An Autonomous Vehicle Based Open Ocean Lagrangian Observatory

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***Abstract*— One of the greatest challenges to understanding ecosystem dynamics in the open ocean is predicting where and when hot spots of biological activity exist and then observing and sampling those features for days to weeks, as they move in a complicated trajectory. It is difficult to apply traditional research vessel-based techniques at the relevant temporal and spatial scales when the biological features could be spinning in an eddy, rising and falling on internal waves, or even actively migrating. To address this challenge the Monterey Bay Aquarium Research Institute (MBARI) is developing an observing system based on a collaborating group of autonomous underwater vehicles (AUVs) and an Unmanned Surface Vehicle (USV). Building on the capabilities of the Long Range AUV (LRAUV) and a Liquid Robotics SV-3 Wave Glider, MBARI has begun deploying arrays of LRAUVs configured with complementary sensors that work together as an Open Ocean, Autonomous Vehicle-based Lagrangian Observatory**.

Keywords—Autonomous Underwater Vehicle, Multi-vehicle collaboration, Lagrangian, Ocean Observatory

I. INTRODUCTION

The open ocean is the largest biome on Earth and the phytoplankton within is responsible for generating over half of the oxygen we breathe, yet it is grossly under sampled and not well characterized with respect to ecosystem structure and dynamics [1]. While basin wide sea surface height [2] and estimates of primary production based on ocean color [3] can be measured using satellite remote sensing to detect mesoscale features at the surface, the interior of the opaque ocean requires in-situ exploration. However, satellite remote sensing can provide invaluable insight into where to explore. Embracing the patchiness of the ocean's biology is essential for understanding its ecosystem structure. None of the ocean's predators, from zooplankton to whales, can survive feeding on the average food supply. Instead, they must find concentrations of food and feast for as long as they can, so one of the challenges to ocean observation and sampling is to find and follow these patches, or hot spots. The base of the oceanic food web starts with the microbial biome that is driven by the sun and therefore focused in the sunlit photic zone as they balance the availability of light and nutrients. Seafloor topography and wind driven upwelling along the continental margins are a major driver for ducting nutrient rich water from the depths up into the sunlit surface waters. Far from shore the physical drivers tend to be much subtler. Mesoscale eddies can lift deeper waters into the lower pressure core and therefore stimulate phytoplankton blooms at the base of the photic zone at ~ 100 meters depth.

Fortunately, remote sensing of the sea surface height can identify the position of an upwelling eddy even though the telltale chlorophyll color signature is hidden from view. In the northern hemisphere, counterclockwise spinning eddies generate upwelling and are called cyclonic cold core eddies. While the locations of coastal upwelling are linked to seafloor and continental margin morphology, and are thus somewhat predictable, the blooms that result from upwelling move unpredictably with the water around them and can therefore be difficult to follow after they have been found.

A. Platforms for Mesoscale exploration

Oceanographers have been following and sampling moving open ocean eddies and upwelling plumes from ships for decades and more recently long endurance autonomous underwater vehicles like buoyancy driven gliders [4], and propeller driven AUVs [5]. As access to oceanographic ships is decreasing, these long endurance vehicles have been demonstrating their strengths for persistent observation. The relatively slow speed (~0.3 m/s) of buoyancy driven gliders can pose mission planning and navigation challenges while sampling in areas of high currents, which include open ocean eddies. However, all of the observational tools have a speed problem of some sort to work around. For instance, satellites only occasionally pass overhead, and while it seems as though a ship traveling at 10 knots with a tow vehicle would have a distinct advantage over a buoyancy glider, Rudnick showed in [6] that for a 1300 km long survey section north of Hawaii a glider took 52 days to complete but produced data showing quite similar large scale variability as the data from fast tow vehicle section that only took 3.8 days to complete. To increase the temporal resolution of a survey it is better to collect many observations in parallel using multiple platforms than a single platform moving quickly [7].

If the intention is to observe a discrete feature like a local hot spot of productivity identified from chlorophyll fluorescence, desirable attributes for an observation system could include:

1. Ability to be in the right general area, guided by local knowledge, satellite remote sensed sea surface altimetry, temperature, or ocean color, a site of known upwelling due to local bathymetry, or by following predators like birds, fish or whales.
2. Ability to sample at a high enough vertical resolution to detect layers < 1 meter thick
3. Ability to detect and return to area maxima, rejecting local maxima due to patchiness
4. Ability to lock into and drift with the targeted water mass while observing, e.g. Lagrangian.

