Field Report: Exploring Fronts with Multiple Robots

Maria João Costa, José Pinto, Paulo Sousa Dias,
João Pereira, Keila Lima, Manuel Ribeiro, João Borges Sousa
Laboratório de Sistemas e Tecnologia Subaquática
Faculdade de Engenharia da Universidade do Porto
mariacosta@fe.up.pt

Trent Lukaczyk
FlightWave Aerospace Systems &
Laboratório de Sistemas e Tecnologia Subaquática
Faculdade de Engenharia da Universidade do Porto
trent@flightwave.aero

Renato Mendes*†,
Maria P. Tomasino*, Catarina Magalhães*
**CIIMAR, Universidade do Porto*
†CESAM, Universidade de Aveiro
rpsm@ua.pt, cmagalhaes@ciimar.up.pt

Igor Belkin
University of Rhode Island
igormbelkin@gmail.com

Francisco Lopez-Castejon, Javier Gilabert
Universidad Politécnica de Cartagena
javier.gilabert@upct.es

Kay Skarpnes, Martin Ludvigsen, Kanna Rajan
Applied Underwater Robotics Laboratory
Norwegian University of Science and Technology
kay.arnes.skarpnes@ntnu.no

Zara Mirmalek
Harvard University
zara_mirmalek@hks.harvard.edu

Alex Chekalyuk
Lamont-Doherty Earth Observatory
Columbia University
chekaluk@ldeo.columbia.edu

***Abstract*—This paper presents a report from a cruise onboard the R/V Falkor oceanographic vessel from the Schmidt Ocean Institute. The goal of this cruise was to demonstrate a novel approach to observe the ocean with multiple underwater, surface, and aerial vehicles, as well with the R/V Falkor also used as the base and control center for all assets. We describe the planning phase leading up to the cruise, the technical approach, developments and timeline of results and decisions made throughout the cruise.**

Our approach combines a set of new technologies that enabled scientists and engineers to obtain a synoptic view of the study area, with adjustable spatial and temporal resolution, and to compare data collected in near real-time to the outputs of computational models. This approach was applied to map the Pacific Ocean's Subtropical front with unprecedented spatial and temporal resolutions.

***Index Terms*—Multi-Robot Systems, Unmanned Autonomous Vehicles, Operational Oceanography.**

I. INTRODUCTION

The oceans are an essential component of Earth's life support system, but we still do not fully understand what is going on there. Current day tools and technologies are however still limited and not as proficient as we would like them to be. The traditional methods (scientific ships' based operations) can't quite achieve the required spatial and temporal resolutions necessary to comprehend the oceans, in a sustained and attainable manner. In May 2018, a cruise took place aboard R/V Falkor from Schmidt Ocean Institute for 20 days in the Pacific waters[1] approximately 800 nautical miles off the coast of Southern California, at the Pacific Subtropical Front (STF). This cruise introduced a novel approach to observe the ocean by using multiple underwater, surface, and aerial vehicles and the scientific ship as the base and control center. This paper presents a field report of the cruise and describes the technologies used in this approach.

This paper is structured as follows. In section II we describe the scientific objectives and motivation for this cruise. Section III discusses related work. Section IV describes the planning process of the cruise. Section V gives an overview of all technologies that were used or developed for this cruise. In section VI, an analysis of what has been done, as well as of the decision making process is documented and, finally we discuss preliminary results and conclusions in section VII.

II. GOALS OF THE CRUISE

The motivation behind our work is to develop and deploy novel robotic technologies for the ocean sciences. The scientific goal of the cruise was to map the STF with unprecedented spatial and temporal resolutions, combining multiple heterogeneous robots and shipborne sensors, using the ship as base and control center.

A. Scientific Objective

The scientific aim of the cruise was chosen to be the study of Pacific Subtropical Front (STF) between 30ºN-35ºN latitude and 130ºW-135ºW longitude. In oceanography, fronts are sites where drastic changes occur within the properties of the waters. In the case of the STF, is where cold waters from the Arctic meet the warmer and more saline waters of

---

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

the tropics. Salinity differences are the main feature to locate the STF. Salinity fronts, however, are difficult to detect using remote sensing (only in the last decade was it possible to do so with satellites and the technology is still evolving regarding spatial resolution and accuracy [1] [2]). In-situ sampling is the most effective way to study the STF, and its sheer size makes it a suitable ocean feature to test and showcase coordinated ship robotic surveys.

B. *Challenges*

The technological challenge was to use all the available technologies (ship observations, robots, biological sensors, etc.) in a coordinated manner to maximize the scientific outputs. This required a truly interdisciplinary work, combining traditional sampling methods with robotic technology, coordinating assets under unreliable, high-latency and low bandwidth communications, integrating visualizations of all collected data, together with outputs from oceanographic models - and doing so non-stop, for the duration of the cruise.

