FK180528 30-day Post Cruise Report

1. **Ship name**: Falkor
2. **Cruise Dates - Day Departed**: 5/28/2018
3. **Cruise Dates - Day Returned**: 6/17/2018
4. **Cruise Number**: FK180528
5. **Departure Port**: San Diego, CA, USA
6. **Arrival Port**: San Diego, CA, USA
7. **Mid-Cruise Port Call (if any)**: none
8. **Mid-Cruise Port Call (if any)**: none
9. **Participating Organizations, Institutions, Foundations, Government Agencies, etc.**:
    - Laboratório de Sistemas e Tecnologias Subaquáticas (LSTS) - Porto University, Portugal
    - CIIMAR - Interdisciplinary Centre of Marine and Environmental Research, Porto University, Portugal
    - Aveiro University, Portugal
    - University of Rhode Island, United States of America
    - Lamont-Doherty Earth Observatory, United States of America
    - Harvard University, United States of America
    - Norwegian University of Science and Technology, Norway
    - Universidad Politécnica da Cartagena, Spain
10. **Funding Sources**:
    - The participating organizations and institutions supported support personnel salaries related to participation in the cruise.
    - The Portuguese Navy provided logistical and operational support to AUV missions that took place during the first three months of 2018 in Sesimbra, Portugal, in preparation for the cruise. Their support is gratefully acknowledged.
    - NASA-Ames, United States of America contributed prototypes of Dimethyl sulfide (DMS) gas sensors to be flown in UAVs.
11. **Describe all of the geographical area(s) where the science occurred**: The Subtropical Front (STF) located between 30N-35N and 130W-135W.
12. **Name of Chief Scientist**: João Tasso de Figueiredo Borges de Sousa

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13. Cruise Objectives:

The main goal of this cruise was to demonstrate a novel system/approach to observe the ocean with multiple unmanned vehicles, deployed and operated from the R/V *Falkor*. This entailed achieving three major scientific objectives, which represent important tasks in operational oceanography, and eight technical objectives transversal to all scientific objectives.

Scientific objectives:
(1) Performing standard oceanographic tasks (vertical 1D profiles, 2D sections, and 3D synoptic surveys);
(2) Performing novel tasks that have not been routinely performed by conventional oceanographic ships or other vehicles;
(3) Performing joint ship-robotic 3D surveys.

Technical objectives:
(1) The provision of distributed acoustic and radio communications infra-structure to support the coordination and control of all assets;
(2) The provision of an inter-operability framework to support all components of the system;
(3) The provision of on-board Artificial Intelligence (AI) based planning and execution control capabilities (to allow autonomous underwater vehicles (AUV), unmanned aerial vehicles (UAV), and autonomous surface vehicles (ASV) to perform complex sampling tasks, cooperatively or isolated, in communications-challenged environments;
(4) The provision of off-board mixed initiative planning and execution control capabilities for the integrated multi-vehicle system enabling remote participation, ocean space management, and adaptation to intermittent, low bandwidth, and delayed communications;
(5) The provision of new UAV- and AUV-based sampling methods for targeted synoptic observations;
(6) The provision of new data assimilation (including remote sensing) and modeling techniques to support real-time decision making for synoptic adaptive sampling;

(7) The study of the new inter-disciplinary science and technology work-practice to be conducted by a resident ethnographer with experience in oceanographic and space missions;
(8) The comparative performance evaluation with respect to traditional sampling methods.

The technical approach built on innovative open-source communication and autonomy software developed by LSTS-Porto University that enables networked underwater, surface and air vehicles to find, track, and sample dynamic features of the ocean.

14. Cruise Summary:

1. Planning the cruise: Selection of target front

To achieve all three oceanographic objectives, ocean fronts were selected as target objects. The main reasons for focusing on ocean fronts fall into two categories:

(1) Ocean fronts are the most robust (stable and persistent) elements of the ocean structure;

(2) Fronts are of paramount importance in a broad variety of processes and applications such as ocean circulation, water mass formation, ecosystem functioning, biodiversity, conservation, climate variability, weather forecasting, fisheries, navigation, and defense, particularly antisubmarine warfare.

Ocean fronts span a wide range of spatial and temporal scale, from meters and minutes on micro-scales to thousands of kilometers and millennia on planetary scales. Our selection of a target front was constrained logistically by a few factors as follows:

(1) The front must have been quasi-stationary and of a sufficiently large spatial scale, no less than meso-scale (100 km in length); large-scale (1000 km in length), climatic year-round fronts are best targets;

(2) The front must be in the NE Pacific, not too far away from San Diego, where *Falkor* was stationed before our cruise;

(3) The front must be outside the U.S. EEZ and Mexican EEZ, and outside MPAs (marine protected areas) or marine sanctuaries.