Trophic energy propagates from a plankton bloom through to predators at higher and higher trophic levels in a slow process that progresses within a discrete patch of water so the ability to document this progression within the Lagrangian frame would be a valuable attribute of an observing system. Analysis of CalCOFI time series data off Monterey Californian by Messie [8] found that the heterotrophic population growth in an upwelling plume off Monterey, California took 10-15 days to transition from upwelling to maximum biomass. This same two-week observation period is relevant to ocean's biological carbon pump, which is responsible for most of the long-term sequestration of CO_2 into the deep ocean sediments. Smith [9] showed that the bodies and fecal pellets sinking below large salp blooms were the dominant source of carbon into the deep sea at Station M off California.

To observe an open ocean process like the transition from upwelling "bloom to bust" an observation system must have sufficient range to reach a remote study site, perform the mission and return to shore for servicing. If endurance or sample payload is limiting, multiple LEAUVs can be deployed in series as a tag-team on site to ensure continuous sampling.

B. MBARI's Tethys-class Long Range Autonomous Underwater Vehicle (LRAUV)

The Tethys LRAUV is a propeller driven, 30cm diameter, 2.3 m long (3.2 m with 3G-ESP), 120 kg (160 kg with 3G-ESP) vehicle depth rated to 300 meters that uses a 1 liter variable ballast system (VBS) and a movable, 30 kg battery pack and is described in [10],[11]. The propeller drive and VBS allow the LRAUV to stop and hover in the water column. The large battery pack, that is about 1/4 of the vehicle mass, allows the LRAUV to travel about 1000 km at 1 m/s and even farther at lower speeds. The existing science instrumentation is described in Table 1.

Table 1: LRAUV Instruments

	Parameter	**Model**
Core	Temp/Salinity/Depth	Seabird GPCTD
	Oxygen	Seabird SBE 43F
	Chlorophyll/OBS	Wetlabs BB2FL
	Ambient Light	LI-COR LI-192SA
	Currents and speed	TRDI Pathfinder
	Through water comms and inter-vehicle location	Teledyne Benthos DAT
Payload	Bioluminescence	Wetlabs UBAT
	Bio-Acoustic	Simrad EK-80 Mini
	Images and video	MBARI GoPro
	Seawater samples	MBARI CANON 15x100ml
	Collection and analysis of seawater filtrate	MBARI 3G ESP 60 sample
	Nitrate	MBARI ISUS

Ten Tethys-class LRAUVs have been built and the fleet has been operated for over 17,000 hours offshore. The vehicles are operated primarily by science lab personnel using a web-based interface from anywhere in the world for missions that last from 24 hours to over three weeks. Typical missions include a transit phase from just outside the harbor, a sampling phase, and a transit back followed by battery recharge, data download, and water sample processing.

Figure 1: Five LRAUVs, one with 3G-ESP payload, two on launch and recovery systems (LARS) and a Wave Glider SV3

C. MBARI's 3rd-Generation Environmental Sample Processor (3G-ESP)

The 3G-ESP is an *in situ* sample collection and handling device that is essentially a laboratory in a can that enables autonomous sample collection and processing [12]. Originally developed for the study of harmful algal 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 2G-ESP has been used in open ocean, deep sea and coastal environments but it is a relatively large device A new version of the ESP has recently been developed as a payload for the LRAUV [13]. This new instrument is based on the concept of reusable cartridges (Fig. 2), self-contained units that carry all necessary sample collection media and reagents for sample preservation or real-time molecular analyses. A typical configuration carries 60 cartridges that can pump several liters of seawater through each cartridge that holds a fine filter and applies a preservative for subsequent analyses that include qPCR, tag sequencing, and metatranscriptomics. In other configurations another type of cartridge could be used to process the sample for delivery to an on-board analytical module that is able to detect target species or compounds like the domoic acid responsible for some toxic algal blooms. On-board species identification can be used by the host platform to adaptively respond or simply report the detections to shore using satellite communications.