III. RELATED WORK

The idea of adapting our technologies to serve scientific applications is something the authors have been working over a decade now. In 2014, an experiment took place off the coast of Algarve (Portugal), where biologists and engineers worked together for studying Ocean Sunfish. Satellite tags were attached to specimen and networked autonomous robots were used to track and sample their surroundings [3] [4]. In 2015, during the REP15 exercise in Azores, a similar exercise was carried out, but this time to study sperm whales [5]. The operations were ship-based and an automated planner running on the ship (EUROPtus) defined the behavior of multiple platforms [6]. In 2017, we teamed up with oceanographers to use our autonomous underwater vehicles (AUVs) to detect and track a river plume front autonomously [7].

Regarding the chosen approach itself, hybrid solutions combining conventional methods and new emergent technologies are not often found. Mainly there are studies demonstrating new methodologies using new technologies and an assessment is made of advantages and disadvantages regarding conventional methods. For instance, [8] presents the “major advances in marine geoscience that have resulted from AUV data”, in [9] a new approach for hydrothermal exploration is presented, using a deep water autonomous vehicle instead of traditional methods. In [10] a hybrid solution is presented - La Jolla submarine canyon system (offshore southern California) was surveyed using a combination of conventional methods and marine robotics. Sections of La Jolla seafloor were mapped using an AUV equipped with a multibeam sonar and a chirp profiler; close-up observations and sampling were done with a Remotely Operated Vehicle (ROV) and finally, minisparker seismic-reflection profiles from a surface ship helped to define the overall geometry of the La Jolla Canyon. Marine robots and technologies are more and more seen as a natural evolution of research vessels and not really captured as a complement to it, although it is recognized that a support surface vessel is still essential for most robotic deployments.

Fig. 1. Fleet of autonomous vehicles deployed from R/V Falkor.

IV. CRUISE PLANNING

The planning of the cruise was done over several months and involved every member of the team, including engineers, scientists and regular contacts with the R/V Falkor crew.

The **assets** used in the cruise were selected and configured to address the specific aspects of the Pacific’s STF front.

- R/V Falkor[2], including underway water sampling, the High-Performance Computer (HPC), towad CTD and CTD Rosette, among other systems;
- Multiple AUVs:
  - some to be equipped with just CTD, with long-endurance (50h+);
  - some to be equipped with CTD and physical and biological sensors, with an endurance of 24h+ and less.
- Aerial Platforms:
  - UAVs carrying Dimethyl sulfide (DMS) sensors, Infra-Red and MultiSpectral cameras;
  - UAVs carrying visible light cameras (also used for outreach);
- SilCam (underwater silhouette camera), which is used to identify and enumerate zooplankton;
- ALF (Advanced Laser Fluorometry) used to do a spectrum analysis of water in near real-time;
- Autonomous Surface Vessels (ASV) such as Liquid Robotic’s WaveGlider[3] which will be used to scout the front;
- Required software developments:
  - Ocean Space Center (OSC), a compelling interface to supervise the fleet of vehicles in real time;
  - On-board deliberation to improve vehicle resilience to failures and predictability of execution.

The cruise plan is briefly described next:

---

[2] Find more about R/V falkor sensors and equipments at https://schmidtocean.org/rv-falkor/operations-and-science-systems/.

[3] More about Wave Glider at https://www.liquid-robotics.com/wave-glider/overview/.

1) Analyze remote sensing data before the start of the cruise to get an updated estimate of STF position;
2) Deploy ASVs to find the STF;
3) Departure of R/V Falkor towards STF position determined by the ASVs;
4) Use AUVs to map the front - performing rows radiator patterns oriented normally to the front, while doing a yoyo profile;
5) Swap AUVs with other previously charged if needed, for continuous operation;
6) Select biological hotspots from the obtained maps and perform surveys with more (biological) sensors in those locations;
7) Determine the daily course of action based on all data collected during the previous days.

In this approach, the ship plays an important part of the expedition other than just being a support vessel. It acts as the "nerve center" where scientists and engineers work together, bridging the traditional science-engineering gap.

V. SYSTEMS AND TECHNOLOGIES

In this section we describe the systems and technologies used for the expedition, as well as the developments required for this cruise.

A. The LSTS Toolchain

The LSTS Toolchain [4] is an open-source software suite for mixed-initiative control (humans in the planning and control loops) of networked heterogeneous unmanned ocean and air systems, capable of handling communication challenged environments [11].

