OBSERVING PROCESSES THAT VARY IN TIME AND SPACE WITH HETEROGENEOUS MOBILE NETWORKS

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The design of a multiplatform ocean observing system involves a variety of decisions, from determining the mix of observational assets, to selecting survey strategies that optimize the effectiveness of the collective system. The challenge is to make the most effective use of available observational tools given the physics of the phenomena under study and the constraints of the platforms and sensors available. In this paper we apply a previously presented sampling theory to the problem of synoptically characterizing Monterey Bay. The baseline observation system used for the analysis is that of the Autonomous Ocean Sampling Network (AOSN) 2003 Monterey Bay experiment, which used a variety of gliders and propeller-driven Autonomous Underwater Vehicles. Our results provide analytical expressions relating survey performance to oceanographic properties and survey system characteristics. We conclude that while gliders are particularly effective at maintaining a continuous presence, faster propeller-driven vehicles can provide a powerful boost to survey system performance, and are particularly well suited to adaptive sampling tasks.

1 Introduction

The ocean varies in space and time, and is comparatively opaque to most remote sensing techniques, making the observation of its interior challenging. Historically, observations have been made by lowering instruments from ships into the ocean's interior. As this is slow and monopolizes a highly capable oceanographic vessel, the use of free swimming Autonomous Underwater Vehicles (AUVs) is attractive. However, the high viscosity of water limits the speed of practical battery-operated vehicles to several kilometers per hour or less. Consequently, surveying interesting sized areas, say tens or hundreds of kilometers on a side, requires many vehicles for synoptic surveys to be accomplished. A very recent development is to use AUVs in large numbers to attempt to obtain a synoptic characterization of the ocean, although the promise of such techniques has been known for some time [1-3]. This paper examines the effectiveness of fleets of AUVs for synoptic surveys. In contrast to earlier, more theoretical work, this paper examines a 2003 field program in Monterey Bay, and uses statistics of variability of Monterey Bay to bound survey effectiveness.

In mid July through early September 2003, the Autonomous Ocean Sampling Network (AOSN) program [4] held an experiment in Monterey Bay (see figure 1). The 2003 AOSN field program brought together a team of investigators from 15 institutions, and with them an unprecedented collection of observation capabilities. In addition to a variety of fixed and crewed observation systems, an extensive fleet of gliders and a

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smaller number of propeller-driven AUVs were deployed in Monterey Bay. The observational array of vehicles was maintained continuously with a maximum of 15 fielded at once, and an average of more than 10 maintained at sea throughout August. Vehicle data was telemetered or brought directly to shore, where it was collected in real-time to feed analysis and real-time modeling systems.

The AOSN 2003 experiment provides the backdrop for this paper. Is it possible to quantify the observational capability that was fielded? While the experiment's goals revolved around demonstrating a real-time coupled observation-modeling system, how effective would the observations have been if the goal had been synoptic surveys? Perhaps most interesting, what can be gleaned from the experience for future experiments?