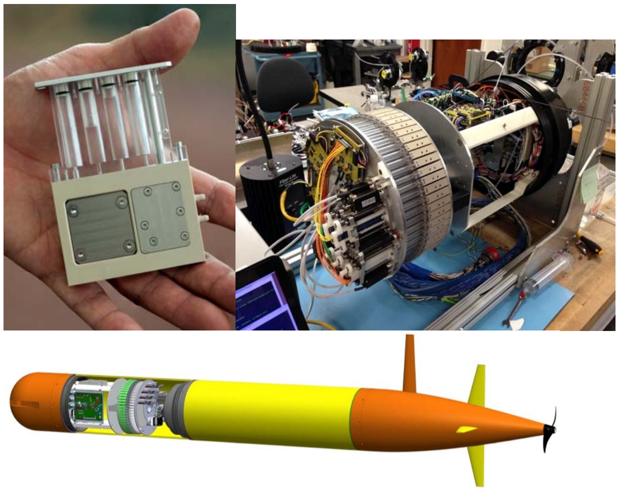

Figure 2: The 3G ESP design is based on a cartridge (upper left),

II. SAMPLING AN OPEN OCEAN EDDY

MBARI recently worked with the University of Hawaii Simons Collaboration on Ocean Processes and Ecology (UH-SCOPE) in the spring of 2018 to investigate the microbial populations that inhabit the Deep Chlorophyll Maximum (DCM) layer within the core of a cyclonic eddy northeast of the Hawaiian Islands. This was an inaugural experiment of a technology transition from MBARI to UH-SCOPE of three LRAUVs and 3G-ESPs for future ship-less operations in the open ocean around Hawaii. This first cruise benefited from operational support from the Schmidt Ocean Institute's R/V *Falkor* so the LRAUVs were delivered on site, and supporting experiments could be conducted in parallel with the robots.

Satellite derived Sea Level Anomaly (SLA) data was used to guide the *Falkor* to a counterclockwise spinning (cyclonic) eddy. Cyclonic eddies usually produce a DCM layer when nutrient rich water is lifted up into the sunlit water. The UH-SCOPE researchers were interested in collecting a time-history of gene expression within the microbial community in the DCM throughout multiple diel (day-night) cycles. An LRAUV mission was conceived to perform the following steps:

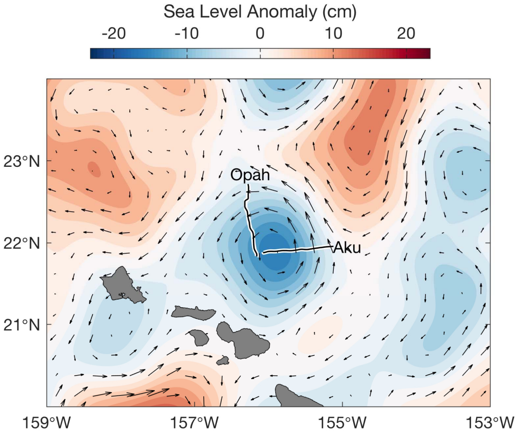

Figure 3: SLA plot showing anti-cyclonic eddies in red and the blue cyclonic eddy described here that includes the section tracks from LRAUV *Opa*h and LRAUV *Aku*

1. Survey the DCM across the eddy – pick a study site
2. Slowly descend to relocate the DCM and identify the temperature at the depth of highest chlorophyll fluorescence
3. Control depth as a function of temperature to ride the isotherm layer at the DCM.
4. Pump ~1 liter of seawater through each filter stack, then preserve the filtrate with RNA-Later, effectively locking the genetic change of the microbes for future analysis ashore.

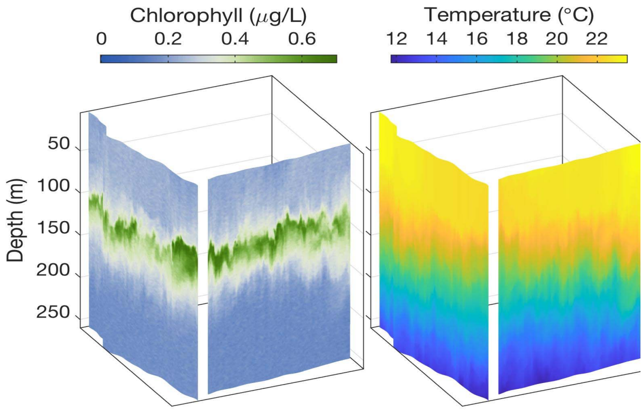

Figure 4: Eddy cross sections of chlorophyll and temperature data from the LRAUV *Opah* and *Aku* tracks shown in Fig. 3.