Ripples is a server-side application for data dissemination and situation awareness. It can send commands to remote assets via Iridium and ingests data from Iridium, GSM and several web services. All data flowing through Ripples is stored in the cloud and can be pushed via Iridium or Web Sockets, serving as a central hub of communications between remote assets. All of these features make Ripples [5] a powerful tool for remote collaborative planning and execution control (as it enables coordination among geographically distributed teams), as well as outreach and educational activities.

Neptus is a distributed command and control framework for networked vehicle systems. It supports all mission phases: planning, simulation, execution and post-mission review and analysis. One important feature of Neptus is its comprehensive plug-in infrastructure, which allows quick adaptation to fit mission-specific requirements by operators and developers.

IMC stands for Inter-Module Communication Protocol which has been designed and built for networked vehicle systems. IMC abstracts hardware and communication heterogeneity by providing a shared set of messages that can be serialized and transferred over different means (UDP, TCP, HTTP, acoustic modem, Iridium). It allows nodes to be discovered over different interfaces and to announce capabilities using transport-agnostic identifiers. In the LSTS Toolchain, IMC is also used for inter-process and inter-thread communication, as well as logging of all information.

DUNE stands for Unified Navigation Environment and is the onboard software running on the vehicles. It handles the interaction with sensors and actuators, as well as logging, communications, navigation and control. DUNE is very portable by being CPU architecture and OS independent, as well as having a small memory footprint. Thanks to its modularity and versatility, DUNE does not only run in our unmanned vehicles (underwater, surface and aerial), but also in our Manta communication gateways [6]. The software is adapted to each system by providing different configurations (set of running tasks and their initial configuration).

B. Developments for this cruise

For this cruise, several new developments were required in different parts of the toolchain.

Since vehicles were to be deployed in the open sea and stay disconnected for long periods of time, **Iridium communications** were improved by creating a new set of IMC messages for planning, configuration and supervision. Using these messages, the vehicles could synchronize its state with Ripples periodically. The state includes the vehicle's location, its currently loaded plan and configurations. The plan is a list of timed waypoints and the configuration a list of key-value pairs, both of which can be read and set by operators across the world using Neptus.

To improve resilience to faults and decrease the need of continuous communications, **plan deliberation** needed to be done onboard the autonomous submarines. A plan deliberation and execution framework was developed so that the behavior of the vehicle was generated onboard, according to the last uploaded configurations (depths, nominal speed, communication periodicity, etc.) and desired path. The vehicle's plan consists mainly of yoyo behaviors between timed waypoints, making sure the vehicle synchronizes with Ripples, with the desired periodicity and, simultaneously, arrives at the planned waypoints on time. In case of failures, the onboard executive replans to approximate the desired behavior or, if the desired behavior cannot be attained, updates its plan and synchronizes with Ripples.

To help the scientists making sense of all the available data (historical data, real-time and model forecasts), a set of plug-ins were also added to Neptus to integrate **model forecasts and remote sensing** in the operator consoles. These plug-ins can visualize data from Copernicus Marine Environment Monitoring Service (CMEMS), local Thredds servers, NASA GIBS, among many others. All these data can be presented as map layers. Near real-time data coming from the vehicles via Wi-Fi and Iridium can also be visualized automatically in Neptus. Finally, real-time data from the ASVs, UAVs and the

---

[4] LSTS Toolchain can be found at https://github.com/LSTS.

[5] Current version of Ripples is accessible from: https://ripples.lsts.pt.

[6] LSTS Manta communications gateway: https://lsts.pt/support_systems/manta

R/V Falkor can also be overlayed to the data in the map, using compatible colormaps.

Given the complexity of the system with multiple assets and dynamic phenomena being targeted by scientists with different needs, a great effort was devoted to building **comprehensive user interfaces**. After mock-up interfaces have been validated with the scientists, four main views of the system have been conceived and developed:

- **Planning View**: This display shows the plans associated to the platforms and estimated state for all platforms assigned to plans (connected or disconnected). Moreover, last received vehicle states are displayed with their age and upcoming locations where vehicles will report back are also shown, together with estimated time of arrival (ETA);
- **Risk Analysis View**: This display shows at a glance the state of all deployed assets and any potential risks. For each deployed vehicle, it will show remaining battery capacity, distance to the ship, communications health and potential collisions with marine traffic. Each line in the table corresponds to one asset and will be colored red if the user shall devote his attention. In case the entire screen is green, all assets are safe and working as expected;
- **Timeline View**: This display is similar to the planning view, but instead of showing just the present (estimated) state of the system it also has a sliding timeline, which the user can drag to predict the state of the system at some point in the future or revise the states of the system for any point in the past. Past states are synthesized from received data and future states are computed taking into account plans assigned to the platforms;
- **Data View**: This display shows a selection of oceanographic models and real-time data coming from the vehicles, to present the scientists with a synoptic view of different ocean parameters such as salinity, temperature, chlorophyll-a concentration or sea level anomalies.

