Autonomous Targeted Sampling of the Deep Chlorophyll Maximum Layer in a Subtropical North Pacific Eddy

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***Abstract*—The overarching logistical challenge in microbial oceanography is acquiring enough samples to provide meaningful scientific interpretation. The number of samples collected during ship expeditions is limited by weather, time on station, and budget. Here we describe a robotic, autonomous vehicle platform equipped with a unique sampling instrument that mitigates some of these constraints. In a joint cruise on the R/V *Falkor*, the Monterey Bay Aquarium Research Institute and the University of Hawaii deployed two of these vehicles in a mesoscale eddy north of the island of Maui. One vehicle collected contextual measurements while circling a freely drifting sampling vehicle. On the sampling vehicle we implemented several behaviors, including sampling every three hours for a 4-day underwater drift while maintaining position within the deep chlorophyll maximum layer (~100m). Results demonstrate the ability to remain with features of interest and point to an exciting future of long-term, directed, persistent sampling.**

I. Introduction

Oceanographers have long known that a complex web of tiny organisms, some harvesting energy of the sun through photosynthesis and others consuming the organic matter produced, fuel the vast majority of life in the ocean. However, revealing the complexities of those chemical transactions in the vast expanse of the open sea is surprisingly difficult: life is not uniformly distributed, and subtle alterations in ocean conditions have profound consequences for "booms and busts" of the microbes that we ultimately depend on. At the most fundamental level, resolving spatial variability in microbial processes requires sampling synoptically in different locations faster than microbial signatures change in time. Accomplishing that task in open waters using traditional ship-based expeditions poses many logistical challenges. Robotic systems, on the other hand, offer an alternative means for accessing and sampling the ocean in ways not possible before, and in ways that uniquely complement the use of manned research vessels. With that in mind, the Monterey Bay Aquarium Research Institute (MBARI) has been working on two synergistic technologies: a 'Tethys-class' Long Range Autonomous Underwater Vehicle (LRAUV; [1]), and an *in situ* sample collection and handling device known as the Environmental Sample Processor (ESP; [2]).

The LRAUV has deployment durations of up to three weeks and is capable of carrying various payloads (Fig. 1). This vehicle, which can fly at 1m/s as well as adjust its buoyancy and drift from the surface to 300m depth, allows for a persistent mobile presence. It is capable of running pre-programmed missions, as well as adaptive targeted sampling missions based on autonomous feature detection and tracking. The standard LRAUV instrumentation suite measures temperature, salinity, light levels, and concentrations of oxygen and chlorophyll.


Fig. 1. MBARI Long Range Autonomous Underwater Vehicle (LRAUV).

The ESP is a "laboratory in a can" that enables autonomous sample collection and processing. Originally developed for the study of harmful algae blooms, the ESP acquires samples via filtration, which can then either be preserved until instrument recovery or analyzed in real-time using DNA and antibody diagnostic technologies. The ESP has been used in open ocean, deep sea and coastal environments (e.g., Fig. 2), but it is a relatively large device.

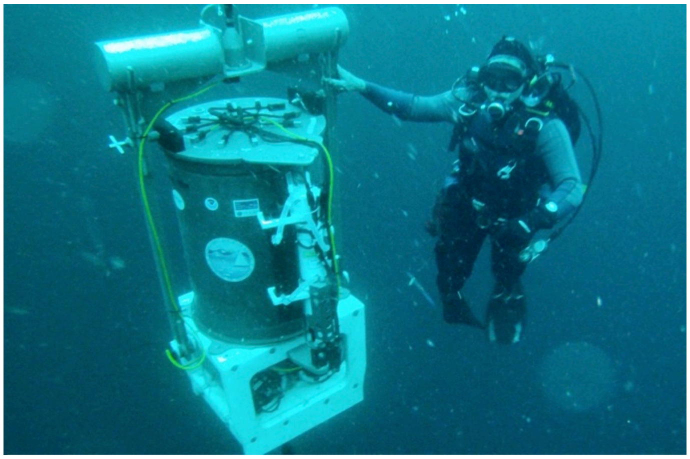
Fig. 2. The original Environmental Sample Processor (ESP) (top), deployed in its pressure housing (bottom).

A new version of the ESP has recently been developed as a payload for the LRAUV. This new instrument is based on the concept of reusable cartridges (Fig. 3), self-contained units that carry all necessary sample collection media and reagents for either sample preservation or real-time molecular analyses. Each cartridge in this deployment carried a filter stack (5.0um/0.2um/0.45 charged) and preservative (RNALater) that was applied to the filter stack after the ESP had filtered up to 2L of seawater. This version of the ESP contains 60 individual cartridges.