The Northern Pacific Subtropical Front (STF) between 30N-35N and 130W-135W was selected since it meets the above criteria, namely:

(1) The STF is a large-scale climatic front;

(2) The STF study area is located ~700 nm west of San Diego;

(3) The STF study area is located outside any EEZ, MPA, or marine sanctuaries.

References:

[1] G. Roden, “Thermohaline structure, fronts, and sea-air energy exchange of the trade wind region east of Hawaii,” Journal of Physical Oceanography, vol. 4, pp. 168-182, April

1974.
[2] R. M. Laurs and R. J. Lynn, “Seasonal migration of North Pacific albacore, Thunnus alalunga, into North American coastal waters: distribution, relative abundance, and association with Transition Zone waters,” Fisheries Bulletin, vol. 75, pp. 795-822, 1977.
[3] J. F. T. Saur, “Surface salinity and temperature on the San FranciscoHonolulu route June 1966-December 1970 and January 1972-December 1975,” Journal of Physical Oceanography, vol. 10, pp. 1669-1680, October 1980.
[4] R. J. Lynn, “The Subarctic and Northern Subtropical Fronts in the eastern North Pacific Ocean in spring,” Journal of Physical Oceanography, vol. 16, pp. 209-222, February 1986.
[5] M. Tsuchiya and L.D. Talley, “Water-property distributions along an eastern Pacific hydrographic section at 135W,” Journal of Marine Research, vol. 54, pp. 541-564, 1996.

2. Planning the cruise: Main phases

The dates of departure and arrival of our FK180528 cruise were, respectively, May 28th and June 17, 2018.
The cruise was organized into the following phases:

(A) Pre-cruise in situ reconnaissance with ASVs that started May 1st;
(B) 3-day transit to the STF;
(C) 1-day for system tests on site STF;
(D) 1-day mapping of the first section of the STF;
(E) 4-day mesoscale mapping of a selected area (approx. 50 NM x 40Nm);
(F) 9-day exploration of the STF;
(G) 3-day transit back to San Diego;

Although a few missions incurred some delays because of weather conditions, no single day was lost to weather and breakdowns.

3. Pre-cruise in situ reconnaissance of the STF

The cruise operation area (30N-35N, 130W-135W) was located approximately midway between California and Hawaii. This area, including the STF, was studied in the 1970s, mostly during NOAA fisheries research campaigns; subsequent studies were concentrated either off California (CalCOFI cruises) or north of Hawaii. Thus, the seminal studies of the 1970s provided the only substantive, systematic in situ data available to us before the Falkor 2018 cruise. Therefore, it was imperative to conduct pre-cruise reconnaissance of the cruise operation area.

We used three remotely piloted autonomous surface vehicles: One Wave Glider operated by Liquid Robotics and two Saildrones (courtesy of Barbara Block and SOI). Both Saildrones were initially located far south of our cruise area. They were re-routed to cross our cruise area during the Saildrones’ return voyage to California. We onboard *Falkor* were not controlling the Saildrones’ paths, yet we were accessing the Saildrones data in near-real-time. The Wave Glider was launched by MBARI specialists off Monterey Bay and was piloted 24/7 by Liquid Robotics. Initially, the Wave Glider was sent west.

After reaching the cruise area, the Wave Glider was sent south to collect data along a meridional section across the entire subtropical frontal zone. The near-surface temperature (SST) and salinity (SSS) data collected by the Wave Glider along the southward section combined with similar data collected by Saildrones along a parallel northward section were crucial during the pre-cruise reconnaissance phase. These data allowed a few fronts to be detected, some of them repeatedly. Near-surface salinity was by far the most important parameter since SSS cross-frontal steps were relatively large, typically around 0.5 psu, while SST steps across the same fronts were rather small (1°C to 1.5°C). Based on TS-data collected by the Wave Glider augmented by Saildrones' data, we were able to identify the STF as the strongest and most robust front in this area.

