Science-driven Autonomous & Heterogeneous Robotic Networks:

A Vision for Future Ocean Observations

from the KISS study

Satellites to Seafloor:

Autonomous Science to Forge a Breakthrough in Quantifying the Global Ocean Carbon Budget

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I. Technical Development Participants

The following personnel participated in the “Science-driven Autonomous & Heterogeneous Robotic Networks” technical development study. This project supported three junior researchers (one postdoctoral scholar, one Ph.D. candidate and one masters candidate) and provided a summer research experience for a local high school student[1].

Andrew Thompson, California Institute of Technology, *team lead*
Steve Chien, Jet Propulsion Laboratory, *team lead*
Yi Chao, Remote Sensing Solutions, *team lead*
James Kinsey, Woods Hole Oceanographic Institution, *team lead*

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Dave Fratantoni, Remote Sensing Solutions & Woods Hole Oceanographic Institution
Carrie Zhang, University of California at Los Angeles

Brian Claus, Woods Hole Oceanographic Institution, *postdoctoral researcher*
James Kepper, Woods Hole Oceanographic Institution, *graduate student*
Zachary Erickson, California Institute of Technology, *graduate student*
Warren Yuan, Arcadia High School (supervised at Caltech), *high school student*

[1] Warren Yuan will be attending Princeton University in the fall of 2018 and is planning to major in Environmental Engineering.

II. Executive Summary

a. Program Goal

The goal of this project was to develop the first algorithms that allow a heterogeneous group of oceanic robots to autonomously determine and implement sampling strategies with the help of numerical ocean forecasts and remotely-sensed observations. Two-way feedback with shore-based numerical models, tested in the field, had not previously been attempted. New planning algorithms were tested during two field programs in Monterey Bay during a 12-month period using three different types of autonomous vehicles.

b. Key Areas of Accomplishment

The three primary successes of the project that involved collaboration across all of the institutions involved in this project include:

- **Development of single- and multi-asset re-tasking algorithms for frontal crossing maximization;**
- **Validation of the above algorithms on multiple deployments across multiple vehicle types (gliders, long-range AUVs, Iver AUVs);**
- **Dissemination of results through peer-reviewed science and engineering journals and presentations at major geophysical conferences.**

Additional accomplishments focusing more directly on the expertise of each institution include:

Caltech

- Multiple, multi-glider deployments in Monterey Bay capturing the evolution of the shelf/slope frontal system across major upwelling events;
- Maturation of physical diagnostics required for front detection and tracking algorithms, and automation of derived hydrographic properties, e.g. spice, potential vorticity;
- Analysis of potential vorticity structure and the role of submesoscale dynamics on tracer advection and subduction in Monterey Bay.

JPL

- Maturation of ocean model predictive control algorithms both as part of the above frontal crossing algorithms as well as for station keeping;
- Validation of the above predictive control algorithms for glider control on multiple deployments and with two glider vehicle types.

RSS

- Development of a 3-domain nested model using ROMS with increasing spatial resolutions from 3km to 1km and 300-meter;
- Delivery on-time of daily ROMS forecast in a timely manner during the field experiment period;
- Validation and analysis of both the ROMS hindcast and forecast using in situ and satellite observations.

WHOI

- IVER deployments and operations for short time scale events on shelf;
- Maturation of IVER technology for multi-AUV deployments including communication, mission planning and data logging upgrades;
- Development and validation of next generation multi-AUV navigational methods for small, inexpensive AUVs.

III. Introduction and Background

In 2013-2014, the Keck Institute for Space Studies (KISS) conducted a study, Satellites to Seafloor, to investigate the premise that autonomous and coordinated groups of heterogeneous mobile robots, working in cooperation with remote sensing and shore-based data assimilation, could significantly advance our ability to obtain the oceanic observations needed to quantify the global ocean carbon budget. The study brought together 32 scientists and technologists from universities, space and oceanographic research institutes, and industry over two workshops. The KISS study focused on identifying the observational capabilities required to quantify upper ocean dynamics that influence the marine carbon cycle; assessing the current capabilities in the ocean robotics, autonomous science, and satellite communities; determining the necessary advances to obtain the desired observations; and developing a collaborative research agenda aimed at solving these problems.

That study determined that the understanding of three key marine carbon cycle processes would benefit from improved observational capabilities: (i) the export of carbon from the surface ocean, including its fine horizontal variability; (ii) the evolution of carbon through the twilight zone (sub-euphotic layer) where the bulk of remineralization occurs; and (iii) the flux of carbon through the seafloor and the identification of physical processes associated with its variability. Improved resolution of the ocean's physical, biological, and biogeochemical properties in three dimensions require in situ measurements, but ship-based surveys were characterized as expensive, of limited endurance and challenging to carry out in remote environments.

A central concept that emerged from the study was the use of fleets of mobile heterogeneous platforms working in a coordinated manner to obtain observations over a broad range of temporal and spatial scales. The heterogeneous robots, which could include autonomous surface vehicles (ASVs), autonomous underwater vehicles (AUVs), Long-Range AUVs (LRAUV), and ocean gliders, communicate with each other via wireless communications (acoustic or optical methods for in-water telemetry; satellite communication for in-air) and with data assimilation efforts on shore. In situ data from these platforms, along with remote sensing data and model output is assimilated on-shore and used to update estimates of scientific parameters and inform decisions about future sampling strategies. The outcomes of these decisions are goals for future observations, which are communicated to the robots. Based on these goals and the state of the robots and sensors (e.g., vehicle and sensor health, remaining power), the robots autonomously re-task and reconfigure themselves to achieve these goals.

Use of heterogeneous robotic arrays has a number of advantages, including the ability (1) to equip more sophisticated platforms with larger, more power consumptive sensors; (2) to match vehicles of differing performance characteristics (e.g., range and speed) to the temporal and spatial scales of different processes; and (3) to allow smaller cheaper vehicles to obtain high density measurements and serve as sentinels that inform larger, more capable vehicles.

