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Coordinated Robotic Exploration of Dynamic Open Ocean Phenomena

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Abstract: The study of dynamic features of the ocean, in which complex physical, chemical, and biological interactions evolve on multiple time scales, poses significant sampling challenges because the required spatial and temporal resolutions are not possible by ship or satellite studies alone. Satellite remote sensing captures only surface effects while expensive research vessels can only make discrete observations in finite periods of time. Our work with *networked* marine robotics in the aerial, surface, and underwater domains is at the vanguard of a new approach to scientific exploration and observation, which brings together several technologies to enable oceanographic vessels and robots to work in tandem, thus expanding the observational footprint of these vessels. We describe a scientific

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cruise in the Spring of 2018 in the open waters of the Pacific where we deployed a fleet of autonomous robots to demonstrate this approach for the synoptic observation of mesoscale and sub-mesoscale features of a frontal zone. We articulate the elements and methods to multi-vehicle coordination and challenges that lie ahead in ocean observation.

Keywords: Multi-domain Inter-disciplinary Ocean Exploration, Networked Marine Robotics, Multi-vehicle operations, Mixed-initiative control

1. Introduction

Due to its vastness and inaccessibility, the ocean remains mostly unexplored. As our perspectives and knowledge of oceanographic processes has deepened, our understanding of the importance of life on Earth and its dependence on the ocean, starting with the role of plankton in generating oxygen while sequestering carbon, has only increased. However, this knowledge has come about using traditional observation methods, using research vessels making discrete measurements which can, and do miss, change over large spatial and temporal scales. Satellite (optical) remote sensing has augmented such efforts especially covering large spatial scales but is constrained by cloud cover, large revisit times and only sample the surface. As a consequence finding, tracking, and sampling dynamic features of the ocean to study physical, chemical, micro-biological, and biological interactions with adequate spatial-temporal resolutions is a significant challenge in the ocean sciences. Fronts, internal waves, plumes, slicks, Lagrangian coherent structures, anoxia, and hypoxia are critical to understanding the bio-geochemistry, ecological transport, and finer-scale ocean dynamics. These structures are transient with short time scales and synoptic *in situ* observations are therefore required. Yet these phenomena and their dynamics have proved to be hard to quantify, from micro-scales to the macro view, with traditional scientific methods.

An important part of oceanographic exploration is the scientific research vessel from which, typically, bio-geochemical samples are obtained. Given the large spatial scales for measurements, either straight-line transects dictate where the next sampling location is planned by the vessel, or in rare cases, each step determines where to sample next. This typically involves stopping the vessel, lowering instruments and making measurements and/or obtaining water samples, with the inherent loss of synopticity. Most research vessels come with a range of sensors that can sample with discrete measurements and in some cases, sample continuously, using underway systems. Yet, these are circumscribed by the reach of the instruments centered on the vessel which makes them laborious and technically challenging for sampling dynamic ocean features. Long-term targeted observations of such features using only traditional ship-based methods are, therefore, not practical for our understanding of processes which are often dynamic, episodic and need a wide-ranging observations across space and time.

The challenges of open ocean exploration are even more daunting. Sampling is driven in large part by scales—phenomena which are vast (1000’s of km^2) yet driven by ocean physics and biology in fine-scale (in the micrometers). While progress has been made in understanding the role and impact of finer-scale processes ($\sim$ 1–100 km) on large-scale and dynamic oceanic structures, many questions remain regarding the sensitivity of the large-scale circulation to the small-scale processes and their complex interaction. Even as the contribution of small-scale processes to the Earth’s climate, to rates of stirring, mixing, and dissipation has long been recognized, it is still difficult to study both large and small scale processes at the same time (van Haren et al., 2004). Small scale unresolved structures in the open ocean are quite challenging for shipboard instruments to detect, both spatially and temporally, and are often difficult to discern in single-point time series or vertical profiles.

Autonomous vehicles can play an important role to survey at those smaller scales even as the observation of large-scale motion can rely on the satellite remote-sensing, ships, and long-endurance systems such as gliders and profiling floats. Traditional ship-based scientific observation, as a result, is slowly being augmented by the use of autonomous robotic platforms, which have enabled the increase in the observational footprint of oceanographic vessels. This comes with a cost, however, in that it increases operational complexity by requiring very different assets to be coordinated in space and time and typically reduces user awareness about the state of all the moving parts during the cruise.

For instance, when studying large-scale phenomena, such as frontal zones, we are interested in obtaining *synoptic* observations, encompassing measurements across spatial as well as temporal scales. This is complicated by motions across horizontal and vertical gradients. As a consequence, the approach we use relies on merging data from multiple available sources while guiding ensembles of unmanned vehicles in real time to target features of interest. By combining data flow from multiple sensors targeting the same area, scientists can produce better models, formulate stronger hypotheses and adopt a requisite range of sampling resolutions as new data is received.

The approach described in this work was demonstrated during the *Exploring Fronts with Multiple Robots* [1] cruise to explore a frontal zone in the open waters of the Pacific, with a range of sensors aboard the research vessel R/V *Falkor*—Schmidt Ocean Institute—augmented by autonomous surface, aerial and underwater vehicles. Our target phenomenon was the Eastern spur of the Northern Pacific Subtropical Front (STF), ∼1500 km from the California coastline (Figure 3). The STF's horizontal gradient has a mean spread of ∼30 km/s; therefore, to capture a section of the front each asset has to travel more than this distance. The size and remoteness of this study area required a new approach to controlling and supervising the robotic assets at sea: the assets needed to operate continuously for prolonged periods of time, adapting to local conditions while maintaining a coherent state despite communication disruptions. Operators and scientists needed to work across shifts making decisions based on past, present, and predicted events discerned from multiple sources, resembling deep space operations (Rajan et al., 2000; Ai-Chang et al., 2004; Bresina et al., 2005; Mirmalek, 2020). Although the scientific motivation and experimental results for this work have been the study of an oceanic front in the Pacific, we believe the technical approach and scientific methodology can apply to other open ocean phenomena.

The novelty of this work is multifold; first, it demonstrates the applicability of coordinated autonomous robotic observation across aerial, surface, and underwater domains using low-cost platforms and relying on integrated networked software infrastructure. Second, it shows how such heterogeneous platforms can be controlled with increased situational awareness from ship and shore. Third, it demonstrates the use of embedded machine intelligence for operational effectiveness, along with responsiveness to human-in-the-loop augmentation of robotic goals—all with intermittent connectivity among multiple robots which can adapt to dynamic environmental conditions over low-bandwidth communication links.

This paper is structured as follows. In Sec. 2, we highlight a range of marine robotic platforms typically in use; we use a subset of these in this work. Section 3 places this effort in the context of other fielded and relevant marine robotic deployments with multiple vehicles at sea. In Sec. 4, the scientific motivation for exploring large phenomena, in particular the STF, is highlighted. Section 5 describes the technical approach, the hardware and software infrastructure which lays the foundation for multi-vehicle coordination and which involves temporal planning, cloud-based synchronization, and onboard adaptation. Section 6 describes the cruise, scientific outcomes, and results from the exploration of the STF in the Pacific. Section 7 wraps up with conclusions and future work.

2. Robotic systems for ocean exploration

A recent trend in oceanography is towards the use of unmanned robotic vehicles that are capable of acquiring *in situ* data and relaying this information over satellite links. They augment the observational footprint of oceanographic vessels to survey mesoscale and sub-mesoscale dynamic features, like the STF, in finer scales to disambiguate space-time measurements (Graham et al., 2012).

[1] https://schmidtocean.org/cruise/exploring_fronts_with_multiple_aerial-surface-underwater-vehicles.

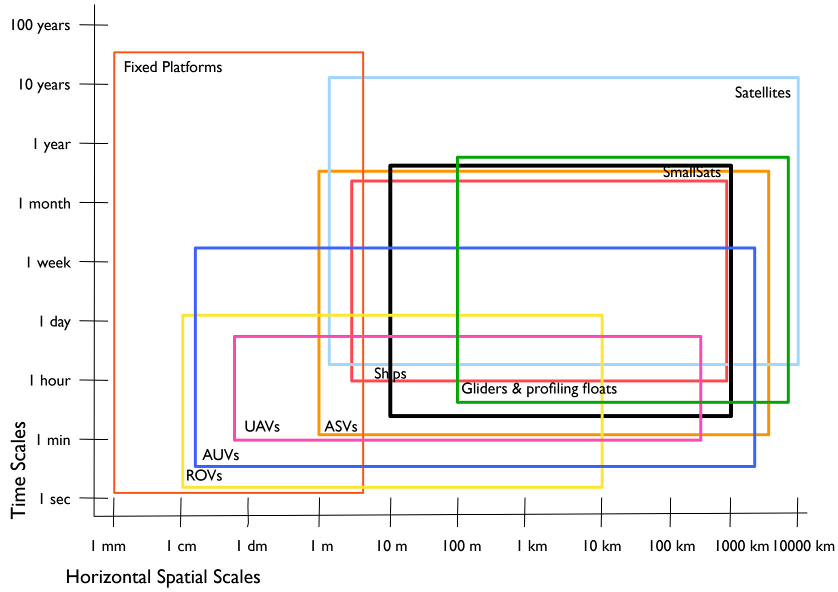
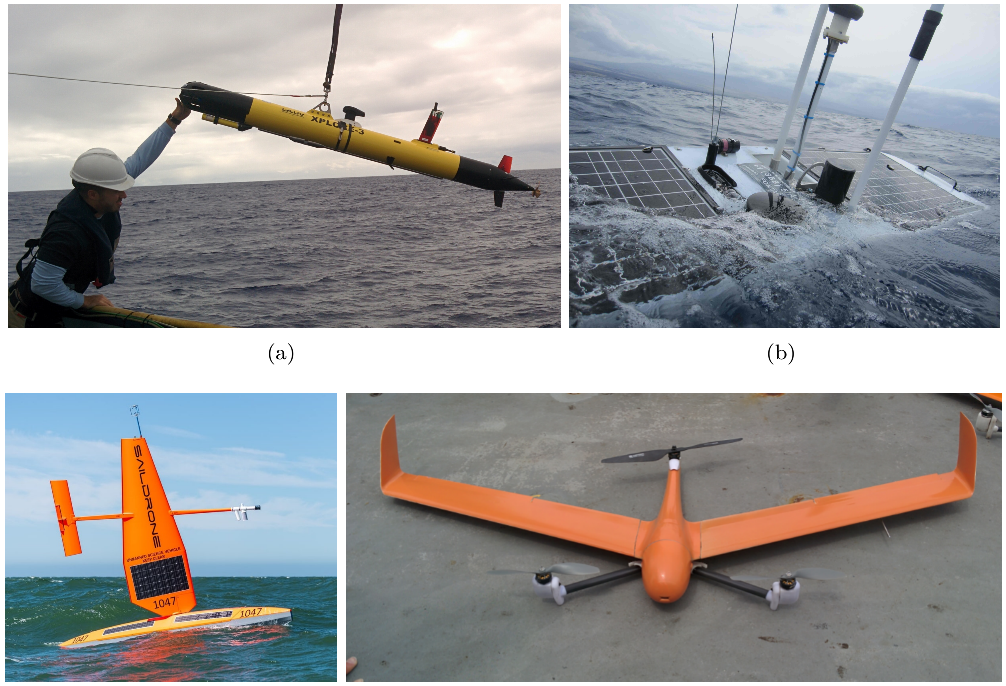


Figure 1. Open ocean exploration is driven by the use of multiple assets and information sources including remote sensing, mobile and immobile robotic vehicles. The X axis shows the spatial scales of measurement within a single deployment, while the Y axis shows scales of observation which conflate both sampling periods and persistence of observation. Cost and ease of deployments are significant factors in maritime exploration. UAVs: Unmanned aerial vehicles, AUVs: Autonomous underwater vehicles, ASVs: Autonomous surface vehicles, ROVs: Remotely operated vehicles. Figure modified from (Haury et al., 1978).