4. Satellite observations before and during the cruise

Several satellite data sources (satellite missions) were extensively used before and during the cruise. Satellite imagery of SST was supplied by AVHRR radiometers flown on NOAA polar orbiters and MODIS radiometers flown on Aqua and Terra satellites operated by NASA. Images of ocean color (CHL proxy) were available from MODIS Aqua and Terra missions. Maps of SSS were available from the SMOS mission operated by ESA. Historical satellite SSS data obtained by the Aquarius mission were available from NASA. Maps of SSH based on satellite altimeter data were available from AVISO.

The cloudy weather before the cruise and during the first 10 days of the cruise hindered satellite observations of SST and ocean color. The first high-quality image of SST from our study area was obtained in the middle of the cruise (June 11). Fortunately, this image has confirmed what was already found from the in-situ data collected by *Falkor*, AUVs, Wave Glider and Saildrones. Also, this image has revealed a large meander or filament of the STF, which has become the focus of our work for the rest of the cruise.

5. In situ observations during the cruise

To demonstrate and validate the power of marine robotics, we designed and executed the most complicated tasks encountered in operational oceanography, namely three-dimensional (3D) surveys of a major open-ocean front. These surveys were conducted using a radiator pattern, with long legs (sections) oriented normally to the front. Three long-range AUVs (with a 50-hour endurance constrained by battery capacity) 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 short-range AUVs enabled frontal 3D surveys to be conducted uninterrupted in perpetuity.

Moving along the radiator pattern, each AUV was going up and down between the sea surface and 100 m (maximum depth of AUVs) while executing a yo-yo profiling of an ocean front. The AUV cruising speed of ~1 knot (0.5 m/s) and descent/ascent angle of 15° (flight path angle) between 0 and 100 m depth enable a horizontal resolution of ~800 m. The AUV survey data were validated with CTD data obtained with two types of CTD probes: (1) standard shipborne CTD equipped with a Rosette (for water sampling), down to 500 m, and (2) towed yo-yo CTD, down to 300 m, at a cruising speed of 2 knots (1 m/s), thus enabling a horizontal resolution of 600 m (distance between two consecutive surfacing) similar to the horizontal resolution achieved by AUVs (800 m). The close correspondence between the horizontal resolutions achieved by AUVs and towed yo-yo CTD facilitates comparison and mutual validation of their data.

A total of 43 casts were performed from the ship to study the role of physical forces on the distribution of biogeochemical and biological communities (Prokaryotic and Eukaryotic communities) across the front.

Two Advance Laser Fluorometry (ALF) instruments were used to perform high-resolution underway fluorescence measurements and analysis of discrete water samples acquired by the casts in the euphotic layer. The ALF data were used to analyze horizontal spatial distributions and vertical profiles of phytoplankton pigments, photosynthetic efficiency, and colored organic matter (COM).

6. Exploring the front

We started by conducting a mesoscale mapping of the front during phase E. We used the data collected during this phase to identify sampling hotspots for phase F. In this phase, we performed high-resolution surveys with other AUVs, equipped with physical and biological sensors, complemented with ship-based measurements and water sampling. Vertical Take-Off and Landing (VTOL) UAVs were tasked to fly over transects made over these hotspots to collect IR, multi-spectral and visible light imagery, as well as to measure concentrations of DMS in the air (DMS is a proxy for some types of biological activities that may take place at fronts). UAVs were also used as data “mules” to transport data from distant AUVs to *Falkor*, as well as communication gateways for “bent” line-of-sight communications with the AUVs. Coordinated ship-robotic survey were also conducted during this phase. In these surveys, *Falkor*, two or three AUVs, and one UAV moved in formation, with speed adjustments for the UAV, to sample the air and the ocean at selected hotspots.

In most of these deployments *Falkor* was also collecting data along transects located far away from the AUVs. Computational models running on the ship's supercomputer helped us interpret the data collected by our systems and adapt our sampling strategies. The small human operator footprint of this mission allowed scientists and engineers to go about detailed analysis and decision making with the help of the visualization tools displaying incoming data in close to real-time. This also enabled the development and testing of advanced front tracking algorithms. A resident ethnographer performed a scientific study of the changing work-practice induced by these new tools and technologies.

7. Development and testing of a new front-tracking algorithm

One of the novel tasks performed by AUVs during the cruise was tracking open-ocean fronts. To date, algorithms for tracking fronts with AUVs have been developed and tried in the coastal ocean only. Such algorithms were used to track mesoscale near-coastal fronts, e.g., river plume fronts (University of Porto algorithm and Stevens Institute of Technology algorithm) or coastal wind-driven upwelling fronts (MBARI algorithm). No algorithm was ever applied to large-scale open-ocean fronts. During the cruise, we have developed a new front-tracking algorithm and successfully tested it by tracking the Subtropical Front, a large-scale climatic open-ocean front.