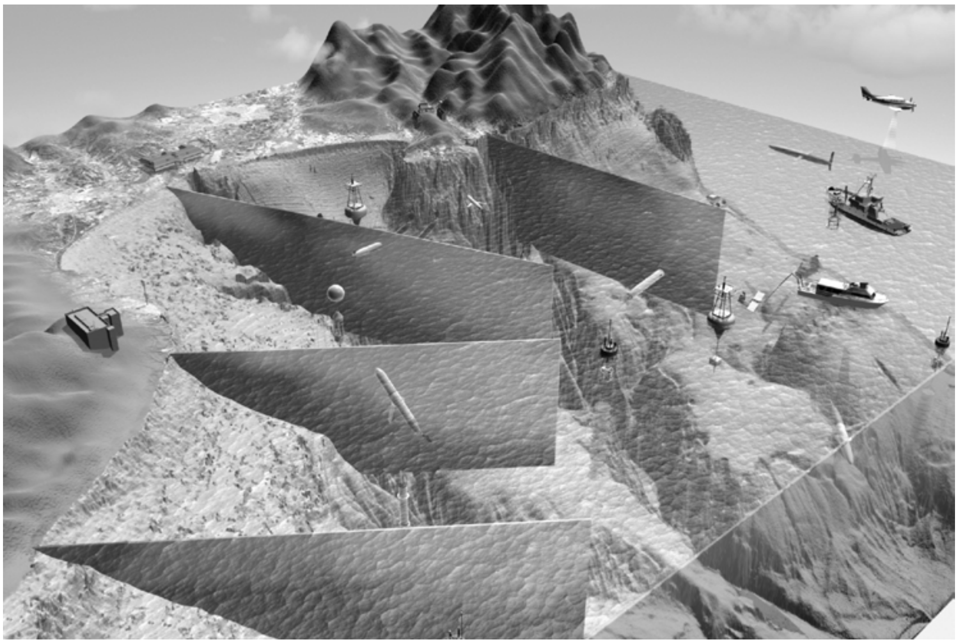

Figure 1: An illustration of the AOSN field program. The vertical sections extending from the shore on the left towards deeper water on the right depict oceanographic sections obtained by glider AUVs. Gliders were used to both patrol the inshore regions where upwelling was expected to have the greatest influence, and the offshore region where the California current interacts with the coastal waters. Faster, propeller-driven AUVs, ships, and aircraft were also employed and are depicted.

2 Variability of the Ocean

Variability of the temperature, salinity, and velocity field of the ocean is strongly dependent on such factors as water depth, seafloor relief, coastlines, and latitude, as well as forcing by the atmosphere, the Earth's rotation, the sun and tides. The ocean is

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typically more variable at its boundaries and less variable in its interior. Ocean processes operate over many orders of magnitude of time and space scales. In general, chemical and biological properties of the ocean have even greater variability than physical properties.

In this paper we build on empirical characterizations of ocean variability. Analysis of Monterey Bay satellite observations by one of us [5] provide correlation lengths and times that can be used as a basis for survey design. In particular, satellite sea-surface temperature measurements for Monterey Bay at the time of the AOSN 2003 field program had a temporal correlation time (1/e folding time) of 2.9 days and a correlation distance of 23 km.

3 Observing the Ocean from a Mobile Platform

When a platform moves through an ocean field that varies in time and space, the platform's measurements mingle temporal and spatial fluctuations of the surveyed process. When the goal is to reconstruct a synoptic field by the non-synoptic samples, the inherent mingling of time and space in the platform's measurements introduces sampling errors that need to be minimized. In this section we outline the nature of the mingling problem, and then frame the synoptic survey problem for multiple mobile platforms.

3.1 Mingling Space and Time

Consider a scalar process (e.g., temperature) $X(t, r)$ where t is time and r is location. Denote its frequency-wavenumber power spectrum density (PSD) by $S_X(\eta,\nu)$, where η is temporal frequency and $\nu=k/(2\pi)$ is spatial frequency (k is wavenumber). As a moving platform makes a line survey at speed u, its measurement of the process X is recorded in a time series $Y(t)$. Denote the PSD of $Y(t)$ by $S_Y(f)$. The mingled spectrum principle [6] reveals the relationship between $S_Y(f)$ and $S_X(\eta,\nu)$:

$$S_Y(f)\Big|_u = \int_{-\infty}^{\infty} S_X\big((f+\nu u),\nu\big)d\nu \tag{1}$$

Thus the mingled spectrum $S_Y(f)$ is the integration over ν of $S_X(\eta,\nu)$ on a line defined by $\eta=f+\nu u$, as illustrated in Figure 2.

3.2 Synoptic Observations with Multiple Mobile Platforms

The fundamental trade-off for a survey with a mobile platform of limited speed is between completing the survey rapidly and obtaining high resolution. For a two-dimensional survey, geometry dictates that the distance the sampling platform must travel is inversely proportional to survey resolution. Thus for an area A, and a survey resolution λ, the total distance a vehicle must cover is $d \cong A/\lambda$. For a vehicle traveling at a speed of v, the total survey duration will be $\tau = d/v \cong A/(v\lambda)$. If the survey resolution is