Figure 1 shows typical space-time ranges of operational assets, both mobile and immobile, Lagrangian and Eulerian, propelled and not, traditional and nontraditional, which have come to augment traditional ship-based measurements. Fixed platforms, such as buoys, for instance, are excellent in being able to provide a wide range of measurements in a tightly circumscribed location, and doing so for years with periodic maintenance. They have proved to be critical in coastal domains and providing continuous *in situ* time series data which have helped understand both the dynamic nature of the domains and the impacts on the changing oceans (Chaffey et al., 2004). On the other end of the scale, expensive Earth-observing satellites and their recent incarnations in Small-satellites, have provided valuable remote-sensing data at very large scales. Yet with the constraints of local weather (especially cloud cover), less-than-frequent revisit times, and the perspective of primarily the ocean's surface, they cannot provide insights into fine-scale dynamics of subsurface processes. Between these disparate sets of tools, *in situ* observations fit the need for discerning process dynamics—our intent in this cruise. Included in these tools are a range of autonomous marine robotic platforms that are the focus of our work.

Some types of unmanned vehicles that are being used routinely in ocean science are the following.

- **Autonomous underwater vehicles (AUVs)**. These vehicles use propulsion for controlled movement within the water column. They can travel relatively quickly and, most importantly, they can carry a diverse range of sensors and have the adequate computational capability for intelligent embedded command/control. A portable long-range AUV targeting oceanographic applications is depicted in Figure 2(a). AUVs, the focus of this effort, have proved to be robust in a number of coastal settings and can carry a range of scientific payloads; the vehicles we use in particular are robust, compact and portable (Sousa et al., 2012; Madureira et al., 2013).
- **Autonomous surface vehicles (ASVs)**. typically maintain near real-time communication links with a remote control station. ASVs can carry multiple sensors, such as water probes and weather stations, but can only collect data close to the water surface. Some ASVs can be



(a) (b)

(c) (d)

Figure 2. (a) A Light autonomous underwater vehicle (LAUV (Sousa et al., 2012; Madureira et al., 2013)) being launched from the R/V *Falkor* in the May-June 2018 cruise in the open Pacific. (b) A *Wave Glider* autonomous surface vehicle (ASV) dispatched from California measured subsurface temperature and provided weather data over satellite links to the *Falkor*. (c) *Saildrone* ASV; two *Saildrones* were used to collect surface temperature over a vast spatial extant. While not part of the initial deployment plans, their serendipitous proximity to the operating area allowed their use for data gathering and significantly added to our understanding of the location of the dynamic frontal feature. (d) The Flightwave Edge vertical take-off and landing (VTOL) unmanned aerial vehicle (UAV) platform was used during the cruise.

synoptic in nature, as they can make a rapid assessment at the mesoscale ($> 50km^2$). They are also referred to as Unmanned Surface Vehicles (USVs). Some examples (of clean-energy vehicles) are provided in Figures 2(b) and 2(c).

- **Unmanned aerial vehicles (UAVs)**. These robotic platforms are used for an ever-increasing range of applications, including ocean exploration, and are relatively new in the oceanographic domain. UAVs can carry a range of payloads to capture the surface properties of the ocean including magnetometers, gravimeters, and gas sensors that can be used to measure additional properties. UAVs can make (super)-synoptic measurements depending on their range and speed. Typically range increases with fixed-wing UAVs which, in some cases, can still take off and land vertically (VTOL) as in the example in Figure 2(d).
- **Gliders and profiling floats**. By relying on buoyancy control, gliders use energy sparingly to move up and down the water column with forward motion. With no other form of propulsion, gliders can stay in the water for sustained periods of time (months) while traveling at low speeds ($\sim\leq 1.5$ knots) and can easily get caught in ocean weather, including strong eddies. For communication, gliders rely on satellite links used sporadically to communicate with their control station when on the surface. Like gliders, profiling floats operate for long periods of time, use buoyancy control and are Lagrangian in nature while going vertically in the water column. ARGO floats (Wong et al., 2020), deployed worldwide, are excellent examples of such systems. The primary difference between floats and gliders is that floats do not control their horizontal displacement and, as such, all measurements are opportunistic with significant limitations in

motion control. Gliders and floats cannot make synoptic measurements. No floats or gliders were used in our field experiment.

Such marine robotic platforms, make continuous measurements in space and time, synoptic or not. With calibrated sensors, the data collected can then be combined to detect oceanographic features over large spatial scales and/or study bio-geochemical processes over time. In the past, while data from multiple sources were often combined opportunistically, our approach explicitly uses coordinated measurements with multiple assets in near real time, while continuously changing and adapting to the *in situ* environmental features being mapped.

3. Related Work

Inter-disciplinary, science-driven, open ocean robotic exploration while becoming more prevalent, is still sparse; explorations where multiple and heterogeneous robotic vehicles have been deployed for scientific exploration, sparser still. But we believe this will likely change in the coming decades (de Sousa, 2021); the work reported in this paper is one step in that direction.

While there are ongoing efforts where robotic assets can be shared over the Internet with end-users for beyond-visual line-of-sight experiments, these efforts are predominantly used for sharing live data feed from ongoing deployments with end users, and not for command/control *in situ* exploration and analysis, like we do in this work. Oceanids C2 (Harris et al., 2020) is one example, which employs a cloud infrastructure to allow access to live data from multiple heterogeneous assets for waypoint-based piloting. This approach, however, relies on a control station to do all the planning since the vehicles are either teleoperated or do not have onboard planning capabilities.

Recent work addressed the problem of tracking a coastal salinity front with three autonomous vehicles, deployed from a small vessel, using a centralized planning approach (McCammon et al., 2021), in which mission plans were validated on the vessel, before being sent to the vehicles. While their planning algorithm was tolerant to communication disruptions, actions were dispatched sequentially onboard the vehicles. Moreover, the user interface displayed beliefs about studied variables, not the real-time expected behavior of all assets and variables. On each shift, a minimum of six researchers was needed to perform tasks such as validating the health of the platforms and supervise the plans being dispatched by the planner. Our approach simplifies awareness and supervision by augmenting the interface with time and allowing the vehicles to adapt received plans onboard with minimal impact to situational awareness. Critically, our efforts are in the open ocean, well beyond the confines of the coastal zone, where there was no guarantee of being able to find the STF frontal zone. Equally, our work involves a rich legacy of software infrastructure used across multiple field experiments (Das et al., 2011; Faria et al., 2014b; de Sousa et al., 2016a; Py et al., 2016; de Sousa et al., 2016b; Chrpa et al., 2017; Fossum et al., 2018; Ferreira et al., 2019; Costa et al., 2018; Dias et al., 2020), and not a bespoke method, emphasizes propelled vehicles with substantial payload and computational abilities which makes for adaptations *in situ*.

The Ocean Infinity seabed mapping campaigns (Rumson, 2018) uses a fleet of AUVs, each paired with an ASV. AUVs and ASVs are connected via an acoustic and localization link, which extends their operational range and keeps navigation errors bounded. The fleet is complemented by a manned vessel from where all assets are monitored and controlled. Although this approach has similarities to the work presented here, the behavior of these fleets is much less dynamic, as are the features being mapped in the benthic environment; we focus on the upper water-column.

Scientific exploration with AUVs, especially in the coastal ocean, is more common especially in the context of specific phenomena of inter-disciplinary scientific interest (Schmidt et al., 1996; Gottlieb et al., 2012; Smith et al., 2011, 2014; Das et al., 2015; Fossum et al., 2019; McCammon et al., 2021). The coordinated use of the underwater, surface, and air vehicles in the harsh open ocean environment is still novel, however.

Typically when multiple vehicles from different institutions are fielded together, each vehicle is operated separately from its control station, in part because, in most cases, these are closed systems,

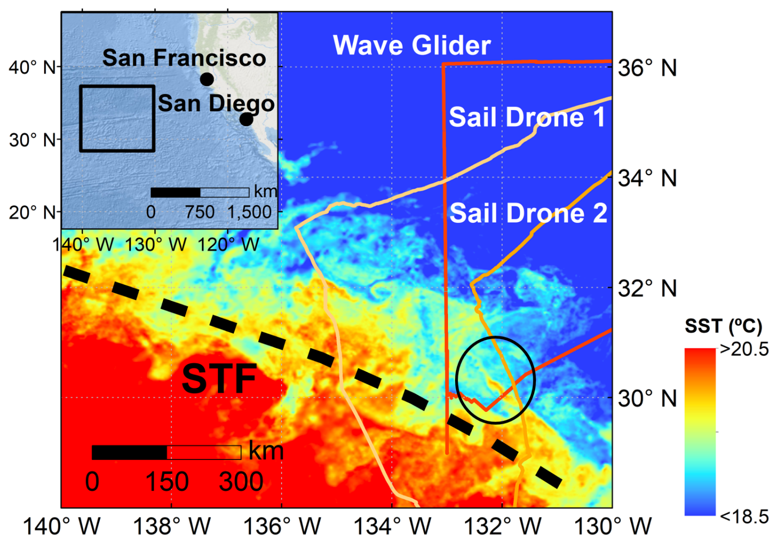


Figure 3. The eastern Pacific region of exploration (inset) with the zoomed-out area of exploration (black square). SST product from Multi-Scale Ultra High Resolution (MUR) database(Chin et al., 2017) from June 8th 2018 is the background against which trajectories of a *Wave Glider* and two *Saildrone* autonomous surface vehicle (ASV) from May 1st to June 10th are plotted. The operational area where AUVs were used is marked with a black circle. The STF (dashed black line) is associated with a rapid change in surface temperature. See Section 6.2 for details.

not inter-operable from a single control station, and the ensemble is manually coordinated (CANON, 2021; Ramp et al., 2009). What is unusual in the work we discuss here, is the breadth and depth of *networked* control of vehicles from a single laboratory, with the exception of the ASVs we use, some of which were already in the operational area making measurements. Such networked systems allow the backbone infrastructure to be designed and applied systematically, impacting situational awareness and ultimately scientific data gathering. The refinement of such past efforts is at the core of this paper.