The new algorithm implements a novel approach termed front-core tracking (FCT) alternatively called front-axis tracking (FAT). This approach is based on ample observations of cross-frontal structure of open-ocean fronts that can be approximated by a linear function between two singular points that are edges or boundaries of the front that separate the front from plateaus on both sides of the front. This approximation is called the ramp model. The ramp model includes two discontinuities (edges or boundaries) and is cardinally different from the classical smooth model of transversal structure of fronts that has no discontinuities.

The new algorithm uses two thresholds that bound the front's core. These thresholds are determined from observations. In our case, the STF core was bounded by 34.1 and 34.5 isohalines that span the STF's axial isohaline of 34.3. The algorithm guides the AUV by bouncing off the front's core edges. Thus, the AUV follows the front's axis very closely, always remaining quite close to the front's axis.

The algorithm was tested by guiding several vehicles along the same front (STF). First, the algorithm successfully guided Wave Glider, then *Falkor*, and then AUVs. Eventually, the algorithm's code was downloaded to an AUV, so that the AUV could track the front using the algorithm, completely autonomously.

8. Conclusions

During the cruise, for the first time, a fleet of underwater, surface and air vehicles (over 10) was used to locate, identify, survey, and track a major large-scale climatic open-ocean front, the Subtropical Front in the NE Pacific between California and Hawaii. The STF was located precisely as predicted from oceanographic data analysis during the planning phase of this cruise. Simultaneous deployment of several AUVs on parallel tracks in a radiator pattern centered at the front enabled an unprecedented submesoscale horizontal resolution of 5 km between cross-frontal sections and a microscale resolution of 800 m along each cross-frontal section. The yo-yo profiling of water column with AUVs moving at 100 cm/s along gently slanted flight paths (15-degree angle), sampling at 4 Hz, enabled a vertical resolution of 2 cm. Swapping two sets of AUVs before each set reaches its endurance limit (based on battery capacity) allowed a 3D frontal survey to continue in perpetuity. *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 *Falkor*, Wave Glider, and AUV along the Subtropical Front.
In summary, our team operated on-site and non-stop for about 2 weeks, our AUVs travelled over 1000 nautical miles underwater for approximately 600 hours, and our UAVs performed over 25 flawless flights with a total duration of approx. 10 hours. All technical and scientific objectives were fully attained during the cruise.

15. **Did you collect Measurements or Samples, including biological specimens?** Yes
16. **Did you deploy and/or recover any Moorings, Bottom Mounted Gear, or Drifting Systems?** No
17. **Equipment Used**: In this cruise we successfully demonstrated and validated a novel approach to observe the ocean with a networked system comprising the *Falkor*, onshore control stations, and multiple underwater, surface, and air vehicles. We used most of *Falkor's* research facilities and instruments, including Conductivity, Temperature, and Depth (CTD) probe, Acoustic Doppler Current Profilers (ADCP), laboratories, and the HPCS. In addition, we deployed the following systems and technologies:

    - 1 Wave Glider ASV (https://www.liquid-robotics.com/wave-glider/how-it-works/), leased from Liquid Robotics, equipped with ADCPs, CTD, and weather station;
    - 2 Saildrones ASV (https://www.saildrone.com/) equipped with a sensor suite, including CTDs, en route back to California from the SOI cruise entitled Voyage to the White Shark Café;
    - 1 IVER2 AUV (http://www.upct.es/urready4os) equipped with CTD, chlorophyll, turbidity, and phycoerythrin (cyanobacteria) sensors, and with a backseat CPU;
    - 3 LAUV AUVs (http://www.lsts.pt/vehicles/lauv) in a long endurance configuration (50h+ at 2 Knots) equipped with CTD, WiFi and satellite communications, as well as satellite emergency locators;