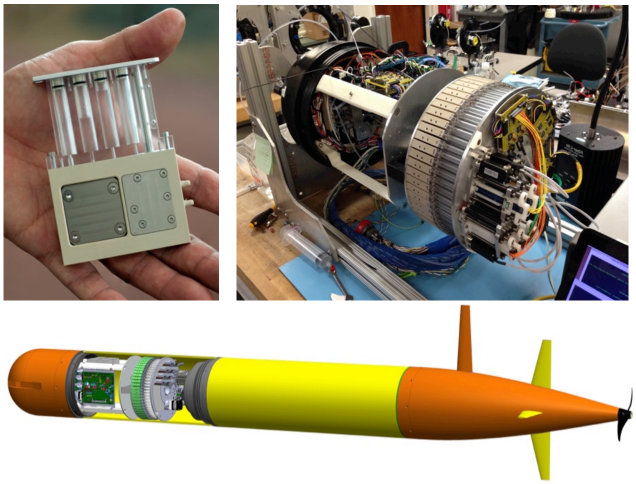
Fig. 3. The latest ESP design is based on cartridges (upper left), 60 of which are loaded around a central ring (upper right). The lower panel shows how the ESP fits within the LRAUV payload bay.

II. Field Experiment

From 17 Mar to 2 Apr 2018 the ESP/LRAUV system was deployed in a collaborative effort between MBARI and the University of Hawaii Simmons Collaboration on Ocean Processes and Ecology (SCOPE) program with operational support provided by the Schmidt Ocean Institute's R/V *Falkor*. The target of this investigation was the deep chlorophyll maximum (DCM; ~100m depth) within a mesoscale eddy north of the Hawaiian Islands. These eddies, which can be quite large (>100km in diameter), are hotspots of biological activity due to their circulation that transports nutrients upward, where greater light intensity enhances photosynthesis. We studied satellite data of sea level anomalies (SLA) for two weeks prior to the cruise to identify and predict eddy locations, and plotted cruise tracks that would transect a selected eddy (Fig 4). The cruise consisted of two ~10 day legs; during both legs, the R/V Falkor stayed in/near the same CCW-rotating eddy as it drifted westward.

During this test of autonomous sampling, we utilized and tracked three named assets: *Aku*—an LRAUV with contextual sensors and an ESP payload, *Opah*—an LRAUV with just contextual sensors, and *Mola*—a Liquid Robotics Wave Glider. All three vehicles were equipped with acoustic devices for ranging and tracking. Each asset was given a specific task, which impacted how long they were deployed. For instance, *Aku* carried the ESP and was instructed to find a feature, drift with it, and sample within that feature (plus sampling above and below the feature for comparison). Once all cartridges had sampled, the vehicle was recovered. *Opah* was programmed to collect contextual data by swimming in a vertical spiral around *Aku*. Finally, *Mola* was instructed to follow *Aku's* drift, providing the R/V *Falkor* with reassurance of *Aku's* location (Fig 5 & 6).

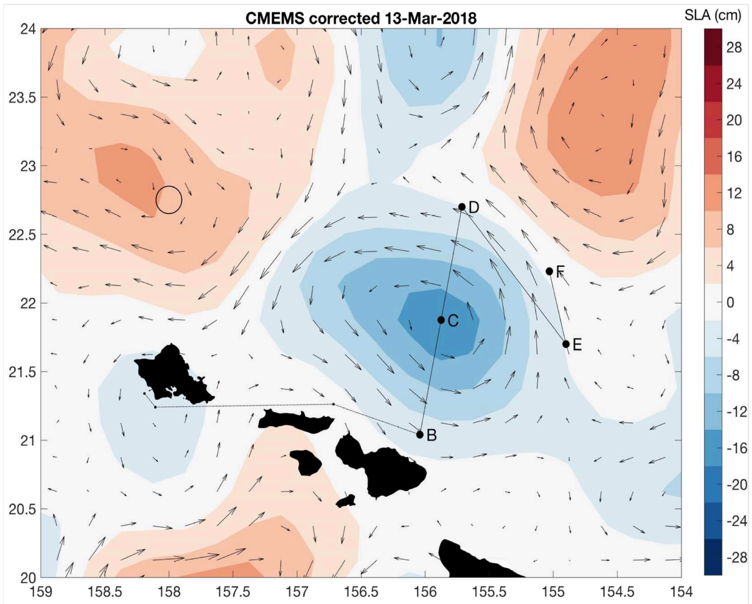

Fig. 4. Typical eddy field plot showing sea level anomaly (SLA), and the proposed ship route with waypoints from Oahu (left) to the north coast of Maui (B) and then bisection of the eddy. Arrows indicate relative current speeds. X/Y axes are longitude/latitude respectively.