4. Scientific Motivation: The Northern Pacific Sub-Tropical Front

An ocean front is a boundary between two distinct water masses characterized by significant horizontal gradients of physical, chemical, and biological processes. They occur on different spatial scales, from several hundred meters up to many thousand kilometers (Belkin and Cornillon, 2007) and are not usually defined as a single occurrence, but more as a feature in a cascade of scales. Although ocean fronts affect all aspects of marine ecosystems, such as biological productivity (Chapman et al., 2020), their real impact and influence remains unknown due to the practical difficulty of simultaneously obtaining physical, chemical, and biological data with high space-time resolution. Fronts in coastal regions, especially those driven by temperature gradients, can often be observed with the naked eye; however finding ocean fronts, like the STF, and recognizing their substructures, amounts to finding a “needle in a haystack.” In addition, the space-time scales in which these evolve, preclude effective observation with an oceanographic vessel.

The STF between 30°N-35°N is a large-scale climatic front, defining a sharp boundary where cold fresh waters from the north meet warm salty waters from the south. It has a strong salinity signature and a weak Sea Surface Temperature (SST) signature, thus making it difficult to find it using remote sensing, even more so because of frequent cloud cover. It is relatively shallow (<300 m) large-scale (∼1000 km) feature which can catalyze the generation of mesoscale (∼50 km) meanders, ‘eddies’ and rings, and sub-mesoscale (∼10) “filaments” and other smaller structures.

This area in the Pacific, including the STF, was studied in the 1970s, and 1980s (Lynn, 1986; Roden, 1974; Laurs and Lynn, 1977; Saur, 1980). These seminal studies provided the only substantive, systematic *in situ* data available to us before our 2018 cruise. Therefore it was imperative to conduct pre-cruise reconnaissance of the cruise operation area. Since the region often has extensive cloud cover, with consequent sparsity in remote sensing data to seed the exploration, *in situ* sampling is the only effective alternative to find and sample the STF. After the front's approximate location is to be found, its study and exploration rely on an adaptive sampling of its various features. Exploration in this context, therefore requires a judicious mix of assets with information derived from multiple sources with different levels of synopticity.

5. Technical Approach

Our approach to open ocean exploration combines multiple assets and sensors tied together in a cohesive networked environment, along with ship-borne assets, to expand the observational footprint of an oceanographic research vessel.

In open ocean exploration, finding a given feature to sample is in and of itself, a challenge in the large expanse. In-situ measurements are required to find features of interest that are hard to detect from remote sensing data, in large part due to prevalent cloud cover and the inherent difficulty to measure salinity from satellite observations. To prevent deploying a large fleet of assets too remote from the targeted feature, and taking into account the operational constraints for the cruise, we deployed unmanned assets to scout a large area ahead of the ship to find the STF. We were able to guide three green-energy ASVs to the estimated (and approximate) location of the front to eventually find its salinity signature and use that to get within proximity to deploy AUVs and UAVs to make fine scale measurements. By systematically narrowing down the spatial scales of observation, we were thus able to establish the presence of the front and confine the operations area for the deployment.

In order to perform a high-resolution map and study of a specific region of the ocean, multiple vehicles had to be deployed to sample in tandem. In our cruise, we used ASVs, UAVs, and AUVs, as well as a number of sensors aboard the *Falkor* from which all assets were being deployed. Figure 4 shows the overall system architecture and network in the context of the exploration of

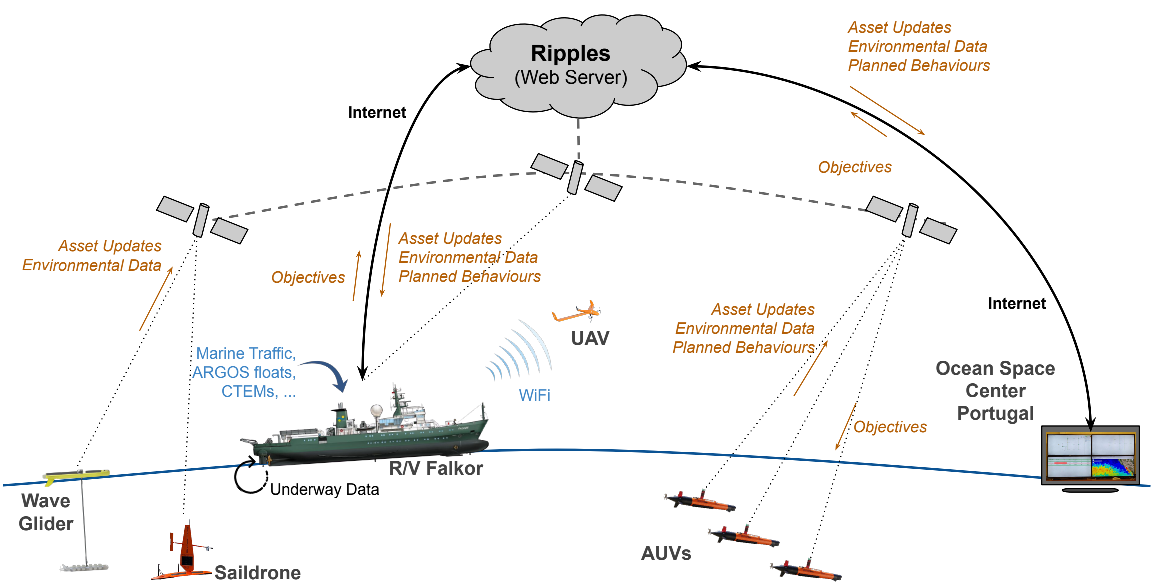


Figure 4. System architecture and infrastructure for the *Exploring Fronts with Multiple Robots* 2018 SOI cruise. AUVs and UAVs operated up to tens of kilometers away from the R/V *Falkor*, ASVs operated even further away.

Table 1. LSTS toolchain components and their description with citations to past work. The components used in this cruise were enabled to support BVLOS operations.

Component	Description	Ref
DUNE	Low-level onboard navigation and control software running on all AUV and UAV platforms.	Pinto et al. (2013b)
NEPTUS	PC-based graphical command and control system for multiple autonomous heterogeneous vehicles. It can integrate data from external assets and other sources of information such AIS receivers, meteorological forecasting services and satellite imagery.	Dias et al. (2005)
IMC	Message-oriented, transport-agnostic binary protocol used by all LSTS toolchain components both for inter-module and intra-module communications.	Martins et al. (2009)
Ripples	Cloud infrastructure used to aggregate and disseminate data from ongoing field deployments, as well as providing simplified web interfaces for following and controlling the operations using a browser; a stripped down alternative to NEPTUS .	Pinto et al. (2018)

the STF. From the *Falkor*, scientists were able to receive real-time measurements from the ship's sensors and robotic assets above, at and below the ocean surface. The way the different assets connected to the ship varied, but all data was aggregated in a cloud to be accessed from the ship, as well as from any other location connected to the Internet, such as the Ocean Space Center, located in Portugal, ten time zones away (Lima et al., 2021).

We have a substantial operational legacy in coastal domains (Pinto et al., 2013a; Faria et al., 2014a; Sousa et al., 2016; Ferreira et al., 2019; Pinto et al., 2018) that greatly simplifies multi-vehicle deployments. Close to shore, platform launch and recovery can occur daily and communication is simplified with vehicles within visual line of sight (VLOS). Bringing these systems and processes to the open ocean, however, required several technological advancements in hardware and software which we describe in the following sections.

5.1. Infrastructure development

To bind all manned and unmanned assets mentioned above, as well as users connecting from different locations around the world, we rely on different components of the open-source LSTS toolchain (Pinto et al., 2013b). A brief summary of its components is given in Table 1. Several parts of the LSTS toolchain underwent modifications to encompass continuous beyond visual line of sight (BVLOS) operations in the open sea. Although most assets are typically deployed and recovered from the research vessel, line-of-sight communications are available only while the robotic vehicles are near the ship and on the surface. AUVs stay disconnected when underwater and consequently need to autonomously decide how to negotiate their transects and when to make measurements.

For operators on the research vessel or on-shore, the lack of observability of AUVs results in a unique challenge related to situational awareness; it is important to estimate and predict vehicle behavior and when/where they will surface, as these are the opportunities to assess the outcome of plan execution, obtain more science and engineering data and potentially alter high-level objectives, all within an iterative cycle. By tightly coupling onboard adaptation on the vehicles with user expectations, it is possible to maintain user awareness of system state even with sparsity in communication links. This was the main reason an improved situation awareness and an early warning collision system, coupled with encoding communication gaps in planning and execution control, were incorporated into a temporal dispatching scheme that we discuss briefly below in Sec. 5.2.

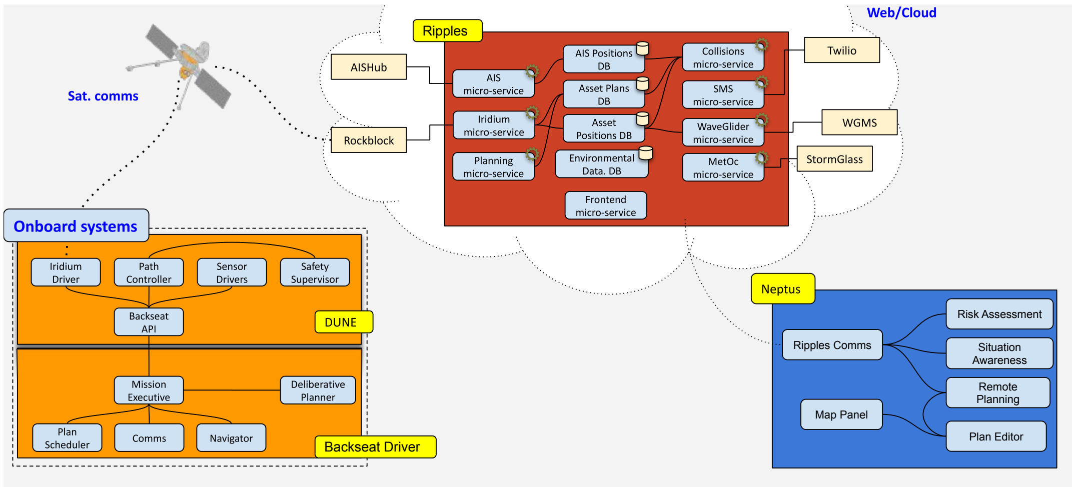


Figure 5. Software block diagram depicting software components used for oceanographic experiments. `DUNE` runs behaviors commanded by its backseat driver, which receives high-level objectives via satellite communications from `Ripples`. `Ripples` connects to a panoply of web services and assets in order to maintain an up-to-date state of execution. `NEPTUS` connects to the vehicles directly over Wi-Fi or also via `Ripples`, using its web-based API. A brief description of these tools is presented in Table 1.

Software enhancements

Figure 5 depicts the system design behind our approach. `Ripples` is primarily used as a communications hub/router accessed using a web API or directly over satellite links when an Internet connection is not available. On its backend, `Ripples` stores every asset's last known state together with predicted future states. Whenever new information about an asset becomes available, it is forwarded to `Ripples` over any viable communication medium. The backend comprises a set of (micro-)services that handle information from multiple sources listed below.