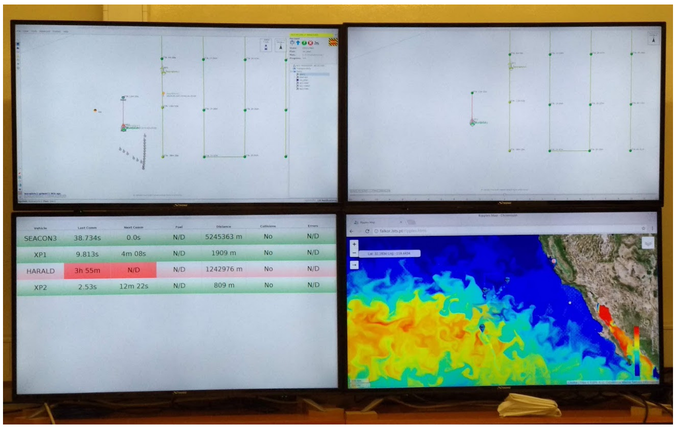
An **Ocean Space Center**, enabling users to visualize all data and interact with remotely deployed assets, was assembled at Porto University during the development of the system. In the end, all four displays mentioned before have been chosen as the default configuration (Figure 2).

C. Autonomous Vehicles

A fleet of autonomous vehicles was used in the cruise, composed mostly of LAUV autonomous submarines and Flightwave's Edge aircraft.

LAUV - Light Autonomous Underwater Vehicle

The LAUV is a lightweight, one-man-portable vehicle, easily deployable, operated and recovered with a minimal operational setup. It supports WiFi, Iridium, GSM and acoustic communications. LAUV is rated for 100m depth and has a diameter of 15 cm, with an endurance varying with size and payload configuration.



Vehicle	Last Comm	Next Comm	Fuel	Distance	Collisions	Errors
SEACON3	38.734s	0.0s	N/D	5245363 m	No	N/D
XP1	9.813s	4m 08s	N/D	1909 m	No	N/D
HARALD	3h 55m	N/D	N/D	1242976 m	No	N/D
XP2	2.53s	12m 22s	N/D	809 m	No	N/D

Fig. 2. Ocean Space Center, used to monitor and plan any deployed assets from Porto.

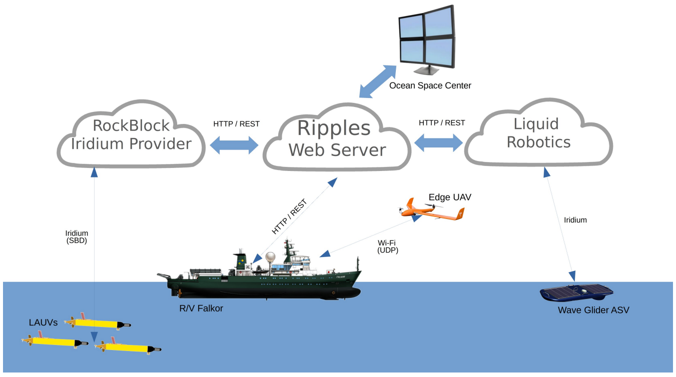


Fig. 3. Simplified Communications Diagram for the cruise.

Upper water column versions of the LAUV were used in this cruise. We started with the following 3 LAUVs:

- **Lauv-xplore-1:** CTD, pH and DO_2 (12 hours of endurance);
- **Lauv-xplore-2:** CTD, Chlorophyll-a and Turbidity (12 hours of endurance);
- **Lauv-Harald:** CTD, Chlorophyll-a, Organic Matter and Dissolved Oxygen (12 hours of endurance).

Three new vehicles (**Lauv-xplore-3**, **Lauv-xplore-4** and **Lauv-xplore-5**) were designed and built using new battery technologies and a new hull for 50h+ endurance. These 3 AUVs were designed to be simple, with one CTD sensor and relying mostly on Iridium for sending data and receiving new commands.

UAVs (VTOL)

Unlike AUVs, the UAVs from LSTS are not developed in-house - the fuselage and the basic avionics are commercially off-the-shelf, remaining electronics and software are then developed by us. VTOL stands for Vertical Take-Off and Landing – these types of vehicles are a hybrid solution between conventional fixed-wing and multirotors. As the name states, they are able to takeoff and land vertically (like multirotors)

Fig. 4. Long-endurance LAUV (Lauv-Xplore-3), being deployed.

and then perform the flight in plane mode. This characteristic makes them perfect for ship-based operations, as they don't require a lot of space and logistics to takeoff and land, but still have the endurance and speed of a fixed-wing. LSTS and Flightwave have been working together to build a VTOL platform tailored for ship-based operations and oceanography. The existing prototype was capable of flight speeds up to 26 m/s and withstand 20 m/s wind gusts. With a wingspan of 130 cm, it could fly under light rain with an endurance of up to 90 min. The payload section is swappable via a twist-lock system, which allows a quick reconfiguration of the platform after landing.