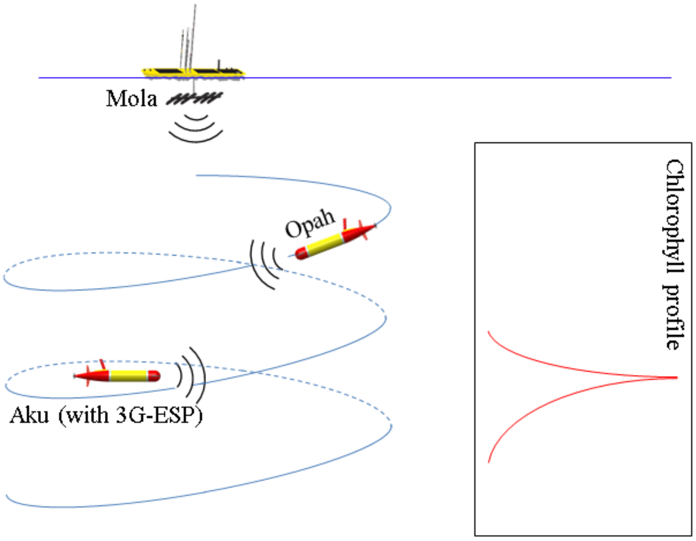

Fig. 5. Typical vehicle behavior during the deployment. *Aku* (with ESP) was instructed to find and passively drift in the DCM (indicated by the Chl profile on right) while sampling every 3 hours. *Mola* (on surface) acoustically tracked *Aku*. *Opah* collected contextual data while flying a spiral pattern around *Aku*.

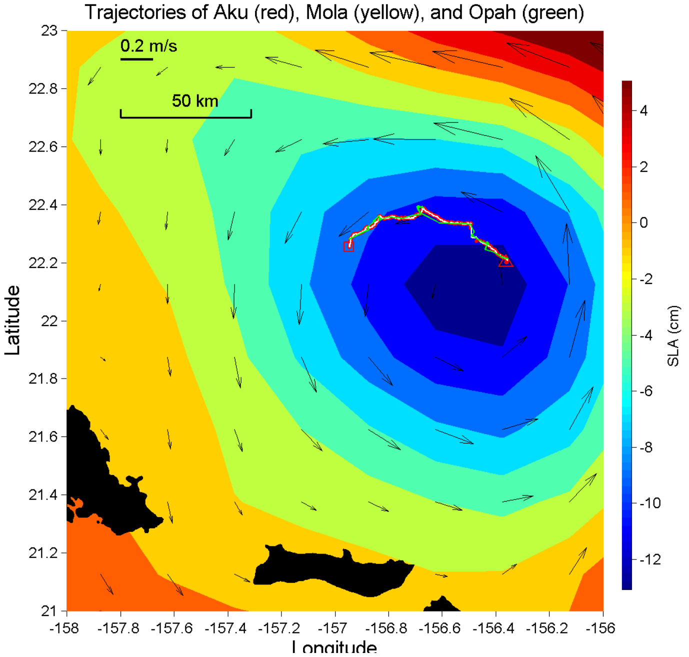

Fig. 6. Vehicle tracks late in Leg 2. Colors show sea level anomaly (SLA). *Aku* (red) was drifting at a depth of ~100m within the DCM with *Mola* (yellow) tracking above. *Opah* (green) was collecting contextual data around *Aku*.

In order to understand the diel cycle of gene expression in microbial populations that inhabit the DCM, we needed a time series of samples from the same water mass over several day/night cycles. Thus, the LRAUV *Aku* was instructed to find the DCM, record the temperature at its center, and then remain (via drifting) at that isotherm. This behavior came about from closed-loop feedback control, and utilized either the buoyancy engine of the LRAUV to move the vehicle up/down, or propeller engagement that had the vehicle fly in ~10m diameter circles.

Over 4 days, *Aku* drifted in the DCM without surfacing. In the first 3 days, it acquired a sample every three hours. Fig. 7 shows the fidelity with which the LRAUV, maintaining its position on the isotherm, followed and sampled the DCM over 3 days. In day 4, *Aku* repeated the cycle of two samples within the DCM (~100m), two samples below the DCM (250m), two samples above the DCM (50m), in order to examine intra-site variability in microbial community structure. These comparison samples, called IAB for in/above/below, were taken after the DCM diel drift samples on both legs.