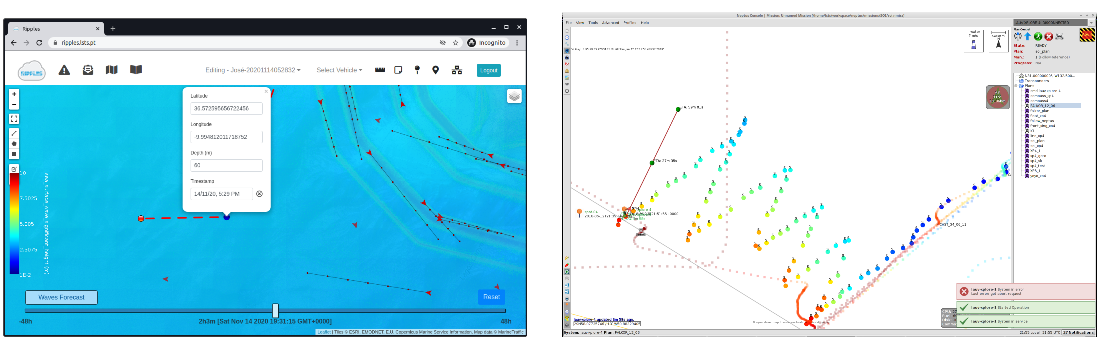
- **Asset telemetry**. provides the current state of the vehicles reported over Wi-Fi or satellite links. The state includes the vehicle position, battery level, and faults if any. Telemetry from vehicles can also be retrieved from other web-based services such as the *Wave Glider* Management Systems (WGMS). It is first converted into `Ripples`-specific format and then stored.
- **Surface traffic positions** provide ship traffic reported over AIS. These can be obtained from local AIS receivers or commercial web services, such as AISHub or MarineTraffic.
- **Asset plans** being executed by the vehicles are also communicated to `Ripples` in the form of desired future states for a specific system. The plans can originate either from operating consoles or from the vehicles.
- **Weather and ocean forecasts** are of critical importance when operating at sea. This micro-service provides these forecasts that are essential for planning, especially for long-endurance AUVs operating in the open ocean. For this reason, `Ripples` can retrieve information from sources such as Copernicus Marine Service (CMEMS)[2] or StormGlass[3]. The forecasts are provided as a time series of future conditions which allows estimating the ocean conditions in the near future, for any given location.
- **SMS alerts** are sent directly to operators' mobile phones, if service is available, using Twilio. `Ripples` can also send information, for example, when a fault or a potential collision with ship traffic is detected.

[2] https://marine.copernicus.eu/
[3] https://stormglass.io/

Multiple users can access the `Ripples` backend simultaneously from ship/shore using a compatible client. Doing so allows users in disparate locations to follow and interact with the operations team while providing scientific context from a diverse range of information sources, critical in open water exploration. The *current* state of all assets, either retrieved from past telemetry or resulting from planned behavior is, in this manner, centralized and synchronized across all clients, whether on `NEPTUS` consoles (see Table 1) or web browsers—both clients co-exist as they target different usage. While `NEPTUS` is used in the field to connect and control different assets in real time, as well as analyze their data online or offline, the `Ripples` frontend is a simplified alternative that can be used to supervise the execution and to access data being uploaded by any user or asset. For each controlled asset, `Ripples` stores its last known state (telemetry snapshot), some of its past state snapshots and, most importantly, its expected behavior in the form of predicted states. Between state snapshots, the system estimates that vehicles move in a straight line and with constant speed. Although currents and lack of navigational information *in situ* can distort a vehicle's movement, it is a reasonable approximation in open ocean exploration where phenomena of interest like fronts and eddies are vastly larger in scale than the navigational error (less than 5% of distance traveled underwater).

A similar approach is used for both known, and controllable, and for third-party platforms. Telemetry received from third-party platforms (e.g., *Saildrones* and the *Wave Glider* used in our cruise), as well as ship traffic sent over AIS are ingested to derive the estimated trajectories of these systems and predict their future trajectories. These predictions are useful while planning, both as a means to design coordinated observation/measurement plans but also to automatically detect potential collisions between autonomous vehicles and surface traffic while obtaining the estimated position of all assets at some future time (e.g., while crossing a frontal jet or eddy). Collision forecasts trigger an alert in the form of an alarm and send as a text message to the operators who subscribed to these via `Ripples`.

The `Ripples` frontend provides different perspectives (or views) that provide situational awareness of the execution and means to alter the behavior of controlled assets. The **default** shows the last known position of all assets and the real time estimates of the present state of all assets on a map. A **risk analysis** perspective shows a quick overview of any system malfunctions such as vehicles not communicating for a sustained period, any reported faults, or forecasted collisions. The **planning** perspective allows changing the top-level objectives by adding points on the map that should be visited by a vehicle, as shown in Figure 6(a). These points may be *optionally* associated



(a) The `Ripples` interface is used to edit plan objectives by dragging a sequence of waypoints and (optionally) assigning a desired time of arrival. AIS positions and estimated future positions are shown as red triangles and dots (each dot separated by ∼10 minutes). A wave height forecast map layer, is also visible. At the bottom a slider can be used to move between real time, past states and future estimated states.

(b) `NEPTUS` console used to supervise the execution of an AUV during operations. Salinity data, uploaded via satellite, is overlayed together with salinity data acquired by an underway CTD system towed by the R/V *Falkor* (using the same colormap). The console also displays the current estimated state, plan and timeline for the upcoming hour.

Figure 6. Situational awareness tools part of the `LSTS` toolchain used in the 2018 cruise.

with a time of arrival. When coordinating multiple assets some of these points will have a common time of arrival so that vehicles reach and depart at approximately the same time to allow scientists to gather collated data for rapid environmental assessment. A multi-screen console composed of different perspectives and NEPTUS consoles formed the Ocean Space Center (OSC) which allowed researchers in Portugal to follow the execution, monitor and control the operations during overnight operations on the *Falkor*.

NEPTUS has evolved over the years to plan and operate fleets of heterogeneous vehicles, while monitoring their execution (Dias et al., 2005; Pinto et al., 2006). To cope with continuous operations, plug-ins were added so that they can also be used as a rich client to the Ripples web API to retrieve and update the latest information on every asset. This is especially useful when multiple clients need to co-exist. To improve situation awareness, a range of plug-ins that mimic the Ripples perspectives have been added to NEPTUS. The advantage of using NEPTUS instead of Ripples is that it can also connect to other systems in the local network onboard a vessel. It can display any *NetCDF* [4] data overlaid on its map. For instance, onboard *Falkor*, consoles displayed the data from Ripples while being also used to control the UAVs in real-time and display incoming data from the ship-borne sensors, as well as data from locally generated oceanographic models.

Embedded on the robotic vehicles, DUNE handles sensor readings, logging, localization, and low-level control, while exposing a backseat API used by an onboard mission executive running on a secondary CPU. The backseat decides when to communicate and where to move by sending guidance commands to DUNE. The backseat API accepts commands that can include desired depth, speed and target position, or any combination of the above. The API also provides options to transmit and receive information to the control station and signals faults, the accomplishment of guidance commands, and data transmissions. The API has been used by a number of onboard deliberative planners in the past (Rajan and Py, 2012; Rajan et al., 2012; Chrpa et al., 2017) when deciding how to autonomously accomplish objectives provided by the users while adapting to local environmental conditions. This autonomous execution, while reducing the cognitive burden on operators, also makes it harder for the operator to maintain situational awareness of execution, as vehicle behaviors will likely change based on *in situ* conditions. For this reason, in this cruise, we chose to force the vehicle to communicate periodically with Ripples and synchronize its plan, as articulated below in Section 5.2.

Hardware developments. Several hardware developments were made to address the challenges of open ocean exploration, especially in the context of large-scale phenomena like the STF. These were aimed at extended AUV endurance and integration of new sensors in AUVs and UAVs.

We developed a new AUV configuration capable to operate continuously at ∼1 m/s for upwards of 50 hours and equipped with an independent emergency locator with global coverage. In order to accomplish these goals, the mechanical design of the vehicle was streamlined to reduce drag, new generation batteries, with a total capacity of 2600 Wh, were installed, and a Globalstar satellite asset tracker was integrated on a second, self-contained, antenna system.

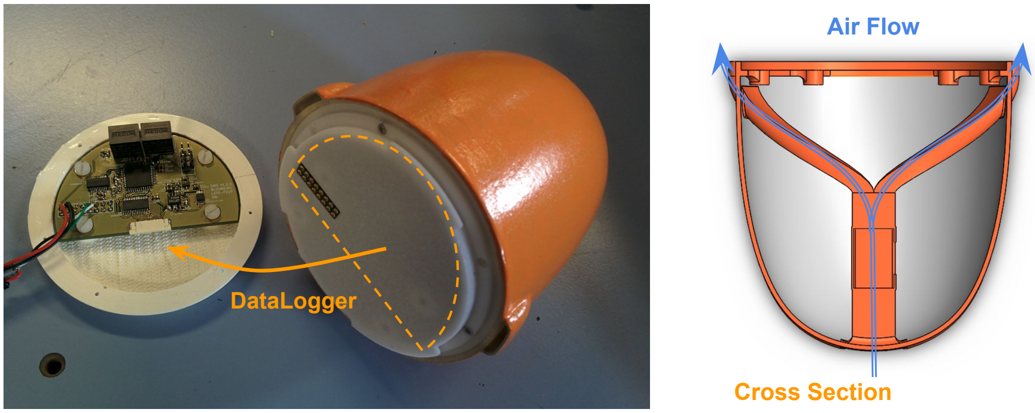
A low-cost Commercial off-the-shelf (COTS) vertical Take-Off and Landing (VTOL) UAV was integrated into the toolchain. Its autopilot, based on the open-source PX4 [5] flight control software, simplified the integration task. While its design included swappable nose cones with different payload sensors (Figure 7), the primary payload used during the cruise was a new Dimethyl Sulfide (DMS) gas sensor[6]. This sensor based on carbon nanotubes (CNT)[7] was used operationally for the first time

[4]Network Common Data Form is a set of software libraries and self-describing, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data. https://www.unidata.ucar.edu/software/netcdf/

[5]https://px4.io

[6]DMS is a volatile sulfur compound produced primarily from the breakdown of the phytoplankton in marine environment.

[7]Carbon nanotube (CNT) are room-temperature resistive sensors that work by passing electrical current across CNTs with a coating that selectively adsorbs the target gas molecule Li et al. (2003).



(a) (b)

Figure 7. The Dimethyl Sulfide (DMS) sensor mounted on the nose cone of the Flightwave Edge UAV from Figure 2. The data logger, shown in (a), acquires analog information from the sensor. The design in (b) was optimized for the air intake into the sensor.

in this cruise. Integration also entailed the design of a new nose cone to optimize the air flow into the sensor which was interfaced with a data logger that was tied into the onboard computational hardware to enable real-time DMS observations. Only raw data was collected from which DMS concentrations were derived post-cruise.