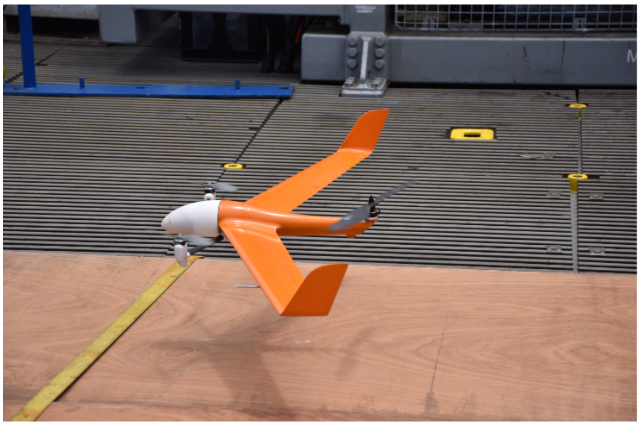


Fig. 5. FlightWave Edge - Tiltrotor VTOL.

Two more vehicles were prepared for the cruise. A few modifications were made to the hardware – smaller and faster companion CPU, added long-range telemetry radios and smaller tail motor (for safer transitions from multicopter to plane mode). Integration with LSTS Toolchain was improved to support automatic takeoff, landing and transition maneuvers, as well as the pre-flight calibration of the airspeed sensor. Regarding payloads to fly in the cruise, three were developed:

- **Thermal Camera:** FLIR Duo R, with geotagging and automatic triggering;
- **Multispectral Camera:** Parrot Sequoia, a standalone module with integrated GPS/light sensor and four narrow-band imagers - Green, Red, Red-Edge and Near Infrared;
- **DMS (Dimethyl Sulfide) sensor:** a prototype payload developed conjointly by NASA-AMES [12] (sensing), Flightwave (airflow) and LSTS (hardware integration).

VI. CRUISE REPORT

In this section a **timeline** of the events and actions that took place during the cruise are presented.

1 month prior to the cruise

Analysis of satellite imagery SST (Sea Surface Temperature) data confirmed that the STF was located roughly 800 miles to the west of San Diego (30ºN-35ºN, 130ºW-135ºW).

May 1st

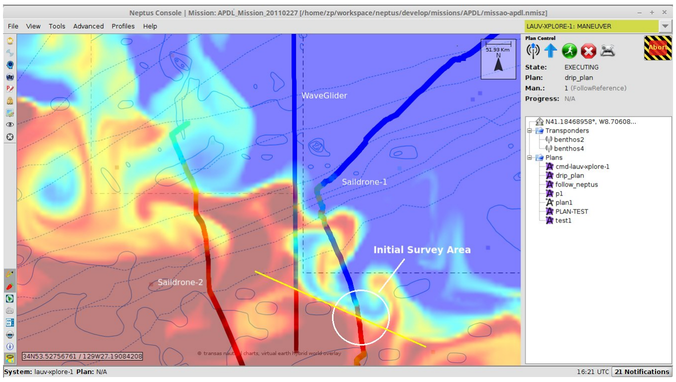
Deploy of Wave-Glider from Monterey Bay towards the region of the estimated front location.

May 27th

Two Saildrones[7] ASVs that were close to the area (courtesy of Barbara Block) were also tasked to cross over the area on their way back to the coast.

May 28th

R/V Falkor departure from San Diego, followed by a 3 day transit. The three ASVs crossed the salinity front while the ship was still underway, making it possible for the science team to circumscribe the front survey area to a 50Nm x 50Nm square.



Neptus Console | Mission: APDL_Mission_20110227 [/home/zp/workspace/neptus/develop/missions/APDL/missao-apdl.nmisz]

LAUV-XPLORE-1: MANEUVER

Plan Control

State: EXECUTING
Plan: drip_plan
Man.: 1 (FollowReference)
Progress: N/A

N41.18468958°, W8.70608...
Transponders
benthos2
benthos4
Plans
cmd-lauv-xplore-1
drip_plan
follow_neptus
p1
plan1
PLAN-TEST
test1

34N53.52756761 / 129W27.19084208

System: lauv-xplore-1 Plan: N/A

16:21 UTC 21 Notifications

Fig. 6. Pre-cruise in-situ reconnaissance on the STF. Sea Surface Salinity model obtained from satellite data (Copernicus, Marine Environment, Monitoring Service) and in-situ ASVs salinity measurements.

