Exploring the Pacific Subtropical Front: adventures in coordinated ship-robotic surveys

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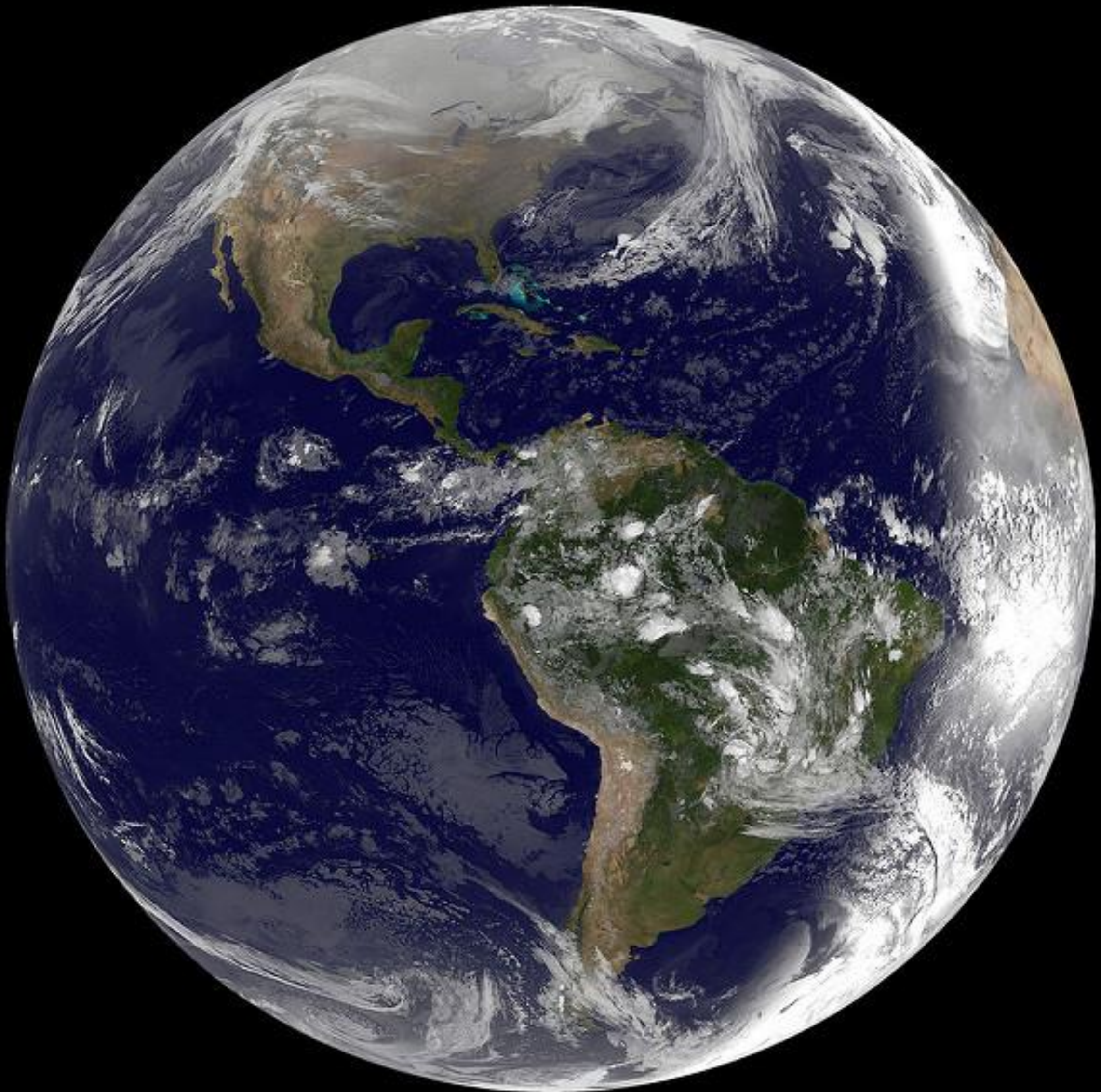
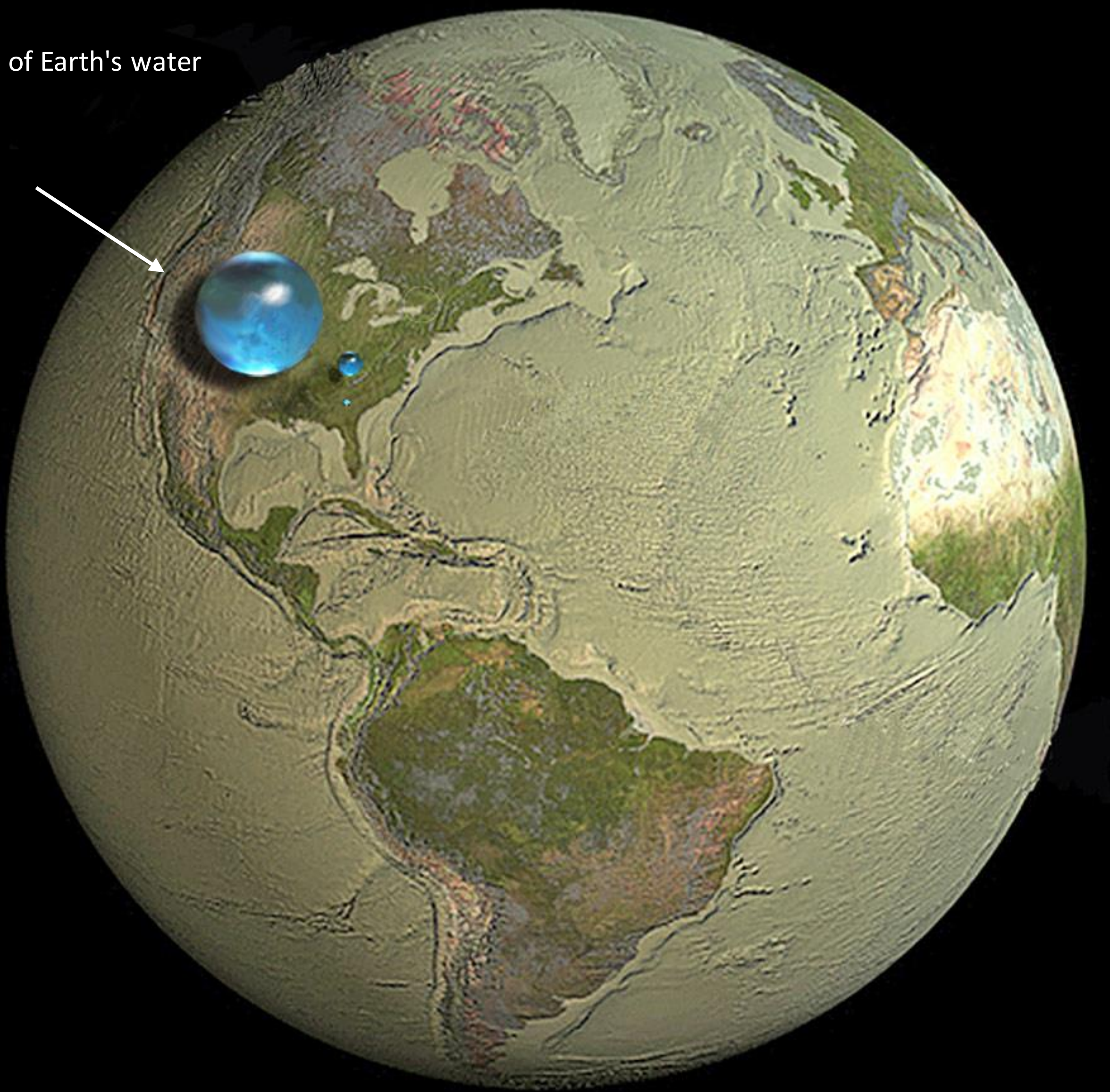
Blue planet