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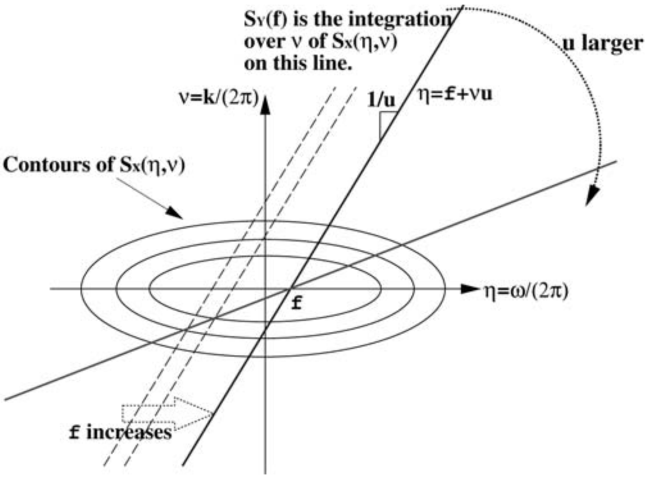

Fig. 2. Illustration of the mingled-spectrum principle. The integration line intercepts the η-axis at $\eta=f$. The integration line slides from left to right to produce the mingled spectrum as function of f. At a higher platform speed, the integration line's slope is smaller.

low, then the survey can be completed rapidly, but the high spatial frequency information is not only lost; it corrupts the obtained low-resolution image via the process of aliasing. If the survey takes too long to complete, then the oceanographic field looks different at the end of the survey than it did at the beginning, which is called temporal smearing.

When multiple vehicles are used to accomplish a survey, the coverage rate is a useful parameter for quantifying survey capability. The cumulative coverage rate corresponds to the sum of the speed of all deployed observational assets, $\sum_{i=1,N} v_i$. Here the cumulative coverage rate is given by the summation of vehicle velocities over the N contributing vehicles, where the ith vehicle has velocity v_i. Thus, if each vehicle can contribute to the oceanographic survey to the maximum of its ability during a survey of duration τ, then the relationship between survey track separation λ and survey duration τ for a given area A becomes:

$$\tau \cong \frac{A}{\lambda \sum_{i=1,N} v_i} \tag{2}$$

What were the coverage rates realized in the 2003 AOSN experiment? Figure 3(a) shows the total number of autonomous platforms deployed as a function of year day in 2003. The majority of these platforms were gliders, with approximate speeds of 0.25 m/s or 0.3 m/s depending on the glider. Propeller-driven AUVs were also used. A typical speed for one of these platforms is 1.5 m/s. Figure 3(b) shows the cumulative survey rate for gliders only, and for gliders and AUVs. The average coverage rate of gliders in the month of August (year days 212-242) was 2.8 m/s. The peak coverage rate, including propeller-driven AUVs, was 7.7 m/s in the same period. Thus propeller-driven vehicles make a substantial contribution, despite their smaller numbers. In effect, because of their higher speed, AUVs more than doubled the coverage rate of the overall system for periods during the experiment. Recalling that AUVs also carry more complete instrument suites than gliders, the effect of AUV deployments can impact other aspects of the observation system as well, although we do not attempt to quantify the benefit of chemical and biological observations here.