In total, the ESP collected 52 diel samples (Leg 1: 27 , Leg 2: 25) and 30 IAB samples (Leg 1: 9, Leg 2: 21). All samples are currently undergoing analysis at the University of Hawaii.

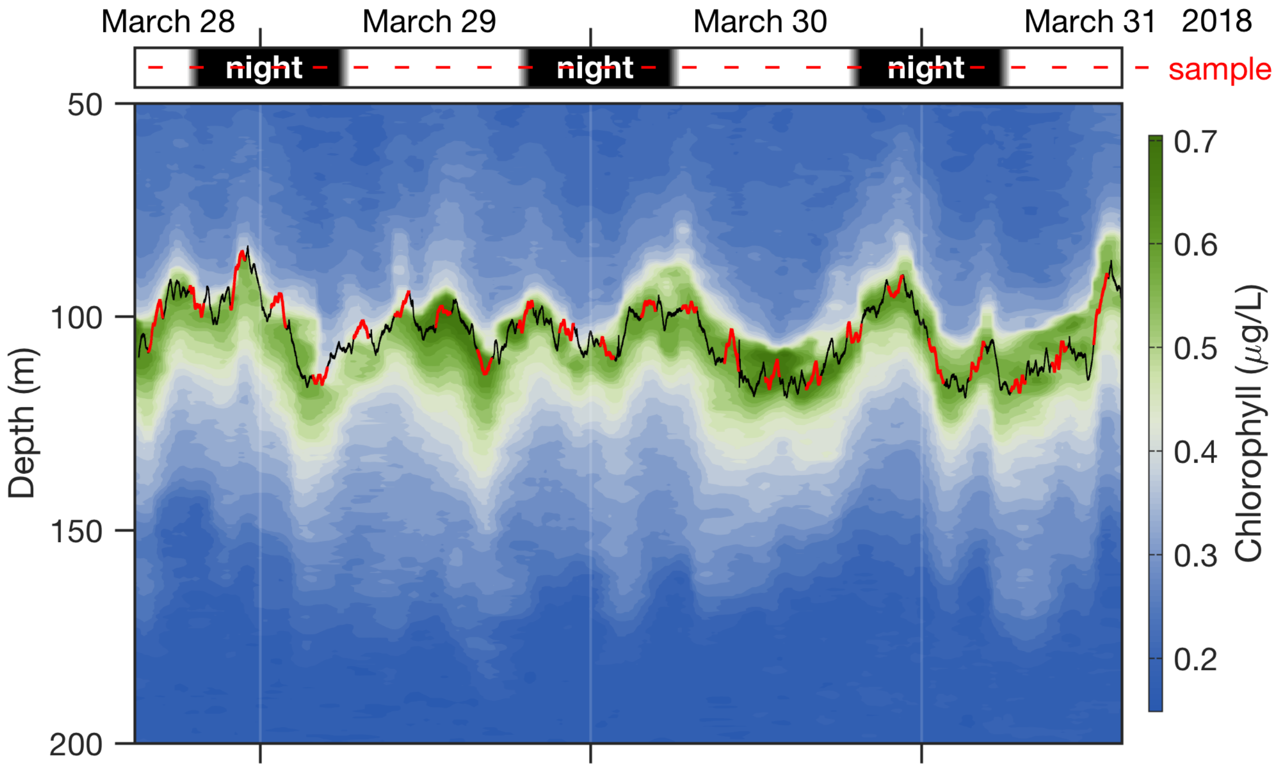

Fig. 7. Sampling regime of ESP/LRAUV for 3 days of a 4-day drift during leg 2 of the R/V Falkor cruise. The LRAUV *Aku* was instructed to find the DCM, and maintain vertical position at the isotherm of the DCM (black/red line). Red portions of line indicate when ESP sampled. LRAUV *Opah* was collecting contextual data (chlorophyll color plot) while circling *Aku*. Note both the DCM oscillation (40-50m) during this time period, and the remarkably close relationship between what *Opah* was measuring contextually, and the position of *Aku* within that feature.

IV. Conclusions

We have demonstrated how a mobile, robotic fleet of vehicles can be used to collect microbial samples in the ocean. In particular, these vehicle/samplers can be programmed to find and remain in certain features for multiple days while being followed and interrogated by other assets for position and status. This automation of sample collection should ultimately provide more samples at less cost than current expeditionary methods. We are on the cusp of a transformation in microbial oceanography; robotic, autonomous sampling (and ultimately processing *in situ*), directed either from shore or from on-board feature-finding intelligence, may finally provide a quantity and quality of the samples that will help unlock the secrets of this vast microbial world.

V. Acknowledgements

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