LRAUV *Opah* was launched on the northern edge of the eddy and commanded to collect a section down to 250m towards the eddy core about 110 km to the SSW (Fig. 3,4). A second LRAUV *Aku* configured with a 3G-ESP was launched on the eastern boundary and commanded to swim west towards the core. Ship transects collecting ADCP current data confirmed the center of the eddy and a surface buoy with a 120m deep drogue was deployed to mark the center of the eddy. As soon as *Aku* arrived at the center she was commanded to dive and search for the DCM, then *Aku* maneuvered and held depth on the autonomously found 21°C isotherm that corresponded to the chlorophyll peak. Once stable *Aku* began collecting archival samples every three hours for about four days.

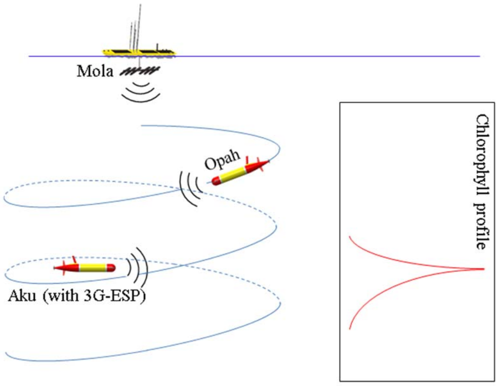

Figure 5: Animation showing multi-vehicle collaboration centered on LRAUV *Aku* which is sampling in the DCM. LRAUV *Opah* is spiraling and profiling around *Aku* to collect contextual oceanographic data. Wave Glider *Mola* autonomously follows Aku, and tracks the position of *Opah* while providing a relay between the subsurface acoustic and above surface radio communications.

A. Tracking and recall capability with the WaveGlider

A Liquid Robotics SV3 Wave Glider *Mola* [14] was deployed to autonomously follow *Aku* using an add-on payload box developed by MBARI to acoustically track and follow submerged assets and provide a gateway between the underwater acoustic and surface radio communications. [15]. A track of one of *Aku*'s missions is shown in Figure 7 and the tracking information was also used to position the *Falkor* close to *Aku* to take CTD casts and collect water samples in roughly the same water as *Aku* was sampling.

B. Contextual data around the sampling site

To address the question of whether *Aku* stayed within the DCM and how the sampling site compared to surrounding areas, a second LRAUV *Opah* was deployed nearby to collect contextual data around the sampling site. *Opah* used an acoustic USBL positioning system to measure the distance, bearing and elevation to Aku, and then used those data to perform a variety of maneuvers to collect water column data around Aku. Figure 6 shows data from *Aku'*s four-day sampling mission with the top panel showing the temperature track from the depth control system. The second panel is the depth and temperature that shows how much depth variation there was. The third panel is the same as the second though with the contextual data from *Opah* overlaid and the fourth panel is depth and chlorophyll, also with *Opah'*s data overlaid, which confirms *Aku* remained in the DCM. The large oscillations near the end are commanded sampling sessions above (50m) and below (250m) the DCM. This basic mission was run four times over the four weeks at sea, clocking over 217 hours underwater with one mid-expedition recharge aboard the *Falkor*.

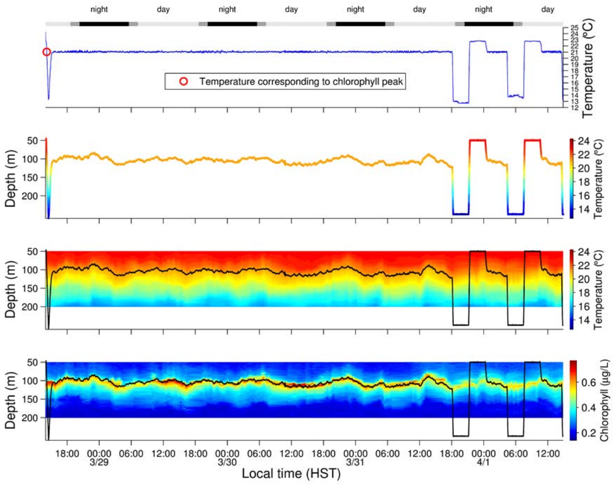

Figure 6: Temperature, chlorophyll and depth verses time for a 4-day sampling mission. Panel one at the top shows *Aku's* temperature control history with the corresponding depth in panel 2. The contextual temperature and chlorophyll data from *Opah* is overlaid in panel 3 and 4 respectively and confirm that *Aku* was sampling in the DCM.