Figure 6 shows where the Wave Glider and Saildrone-1 crossed the front. The ship was directed to the eastern most location of the front to minimize the distance to travel.

May 30th

Arrival of R/V Falkor to the front area and deployment of the AUVs to start mapping the front.

Figure 7 presents the paths performed by the AUVs. We first started by doing a high-resolution survey (1 Nm lawn

---

[7] More about Saildrone at https://www.saildrone.com/.

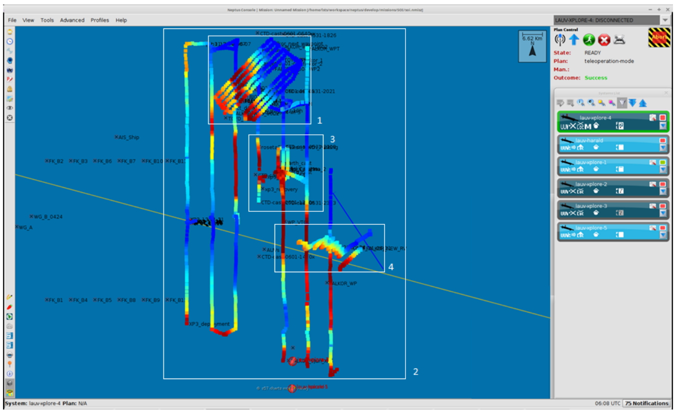


Fig. 7. Mapping the front with AUVs. Color gradient for saliniy measurements.

mower pattern) on the initial area (highlighted by white box number 1 in the map). We then proceeded to do a large-scale mapping with the AUVs (5 Nm resolution), depicted in Figure 7 by the white box number 2. By doing so, the data collected showed that we may not have been in the main front, since the salinity thresholds were crossed twice (in and out of the front). At this point, the numerical models running on the HPC proved useful to shed some light on the data collected by then (clouds precluded the use of remote sensing data). The output of the ROMS model[8] running on the HPC seemed to confirm the presence of a front jet. During the large-scale mapping we also used the collected data to select potential biological hotspots (front boarder, chlorophyll peaks, etc, – white box number 3 shows one of those locations). We used these areas to perform coordinated surveys with the biological AUVs, the UAVs (and respective payloads) and the ship (CTD casts, water sampling, ALF measurements, etc.). White box number 4 shows the results of a new front tracking algorithm tested during the cruise with the Wave Glider and and integrated onboard one of the AUVs [13].

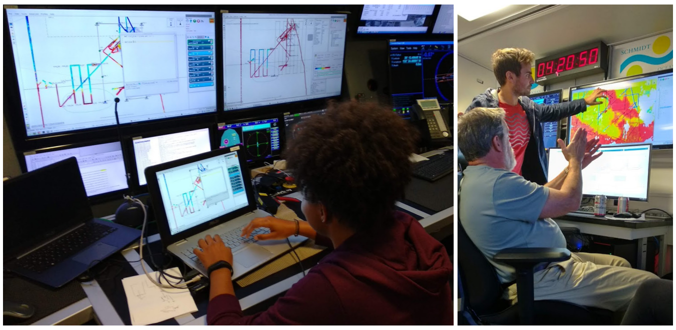


Fig. 8. Two views from the Science Control Room onboard R/V Falkor. Operators monitoring the state of all assets (left) and scientists discussing incoming data and next actions (right).

June 11th

This was the only day in which clear satellite observations of SST (sea surface temperature) and ocean color were feasible because of clear skies. The satellite imagery had a direct correlation with the collected data by the AUVs and confirmed the assessments made regarding the existence of jet detaching from the front (refer to Figure 9).

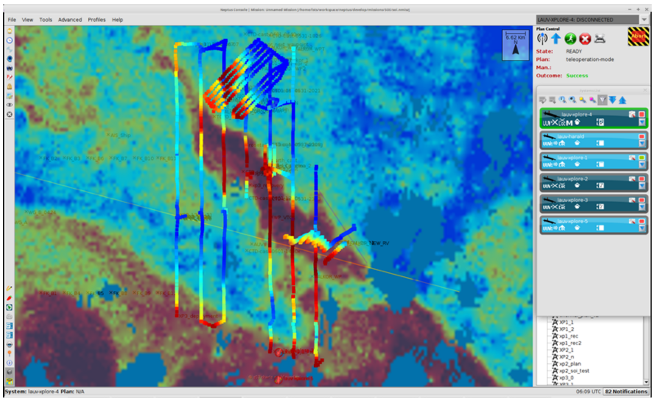


Fig. 9. SST satellite imagery and CTD data collected by AUVs confirmed the presence of a front jet.

