Optimal Asset Distribution for Environmental Assessment and Forecasting Based on Observations, Adaptive Sampling, and Numerical Prediction

N.E. Leonard, R.E. Davis, D.M. Fratantoni, P.F.J. Lermusiaux,
J.E. Marsden, S.R. Ramp, A.R. Robinson, H. Schmidt, R. Bachmayer

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1 Executive Summary

The recent proliferation of unmanned air and undersea vehicles has spawned a research issue of pressing importance, namely: How does one deploy, direct and utilize these vehicles most efficiently to sample the ocean, assimilate the data into numerical models in real or near-real time, and predict future conditions with minimal error? A corollary to this central issue would be: What constitutes the minimal necessary and sufficient suite of vehicles required to constrain the models and provide accurate ocean forecasts? Implementation of an appropriate sampling plan requires an assessment of the initial oceanographic situation, understanding the capabilities and limitations of individual vehicles, vehicle coordination and control, and numerical models equipped to assimilate and utilize data which were irregularly sampled in space and time.

The Adaptive Sampling and Prediction (ASAP) program proposed here will directly address the questions above with a focused research effort in and around the Monterey Bay, California. A combination of gliders, propeller-driven AUVs, research aircraft, and ships will be used to adaptively sample three-dimensional upwelling and relaxation processes off Point Año Nuevo at the north entrance to the bay. Quantitative metrics have been defined to guide the adaptive sampling scheme, including a coverage metric for minimizing synoptic error, a dynamic variability metric for maximizing sampling of important physical phenomena, and an uncertainty metric. A modular approach allows metric optimization via cueing on several different measures of ocean variability: a) synoptic observational error minimization using coordinated control; b) feature tracking; c) maximizing the skill of the Error Subspace Statistical Estimation (ESSE) forecast from the Harvard Ocean Model; d) optimal assessment of the ocean acoustic propagation environment; and e) efficient glider navigation using Lagrangian Coherent Structures (LCS).

The unifying scientific goal of the ASAP experiment will be to construct a volume and heat budget for the three-dimensional upwelling center off Point Año Nuevo, CA during upwelling, relaxation, and transition events. The centerpiece of the initial three-year effort will be a month-long field program in the Monterey Bay during June 2006, a month when several events and transitions can be captured. A second major experiment is planned in the Monterey Bay during June 2008. The program will be executed by a multi-disciplinary team consisting of physical oceanographers, marine acousticians, control systems engineers, and numerical modelers. The operational principals thus derived are portable and relevant to a wide variety of space and time scales. The expected project outcome is superior sampling strategies for AUVs of all types, improved data assimilation, and improved model forecast skill, resulting in the most efficient use of these vehicles in operational scenarios.

1.1 Experimental Plan

Three field efforts will be conducted as part of the proposed ASAP project: A pilot study in summer 2005 and the first main effort in June 2006 and the second main experiment in June 2008. The time leading up to the experiments will be used to purchase and test equipment and further refine the vehicle control theory. The year following the main field program will be dedicated to analysis. The 2005 pilot study will be one week in duration and will be used to test equipment, vehicle control, and experimental concepts. Since climatology is not critical for the pilot study, the month of August has been chosen to allow for historically good weather. The information flow between the field team and the numerical modelers will also be fine-tuned during the pilot study. The main effort will be held during June 2006, the month when maximum coastal upwelling historically occurs. The project will be one month in duration to allow the capture of several upwelling and relaxation events. Importantly, previous observations have eluded earlier attempts with fixed assets, which invariably miss important aspects of the dynamics. The ASAP experiment will circumvent these difficulties by using mobile sampling strategies that minimize the sampling/prediction errors and capture the essential elements of

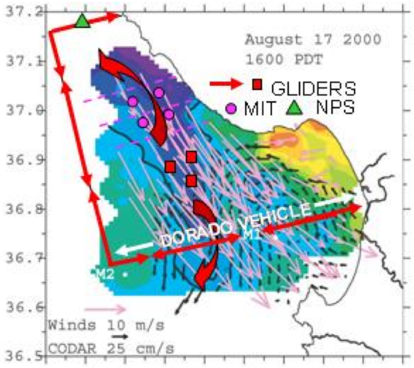

Figure 1: Sea surface temperature from August 17, 2000 as observed from the TWIN OTTER aircraft at an altitude of 133 m. The wind vectors are shown in magenta, CODAR surface current vectors in black. The plot serves as a locator map for the observational plan.

the circulation, regardless of where it may form. The operational plan is described below for the main field effort, with the pilot study a much reduced version of the same concept.