Autonomy is critical for a number of reasons. First, the vast amount of required data — both science (necessary for data assimilation) and engineering (necessary for vehicle constraint information) — may exceed available telemetry bandwidth. Thus information needed to make decisions will reside at sea and require autonomous decision-making. This would allow more critical data, specifically, science data, to be transmitted ashore. Second, under the current paradigm, humans are still involved in most operations. As the number of robots grows, this approach will become unsustainable and requires autonomy to relieve humans of many tasks. This study seeks to increase the level of autonomy such that humans will focus primarily on tasks to which they are uniquely suited, such as interpretation of assimilated results and high-level decision making. This vision is not entirely new — seminal papers by (Curtin *et al.* 1993, Stommel 1989) spoke to the vision of large-scale, coordinated autonomous sampling 25 years ago. However, an end-to-end implementation has yet to be achieved. Numerous efforts, both past and ongoing (see references in Thompson *et al.* 2017), continue to progress toward this goal and have advanced multiple technologies such as marine robots, in-water communications, and autonomy.

While many of the elements necessary for adaptive sampling with multiple heterogeneous ocean robots have been previously developed and tested in the field, no previous project to date has integrated all of these elements into a single experiment. The primary project goals were:

1. Design a framework in which a fleet of heterogeneous ocean robots, both surface and underwater, receive directives from shore-based models that consider the health, navigation, and communication characteristics of the robots.

2. Develop algorithms to autonomously determine sampling strategies to maximize information gain from in situ observations using shore based data assimilation and forecasting models.

3. Implement and assess the technologies in annual multi-week experiments in which multiple AUVs and gliders cooperatively observe the physical and bio-geochemical dynamics of the upper ocean.

4. Combine data from ocean robots and remote sensing platforms with a Regional Ocean Modeling System (ROMS) to autonomously plan future robot trajectories.

Ultimately, this project provides solutions for in situ ocean monitoring that complements NASA space-based measurements for ocean science. Specifically, in situ planning algorithms can be used to collect measurements that enhance NASA observations of sea surface temperature, ocean color, sea surface height and salinity. These in situ measurements can be incorporated into climate models with broad reaching implications for predicting sea level rise, ocean heat uptake and ocean carbon storage. These new algorithms may also reduce validation costs for NASA ocean missions. Finally, these algorithms provide a framework for designing exploratory missions to extra-terrestrial ice-covered oceans with multiple autonomous vehicles.

IV. Outcomes

a. Results of the technical development program

i. Field Programs

During this technical development program, two intensive field programs were carried out in 2016 and 2017. Here we focus on the efforts during the 2017 experiment due to the larger number of vehicles in the water. The field program consisted of multiple experiments with a heterogeneous fleet of assets operating from April 12 through June 21. These experiments consisted of testing front detection and tracking technique developed utilizing multiple vehicles to delineate and track a dynamic ocean front. The field program was performed in collaboration with the Monterey Bay Aquarium Research Institution (MBARI) Spring 2017 CANON program. Figure 1 shows a map of the field program region.

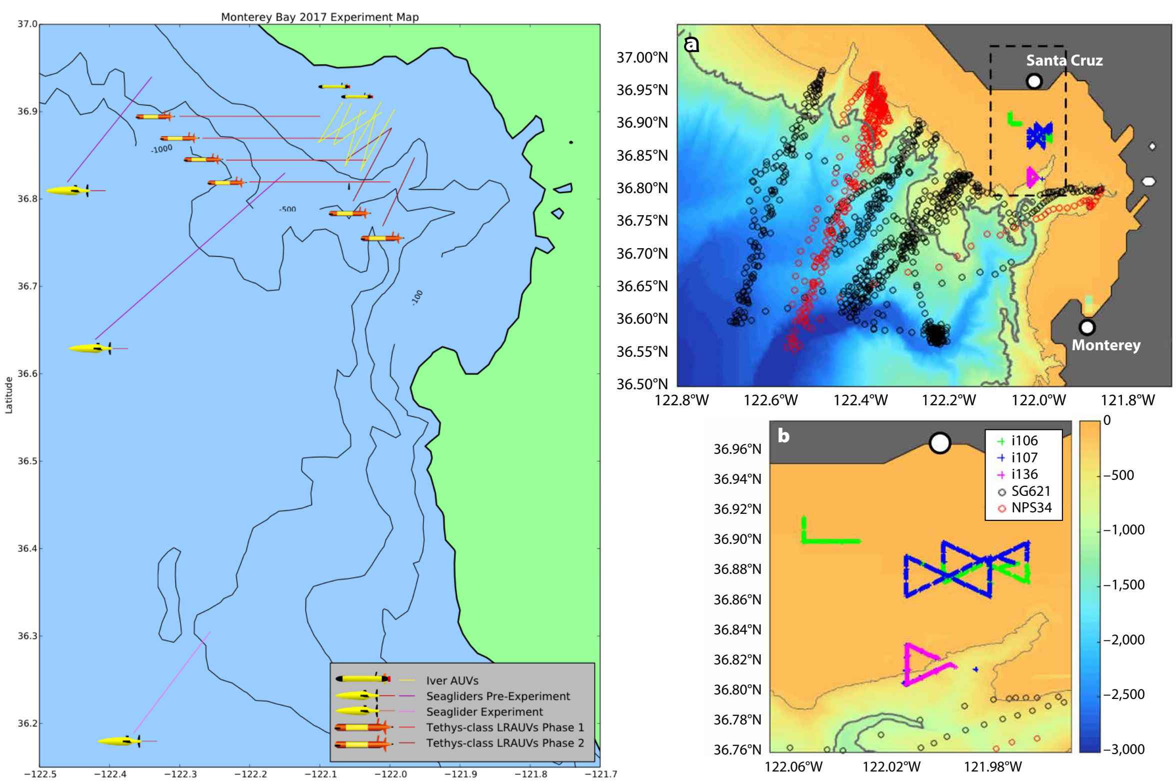

Figure 1. *(Left) Maps of the Monterey Bay, location for the 2016 and 2017 KISS field programs. The operation regions of the Iver AUVs (2016 and 2017), Seagliders (2016 and 2017), and Tethys-class LRAUVs (2017) are shown. (Right) Inset maps showing the position of the glider (circles) and Iver AUV measurements in 2016.*

The first experiment utilized the Tethys-Class Long Range Autonomous Underwater Vehicles (LRAUV), developed and operated by MBARI. This experiment consisted of two phases. The first phase occurred between May 01 and May 04, 2017. During this period we tested the front tracking algorithms developed for this effort. Four LRAUVs were used in total, one under direct control of the KISS planner and three providing data in order to inform the decisions for the planner. An onboard upwelling front detection technique developed by MBARI was used during this phase of the experiment. The second phase of the experiment occurred on May 07, 2017. Once again, the front delineation and tracking techniques were tested. Two LRAUVs, both under control of the KISS planner, were used. The upwelling front detection was replaced with a lateral gradient front detection technique developed by the KISS team.