5.2. Planning and execution

In previous efforts, our multi-vehicle plans have been created in a distributed manner, with an off-board planner dividing the workload among vehicles and having the vehicles, in turn, adapt the synthesized plans onboard (de Sousa et al., 2016a; Ferreira et al., 2019; Chrpa et al., 2017). These deployments targeted mapping the ocean floor (where phenomena of interest are static) or mapping dynamic features in the water-column, with the need for adaptation with no human intervention (Das et al., 2015; Fossum et al., 2019). Although the operator input has been minimal in our previous approaches, awareness about the present and future behavior of the vehicles got occluded by changes happening while the vehicles were disconnected from the operator. For instance, in ocean floor mapping, which entails having AUVs following the terrain at a prescribed depth, it is not feasible to provide a good estimate for the time it takes the AUV to travel between two waypoints, simply because the terrain may be too complex to follow. Then, it will also be difficult to predict when/where the vehicle is going to resurface. In this work, we extended the planning system focusing on the predictability of the fleet, by forcing the onboard execution system to adapt its execution to match the expected high-level goals (and respective deadlines), as defined by the users and on-shore planners. Moreover, we have allowed these high-level objectives to also be generated onboard the vehicles, under the condition that new plans are synchronized with the on-shore planners before starting execution.

In our approach, high-level objectives in the form of waypoint locations associated with an *optional* time of arrival are provided by users or automated **planners**. These waypoints represent locations and instants where the vehicle surfaces and re-synchronizes its current plan with `Ripples`. At synchronization, it can transmit new or remove existing objectives. Whenever a new plan is scheduled (or modified), it is re-synchronized with `Ripples`, which requires the vehicle to surface and call home. High-level plan changes are expensive, not only because they require the vehicle to resurface, but also because previous user expectations cease to be met, impacting user awareness and decision making.

Algorithm 1. The onboard waypoint scheduling and temporal dispatch algorithm central to open water exploration.

```
Input: plan[] : a partially scheduled list of waypoints
plan.insertAt(0, createWaypoint(getCurrentPosition(), getCurrentTime()));
lastScheduledWaypoint ← 0;
dist ← 0;
for i ← lastScheduledWaypoint + 1 to plan.size() − 1 do
    dist ← dist + distance(plan[i − 1], plan[i])
    if isScheduled(plan[i]) then
        deltaTime ← plan[i].eta − plan[lastScheduledWaypoint].eta
        speed ← dist/deltaTime
        for j ← lastScheduledWaypoint + 1 to i do
            plan[j].eta ← plan[j − 1].eta + speed ∗ distance(plan[j − 1], plan[j])
        lastScheduledWaypoint ← i
for i ← lastScheduledWaypoint + 1 to plan.size() − 1 do
    plan[i].eta ← plan[i − 1].eta + nominalSpeed ∗ distance(plan[j − 1], plan[j]
i ← 0
while i < plan.size() do
    if plan[i + 1].eta − plan[i].eta > commTimeout then
        n ← (plan[i + 1].eta − plan[i].eta)/commTimeout
        insertIntermediateWaypoints(plan[i], plan[i + 1], n)
        i ← i + n
    i ← i + 1
```

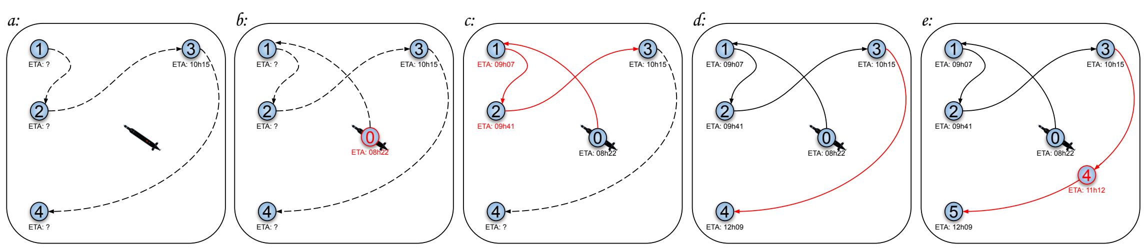


Figure 8. Depiction of an execution of Algorithm 1. The scheduling algorithm is used to assign an estimated time of arrival to all waypoint objectives.

On every communication opportunity, any changes to objectives are sent to the vehicle ensuring that the onboard **scheduler** will go through the new list of waypoints, update the execution schedule and validate it by taking into consideration the battery level and motion capabilities. If the plan is invalid given any of these constraints, it is replaced by an empty plan tantamount to idling at the surface. This process, therefore, results in a fine balance between what is traditionally noted as "fail operational" (where an onboard executive can "patch' a plan) and "fail safe" (where the executive relies on more expensive human intervention) in spacecraft operations (Muscettola et al., 1998).

The partial plan provided to the scheduler consists of a sequence of strictly scheduled and unscheduled waypoints which Algorithm 1 grounds into a sequence of scheduled waypoints. The algorithm uses the current location of the vehicle and the current time as the plan's initial waypoint (step b in Figure 8). It then uses the already scheduled waypoints to project the schedule of the remaining waypoints. It does this by first finding consecutive waypoints which have a waypoint scheduled immediatly before and after, to which it assigns a speed-of-travel according to the distance to be traveled and time available, while assuming no adverse environmental conditions (step c in

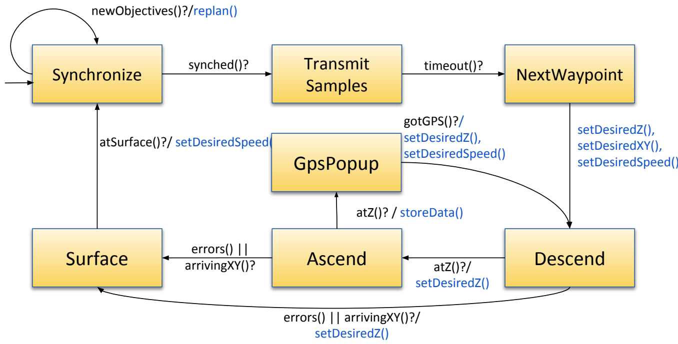


Figure 9. A simplified state diagram of onboard execution. The vehicle travels in a saw-tooth pattern and will periodically breach the surface to reacquire its position and calculate a new speed of travel. When arriving at intermediate waypoints, it synchronizes the state of plan execution with `Ripples` and opportunistically transmits collected data.

Figure 8). If after going through all intermediate waypoints, there are waypoint(s) of the plan that are not scheduled, the algorithm assigns a nominal speed to them (step d in Figure 8). After scheduling all user-defined waypoints, if any two waypoints of the plan are too far apart, additional waypoints are inserted in order to enforce the vehicle to communicate periodically with `Ripples` (step d in Figure 8).

Between two waypoints, the onboard execution system may alter the plan in the face of unexpected situations, such as strong currents and sensor failures, as well as when new objectives are posted onboard in response to locally perceived events. Whenever this impacts the ongoing plan, the vehicle resurfaces and synchronizes these changes with `Ripples` over satellite communications. Forcing synchronization and periodic communications serves multiple purposes. First, it improves awareness on ship/shore by bounding uncertainty about the vehicles. Second, if the operator wants to change the vehicle plan s/he knows when the objectives will be received by the vehicle and when to expect a new plan from the vehicle. Third, these periodic communications are used opportunistically to transmit (environmental) data.

The saw-tooth yo-yo pattern is typically used in upper water column oceanographic surveys. In our framework, the AUVs follow this pattern between consecutive waypoints, with the onboard **executive** deciding how the vehicle moves in terms of speed, heading and depth and to simultaneously acquire useful data and arrive safely, on time, at the next waypoint. Figure 9 depicts a state diagram of the vehicle's behavior between waypoints, as defined by the executive used in our cruise. The vehicle moves up and down the water column and, when traveling close to the surface it will breach periodically to acquire a new GPS fix. With every GPS update, the executive recalculates a new speed of travel to reach the next waypoint at the planned time of arrival. When the vehicle finally arrives at the next waypoint, it receives any new objectives (possibly creating a new plan). Before submerging again at the scheduled time, it will opportunistically transmit environmental data.

The behavior between scheduled waypoints is similar irrespective of how the waypoints have been posted or generated in the first place. Users can post scheduled or unscheduled waypoints via `Ripples`. Alternatively, these objectives can be posted from automated planners, which generate objectives using the equivalent expressiveness. Automated planners can either be running onboard the vehicles or elsewhere with `Ripples` access. We have tested different planners using this backseat approach (Rajan and Py, 2012; Chrpa et al., 2015; Mendes et al., 2018; Dias et al., 2020), some more deliberative, while others more reactive. Even though straight line (in the x-y plane) "yo-yo" transects are the most commonly used motion pattern for upper water exploration, adaptive motion patterns are more effective when it comes to tracking dynamic ocean features. This is one application in which automated planners excel.

Algorithm 2. A front following algorithm used onboard AUVs to track the STF. From Belkin et al. (2018).

```
Input: ang_inc: Angle increment after bouncing off crossing
Input: min_sal: Minimum salinity threshold
Input: max_sal: Maximum salinity threshold
/* assumes that vehicle starts moving south towards maximum salinity */
towards_max ← true
last_crossings ← [ ]
moveTowards (180 − ang_inc)
while true do
    if towards_max & readSalinity() > max_sal then
        last_crossings.insertAt(0, getCurrentPosition())
        towards_max ← false
        wall_angle ← 90
        if last_crossings.size() > 2 then
            wall_angle ← angleBetween(last_crossings[2], last_crossings[0])
            last_crossings.removeAt(2)
        moveTowards (wall_angle − 90 + ang_inc)
    else if !towards_max & readSalinity() < min_sal then
        last_crossings.insertAt(0, getCurrentPosition())
        towards_max ← true
        wall_angle ← 90
        if last_crossings.size() > 2 then
            wall_angle ← angleBetween(last_crossings[2], last_crossings[0])
            last_crossings.removeAt(2)
        moveTowards (wall_angle + 90 − ang_inc)
```

An opportunistic front tracking algorithm

During the course of the cruise, we deployed a new front tracking algorithm (Belkin et al., 2018) which works by first guiding the vehicle towards the interior of the salinity gradient and then maintaining the vehicle inside it by bouncing in between two salinity thresholds. Bouncing, in this case, implies calculating an angle that drives the vehicle along the front by estimating its shape. A simplified pseudo-code is provided in Algorithm 2.

An agent that reads salinity measurements directly from the CTD and generates a new waypoint when it detects a crossing. As a result of this newly added waypoint, the scheduler will create a series of waypoints in between the current position and the new waypoint. The AUV will then travel in the required direction, with periodic surfacing for communications. Whenever new waypoints are generated, the plan is synchronized with `Ripples`. The open source code for this implementation is freely available.[8]

6. Study of the Northern Pacific Sub-tropical Front

The cruise between May 28th and June 18th 2018 served as a demonstration of our networked approach where an engineered system was used to **find**, **map**, **sample**, and **track** one segment of the large Pacific sub-tropical front using a research vessel as the center of operations to operate an ensemble of heterogeneous unmanned vehicles continuously for over 15 days (transits from and to San Diego took approximately 3 days each way). The STF is a feature that evolves in space and time ranging from minutes to days and from meters to hundreds of kilometers. After finding its approximate location with the help of the ASVs, our networked approach, was then used to

[8] https://github.com/zepinto/imc4j/blob/feature/front_following/src-backseat/pt/lsts/autonomy/soi/FrontTracking.java

Table 2. Timeline of the 2018 cruise in the Pacific.