The observational region will extend from the center of the Monterey Bay to just north of the upwelling center surrounding Pigeon Point and Cape Ano Nuevo (Figure 1. (1) Prior to the start of the vehicle deployments, the boundary of the box will be surveyed by ship for purposes of model initialization. This can be done using vehicles in the future, but for now, it is best done by ship as it is not critical to the technology to be demonstrated. The shipboard CTD data also provides an accurate estimate of the prevailing T/S relationships which are useful in glider sensor calibration. A mid-sized UNOLS research vessel such as the POINT SUR will be used for this purpose. Six days of POINT SUR time are requested in summer FY06 for this experiment. (2) As a next step the shallow (WHOI) and deep (SIO) underwater gliders will be deployed using a smaller research vessel such as the SHANA RAE out of Santa Cruz. The vehicles will operate in an adaptive sampling mode in order to optimize the three sampling metrics defined in §**??** (maximize coverage, maximize sampling of significant dynamics and minimize model uncertainty). The three boundaries (Figure 1) will be observed during the course of the experiment according to the need to minimize sampling error and model uncertainty. As appropriate, given the ocean events, some gliders will form cooperative subgroups in order to track the development and movement of features such as cold filaments. These vehicles will not only observe the location of the filaments, they also will track the local change in the heat content within the upwelling filaments. (3) The southern boundary will also be patrolled occasionally by a DORADO propeller driven vehicle, owned and operated by cooperating investigators at MBARI [J. Bellingham and F. Chavez]. This line goes through surface buoys M1 and M2, also maintained operationally by MBARI. These buoys have a very complete suite of sensors including current, temperature, and salinity in the upper ocean and wind, temperature, and solar insolation in the atmosphere. (4) Inside the box, two Odyssey vehicles will cooperate to map both the interior and high-gradient regions of the upwelling center using both direct observations (CTD, ADCP) and acoustic tomography techniques (Figure 1, dotted magenta line). These vehicles are best deployed by the MBARI vessel ZEPHYR, purpose-built for handling these vehicles. (5) A low-flying (33 m) aircraft will map the region to observe the air and sea surface temperatures, dew point, wind stress, and turbulent fluxes of heat and momentum from the atmosphere to the ocean. This will be done using the TWIN OTTER aircraft owned and operated by the Naval Postgraduate School. Two kinds of flights will be conducted. Large-scale surveys require about 5 hours per flight and will be done approximately weekly during the main field effort. The purpose of these flights is provide the synoptic context for the upwelling center and update the SST for the numerical models. The smaller-scale flights will focus on the upwelling center, the region inside the box (Figure 1). These flights will be adaptive based on atmospheric forecasts, and will be clustered around the times of rapid change from the upwelling to downwelling states and vice-versa. About four short flights of 2.5 hours each are envisioned per transition. These may take place at the rate of 2-3 per day when they are most needed. (6) An additional mooring will be deployed along the northern glider line as a calibration check and to make a minimal suite of meteorological observations in that region. This mooring will be complimentary to buoys M1 and M2 on the southern line but will be smaller and less comprehensive. The data will be transmitted to shore in real time via and acoustic modem/wireless internet network. (7) All observations will be delivered to the modeling and adaptive sampling team in real or near-real time. Various modular adaptive control schemes will be applied to the vehicle movements based on both observational data and model output as available, as described in that section of this proposal.