The second experiment consisted of two Iver AUVs, owned and operated by Woods Hole Oceanographic Institution (WHOI). This experiment occurred on May 04, May 09, and May 11, 2017 on the shelf in Monterey Bay. The purpose of this experiment, once again, was to test the front tracking algorithms. May 04 consisted of a system checkout, preparing for the later deployment days. On May 09 and May 11 the front tracking algorithms was tested, with each vehicle completing two transects per day. During this experiment the lateral gradient front detection technique developed by the KISS team was used.

The third and final experiment consisted of a single Seaglider, provided by California Institute of Technology, and operated off the coast of Point Sur, California. The experiment occurred from June 07 to June 21, 2017. During June 07 to June 15 the glider was in a region of strong surface currents, preventing significant forward movement. The target region was relocated and the glider successfully operated from June 15 to June 21. During this time the front tracking algorithms were tested with the lateral gradient front detection developed by the KISS team. Beyond the front-tracking activities, the ocean gliders were operated continuously between 12 April and 24 July collected science data that will be used to better understand transitions in ocean surface and bottom boundary layers across major upwelling wind events.

In addition to the primary field program, part of the KISS team assisted in a station keeping experiment for the (Surface Water and Ocean Topography) SWOT mission from July 01 to July 19, 2017. This experiment leveraged software developed for the KISS program in order to improve the station keeping abilities of underwater gliders. This experiment used the Seaglider from Caltech and a Slocum Glider provided by Rutgers University.

ii. Planning Algorithm Development

A planning algorithm to perform front delineation and tracking was developed for the 2017 field program. The algorithm development consisted of two main components, front-crossing detection using lateral gradients and front-geometry estimation and vehicle retasking using the front-crossing detection information from multiple vehicles.

The lateral gradient front detection algorithm was developed as an extension to the work performed in 2016. The goal of this algorithm is to identify a front location in data from a single vehicle transect. While during this field program temperature data was used, other oceanographic properties are also suitable. This algorithm operates as follows. Data from a single transect is gridded and smoothed, then the temporal gradient is calculated. We assume that the distance is linearly correlated with time. The gradient is summed over some target depth range and the standard deviation is calculated. A potential front candidate is identified when this summed gradient value is greater than a previously specified number of standard deviations. A front is then selected from the candidates based on the lateral size of the front boundary region. This algorithm allows the planner to make decisions based on the data received from previous vehicle transects.

In order to utilize this information, another algorithm was developed in order to track an ocean front as it evolves over time. This algorithm uses the front crossing data from multiple vehicles equally spaced on near parallel transects. The front is estimated by fitting a linear model to the latest front crossings for each vehicle. When a transect for a specific vehicle is completed, the vehicle is retasked with a new transect that is orthogonal to the latest estimated front. During the 2017 field program the lateral gradient front detection technique developed by the KISS team as well as another upwelling front detection technique developed by MBARI and implemented onboard the LRAUVs was used. Figure 2 shows an example of the lateral gradient front detection algorithm as well as the front tracking algorithm in use for the Iver AUV experiments during the field program.

In addition to the planning algorithm, an interface between each vehicle and the planning software was developed. This interface allows the planner to receive GPS and scientific data from the vehicle and send commands to the vehicle with no human intervention.

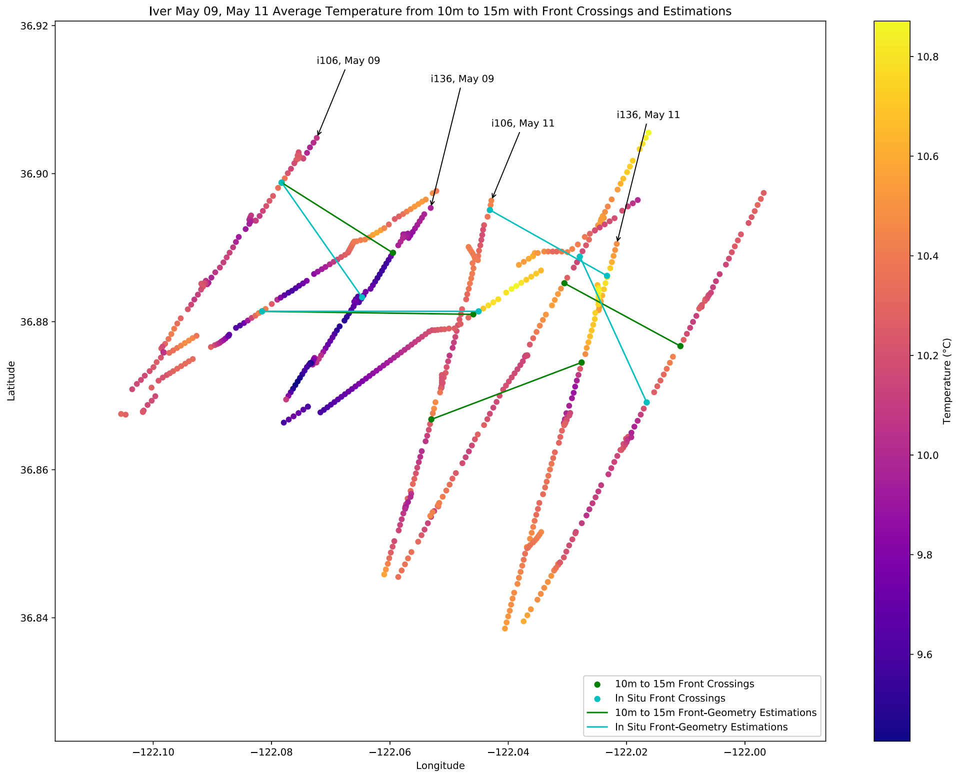

Figure 2. *Map view of the temperature averaged from 10 to 15 meters for the Iver transects on 09 and 11 May, 2017. Front crossings and front-geometry estimations used during the experiment are indicated with a blue dot and blue line respectively. Front crossings and front-geometry estimations using data from 10 meters to 15 meters during the experiment are indicated with a green dot and green line respectively. The start location for each vehicle for each day is labeled.*

iii. Model development

During the KISS field experiments, a ROMS-based coastal ocean modeling and data assimilation system is used to provide nowcast and forecast on the daily basis. The innermost ROMS domain covers the greater Monterey Bay region to about 75 km offshore with a horizontal resolution of approximately 300 m. It is nested within an intermediate ROMS domain with a horizontal resolution of 1.1 km covering the coast from Pt. Reyes to Morro Bay out to about 250 km offshore. The outermost ROMS domain covers the entire California coastal ocean from north of Crescent City, California to Ensenada, Mexico with a resolution of 3.3 km (see Figure 3). In the vertical there are 40 unevenly-spaced sigma levels used in all three ROMS domains with the majority of these clustered near the surface to better resolve processes near the surface.