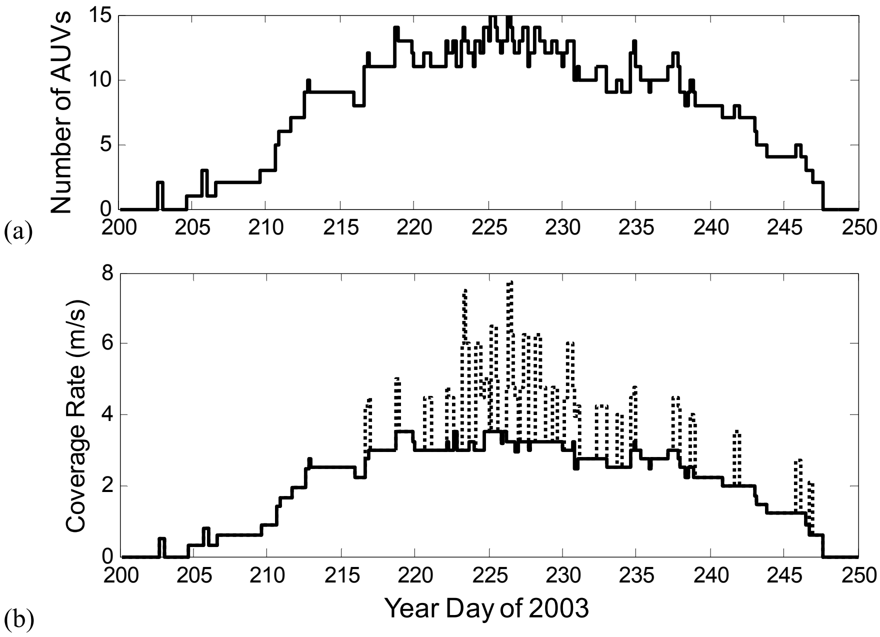

Figure 3: (a) The total number of AUVs, both glider and propeller-driven deployed as a function of year day in 2003. (b) The cumulative survey rate of the gliders only (solid line) and gliders plus propeller-driven AUVs (dashed line) during the same period.

4 Optimal Survey Strategies

4.1 Optimizing Coverage for Grid Surveys

In the preceding sections, we simplified oceanic variability to two parameters: a temporal and spatial correlation length, and we lumped the entire performance of the survey system into a single parameter, the coverage rate. To relate these to survey performance, we draw on previous work [2,3] in which a survey is characterized by an error metric, $\varepsilon_{\text{total}}$, which is the ratio of the energy in the error field to the energy in the 'true' field. The error field is the difference of the reconstructed field and the 'true' field. The range of values is: $0 \le \varepsilon_{total} \le 1$ depending on whether the reconstructed field has been captured accurately ($\varepsilon_{\text{total}}$=0) or not at all ($\varepsilon_{\text{total}}$=1).

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The error parameter is evaluated by obtaining the contributing errors from temporal smearing and spatial aliasing separately, then combining them as though they were statistically independent. The temporal error contribution, ε_τ, is given by integrating the temporal autocorrelation function *R(t)* across the survey interval ($-\tau/2$ to $\tau/2$). The spatial error contribution, ε_λ, is determined by the fraction of the spatial power density spectrum $P(\mathbf{k})$ sampled by the vehicle survey pattern, where the sampled space is Ω and the entire wavenumber space is $\Omega+\Psi$.

$$\varepsilon_\tau = \int_{-\tau/2}^{\tau/2} R(t)dt\,, \quad \varepsilon_\lambda = \frac{\int_{\Omega} P(\mathbf{k})d\mathbf{k}}{\int_{\Omega+\Psi} P(\mathbf{k})d\mathbf{k}} \tag{3.4}$$

The total error for the survey is given by:

$$\varepsilon_{total} = 1-(1-\varepsilon_\lambda)(1-\varepsilon_\tau) \tag{5}$$

While the results above make no assumptions about the nature of the spatial power spectrum or temporal autocorrelation function, a useful approximation is to assume an exponential autocorrelation function in space and time. An exponential autocorrelation function is determined by just one parameter, the correlation length (or time) and is mathematically tractable. This allows us to use the correlation scales provided in Section 2. Assuming a process with a correlation length of λ_o and correlation time of τ_o, we obtain the following error contributions:

$$\varepsilon_\lambda = \sqrt{\frac{\lambda^2}{\lambda^2+\pi^2\lambda_o{}^2}}, \quad \varepsilon_\tau = 1+\frac{2\tau_o}{\tau}\left(e^{-\frac{\tau}{2\tau_o}}-1\right) \tag{6,7}$$

4.2 Survey Optimization Applied to AOSN 2003 Experiment

The expression of survey error as a function of correlation length and time scales allows the analysis of survey performance of the AOSN 2003 experiment. In particular, the objective is to analyze how effective the observations could have been if the platforms had been deployed to optimize a grid survey. In practice, the AOSN experiment had a variety of objectives, and maintaining an optimal array was only one of those goals.

The total survey error for a correlation length of 23 km, and a correlation time of 2.9 days is shown in Figure 4. The two lines crossing the figure show surveys corresponding to the 2003 coverage rates for an area of 10,000 km^2. The dashed line corresponds to the August 2003 average glider coverage rate of 2.8 m/s. The solid line corresponds to the peak coverage rate of 7.7 m/s, which was only realized for a short period.