VII. RESULTS AND CONCLUSIONS

During this cruise we were able to successfully perform mesoscale mapping (50 Nm x 40N m) with unprecedented sub-mesoscale resolution using multiple long-range AUVs. Satellite SST data validated the (surface) data collected by the multiple assets (Figure 9). 3D maps of the front with unprecedented resolution are presented (Figure 10). As one can easily perceive in Figure 10, both the jet detaching from the front and the boundary of the front were "captured" by the AUVs.

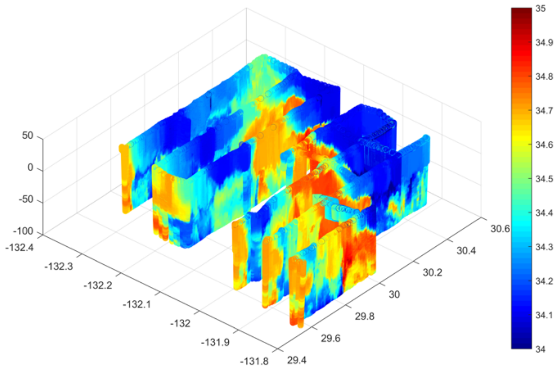


Fig. 10. 3D view of the front (salinity data collected by AUVs).

To complement the high-resolution map of the front jet, we also performed coordinated sampling using AUVs with biochemical sensors, R/V Falkor (ADCP, ALF, water sampling, etc.) and UAVs (thermal camera) (Figure 11).

Lastly, we successfully carried out continuous operations throughout the entire cruise, operating the AUVs using satellite communications. In total, our AUVs did over 600 hours of operation and traveled around 1000 Nm. Our UAVs performed

---

[8] More about ROMS model at http://www.ocean-modeling.org/index.php?page=models&model=ROMS

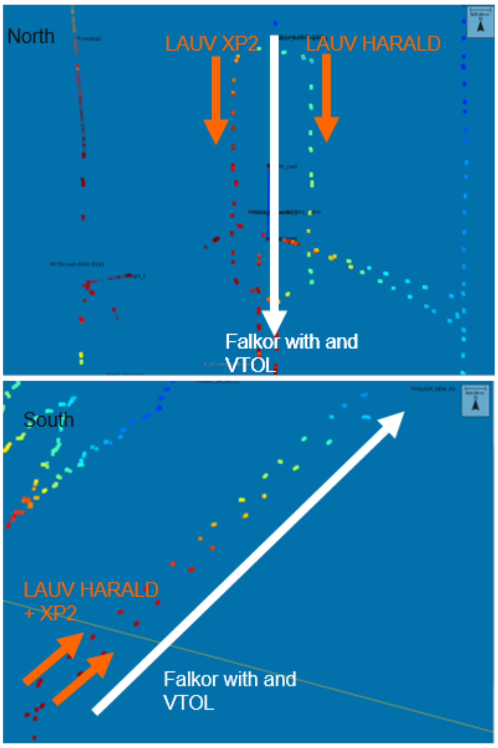


Fig. 11. High-resolution coordinated sampling from the air, surface and underwater.

21 successful flights. Persistent operations were carried out by having 4 daily shifts with 2 operators per shift.

The LSTS Toolchain and its extensions enabled continuous supervision of all assets onboard the ship as well as comprehensive displays of all sources of data, in several time scales.

The Ocean Space Center, enabled coordination with a team of on-shore scientists to follow the cruise results and suggest new scientific targets.

Most of the collected data is still being processed as are most of the taken water samples. As such, most of the scientific results from this cruise are still to be published.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the Schmidt Ocean Institute for the Exploring Fronts with Multiple Robots cruise. The support of the Portuguese Navy during the preparation of the cruise is also gratefully acknowledged. This work was also partially funded by project ”MARINFO - Integrated Platform for Marine Data Acquisition and Analysis”, supported by Norte Portugal Regional Operational Programme (NORTE 2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund (ERDF). R.M. benefits from a Post-Doctoral grant (SFRH/BPD/115093/2016) given by the Portuguese Science Foundation (FCT).

REFERENCES

[1] V. Klemas, “Remote sensing of sea surface salinity: An overview with case studies,” *Journal of Coastal Research*, vol. 27, no. 5, pp. 830–838, 09 2011.