ROMS is an open-source model developed by the oceanographic community. It is a free-surface, hydrostatic, three-dimensional primitive equation regional ocean model (Shchepetkin and McWilliams, 2005, 2006; Marchesiello et al., 2001). The horizontal discretization uses a boundary-fitted, orthogonal curvilinear formulation. Coastal boundaries are specified as a finite-discretized grid via land/sea masking. The vertical discretization uses a stretched terrain-following coordinate (S-coordinate) on a staggered grid over variable topography (Song and Haidvogel, 1994). The stretched coordinate allows increased resolution in areas of interest, such as the thermocline and bottom boundary layers. ROMS uses a sigma-type vertical coordinate in which coordinate surfaces follow the bottom topography. The tidal forcing is added through lateral boundary conditions that are obtained from a global barotropic tidal model (TPXO.6) (Egbert and Erofeeva, 2002; Egbert et al., 1994), that has a horizontal resolution of 0.25 degrees and uses an inverse modeling technique to assimilate satellite altimetry cross-over observations. Eight major tide constituents at the diurnal and semidiurnal frequencies (M2, K1, O1, S2, N2, P1, K2 and Q1) are used. The atmospheric forcing required by the ROMS model is derived from hourly output from operational forecasts performed with the NCEP NAM 5-km North American model. The daily 00 UTC forecasts are used. Lateral boundary conditions for the CA domain are derived from global HYCOM forecasts [http://hycom.org].

An essential component of the nowcast and forecast system is the data assimilation scheme, a mathematical methodology for optimally synthesizing different types of observations with model first guesses (that is, forecasts). A new two-step multi-scale (MS) three-dimensional variational (3DVAR) data assimilation algorithm is used here. This MS-3DVAR scheme is a generalization of the 3DVAR methodology of Li et al. [2008a, 2008b] and is described in detail in Li et al. [2015a, 2015b]. The ROMS nowcast/forecast system is run daily in near real-time. The system incorporates all available real-time streams of data gathered from in-situ or remote platforms, and is executed following the procedures of numerical weather prediction at operational meteorological centers. An assimilation step is carried out every 6 hours. The near real-time operation schedule during the KISS August 2016 field experiment is shown in Table x.1. This schedule was designed to minimize the time lag between nowcast and forecast model times and real time and to insure that the 48-hour model forecast was available by 0500 local time (PDT). More details on our modeling system including the data assimilation methodology and a validation of the operational results can be found in Chao et al. [2013, 2017].

As an example of the significant impact that increased horizontal resolution can have on the fidelity of the assimilation of small-scale features in the model fields, Figure 4 shows the daily mean SSTs on 5 Apr 2016 as observed by AVHRR/MODIS as well as the daily of the model nowcasts with increasing resolutions from 3 km to 1 km and 300 m. Certain submesoscale features associated with eddies and filaments that are not well simulated by the relatively coarser models at 3 km and 1 km resolutions are clearly reproduced by the model at 300 m resolution.

Table 1. *Operational schedule for the ROMS nowcast and forecast system.*

Product	Valid Time (UTC)	Delivery Time (PDT)	Hours behind real time (hrs)
09 UTC Nowcast	0900	1200	9
15 UTC Nowcast	1500	1800	9
21 UTC Nowcast	2100	0000	9
03 UTC Nowcast	0300	0200	7
03 UTC 48hr Forecast	0300	0500	10

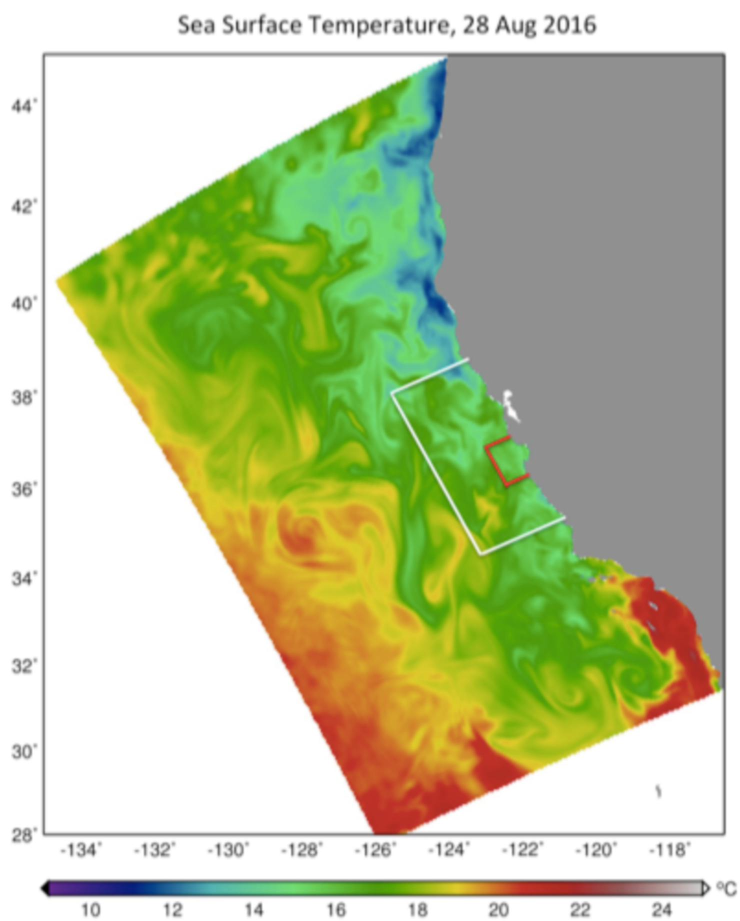

Figure 3. *Daily mean ROMS sea surface temperatures for 28 August 2016 on the ROMS CA-3 km model domain (colored region). The white box shows the domain covered by the 1.1km resolution intermediate nest and the red box the domain of the 300m resolution innermost nest targeting Monterey Bay.*