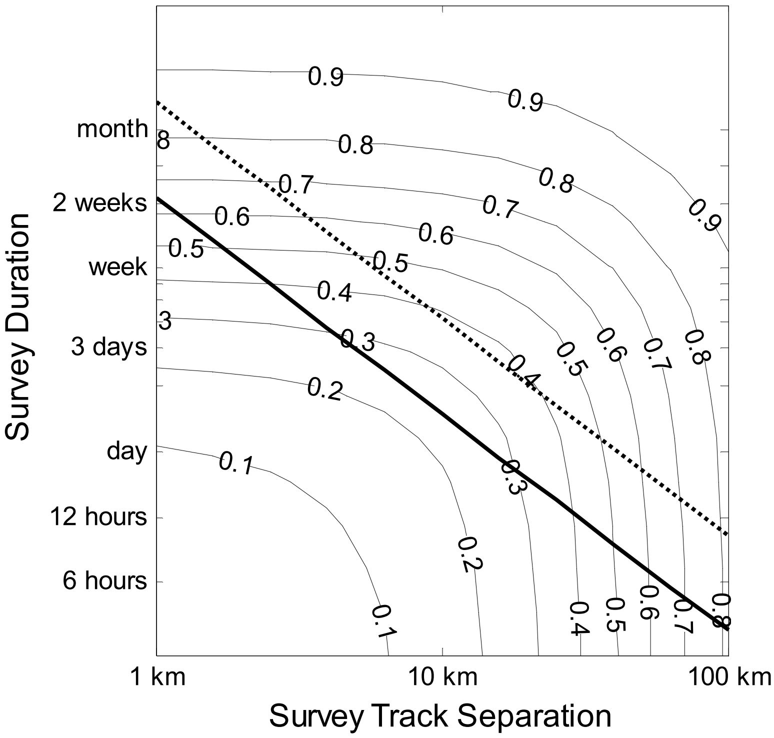

Figure 4: Survey error field for an oceanographic field with correlation scales of 23 km and 2.9 days. The contours show the total error as a function of survey track separation and survey duration. The lines show the range of surveys for a 10,000 km^2 area with coverage rates of 2.8 m/s (dashed line) and 7.7 m/s (solid line).

5 Conclusions

We have demonstrated a methodology for evaluating survey performance when the objective is synoptic reconstruction of an oceanographic field. The performance of the observation system is described in terms of its coverage rate. Estimates for the correlation scales of the oceanographic fields are required to determine the survey error field as a function of total survey duration and survey track spacing. With this information, one can explore design trades such as the effect of varying the survey area, increasing the number of assets, and changing the mix of mobile platforms.

The analysis of the 2003 AOSN field program highlights the effectiveness of the glider array. The propeller-driven AUV contribution is significant during the intervals the vehicles are active, due to their much greater speed. Possible strategies to more effectively employ the propeller-driven AUVs include: a) concentrate use of the AUVs in intervals to obtain periodic high quality surveys, and b) use the gliders to maintain a uniform sampling array, and the faster propeller-driven vehicles to conduct adaptive sampling.

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The strategy to concentrate AUV operations could be particularly effective when the objective is to periodically provide synoptic fields, for example to initialize real-time oceanographic models. Consider the case of the 10,000 km^2 survey of Monterey Bay. For a coverage rate of 7.7 m/s, the minimum survey error would be about 0.24, and the survey duration would be 1.7 days. This could either be accomplished with five propeller-driven AUVs operating at 1.5 m/s, or 26 gliders operating at 0.3 m/s, or, as in the actual experiment, a mix of gliders and AUVs. If the objective is to maintain a continuous synoptic map of the Bay, then the sensible option is to build an all-glider observation system. However, if the desire is to have periodic but high quality surveys of the Bay, AUVs may be a more attractive solution. The most likely scenario is that both a continuous presence and periodic intensive surveys are desired. In this case, a mix of assets will be attractive.

Finally, the results above highlight the need for more sophisticated techniques to obtain synoptic realizations of the ocean. Perhaps the most useful application of this work will be to provide a basis for evaluating the performance of adaptive sampling strategies. This analysis establishes a baseline survey performance against which surveys resulting from adaptive sampling can be compared. Development of proven adaptive sampling techniques is critical, as these will provide the method to make future observing systems more effective and less costly.

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