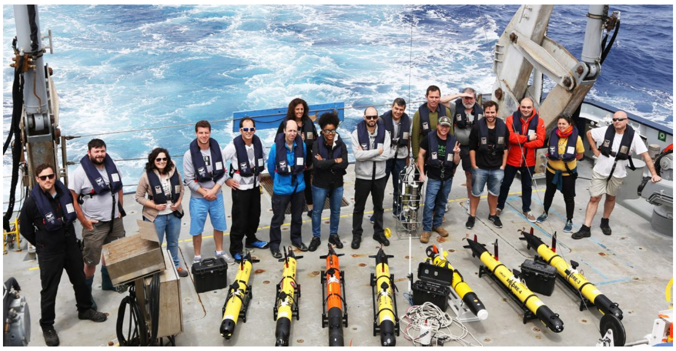


Fig. 12. The #OceanRobotsTeam poses with the AUVs fleet, onboard R/V Falkor.

[2] H.-Y. Kao, G. S. E. Lagerloef, T. Lee, O. Melnichenko, T. Meissner, and P. Hacker, “Assessment of aquarius sea surface salinity,” *Remote Sensing*, vol. 10, no. 9, p. 1341, 2018.

[3] J. Pinto, P. Dias, J. Pereira, R. Caldas, T. Rodrigues, J. Sousa, F. Py, and K. Rajan, “Mixed-initiative interaction for tracking of ocean sunfish,” *IFAC-PapersOnLine*, vol. 48, no. 2, pp. 94 – 99, 2015, 4th IFAC Workshop onNavigation, Guidance and Controlof Underwater VehiclesNGCUV 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2405896315002554

[4] L. L. Sousa, F. López-Castejón, J. Gilabert, P. Relvas, A. Couto, N. Queiroz, R. Caldas, P. S. Dias, H. Dias, M. Faria *et al.*, “Integrated monitoring of mola mola behaviour in space and time,” *PLOS one*, vol. 11, no. 8, p. e0160404, 2016.

[5] J. B. de Sousa, J. Pereira, J. Pinto, P. C. Lourenfo, J. M. Galocha, J. Fontes, M. Silva, K. Rajan, T. A. Johansson, J. Alves, A. Munafò, K. Pelekanakis, R. Petroccia, M. C. Silva, and M. Incze, “Rapid environmental picture atlantic exercise 2015: A field report,” in *OCEANS 2016 MTS/IEEE Monterey*, Sept 2016, pp. 1–6.

[6] F. Py, J. Pinto, M. A. Silva, T. A. Johansen, J. Sousa, and K. Rajan, “Europtus: A mixed-initiative controller for multi-vehicle oceanographic field experiments,” in *2016 International Symposium on Experimental Robotics*, D. Kulić, Y. Nakamura, O. Khatib, and G. Venture, Eds. Cham: Springer International Publishing, 2017, pp. 323–340.

[7] R. Mendes, J. Pinto, J. M. Dias, J. C. B. da Silva, and J. B. de Sousa, “Using an autonomous underwater vehicle to track the frontal region of a river plume,” in *AGU Oceans Science Meeting*, 2018.

[8] R. B. Wynn, V. A. Huvenne, T. P. L. Bas, B. J. Murton, D. P. Connelly, B. J. Bett, H. A. Ruhl, K. J. Morris, J. Peakall, D. R. Parsons, E. J. Sumner, S. E. Darby, R. M. Dorrell, and J. E. Hunt, “Autonomous underwater vehicles (auvs): Their past, present and future contributions to the advancement of marine geoscience,” *Marine Geology*, vol. 352, pp. 451 – 468, 2014, 50th Anniversary Special Issue. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0025322714000747

[9] C. R. German, D. R. Yoerger, M. Jakuba, T. M. Shank, C. H. Langmuir, and K. ichi Nakamura, “Hydrothermal exploration with the autonomous benthic explorer,” *Deep Sea Research Part I: Oceanographic Research Papers*, vol. 55, no. 2, pp. 203 – 219, 2008. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0967063707002580

[10] C. Paull, D. Caress, E. Lundsten, R. Gwiazda, K. Anderson, M. McGann, J. Conrad, B. Edwards, and E. Sumner, “Anatomy of the la jolla submarine canyon system; offshore southern california,” *Marine Geology*, vol. 335, pp. 16 – 34, 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0025322712002150

[11] J. Pinto, P. S. Dias, R. Martins, J. Fortuna, E. Marques, and J. Sousa, “The lsts toolchain for networked vehicle systems,” in *2013 MTS/IEEE OCEANS - Bergen*, June 2013, pp. 1–9.

[12] J. Li, G. Yu, Y. Lu, C. Hsiung, A. Hannon, D. Kim, and S. Dennis, “Nanotechnology based cell-all phone-sensors for extended network chemical sensing,” in *Sensors, 2012 IEEE*. IEEE, 2012, pp. 1–4.

[13] I. Belkin, J. Pinto, R. Mendes, F. Lopez, and J. Sousa, “A new front-tracking algorithm for marine robots,” in *Autonomous Underwater Vehicle Symposium, OES preprint*. IEEE, 2018.