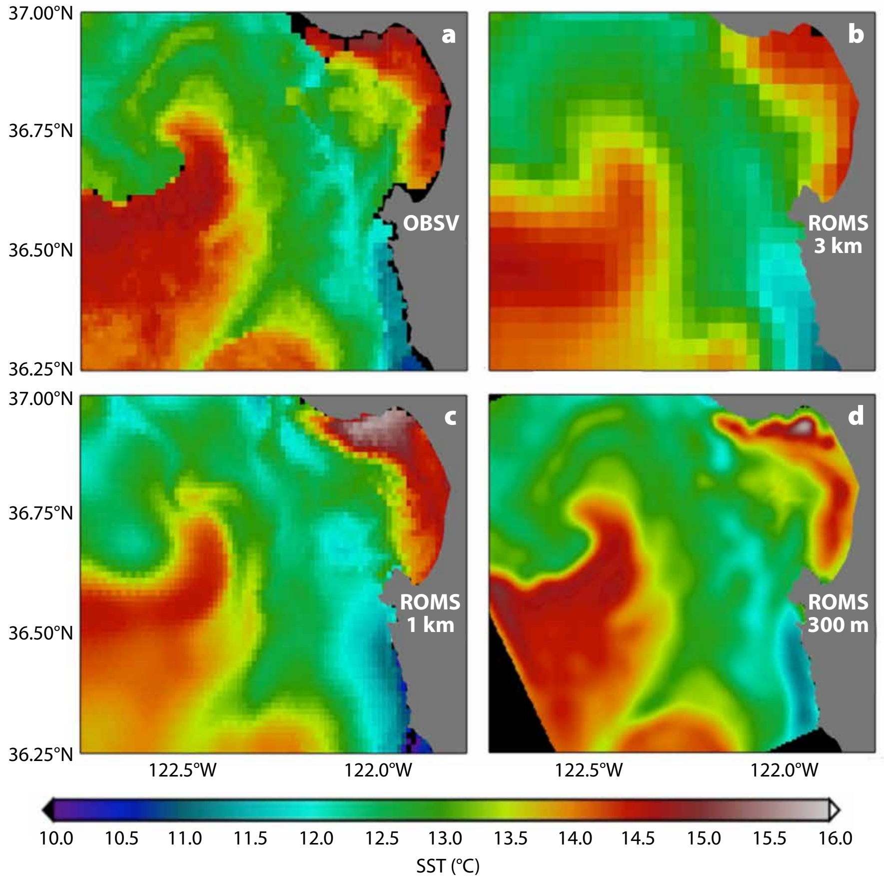

Figure 4. *Sea surface temperatures (°C) for 5 April 2016 as observed by AVHRR and MODIS satellite (a) and as simulated in the three nested ROMS domains, (b) California 3km, (c) central California 1km and (d) Monterey Bay 300m.*

iv Scientific results

Early work on the analysis of the glider and LRAUV data has focused on front detection and validate more of the engineering aspects of the technical development goals. Nevertheless, we collected a vast array of high-resolution physical and biogeochemical observations that will provide a unique view of the evolving frontal structure of continental shelf and slope in Monterey Bay.

Figure 5 shows a typical glider section across the continental slope and to the shelf break; this particular section comes from September 2016. The upper panels show the hydrographic structure of the slope, consisting of a warm and fresh near-surface mixed layer as well as deeper tracer gradients emanating from seafloor. The buoyancy data (panel c) shows that a along-slope jet in thermal wind balance sitting near the shelf break coincides with strong lateral temperature, salinity and spice gradients that appear to show a subductive feature into the ocean interior. This feature is predominantly along density surfaces, indicating the role of mesoscale and submesoscale lateral stirring.

Our goal for future work is to observe the evolution of this frontal structure across a major upwelling event that occurred during our 2017 field experiment between May 4 and May 9 (Figure 6). The upwelling event is characterized by a significant modification of the temperature and salinity properties over the continental shelf and a shift in frontal positions over the continental slope. The impact of these changes in exchange between surface and bottom boundary layers has not previously been analyzed. We will use diagnostics such as lateral buoyancy gradients, mixed layer depth and bottom boundary layer thickness and potential vorticity to infer the types of instability properties that might be active during our study period.