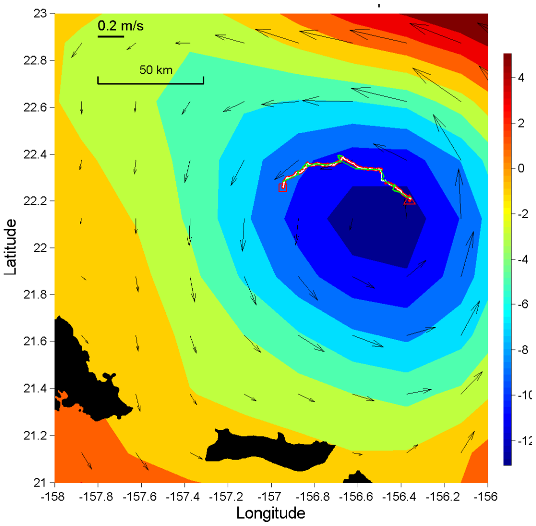

Figure 7: Trajectories of Aku (red), Mola (yellow) and Opah (green) from 3/28/18 to 4/1/18 overlaid on a 4/1 satellite SLA Map. The vehicles moved 100 km over the four-day mission.

III. CONCLUSIONS

An open ocean Lagrangian observatory was demonstrated using two LRAUVs and a Wave Glider. 82 liters of seawater filtrate were collected, preserved and archived in one-liter increments at 3-hour intervals over 9 day-night cycles, from within, above or below the Deep Chlorophyll Maximum layer at the center of a cyclonic eddy NE of Hawaii. The important characteristics of this system are:

1. Long endurance autonomous vehicles
2. On-board autonomy is used for targeted sampling
3. Lagrangian drift to follow a discrete patch of water
4. Multiple vehicles work together to collect samples and contextual data around the sampling site
5. Surface support vehicle to provide accurate subsurface tracking and acoustic/RF gateway.

Future deployments of this system will expand on this basic configuration by adding additional LRAUVs with complementary payloads. By adding a third LRAUV with a bio-acoustic payload, the animals in the deep scattering layer can be exposed and some identified as they migrate up and down through the DCM past the sampling vehicle. The archived samples in the 3G-ESP can be analyzed for the traces of eDNA left not only by the animals viewed in the sonar, but also animals that may have visited the patch days or more before the experiment. LRAUVs fitted with cameras and lights can maneuver in formation with the bio-acoustics vehicle to provide visual validation and a vehicle equipped with a bathyphotometer can identify some of the animals by the flash patterns of their bioluminescence, as most of the open ocean animals generate some sort of bioluminescence. This array of collaborating autonomous vehicles can work hundreds of kilometers from land, without a ship and be controlled by scientists, not just the engineers that developed them. Future deployments of collaborating groups of autonomous vehicles working over the horizon can be tasked to investigate questions about the biology of everything from microbes to whales, physical and biogeochemical processes that require high spatial and temporal resolution or adaptive sampling of distributed and simultaneous measurements. We have shown here how this system was used to observe a unique patch of water in a Lagrangian reference frame for extended time periods that were appropriate to document the changes in the biome.

ACKNOWLEDGEMENTS

This work would not have been possible without support from David and Lucile Packard Foundation through MBARI, the National Science Foundation (OCE-0962032 and OCE-1337601), the Simons Collaboration on Ocean Processes and Ecology (SCOPE) and the Schmidt Ocean Institute for ship time. Chris Scholin, Chris Preston, Roman Marin, Jim Birch, Tom O'Reilly, Bill Ussler, Brent Roman, Ed DeLong, Dave Karl, Sam Wilson, Gabe Foreman, Steve Poulos, Anna Romano, Hans Ramm, Benedetto Barone and the crew of the *Falkor* all contributed to the success of this experiment. Jon Erickson, Ed Mellinger, Denis Klimov, Brent Jones, Carlos Rueda, Paul Coenen and Jim Bellingham are all significant contributors to the LRAUV.

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