Date	Event Description
April 28th	Analysis of remote sensing SST imagery and numerical model data to identify the location of the STF
May 1st	Deployment of *Wave Glider* towards the estimated study region
May 27th	Two *Saildrone* ASVs tasked to transit to the study area from a previous mission
May 28th	The *R/V Falkor* departs from San Diego; the ASVs spot the apparent frontal zone
May 30th	The arrival of the *Falkor* in the study area and deployment of AUVs
June 8th	The first viable SST remote sensing images confirm the existence of a frontal jet
June 16th	Start of *Falkor's* return transect to shore

Table 3. Assets used in the cruise include a diverse array of platforms and sensors for observation of a number of key ocean variables, including temperature, salinity, depth, planktonic density, chlorophyll concentration amongst others.

Asset	Description
R/V *Falkor*	Equipped with underway water characterization system, High-Performance computing cluster (HPC), underway CTD (conductivity, temperature, density), CTD and water sampling system Rosette, ADCP (Acoustic Doppler Current Profiler), weather stations, an Advanced Laser Fluorometer (ALF) for spectrum analysis of the water-column in near real time (Chekalyuk et al., 2014), AIS, radar, etc.
AUVs	3 equipped with CTDs and long-endurance (>50 hours) and 3 other vehicles equipped with CTDs and physical and bio-chemical sensors, with an endurance >24 hours [Figure 2(a)].
UAVs	3 FlightWave Edge-130 UAVs with Dimethyl sulfide (DMS) sensors, infra-red or multi-spectral cameras and 1 UAV carrying visible light cameras for outreach purposes [Figure 2(d)].
ASVs	Two *SailDrones* and a *Wave Glider*.

map sub-mesoscale features with multiple assets, and to select the locations where to perform high-resolution surveys with AUVs equipped with physical and biological sensors which was complemented with ship-based measurements and water sampling. We also used this infrastructure to perform coordinated ship-robotic surveys and to task an AUV, running Algorithm 2 onboard, to track a segment of the front. A brief timeline of the cruise is shown in Table 2 and the main operational and scientific results follow.

6.1. Assets

This multi-disciplinary research cruise relied not only on the operation of the robotic assets but also on their teaming with a manned ship from where they were deployed and recovered. This approach to scientific exploration in the open sea brings together an infrastructure to enable ships and robots to work cooperatively in tandem, expanding the near-synchronous observational footprint of traditional methods. The software infrastructure allowed us to coordinate and aggregate information from remote sensing and model products, deployed autonomous assets, and the real-time measurements collected by the research vessel's sensors (Table 3), with all information centralized in `Ripples` and made accessible over the Internet.

The main sensors aboard the *Falkor* used in this cruise included an Acoustic Doppler Current Profiler (ADCP) that measures current profiles at different depths directly below the vessel, a rosette that was lowered from the ship to make vertical profiles with a Conductivity Temperature Density (CTD) and to collect water samples for posterior laboratory analysis onboard and on-shore, an underway hull-mounted thermo-salinograph,[9] a towed CTD sensor to perform vertical profiles of up to 300 m depth, weather stations to monitor humidity, barometric pressure, temperature and winds, an AIS receiver and radar, for monitoring surface traffic. These instruments aboard the *Falkor* were augmented with additional cutting-edge technologies, including two Advanced Laser Fluorescence (ALF) sensors that perform high-resolution underway fluorescence measurements and analysis (Chekalyuk et al., 2014).

6.2. Finding the front

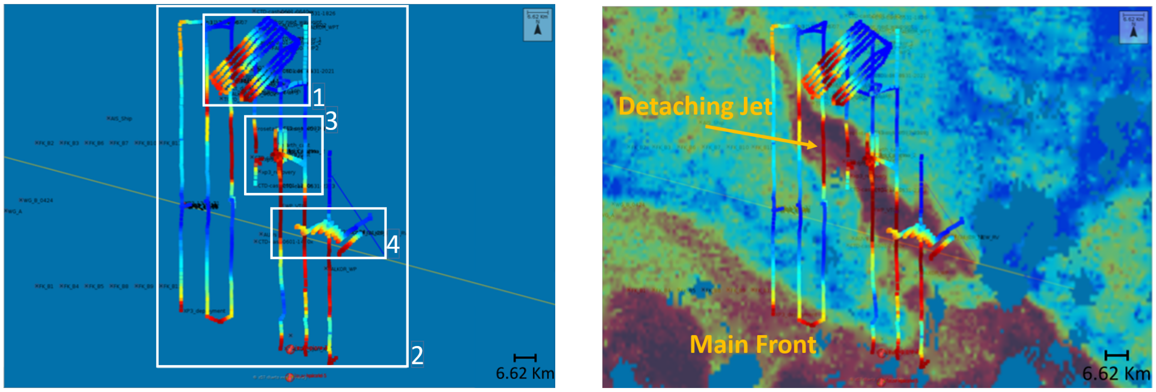
Finding the front in itself was challenging and was initiated by analyzing remote sensing data while still on shore. Although salinity is the dominant gradient in the STF, the coarse spatial resolution (>40 km) provided by the available satellite-derived salinity products is insufficient to detect the front and select the operations area for the cruise. To alleviate this challenge, we resorted to using sea surface temperature (SST) as a proxy for finding the front. Although not dominant in the STF, SST can help localize a frontal region, especially in the open ocean, as its remote sensing imagery has both meso and sub-mesoscales. In addition, the variations on surface salinity and temperature are strongly correlated. Therefore we planned to use SST as a *prior* to create a synoptic view of the study area during the cruise. However, continuous cloud cover, including a month prior to the cruise, precluded that possibility. Infrared and color remote sensing products can also provide strong validation and indirect measurements of open ocean processes, but need cloud-free access to the upper ocean, while large-scale synthetic ocean models cannot resolve sub-mesoscale and small-scale dynamics of ocean features, including fronts. We, therefore, resorted to a mix of the two approaches. A qualitative analysis based on monthly averages of previous years indicated that the STF should be located roughly 1500 km to the west of San Diego (30°N–35°N, 130°W–135°W). Predictions from CMEMS,[10] a large-scale ocean model, were used to fill in the gaps left by remote sensing.

Based on the climatological analysis of the remote sensing data and daily predictions from large-scale ocean models, two *Saildrones* and a *Wave Glider* ASVs were deployed ahead of the ship for fine scale scouting of the front as a means to narrow down the survey area; typically, such search is performed with the research vessel itself, at a much higher operational costs. Using robotic platforms spread over hundreds of square kilometers, allowed a larger spatial coverage within a shorter period of time. In this case, temperature and salinity data collected by the ASVs suggested frontal crossings at different locations, tens of kilometers apart. `Ripples` ingested this data as well data from other sources, such as CMEMS predictions of sea surface salinity and temperature, to generate maps that enabled scientists to rapidly interpret measurements, and over several days, circumscribe an initial area of interest indicated by a black circle in Figure 3.

6.3. Mapping the front

Upon arrival at the study area, three AUVs were deployed to begin a high-resolution mapping (radiator pattern with a ∼2 km separation between tracks) of the frontal zone [Figure 10(a)—box 1]. Concurrently, the *Falkor* explored the area using the underway thermo-salinograph and the towed CTD. Oceanographic data collected by the AUVs were transmitted periodically over satellite links whenever the vehicles arrived at each waypoint at the surface. On these scheduled synchronizations, the vehicles updated their plan with the central `Ripples` server and sent *sub-sampled* data for rapid ship/shore assessment by scientists. This rapid assessment, complemented by the data previously collected by ASVs, and a qualitative analysis of remote sensing data available and predictions from ocean models, worked as a “prior” to inform human decision making for the next set of observations.

[9] A sensor that samples salinity and temperature from an inlet on the ship’s hull.
[10] https://marine.copernicus.eu/



(a) (b)

Figure 10. (a) `NEPTUS` screenshot displaying AUV data. Boxes represent scales of sampling across the salinity front for the STF. Each of Nos. 1, 3, and 4 represent surveys in high resolution while No. 2 represents a more expansive survey by AUVs. In so doing, we used No. 2 to inform the higher resolution missions. (b) Surface salinity collected by AUVs and superimposed in the background on the AUV tracks from figure (a), a SST remote-sensing image from June 8th, which confirmed the presence of a frontal jet, partially detached from the main front. The color gradient represents salinity measurements sent over satellite comms and acquired by CTDs mounted on AUVs.

While the AUVs were performing the initial mapping, scientists tasked the *Falkor* to move 80 km south for a rapid exploration of the front and to make a surprising discovery: the salinity thresholds that defined the front were crossed twice (in and out of the "front"), contrary to the typical pattern of the front. At this point, the numerical models running onboard the vessel's High-Performance computing cluster (HPC) proved useful to shed some light on the data collected, especially given the still-ongoing lack of current remote sensing data due to cloud cover.

This discovery, and subsequent analysis, proved fundamental to determine the next exploration step: to perform a mesoscale mapping centered at the front, and covering a 75×90 km^2 area, with an unprecedented sub-mesoscale horizontal resolution of 5 km between cross-frontal sections [Figure 10(a)—box 2] and a micro-scale resolution of 800 m along each cross-frontal section [Figure 10(a)—box 3].

These surveys were conducted (also using a radiator pattern), with long sections oriented perpendicular to the front. Three long-range AUVs (with a 50-hour endurance) were deployed simultaneously along parallel tracks crossing the front. Before the end of their deployment (after 40 hours), the three long-range AUVs were swapped with three short-range AUVs (with a 24-hour endurance). After the swap, the long-range AUVs were charged for 10 to 12 hours. Then, the three short-range AUVs were swapped with the three fully-charged long-range AUVs and the survey continued while short-range AUVs were charged for 6 to 8 hours. Swapping long-range AUVs with those short-range enabled frontal 3D surveys to be conducted uninterrupted. Moving along the radiator pattern, each AUV was doing yo-yo's between the surface and 100 m, with a speed of $\sim$2 knots (1 m/s) and descent/ascent angle of 15°between 0 and 100 m depth to enable a horizontal resolution of $\sim$800 m. 3D maps of the area under study were produced using the data sampled by the three AUVs synchronously traveling through the feature of interest (Figure 11). The synchronicity of the mapping was the result of the onboard execution system that committed the AUVs to scheduled surface waypoints provided by the users. With AUV transects reaching distances of up to 40 km from the research vessel, `Ripples` 's capabilities to estimate future states and to perform automated risk assessment (also to be cognizant of and prevent potential intersections with ship traffic) were instrumental to plan for deployment and recovery rendezvous locations with AUVs and above all, to minimize operator burden through long shifts.

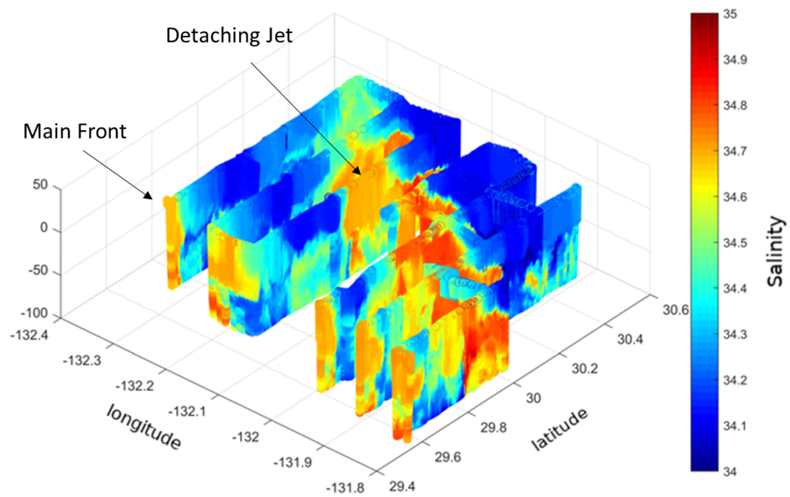


Figure 11. 3D view of the STF using AUV salinity data [Figure 10(a),—box 2]. Both the jet detaching from the front and its boundary is visible. Z axis corresponds to depth in meters.