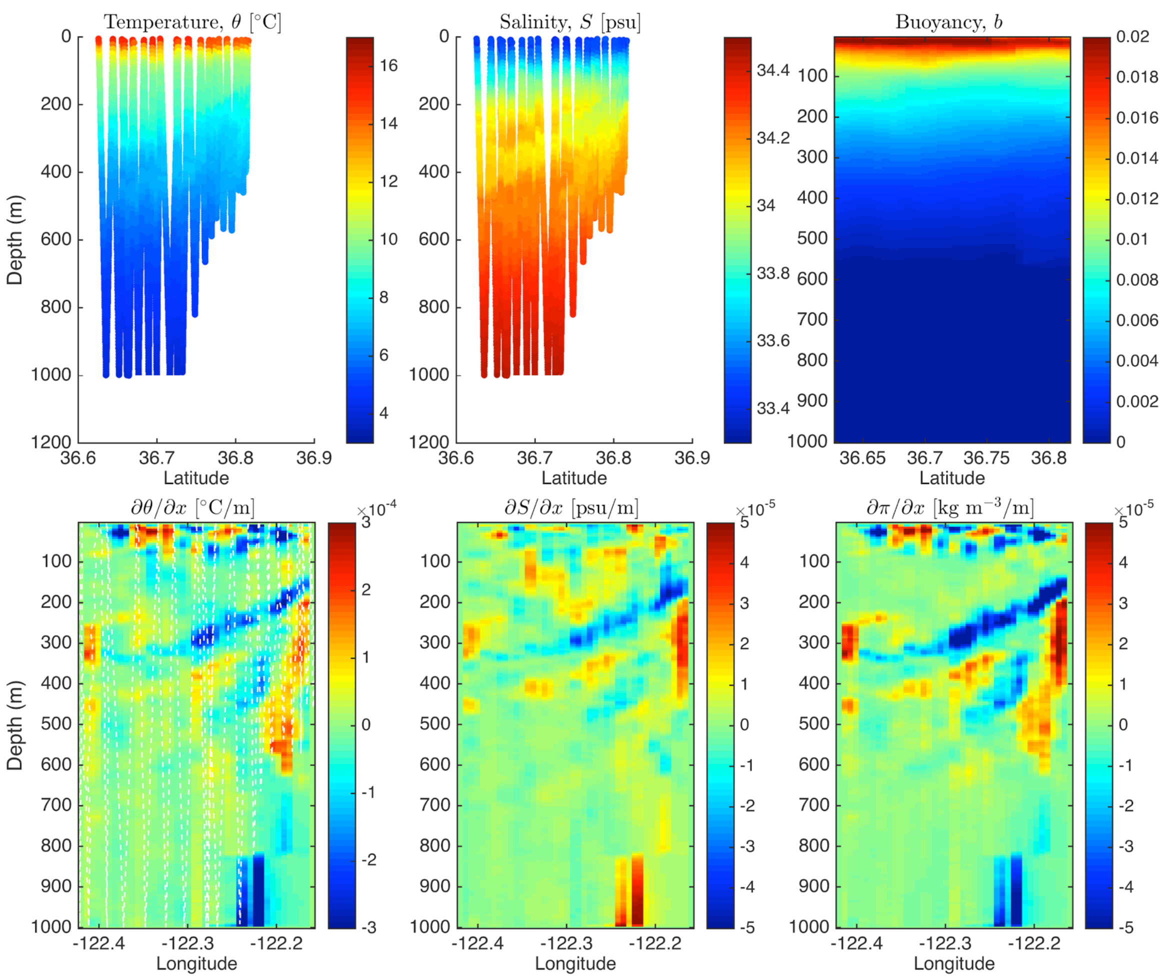

Figure 5. *Typical hydrographic transect obtained by the Caltech Seaglider across the continental slope and shelf. (Top) Potential temperature, salinity and buoyancy (density) along the section. (Bottom) Lateral gradients of temperature, salinity and spice corresponding to the upper panels.*

b. Publications

1) Thompson, A.F., Y. Chao, S. Chien, J. Kinsey, M.M. Flexas, Z.K. Erickson, J. Farrara, D. Fratantoni, A. Branch, S. Chu, M. Troesch, B. Claus, and J. Kepper. 2017. Satellites to seafloor: Toward fully autonomous ocean sampling. *Oceanography* **30**, 160–168.

Overview of the KISS project summarizing the proposed approach of a closed loop of numerical model prediction, vehicle path-planning, in situ path implementation, data collection, and data assimilation for future model predictions. Results from the first field experiment are shown. This manuscript was an invited contribution to the Special Issue on Autonomous and Lagrangian Platforms and Sensors (ALPS).

2) Flexas, M., M.I. Troesch, S. Chien, A.F. Thompson, S. Chu, A. Branch, J.D. Farrara, and Y. Chao, 2017. Autonomous sampling of ocean submesoscale fronts with ocean gliders and numerical forecasting. *J. Atmospheric and Oceanic Technology.* in press.

Presents the results from a 9-day experiment focused on autonomous optimization of the sampling strategy of an ocean glider using a 48-hour numerical forecast, feature-detection techniques, and a planner that controls the observing platform. Based on model estimations, the sampling "gain", defined as the magnitude of isopycnal tracer variability sampled, is 50% larger in the feature-chasing case with respect to a non feature-tracking scenario; this was validated in the field experiment.

3) Claus B., J.H. Kepper IV, S. Suman, J.C. Kinsey, 2017. Closed-loop one-way-travel-time navigation using low-grade odometry for autonomous underwater vehicles. J. Field Robotics, **00,** 1–14.

Presents methods for one to many acoustic navigation methods based on an AUVs equipped with acoustic modems and synchronized clocks. No other requirements are necessary for closed loop, bounded error navigation.

4) Kepper J.H. IV, B. Claus, J.C. Kinsey, A Navigation Solution using a MEMS IMU, Model-Based Dead-Reckoning, and One-Way-Travel-Time Acoustic Range Measurements for Autonomous Underwater Vehicles, submitted to *Journal of Oceanic Engineering*. In revision. Dec. 2017.

Companion paper to above submission which extends those methods through addition of a consumer grade inertial measurement system. By doing so the accuracy of the method is improved during dynamic maneuvers and environments in which the assumptions of the prior method break down.

5) Branch, A., E.B. Clark, S. Chien, M.M. Flexas, A.F. Thompson, B. Claus, J.C. Kinsey, D.M. Fratantoni, Y. Zhang, B. Hobson, B. Kieft, and F. Chavez, 2018. Front Delineation and Tracking with Multiple Underwater Vehicles. *J. Field Robotics.* submitted.

This work describes a method for detecting and tracking ocean fronts using multiple autonomous underwater vehicles. We present the results from several experiment periods totaling weeks, in and around Monterey Bay, California in May and June of 2017. We show the capability of this method for repeated sampling across an ocean front using a fleet of three types of platforms.

6) M. Troesch, S. Chien, Y. Chao, J. Farrara, J. Girton, and J. Dunlap, 2018. Autonomous Control of Marine Floats in the Presence of Dynamic, Uncertain Ocean Currents. *Robotics and Autonomous Systems*, submitted review.

This paper describes a method for controlling the latitude and longitude position of vertically profiling floats by creating a dive plan using an imperfect ocean current model. It is shown through simulation that planning a dive sequence, even with an imperfect ocean model, can improve the ability to remain near a latitude and longitude position and that using continuous planning (re-planning the remainder of the path using the actual position of the float when it is available instead of only planning once at the beginning of the path) can lessen the effects of planning with imperfect models. Results are also presented from an ocean deployment that show that model-based control can improve vertical profiling float control, even when using imperfect models.

7) Clark, E.B., A. Branch, S. Chien, F., J. Farrara, Y. Chao, D. Fratantoni, D. Aragon, O. Schofield, M. M. Flexas, and A. Thompson, 2018. Stationkeeping with Underwater Gliders using a Predictive Ocean Circulation Model. *J. Field Robotics*. In prep.

This work describes a method for station keeping with underactuated ocean gliders by using a predictive ocean current model to anticipate control disturbances due to ocean currents and minimize them using dynamic control schemes. We present the results of two field deployments in Monterey in 2016 and 2017, and develop a simulation framework for evaluating stationkeeping performance under a range of conditions. We compare the results of the field deployments and the simulation, and then use the simulation to conduct a further feasibility study of fulfilling SWOT calibration and validation requirements using an array of virtual moorings implemented with station keeping gliders.

