

Adaptive Sampling and Forecasting Plan

AOSN-II MB'03 Project

Naomi Leonard
Chair, Adaptive Sampling Working Group

Allan Robinson
Chair, Numerical Modeling Working Group

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I. INTRODUCTION

AOSN-II is an ONR-sponsored, multi-institutional, collaborative research program with the central objective “to quantify the gain in predictive skill for principal circulation trajectories, transport at critical points and near-shore bioluminescence potential in Monterey Bay as a function of model-guided, remote adaptive sampling using a network of autonomous underwater vehicles” (cf. Curtin, T.B., AOSN-II: Monterey Bay Predictive Skills Experiment, Initial Notes, May 21, 2002). The overall goals of adaptive sampling are presented below; a most important purpose of adaptive sampling is to provide data for updating and evaluating forecast models.

In AOSN-II, the underwater vehicle network features a fleet of autonomous underwater gliders. Gliders are small, relatively simple and inexpensive, winged, buoyancy-driven submersibles that have high endurance and are strongly influenced by the currents. Adaptive sampling by the glider network should exploit these capabilities (e.g., by taking advantage of current forecasts to steer gliders efficiently) as well as the opportunity to use the glider network itself as a re-configurable sensor array.

MB'03, the first experiment in the AOSN-II program, is scheduled to take place in and around Monterey Bay in August 2003. There will be a number of data-collecting assets in addition to the glider network. In this document, we describe only the adaptive sampling and forecasting plan for the autonomous underwater glider network. This adaptive sampling and forecasting plan describes the method for directing the glider fleet (10 to 12 gliders) for efficient scientific data collection. The organization of this document is as follows. We begin in Section II by defining feedback control and its use in adaptive sampling. In Section III we describe the goals of adaptive sampling. Finally, in Section IV we list and discuss the five steps that will comprise the glider network adaptive sampling plan. These five steps can be summarized as follows:

- 1. Forecasting with HOPS-ESSE and ROMS.**
- 2. An integrated interpretation of the forecasts, forecast errors and dynamical hot spots (physical and/or coupled physical/biological).**
- 3. Analysis of the circulation fields by Lagrangian Coherent Structures (LCS).**

4. **A collective decision by a Real Time Operations Committee ("War Room") as to what features and regions to be adaptively sampled the next day.**
5. **The implementation of optimal coordinated motion using feedback control.**

II. FEEDBACK CONTROL

Feedback control is an important, new ingredient in the adaptive sampling plan for the AOSN-II MB03 project. It is one of several distinguishing features of this experiment. Feedback is the central tool in the design of automatic control systems and refers to the regular use of measurements of system state in the algorithm for determining the control signal, i.e., the signal for actuating the system. In its simplest form, a control law derived using feedback looks like a function of the error between the desired output signal and the measured output signal. Feedback is unnecessary when the system to be controlled and its environment are perfectly well known. In that case one can compute an optimal plan for control without regard to measurements. Feedback becomes significant when there is uncertainty, disturbances or noise of any kind in the system description. In this case, well-designed feedback algorithms provide robustness, i.e., in the presence of the uncertainty, disturbances and noise, feedback provides guarantees on stability and performance.

In the context of this adaptive sampling plan, the system to be controlled is a glider fleet in a dynamic ocean environment. The dynamics of this system are most certainly fraught with uncertainty, disturbances and noise. Feedback in this context refers to the use of measurements (glider GPS fixes, temperatures, etc.) at regular time intervals to update the motion plan for the gliders. The forecast data (notably the currents) are also used at each motion plan update. In MB'03 there are two relevant time scales for system feedback. One is the daily time scale in which updates are made by a Real Time Operations Committee (see Step 4, Section IV). The second, faster time scale refers to the frequency at which the glider surfaces and establishes communication (on the order of every two hours). At this faster time scale, the feedback control is automatic (see Step 5, Section IV).

The use of feedback control to automatically, on-line update motion plans for gliders in adaptive sampling advances the state-of-the-art from the track lines computed in previous experiments. Feedback here affords the opportunity to use the gliders most efficiently and effectively by allowing them to change plans on-line in response to state and environmental measurements.

Feedback works best with as frequent an update rate as possible. In AOSN-II MB'03, the gliders will not be equipped with acoustic modems and so we are limited to the frequency at which the gliders surface and establish communication (approximately every two hours).

III. GOALS OF ADAPTIVE SAMPLING

There are several adaptive sampling goals, and there are also a number of logistical constraints of the overall operation. In this section, we describe the adaptive sampling goals. The adaptive

sampling plan in Section IV addresses these goals for MB'03 within the constraints of the platform and system operations. The goals for adaptive sampling are as follows:

- A. Sampling should provide the best possible data for the purpose of the scientific hypotheses. I.e., data should be collected in such a way that it is most useful for understanding the science, dynamics and processes associated with upwelling, relaxation, coastal deep-sea interactions and aspects of the coupled ecosystem dynamics and bioluminescence.
- B. Sampling should provide the best possible data for the purpose of providing accurate and efficient forecasts and for evaluating and further developing relevant and useful predictive skill metrics. I.e., data should be collected in regions of greatest model uncertainty and/or in sub-regions of most energetic dynamic activity so that the model can be optimally updated with new data.
- C. Sampling should be most efficient, making best possible use of the unique endurance and maneuverability capabilities of gliders. I.e., current measurements and predictions should be used to advantage by means of feedback control to guide the gliders.
- D. To accomplish goals A-C, sampling should make best possible use of coordination of the glider *network*. I.e., with feedback control, coordination should aid in locating regions of interest (e.g., by means of gradient climbing) and in delivering useful collective sampling data (e.g., by collecting gradient information across fronts).