This multi-AUV mesoscale mapping took approximately four days. It was coordinated with a sequence of vertical casts performed by the Rosette aboard the *Falkor*, to take CTD measurements and collect water samples down to 500m with the vessel stopping for less than one hour for each cast. The casts in turn, were coordinated with the trajectories taken by the AUVs for optimal coverage as a way to ground truth measurements. The data collected in this process, including ADCP profiles measured from the *Falkor*, as well as the preliminary laboratory analysis of the water samples, performed onboard the vessel enabled scientists on ship and shore to develop insights to explain the observations and to select additional sampling points to reduce uncertainty.

The collected data visualized in `NEPTUS` and `Ripples` consoles together with the first (almost) cloud-free SST remote-sensing image obtained since departure on June 8th, enabled the development of a new picture of local ocean dynamics. The data showed a direct correlation between temperature and salinity collected by the AUVs and confirmed the existence of an ocean structure partially detached from the main front as shown in Figure 10(b), with surface velocities in the order of 1 m/s—these are unusually strong currents in the open ocean. Scientists then determined that the initial estimated position of the frontal location actually corresponded to a frontal jet, a sub-mesoscale spiral-like feature [Figures 10(b) and 11]. Such a feature has rarely been observed and never at this level of detail at such scales. The ability to overlay data from multiple sources (including real-time and remote sensing), as well as the possibility for the scientists on shore to interact with those onboard, supported the agile decision-making made during the cruise.

6.4. Exploration and scientific analysis

The data collected during the mesoscale mapping was used to plan the subsequent exploration of a segment of the front, including the jet. In this phase, high-resolution surveys with AUVs equipped with physical and biological sensors, complemented with ship-based measurements and water sampling, were performed. Vertical Take-Off and Landing (VTOL) UAVs were tasked to fly over selected areas to collect infra-red, multi-spectral and visible light imagery, as well as to measure concentrations of DMS in the air.[11] UAVs were also used as data "mules" to ferry data from distant AUVs to the *Falkor*, as well as communication gateways for "bent" line-of-sight communications with the AUVs.

[11] DMS is a proxy for some types of biological activities that may take place at fronts.

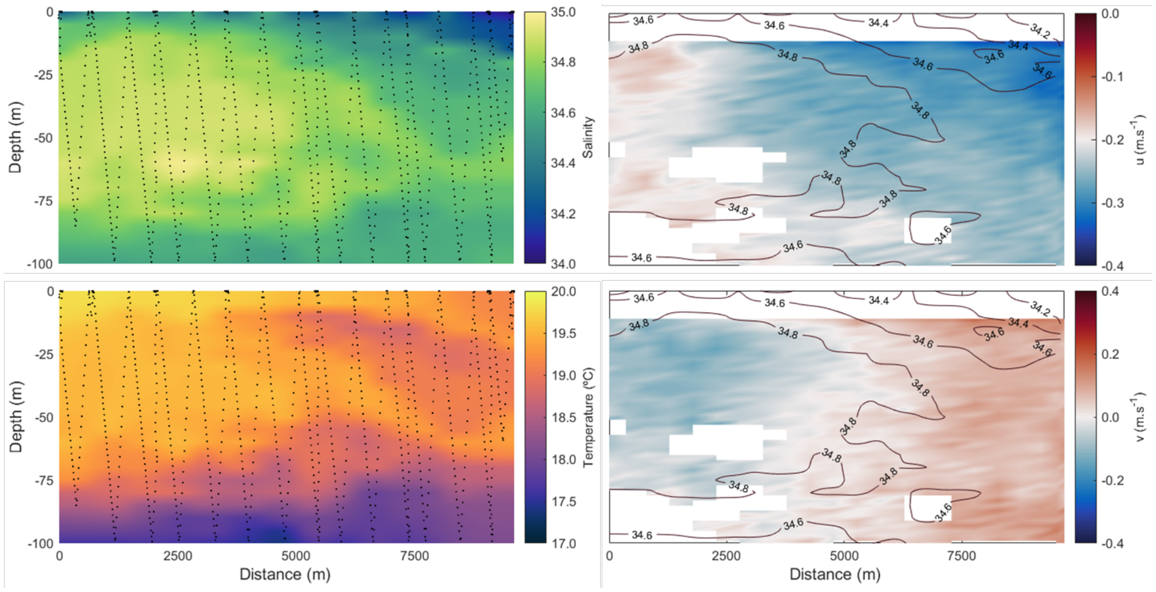
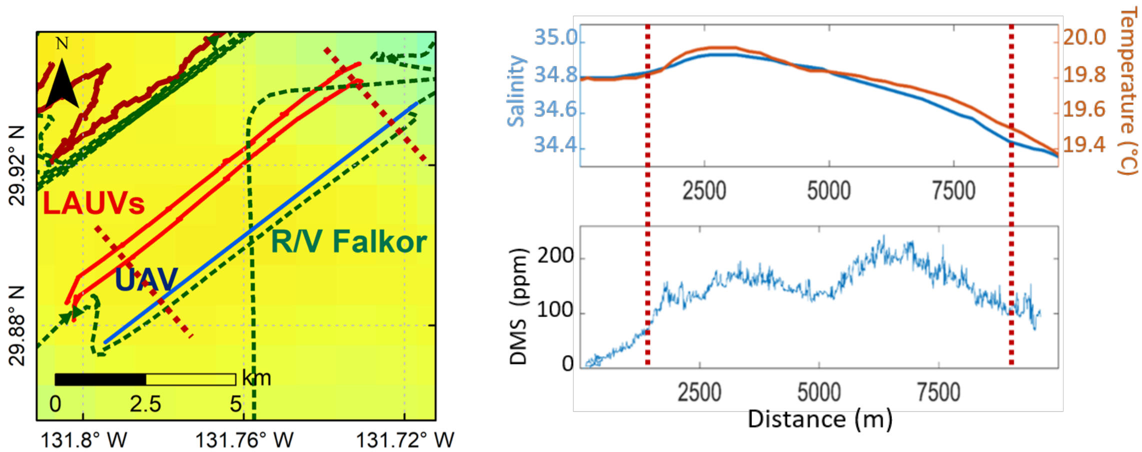


Figure 12. Observations obtained almost simultaneously by two AUVs and the *Falkor* ~10 km across the jet section on June 10th [see Figure 13(a)]. Left panel - contour map of water column salinity and temperature based on the AUV yo-yo data (black dots). Right panel - contour map of *u* and *v* components of currents measured with an ADCP

In one coordinated survey, the *Falkor*, 2 AUVs, and 1 UAV moved in formation along a straight line at the boundary of the jet [Figure 13(a)], while two other AUVs were performing another mapping task. At this time, four AUVs were being supervised by a single operator on the ship, and a second operator was in charge of supervising one UAV over the radio. Using the combined potential of our software infrastructure, the asset positions (received and estimated) were visible in all consoles, allowing AUV and UAV operators to collaborate and monitor data from any of the vehicles in real time. `Ripples` and `NEPTUS` consoles were also available at the bridge, where the captain and the crew could adjust the ship's position and velocity with full awareness of AUV locations and UAV flight patterns.

The results from this coordinated survey are the most representative example of this approach's advantage for future science expeditions. As the ship could not be controlled automatically from `NEPTUS`, the desired speed and course for the ship were generated with the help of a simulated ship for which a coordinated motion plan was derived. The ship captain used the `NEPTUS` display of the locations of the simulated ship and of *Falkor* to execute the prescribed plan. The salinity and temperature data collected by the AUVs across the jet matched with surface structure distinctively observed in a SST image [Figure 10(b)]. The vertical thermohaline structure of part of the jet spiral arm was resolved with an unprecedented spatial resolution with the data collected by AUVs (Figure 12). The higher salinity and temperature patches on the left side of Figure 12 were detected from 75 m down to 100 m depth.

The area of influence of the jet was larger than expected from the consideration of the satellite image. As it progressed northeastward, this feature went deeper, while being capped by a layer of colder and less saline water (Figure 12). These results are consistent with the subduction of denser water from near the surface, which provides evidence of instability associated with the structure detaching from the main front to the south [Figure 10(b)]. The scale of the jet also suggests a strong horizontal shear and a cross-frontal convergence which is revealed by vertical profiles of the water velocity collected synchronously by the ADCP aboard the *Falkor*. Closer examination indicated that the rapid horizontal shift in magnitude and direction of u and v velocity components



(a)

(b)

Figure 13. (a) Location of the second coordinated ship-robot survey conducted at the northwestern boundary of the frontal jet [Figure 10(a)—box 4]. The dashed red lines marked the approximate edges of the frontal boundary. (b) Observations were obtained near-simultaneously by one of the AUVs, the *R/V Falkor* and the UAV along a ∼10 km cross jet section on June 10th. (Top) Surface temperature (orange) and salinity (blue) collected by underway instruments on *Falkor* (3 m depth). The vertical dashed red lines mark approximately the limit of the salinity and temperature plateaus that are edges of the front as shown in Figure 13(a). (Bottom) DMS data acquired by the prototype sensor mounted on the UAV.

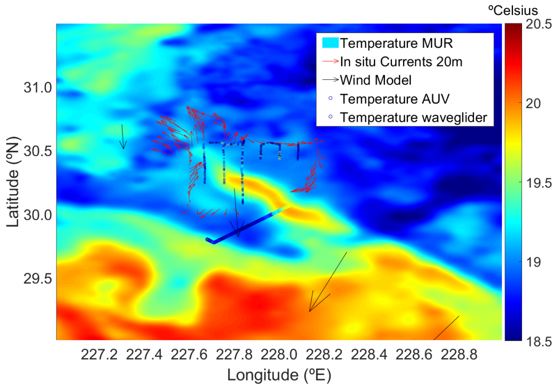
was concentrated over a narrow region, implying large shear and convergence rate (Figure 12) and, possibly, strong vertical advection, which may have a critical impact on biological processes.

Post-cruise data fusion and analysis revealed evidence of sub-mesoscale instability associated with the jet detaching from the main front and near locations associated with horizontal convergence. The jet was analyzed in detail using Finite-Size Lyapunov Exponents (FSLEs) (Santos-Ferreira et al., 2020). FSLE are produced by a new, satellite altimetry-based product [Figure 14(b)], derived from Aviso+,[12] that can be used to identify small-scale oceanic structures. FSLEs were consistent with the available SST [Figure 14(a)] and *in situ* data [Figure 14(b)] and reveal that the frontal instability is part of a spiraling counter-clockwise arm of a sub-mesoscale eddy. This suggests that FSLE maps can be a useful remote sensing product for planning open ocean exploration.