7) Branch, A., M. Troesch, M. Flexas, A. Thompson, J. Ferrara, Y. Chao, S. Chien, "Predictive control for glider station keeping," *AI in the Oceans and Space Workshop, International Joint Conference on Artificial Intelligence*, Melbourne, Australia, August 2017.

8) J. Farrara, Y. Chao, H. Zhang, 2018. Multi-Scale Nested Modeling, Data Assimilation and Real-Time Forecasting in the Monterey Bay, California", Geophys. Res. Letts., In prep.

This work describes a 3-domain nested model using Regional Ocean Modeling System (ROMS) with assimilation of real-time in situ and remotely sensed (including both land-based and satellite platforms) observations to enable real-time forecasting. We used this forecast product during a number of field experiments to enable smart deployment and adaptive sampling of gliders and autonomous underwater vehicles (AUVs). The model simulation and forecast are validated against the independent data being collected to assess the forecast skill.

c. External funding proposed and received

***Observations of Three-dimensional Transport Pathways and Biogeochemical Fluxes in the Southern Ocean using Autonomous Gliders* (NSF)**

Both the scientific and technical aspects of the KISS study and technical development project were instrumental in a recently funded NSF project: "Observations of Three-dimensional Transport Pathways and Biogeochemical Fluxes in the Southern Ocean using Autonomous Gliders." (Caltech, 2018-2021). A technical summary is provided below.

We propose to deploy two autonomous ocean gliders in the Indian sector of the Antarctic Circumpolar Current, coincident with one or more semi-Lagrangian Argo floats equipped with biogeochemical sensors through the SOCCOM project. The gliders will be piloted to track the Argo float for a period of at least four months, resolving the mesoscale and submesoscale structure surrounding the float as well as variability occurring at periods shorter than the float's 10-day sampling interval. Measurements of the upper ocean hydrographic and velocity fields will permit an analysis of hydrodynamical instabilities within the mixed layer and their impact on vertical transport and exchange across the base of the mixed layer. The glider data will also be combined with the float observations and remote sensing products to derive vertical tracer fluxes, with the goal of quantifying the partitioning of export between sinking and advective pathways. Ultimately, this project will provide observations of the physical processes that contribute to high-frequency spatial and temporal variability in Southern Ocean tracer distributions and will provide a significant step towards describing the mechanisms that influence physical and biogeochemical distributions and transport pathways in the Southern Ocean.

***Persistent, Long-Range Gliders to Survey Sub-Ice Environments* (NASA PSTAR)**

Thompson and Chien were co-I's (Craig Lee, UW, PI) on an unsuccessful NASA Planetary Science and Technology through Analog Research proposal in 2016. Although unsuccessful, a similar project is now underway. Craig Lee was a participant in our original Satellites to Seafloor KISS study. A brief summary of the PSTAR is provided below.

The project would adapt and deploy long-range ocean gliders underneath Antarctic ice shelves. Technology objectives included: navigation from a single acoustic beacon, analogous to the exploration from a single point of penetration through the shell of an ice-covered ocean world; execution of extended (hundred-kilometer) surveys radiating from a designated insertion point; persistent sampling under ice for multi-month periods; fully-autonomous decision making; and data transfer from gliders to subsurface data loggers. Scientific objectives included: documenting scales of physical (temperature / salinity) and biological (oxygen, optical backscatter) variability under an Antarctic ice sheet, with lateral resolutions of 1-5 km and vertical 1-5 meters; making high-resolution measurements to investigate regions of strong property gradients, elevated mixing and elevated oxygen/backscatter (potential markers for biological activity); development and evaluation of numerical models of the cavity circulation.

***SWOT Ocean In Situ Cal/Val: 2017 Monterey Bay Pilot Experiment* (NASA)**

Leveraging the KISS project, a team of scientists from RSS, Caltech and JPL carried out a field experiment during July-September 2017 right after the KISS experiment. This experiment is considered as a pilot experiment to support the SWOT satellite mission. One of the SWOT requirements is specified in terms of the cross-track averaged wavenumber spectrum of measurement errors in the wavelength of 15-150 km. This requirement cannot be validated by conventional altimeter satellites. The original plan was to validate this requirement using AirSWOT. Given the fact now that AirSWOT cannot be used to validate this requirement, a field experiment is therefore proposed as an alternative method to validate the SWOT data.

During this SWOT pilot experiment, we used one Seaglider used by the KISS experiment plus one additional Slocum glider provided by Professor Oscar Schofield at Rutgers University. We selected the Monterey Bay simply because it is co-located with our KISS experiment plus there is an existing mooring (known as M1) equipped with 11 CTD (Conductivity, Temperature, Depth) sensors in the upper 300 meters. Both the Seaglider and Slocum gliders are able to keep stations near the M1 mooring. Furthermore, both gliders are able to reproduce the dynamic height calculated from the vertical profiles of temperature and salinity measured by the M1 mooring.

CAST and Kerckhoff Marine Laboratory activities
Collaboration with Becky Castaño & Gail Woodward (JPL)

The new Center for Autonomous Systems and Technology (CAST) on campus as well as the plans to refurbish Caltech's Kerckhoff Marine Laboratory present opportunities for a continued presence in marine autonomy at Caltech and JPL. Kerckhoff, in particular, has been identified as a possible future site for testing marine robotics and software that might be used for future exploration of extreme ocean environments. We have maintained an active dialogue with both Becky Castaño and Gail Woodward at JPL during our technical development project. Becky (team lead of our original KISS study) is leading a team to develop a plan for under ice-shelf exploration using BRUIE.

THOR: Terrestrial Hazard Observing and Reporting
Collaboration between Andy Thompson (GPS) and Beverley McKeon (EAS)

Thompson and McKeon were recently selected for a joint THOR / CAST award through the Terrestrial Hazard Observing and Reporting initiative in GPS and EAS. This project will take advantage of a unique opportunity to participate in an in situ field program with colleagues in South Africa and Sweden, surveying the Southern Ocean's marginal ice zone (MIZ). The project involves the deployment of multiple ocean gliders, surveying both in the open ocean and under ice, as well as autonomous surface vehicles (Wavegliders).