MB'03 is the first experiment in the AOSN-II program. Accordingly, the adaptive sampling plan aims to make useful progress in a balanced consideration of the above four goals. A long-term goal is for a sustainable, autonomous adaptive sampling system. The introduction of feedback control should make an important contribution toward automating the adaptive sampling plan.

IV. STEPS OF ADAPTIVE SAMPLING PLAN

The steps of the adaptive sampling plan are described below. For further details see Robinson, A., AOSN-II Numerical Modeling Group Meeting, Nov. 13, 2002, Report communicated in email dated Dec. 4, 2002 and Leonard, N., AOSN-II Adaptive Sampling Working Group Meeting, Nov. 12, 2002, Report communicated in email dated December 15, 2002.

1. Forecasting with HOPS-ESSE and ROMS.

In this step, the two models, in parallel, provide forecasts of physical fields and aspects of the coupled physical/biological fields in 3D. The glider data available are assimilated into the forecast models. Ensemble forecasts will be carried out and forecast errors as well as fields will be provided.

2. An integrated interpretation of the forecasts, forecast errors and dynamical hot spots (physical and/or coupled physical/biological).

In this step, the results of Step 1 are integrated to produce a single forecast with forecast errors for use in the analysis, collective decision making and feedback control routines (Step 3, 4 and 5 below) until the next forecast update. Further, an integrated identification of dynamical hot spots is made. The hot spots consist of regions (center, shape, size and distribution) of scientific interest, model uncertainty and energetic dynamical events. The regions will be assigned priorities.

3. Analysis of the circulation fields by Lagrangian Coherent Structures (LCS).

The circulation fields will be analyzed using the method of Lagrangian Coherent Structures (LCS). This consists of running the MANGEN code on the (integrated) forecast 3D current fields from Step 2 (and possibly on the HF radar data). The MANGEN code produces curves corresponding to paths that can serve as efficient channels for glider motion (i.e., paths of maximal flow). The analysis will make use of several 2D computations at different depths (longer-term goals involve full 3D analysis). The results of this analysis will influence the collective decision in Step 4 below. The results will also be used in the adaptive sampling feedback control of Step 5 (i.e., the feedback control algorithms make use of the location of efficient channels as well as the scalar field that MANGEN produces from the vector current field).

4. A collective decision by a Real Time Operations Committee (“War Room”) as to what features and regions to be adaptively sampled the next day.

The Real Time Operations Committee (RTOC) will meet daily and update a three-day plan. The daily plan for the next day will be firm. The daily plan for the second day will be articulated but with final priority to be determined at the next RTOC meeting. The daily plan for the third day will be anticipated to provide continuity for the planning.

Given the results of Steps 2 and 3 above as well as the locations of the gliders, the RTOC will decide which features and regions should be adaptively sampled over the course of the next day(s). This decision will lead to the allocation of the gliders. Typically, 5-6 of the gliders will be used as routine gliders for regional-scale surveys (repeated transects) and 5-6 of the gliders will be tasked gliders used for adaptive sampling of frontal structures. For example, if there are two frontal regions of equal size to be adaptively sampled, 3 of the tasked gliders will be allocated to one of these frontal regions and the other 3 of the tasked gliders will be allocated to the other of these frontal regions. The remaining 5 or 6 routine gliders will get updated transect assignments.

The determination of which regions to be sampled will also include a decision on the pertinent scales to be captured by the adaptive sampling. This will inform choices of design parameters in Step 5 below such as the spacing between gliders that are sampling the same region.

It is likely that on some days, the RTOC will only need to moderately adjust some of the adaptive sampling parameters, e.g., one region of interest might have moved or grown slightly such that the glider allocations are unchanged and only goal point locations need slight modification.

5. The implementation of optimal coordinated motion using feedback control theory.

Given the adaptive sampling features and regions, scales and corresponding glider allocation determined in Step 4, additional design parameters for the optimal feedback control routines will be selected for the next day. This includes the assignment of inter-glider spacing (or the assignment of parameters in the rule for adjusting inter-vehicle spacing in response to measurements). This also includes parameters that define the path of the gliders as they pass through and across the front. For example, if the gliders are to make a sawtooth pattern (in the horizontal plane) across a front, these parameters would define the frequency and magnitude of the sawtooth (or the parameters that define the rule for adjusting these parameters on-line in response to measurements). If the results of the LCS suggest certain advantageous routes, then the associated control design parameters will be set. For example, intermediate attracting surfaces can be defined to be used automatically in the feedback routine.

The optimal coordinated motion plan is then computed automatically on the faster time-scale. This time scale refers to the frequency at which the gliders surface and establish communication. This is expected to be on the order of every two hours. Essentially, when each glider surfaces, it gets a GPS fix and communicates this and some of its measured data (notably recent temperature and dead-reckoned positions) to the central computer. This data is used together with the integrated forecast data to compute an updated path for the glider over the next cycle, i.e., until it surfaces and establishes communication again. The path is computed so as to optimize over the various performance requirements which include getting to the goal point as quickly as possible and moving in a coordinated way with the other gliders. When the gliders are relatively near to a front, the objective of the control will be to balance an attraction to the predicted goal point with the maintenance of a uniform formation also with an attraction along the measured temperature gradient (to correct for error in prediction of the front). The method for computing the path of each member of the fleet is the method of artificial potentials and virtual bodies (APVB). The method takes into account the forecast on the current so that the motion is efficient. The path is then communicated to the gliders in the form of way points. The low level control on the gliders are used to follow these way points.