- 3 LAUV AUVs (http://www.lsts.pt/vehicles/lauv) equipped with several types of sensors (CTD, fluorometer, turbidity, O2 and cameras), WiFi and satellite communications, acoustic modems, satellite emergency locators and battery packs enabling 24h+ endurance;
- 3 vertical takeoff and landing (VTOL) Edge UAVs capable of up to 90min of flight time equipped with WiFi communications, IR, multispectral and visible light cameras, and Dimethyl sulfide (DMS) gas sensor developed by NASA-Ames. The Edge UAVs were also used to support "bent" line-of-sight communications with AUVs operating beyond direct line of sight communications;
- 2 DJI Mavic quadrotors equipped video cameras used for media coverage;
- 6 Manta communication gateways (http://www.lsts.pt/support_systems/manta) with communications support for WiFi, acoustic modems, satellite communications, and long-range communications with UAVs.
  SUNA nitrate sensor and In-situ FIRE (fluorometer induction-relaxation) sensor mounted on *Falkor's* CTD Rosette to record photosynthetic activity at fronts and eddies.
- 2 Advance Laser Fluorometry (ALF) instruments were used to perform high-resolution underway fluorescence measurements and analysis of discrete water samples acquired by the casts in the euphotic layer.
- SIL camera prototype provided by SINTEF, Norway mounted on *Falkor's* CTD Rosette to film phytoplankton and zooplankton.
- High resolution oceanographic models of the front, required for detailed planning and execution control, ran on *Falkor's* HPCS. We used other model outputs as boundary conditions for a model developed by UPCT with higher spatial and temporal resolution to support planning activities for this cruise.
- Shipboard ocean space center (OSC) comprised of control stations interfaced with *Falkor* systems (HPCS, radar, AIS, and communications) and augmented with Manta communication gateways. The OSC supported 24/7 ocean space management, ingestion and visualization of remote sensing data, as well as of model outputs, mixed initiative planning and execution control (i.e., allowing the intervention of scientists in the planning and control loops), and outreach activities.
- The networked system used in this cruise builds on the innovative open-source communication and autonomy software tool chain (https://lsts.fe.up.pt/toolchain) developed by LSTS-Porto University. The software tool chain includes:
  Ripples – Web application including a communications hub to communicate with all deployed assets, as well as with the Internet, and tools for remote visualization, integrated shipboard situational awareness, operator-assisted planning, tasking, control, and supervision. Ripples enabled remote

collaborative planning and execution control, and supported outreach and education activities.

Neptus – Distributed off-board command and control framework supporting planning, execution control, and post-mission analysis for networked vehicle systems. Neptus, extensible with visual widgets, vehicle behaviors, and configurable data visualizations, is at the core of the OSC, and will also support performance evaluation of the SINVS.

IMC – Protocol for networked autonomous underwater, surface and air vehicles operating in communications challenged environments. There is a discovery mechanism using different broadcasting mechanisms to identify end-points exposed in the network (over UDP, TCP, HTTP, acoustic modem, Iridium, etc.). Links among devices are dynamically created during execution.

Dune – Onboard software framework providing logging, communications, navigation, and control functions for all supported vehicles, with a small memory and computational footprint to run virtually on any POSIX-compliant system. There is also support for disruptive tolerant networking (DTN).

The Dune-IMC-Neptus-Ripples software toolchain enabled us to control unmanned and manned vehicles in several unprecedented ways, namely operating non-stop for most of the cruise with just one operator in the control room. The Dune-IMC software ran on-board all the AUVs and UAVs used in the expedition for autonomous planning and execution control.

Finally, a new front tracking algorithm was developed and deployed during the cruise. This was done in an incremental fashion. The algorithm was first tested with the Wave Glider before being tested with the R/V Falkor. In these tests, a scientist used the algorithm to generate waypoints based on the observed data. Finally, the algorithm was transitioned to one LAUV and successfully demonstrated at sea.

18. **Total number of CTD casts completed during the cruise:** 43
19. **Total number of AUV dives completed during the cruise:** 22
20. **Total number of ROV dives completed during the cruise:** 0
21. **Total number of ROV samples collected during the cruise:** 0
22. **Total number of Unmanned Aerial Vehicle (UAV) or other vehicle deployments during the cruise:** 3 Edge Vertical Take Off and Landing UAVs performed 20 flights. 2 Mavic DJI Drones performed 6 flights.
23. **Total amount (TBs) of data collected during the cruise:** 0.376
24. **Other interesting Facts about this cruise:** Area of operations: approx. 40 NM x 50 NM.
    AUV operations: 22 missions totaling 596h and over 1000NM.
    UAV operations: 500 minutes and 26 flights.
    Ocean space center operations: 4 daily shifts / 2 operators per shift.

HPC: run ROMS model for study area.
Outreach sessions: reached over 3400 people including students from over 20 schools in Portugal, Spain, Cape Verde, Mozambique, Norway, United States of America and Italy.
Celebrated World Oceans day with dedicated live sessions with two other ships.
Connected live with António Costa, the prime minister of Portugal, while visiting the MIT.