Supplementary observations include the shore-based CODAR HF radar current mapping network, which it is anticipated will cover the entire area by 2006. These instruments provide hourly current vector maps in approximately 1 km range cells. The observations compliment the *in situ* observations by providing complete maps of the surface currents, which allow direct computation of the along- and across-shore correlation scales for data assimilation purposes. Similar calculations can be performed on the aircraft SST to find the correlations scales for temperature. These two data sets provide a very complete picture of how features are moving around within the observation region.

Glider Objectives in the Experiments Buoyancy-driven autonomous underwater gliders provide a flexible, economical and reasonably covert way to maintain observations in an ocean region. They have operational lifetimes of many weeks to many months that are achieved by moving forward slowly at O(25 km/day). Because they surface every few hours for satellite locating and communication, gliders can easily be controlled, either singly or in groups, on the time scale of hours. Therefore, for the purpose of the proposed experiments, direct inter-vehicle communication does not provide significant advantages over the indirect communication and navigation scheme as it was used for AOSN II.

The challenges of low-level glider control are less sophisticated than the scientific and adaptation objectives, but are essential to sustaining effective use of gliders on a 24-hour per day basis. In the 2003 AOSN II experiment, several control errors led to groundings and gliders that were unnecessarily blown off their target tracks by currents. The press of data quality control and operational monitoring of vehicle performance required more than two fulltime people to operate a fleet of 12-15 gliders. Minimal requirements are software support to effectively and accurately control vehicles in response to predicted currents, desired sampling paths and any vehicle anomalies (for example, a failed altimeter or poor communication). An effective control aide would also alert operators to malfunctioning altimeters, impending dangers of grounding, unexpectedly strong currents or any other operating anomalies. Developing such an operating aid will be a collective goal of ASAP.

Because developing and demonstrating adaptive sampling capabilities will be a goal of ASAP we cannot specify the observational array. We can, however, outline the archetypical sampling strategies from which our adaptive arrays will be constructed. To maximize the ability to observe budgets for the Año Nuevo upwelling center we could establish a well-measured perimeter from gliders that patrol relatively short segments (20-30 km) of the perimeter. With net speeds of O(25 km/day), this would give adequate sampling of interfering noise such as that from internal tides and high spatial resolution. At another extreme, much less dense sampling spreading well beyond the upwelling control box would improve the ability of models to predict the timing and structure of ocean responses to varying winds. An even more adaptive sampling strategy might be called ”feature sampling.” Here an unusually significant feature might be detected in model forecasts or by observations and defined to be important target for local high-resolution adaptive sampling. The allocation of gliders to combinations of these prototypical arrays in response to observations, model predictions, and the sensitivity of prediction skill to observation placement will be the goal of adaptive sampling.

The primary glider observations will be frequent sampling of temperature and salinity profiles and vertically integrated velocity obtained from measured velocity through the water and navigation (.e. set and drift). The WHOI 'Slocum' gliders will also report profiles of chlorophyll-a fluorescence and optical backscatter at two wavelengths. The SIO 'Spray' gliders will also measure velocity shear using a 600-kHz Acoustic Doppler Current Profiler. Combining these shear measurements with set and drift will provide absolute velocity profiling that will be of particular importance in defining Ekman transports and the depth to which momentum is mixed in the surface and bottom boundary layers.

2 Project Schedule and Milestones

Period 1	Kickoff Meeting	Spring/Summer 2004 (at Princeton)
Period 2	Progress meeting	Winter/Spring 2005 (at Naval Postgraduate School)
Period 2	Pilot Experiment	August 2005 (at Monterey Bay)
Period 3	Pilot Followup/Review	Winter 2006 (at Princeton)
Period 3	First major experiment	June 2006 (at Monterey Bay)
Period 3	Hotwash Meeting	August 2006 (at Woods Hole Oceanographic Inst.)
Period 4	Workshop	Early spring 2007 (at Princeton)
Period 5	Planning meeting	Summer/Fall 2007 (at Harvard)
Period 6	Second major experiment	June 2008 (at Monterey Bay)
Period 6	Hotwash Meeting	August 2008 (at Naval Postgraduate School)
Period 7	Workshop	Early spring 2009 (at Princeton)

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