Our objective is to build upon the KISS framework in order to autonomously update sampling patterns to optimize the measurements made by in situ platforms (Thompson et al. 2017). To test this method, the Thompson group will pilot the Caltech glider along 100 km transects to measure temperature, salinity and depth-averaged horizontal velocity fields. These measurements will be returned in real time and used to initialize high resolution numerical simulations led by the McKeon group. These models will be used to simulate the turbulent heat flux that are not directly resolved by the gliders. The strength of the turbulent fluxes will used to update the glider dive profiles during the subsequent transect. Our goal during this field program is to demonstrate this 'human out-of-the-loop" framework, which can be used to support proposals focused on more extensive implementations. Major goals of this project are (i) to improve our understanding of boundary layer turbulent fluxes in the ocean's MIZ and their impact on sea ice extent, and (ii) to explore the feasibility of using a combined in situ robotic and modeling approach to optimizing sampling strategies in the MIZ. This work builds on scientific expertise in both the Thompson (GPS) and McKeon (EAS) labs as well as technical advances that were established during a recent KISS Technical Development project involving Thompson; this work would serve as seed funding for larger efforts linked to CAST.

V. Future Work

There are numerous opportunities to extend the work carried out during this technical development program, which are summarized in the following section. Our team has at least three other papers in preparation, therefore we continue to have frequent team meetings. We plan to continue full group meetings roughly every month for the next year and more frequent meetings in smaller groups.

SWOT Ocean In Situ Cal/Val: Proposed Pre-Launch Field Experiment

Encouraged by the results from the SWOT pilot experiment, a pre-launch field experiment at the SWOT cross-over location of the California coast is being planned to address a number of questions. At the SWOT cross-over location off the California coast, can gliders keep their stations within a specified "watch circle" of a few km? How deep should a glider profile in order to capture the majority of the upper ocean dynamic height variability? Can a glider be operated for a period of 90 days without being recovered for battery recharging or replacement?

In order to address these questions, a pre-launch ocean in-situ field experiment is proposed for the summer of 2018 as a risk mitigation effort. The primary objectives of this proposed field experiment at the SWOT cross-over location off the California coast over a period of 90 days are to (i) characterize the dynamic height variability and determine the minimum depth required to capture this variability, (ii) demonstrate the station-keeping capability of Slocum hybrid gliders, and (iii) quantitatively assess the ability of gliders to reproduce the dynamic height variability measured by the full-depth mooring. At the time of this report being submitted, the proposal for this SWOT pre-launch field experiment is still being reviewed by the JPL SWOT project office.

Earth Ventures Suborbital proposal: Ocean Submesoscale Currents and Vertical Transport

Team lead Thompson is a member of the science team on the Notice of Intent submitted in January 2018 to the Earth Ventures Suborbital competition. The overarching goal of this proposal is to test the hypothesis that submesoscale ocean dynamics make important contributions to vertical exchange in the upper ocean. The proposed mission will apply novel in situ and remote sensing techniques to provide an unprecedented view of the dynamical transition in upper-ocean circulation between the mesoscale and submesoscale. Our team is currently advocating for the inclusion of the autonomous planning algorithms for the proposed heterogenous robotic array that would be a part of the field component of this project, including 6 Waveglider, 6 Seagliders and multiple Lagrangian floats. The proposal deadline is April 2018.

VI. Conclusions

The technical development stage of this project has led to the development of an autonomous planner for application to robotic marine observing systems that is adaptable to various locations and scientific goals. The implementation of this planner was assessed across two comprehensive field experiments in Monterey Bay in the fall of 2016 and the spring and summer of 2017. A key success of this project was the ability to efficiently exchange information about oceanic and vehicles conditions between in situ assets, the planner and a custom 300-m ROMS circulation model. Collaboration with partners at MBARI and JPL allowed for more extensive testing than was originally planned, and provides a platform for the continuation of this work through alternative funding sources. Opportunities for extending our activities to exploration of Ocean Worlds (and Earth analogs) in upcoming years have been identified. Key conclusions from the project include:

1) Increased autonomy in the implementation of science-based sampling goals will be required for future ocean observing systems due to the increased number of robotic platforms, the diversity of these platforms' capabilities and sensor payloads, and the desire to explore extreme environments with limited communications. Planning optimally involves data streams from in situ vehicles and alternative (remote sensing) sources, combined with numerical forecasts, to provide information for mission updates. This framework guided the planner development during this project.

2) The planner algorithms were validated during two field experiments across different vehicle types with different capabilities and sensor payloads and through interaction with a numerical forecast model. Full implementation across multiple types of vehicles was not achieved, largely due to the limited duration of the field program and logistical challenges related to weather events and the study's scope. Nevertheless, collaboration with colleagues at MBARI and JPL permitted robust testing of the planner, and has established paths for future collaboration and planner development.

3) The work completed during this technical development project is directly applicable to upcoming field programs in oceanography, including SWOT Cal/Val activities and and upcoming Earth Ventures Suborbital proposal. For the former, members of our KISS team have been actively engaged in determining how an in situ experiment with up to 20 gliders could be used to measure sea surface height coincident with the SWOT launch. For the latter activity, a heterogeneous robotic observing system is specifically being targeted to link with combined measurements of surface winds and surface currents obtained from the new Doppler Scatterometer designed at JPL.

4) Our team continues to collaborate on publications arising from this project, including science-focused manuscripts that will involve our partners at MBARI. Ambitious extensions of this work to test scenarios for exploration of Ocean Worlds, specifically under-ice-shelf exploration in Antarctica, are on-going with colleagues at JPL and the University of Washington.

VII. Acknowledgments

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We are grateful to our collaborators at MBARI and JPL, especially Francisco Chavez and Brett Hobson at MBARI and Lee Fu and Jinbo Wang at JPL. Through interaction with these two groups we were able to carry our a more extensive field program than was originally envisioned in our proposal. We also received helpful feedback from Becky Castaño and Gail Woodward at JPL about future applications of the autonomous planning software developed during this project, potentially through future activities coordinated with Caltech's Center for Autonomous Systems and Technology (CAST) and the Kerckhoff Marine Laboratory. We look forward to future collaboration with these partners.

We would also like to acknowledge a number of colleagues that made the field programs possible. Ben Hodges (U. Rhode Island) provided access to the Iver AUVs, Brett Hobson and Francisco Chavez (MBARI) graciously allowed us to control a number of their LRAUVs during their CANON experiments as well as LRAUV testing and validation deployments. Partial support for the Caltech gliders was provided by the Division of Geological and Planetary Sciences. Finally, we thank Captain Jim Christman for his experience and advice during the vehicle deployments and recoveries from the R/V Shana Rae during both the 2016 and 2017 field programs.

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