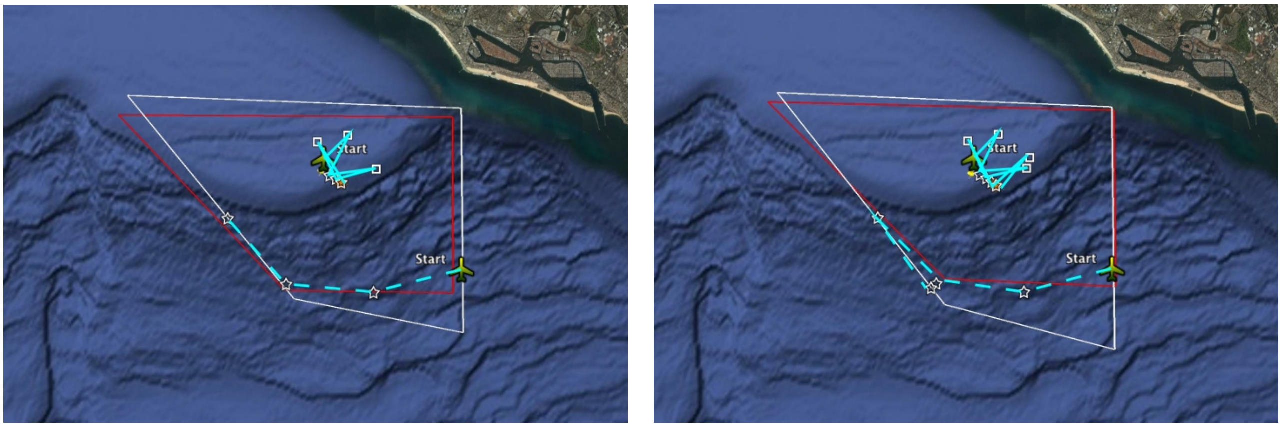
For the plume considered in this paper, we observed good coverage of the internal plume area by the centroid tracking vehicle, but generally poor performance for the boundary tracking vehicle. Both path plans benefited from the fact that the surface current velocities were small in magnitude, both predicted and measured. Although we always planned for the boundary tracker to be on the leading edge of the plume, via ROMS predictions, the direction of the currents given by the HF radar measurements (assumed as ground truth) advected the plume in a different direction. For an actual deployment, this behavior may become a reality. Additionally, we may experience a situation when the magnitude of the predicted current, not just the direction, differs from actual currents. For the path plans proposed here, and considering the sampling platform, this type of situation would result in poor guidance



(a) Day 3, $T = 0$ hrs (b) Day 3, $T = 4$ hrs



(c) Day 3, $T = 8$ hrs



(d) Day 3, $T = 12$ hrs (e) Day 3, $T = 16$ hrs

Fig. 8. Results of the path planning for the third day of the plume tracking mission. The ROMS predicted evolution is given by the white polygon. The HF radar predicted evolution is given by the red polygon. The selected waypoints that define the path are given by the stars. When visible, the predicted centroid of the plume is given by the orange dot. Additional waypoints to be visited by the centroid tracking vehicle are depicted by the squares. The centroid tracking vehicle follows the solid line path and the boundary tracking vehicle follows the dashed line path. Image created by use of Google Earth.

of the glider to track the plume. This motivates further study in examining ROMS predictions for AUV path planning.

The work presented here does neither validate nor condemn the planning methods described, but provides an initial qualitative assessment for their practical implementation. Predicting the evolution of a dynamic ocean feature is a complex task using either an ocean model or measured data. One aspect shared between both methods is that the provided velocity data are not continuous functions spatially or temporally. Thus, there is an interpolation step that is required to generate a continuous evolution. Due to this interpolation, different errors can be introduced to each of the separately generated fields. To this end, work is ongoing to qualitatively assess differences between HF radar measurements and surface velocity predictions from ROMS, as well as assess the validity of ROMS 4-D predictions for both physical and biological measurements, e.g., 4-D current velocity, chlorophyll concentration and temperature. The authors are collaborating for a long-term study of multiple areas along the southern coast of California for this analysis. Additionally, it is of interest to accurately assess the predictive capabilities of ROMS in regions where the bathymetry rapidly changes, i.e., shelf regions in southern California. The plume considered in this paper occurs near such an area of interest, and serves as a preliminary analysis and motivation for a more detailed examination.

Depending on the feature of interest to be studied, the method used for path planning may vary greatly. Currently, there are few established and repeatedly implemented methods for path planning and trajectory generation, e.g., lawnmower pattern, transect lines or a regular grid. However, these techniques are not known to be optimal or even efficient for any given mission. The important aspect of the planning process is making sure that the vehicle is in the best location to collect the data necessary for the problem at hand. In the area of ocean science, this is an open problem. Accurate assessment of separate planning techniques requires simultaneous deployment of vehicles running different missions. From the viewpoint of ocean science, the *better* path for an AUV need not be the fastest or most energy efficient, but it simply has to collect the most interesting data.

ACKNOWLEDGMENT

This work was supported in part by the NOAA MERHAB program under grant NA05NOS4781228 and by NSF as part of the Center for Embedded Network Sensing (CENS) under grant CCR-0120778, by NSF grants CNS-0520305 and CNS-0540420, by the ONR MURI program (grants N00014-09-1-1031 and N00014-08-1-0693) by the ONR SoA program and a gift from the Okawa Foundation. The ROMS ocean modeling research described in this publication was carried out by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

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