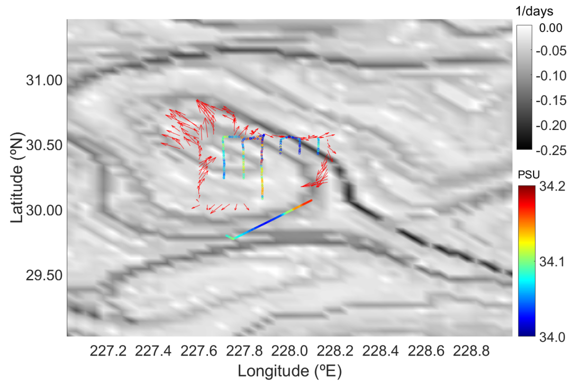
In oligotrophic environments, as in the study area, where the available nutrients offer little to sustain life, primary biological production responds to upward nutrient inputs into surface layers by sub-mesoscale vertical velocities which are often associated with frontogenesis mechanisms. These mechanisms lead to the intensification of fronts through lateral strain and enhancing vertical velocity in the case of sub-mesoscale dynamics (Mahadevan, 2019). Due to the temporal and spatial scales involved, sub-mesoscale fronts can exhibit locally increased biomass; ALF measurements support those observations. The results showed a high spatial correlation in the variability of salinity and chlorophyll biomass at the surface layer, specially during large-scale mapping. Also, both sharp frontal gradients and more moderate gradual changes in phytoplankton biomass were found during the coordinated underway sampling across the frontal zone. The impact of the biochemical results of continuous measurements from the ALF instrument suggests a possible integration of these sensors onboard unmanned vehicles for automated real-time analysis and identification.

Taking the linked association between the biochemical changes and the frontal jet into consideration, a UAV was flown over the frontal edge, synchronously with the ship and AUVs, in

[12]https://www.aviso.altimetry.fr



(a)



(b)

Figure 14. On June 7th, 2018 (a) SST product from MUR database (Chin et al., 2017) and (b) finite-size Lyapunov Exponents. Both images represent the *in situ* currents measured by ADCP (red arrows) onboard the *Falkor*, the wind velocity from CMEMS model (black arrows), and tracks of the *Wave Glider* and AUVs color-coded by temperature and salinity respectively in (a) and (b). The track of the *Wave Glider* is very close to a straight line in the SW-NE direction approximately at 30.0°N in the images and the AUVs surveys are located around 30.5°N.

order to evaluate the performance of the CNT sensor (Figure 7) in detecting DMS from the air. Since the CNT sensor was an early prototype, it had not been used before at sea and it was not calibrated or validated to obtain precise measurements of DMS in these conditions. Nonetheless, the resistance changes of different detectors were being logged, transmitted and plotted live in NEPTUS, as calibrated results could be calculated later. The actual DMS results were available after on-shore post-processing when relative resistance changes resulting from adsorption were evaluated against laboratory-derived models to estimate gas concentrations. Preliminary results of the cross-jet flight path show two distinctive DMS peaks [Figure 13(b) - bottom panel] at the region between the two density plateaus [Figure 13(b) - top panel], i.e., in the higher salinity and temperature horizontal gradient, as well as in the area of larger horizontal velocity shear (Figure 12). Additional development work also needs to be performed to characterize the sensor's performance. After subsequent lab-based on-shore analysis, biogeochemical water samples which were taken at the surface also demonstrated a peak of nitrite (NO_2) at the same location.

The ship's winch, with which the rosette is lowered and is typically the most important sensor to use in an oceanographic expedition, had a malfunction mid-cruise and ceased to work. In a traditional expedition, this would have had a substantial impact as typically, no other ways would exist to collect data from depth. However, operations on the *Falkor* never stopped, as also the stream of data collected with all robotic assets never ceased. In a latter part of the cruise a new makeshift CTD winch was put together and water samples could be collected.

After exhaustive **mapping** with multiple assets (Figure 11), we tested more autonomous behaviors with our infrastructure. The automated front tracking algorithm (box 4) (Belkin et al., 2018) was opportunistically designed and tested with a *Wave Glider* and the *Falkor* by manually guiding these assets. For this, the scientists monitored the salinity readings and whenever a certain threshold was crossed, they calculated the new direction. This type of control is demanding and practical only for surface assets where data can continuously be streamed over viable communication links. Subsequently, it was embedded on an AUV using an automated planner which generated high-level objectives by implementing Algorithm 2. In open ocean fronts, the width of the frontal region can be large (>250 m) and the gradient could not be defined by a simple step function, as in other domains where the fronts can be extremely narrow (< 50 m) (Pinto et al., 2018). So, instead of driving the vehicle to each side of the front indefinitely, Algorithm 2 **tracks** the STF by first driving it to the front and then maintaining it *inside* the frontal area. In the case of AUV tests, survey transects were generated onboard according to the locally perceived salinity variations and every change of plan was synchronized with `Ripples` which maintained awareness of the operators, crucial for this test at sea.

6.5. Discussion

The scientific results would have not been possible were it not for the infrastructure that was made available for this cruise to provide situational awareness on present and future states of assets and environmental conditions. In research cruises at this scale, the exposure to failure is a constant. Early in the cruise, primarily for testing hardware, one AUV had a servo-motor problem which was fixed onboard on the same day. No other issues were experienced by the AUVs. The impact of the failure of the ship's winch would have been dire had they not been compensated by data collection from the ensemble of robotic assets, most of which were equipped to provide measurements in the upper 100 meters. Overall, six AUVs were deployed for multiple missions while completing over ∼1800 km of in-water transit while UAVs performed 21 successful flights. The software and hardware infrastructure proved to be robust and resilient addressing significant operational and logistical challenges to maintain 24×7 operations.

Persistent operations were achieved with four six-hour shifts per day, with two operators per shift. At every time there was an operator responsible for the health of the ensemble of vehicles (simplified by a risk assessment perspective provided by the software), but this responsibility could be swapped among the two operators throughout the shift. The chief scientist would sketch out the plan for the day in the morning and (possibly) change it according to incoming data and other scientists' inputs. During UAV operations, one operator took responsibility for the operation paired with another responsible for AUVs. Although it would be feasible to monitor and control all UAVs and AUVs from a single `NEPTUS` console, the necessity to communicate with a (third) safety pilot for take-off and landing led us to decide on this separation of tasks.

7. Conclusions

During this 2018 open ocean cruise, a fleet of underwater, surface, and aerial vehicles was used to locate, identify, survey, and track a major large-scale climatic front, in the North East Pacific between California and Hawaii. Simultaneous deployment of several AUVs on parallel tracks centered at the front enabled an unprecedented sub-mesoscale horizontal resolution of 5 km between cross-frontal sections and a micro-scale resolution of 800 m along each cross-frontal section. The yo-yo based profiling of the water column with AUVs moving at 100 cm/s along gently slanted flight paths, sampling at 4 Hz, enabled a vertical resolution of 2 cm. Swapping two sets of AUVs before each set reached its endurance limit allowed a persistent 3D frontal survey. The *Falkor*, 3 AUVs, and 1 UAV performed coordinated ship-robotic surveys by moving in formation to sample selected areas, above and underwater. A new front-tracking algorithm was designed and tested by successfully guiding the *Falkor*, Wave Glider, and AUV along the STF.

The outcome of this cruise is not just scientific or technological; it also provides future blueprint on how oceanographic expeditions can leverage the use of *networked* robotic platforms to increase a ship's sensing footprint and operational flexibility. In this effort, we present an approach using networked manned and unmanned assets to explore the ocean over large spatial and temporal scales and demonstrate its feasibility by reporting results from a 15 day deployment in the open ocean.

By the very nature of the exploration process, not all aspects of a cruise in such harsh environments are likely to be successful. We experienced equipment failure and lack of correlated measurements across multiple sensors and platforms; yet demonstrated how multiplicity and heterogeneity of assets ultimately help in making observations at scale. Further, not only can such an ensemble of vehicles provide high-resolution data across vast spatial and temporal scales, but they also change the *way we explore* by extending the footprint of a vessel and human senses.

Cruise results include valuable and generative lessons on exploring the open ocean with a multi-disciplinary team of scientists and engineers controlling heterogeneous assets. Coordination of information and multi-vehicle activities was required, not only for all of the assets, but also for decision-making towards high-resolution observation of scientific interest. The dichotomy of "exploration versus exploitation," for instance, remains a major challenge in a daily decision-making cycle, driven by admittedly a simple question: "where and when to sample" the water column. Yet it hides a complex set of technical, scientific and even intuitive biases designed into such an undertaking. Initial exploration efforts leaned towards being risk-averse, while the adopted workflow was tested. As events progressed, operationally riskier outcomes were adopted organically, including the decision to design and implement a front-tracking algorithm *while at sea*; this is a common strategy in an exploration of any kind (Bellingham and Rajan, 2007).

Our infrastructure combines an effective situational and operational awareness, where the team was able to track the state of every deployed asset and, at the same time, follow the scientific findings throughout the cruise, on ship and shore. Such a methodology is even more important in circumstances where a team is physically separated, resulting in a shared understanding of the evolution of activities past, present and future (Lima et al., 2021). The use of `Ripples`, which was aggregating data from multiple fielded assets, made it possible for scientists on shore to use a command/control interface similar to the one available onboard, and through it aided in the understanding of what was being measured and deciding where (and when) to go and what to sample. At any time, the users could supervise the events planned for the upcoming hours or even days ahead, which streamlined choosing of rendezvous points for recovering assets.

Although the use of temporal dispatching and periodic synchronization provided much-needed predictability on the behavior of all assets, by using onboard scheduling and distributed planning, we allowed the system to adapt to dynamic circumstances while still maintaining situational awareness for scientists and operators. Such a bidirectional planning approach, allows objectives to be posted both from the software planning systems onboard vehicles, as well as from ship/shore in response to observations from any source. In our cruise, this was most evident while testing the front tracking algorithm with all behaviors being generated onboard an AUV but without losing track of its execution. In doing so, the approach decreases the burden on operators and is scalable with the respect to the operation of ensembles of autonomous vehicles, especially over high-latency and fallible networks.

In the future, other autonomous behaviors and local adaptations can be added to the vehicles via the addition of other onboard planners. Although current planners use only local information to generate high-level objectives to decide their behavior, other information such as ocean current predictions and planned behavior of other assets could be downloaded from `Ripples` and used for local adaptations. Currently, our system estimates that vehicles travel in straight lines between planned waypoints, but this can be relaxed, providing more time for vehicles to explore between planned synchronizations. We foresee the inclusion of other kinds of planning systems that will automate entire scientific methodologies by ingesting data from deployed assets, remote sensing and weather forecasts and decide new tasks, while still allowing local adaptation and exploration to be happening onboard.

This work was a sizable step forward in ocean exploration, demonstrating scientific value in combining traditional and more novel methods for the exploration and sampling of dynamic open ocean phenomena. By using a fleet of unmanned vehicles and a system that simplifies their operation and provides requisite situational awareness, we envision that such operations will become more ambitious and span across larger areas and open the door for fully remote operations and cruises—a future where scientists can guide multiple heterogeneous assets and access their data in near real time from shore with research vessel support becoming an option.

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