Source: https://goes.gsfc.nasa.gov/

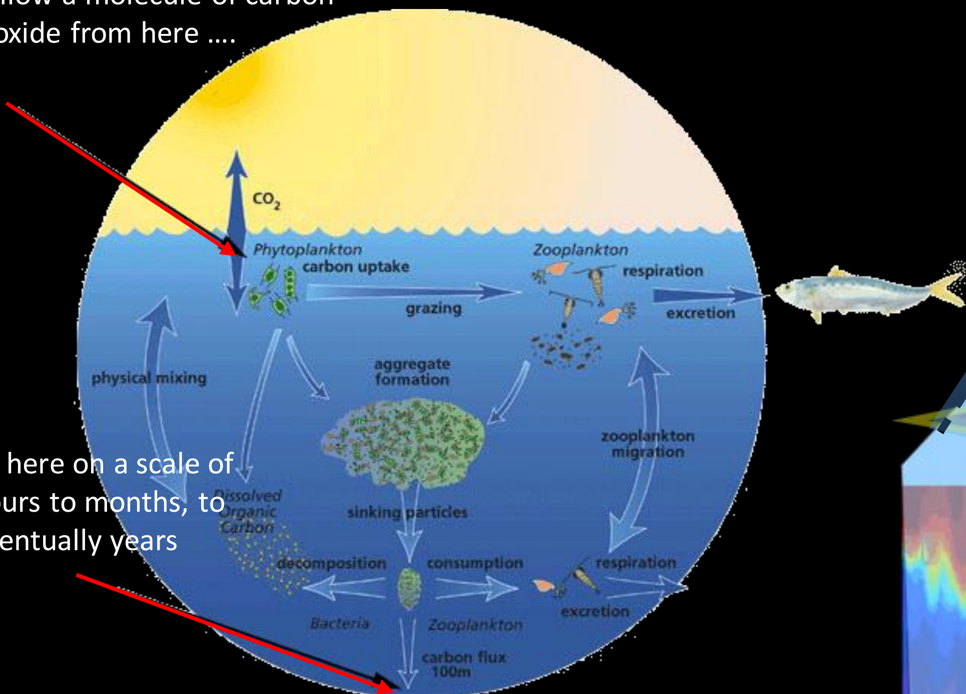
Thin blue layer



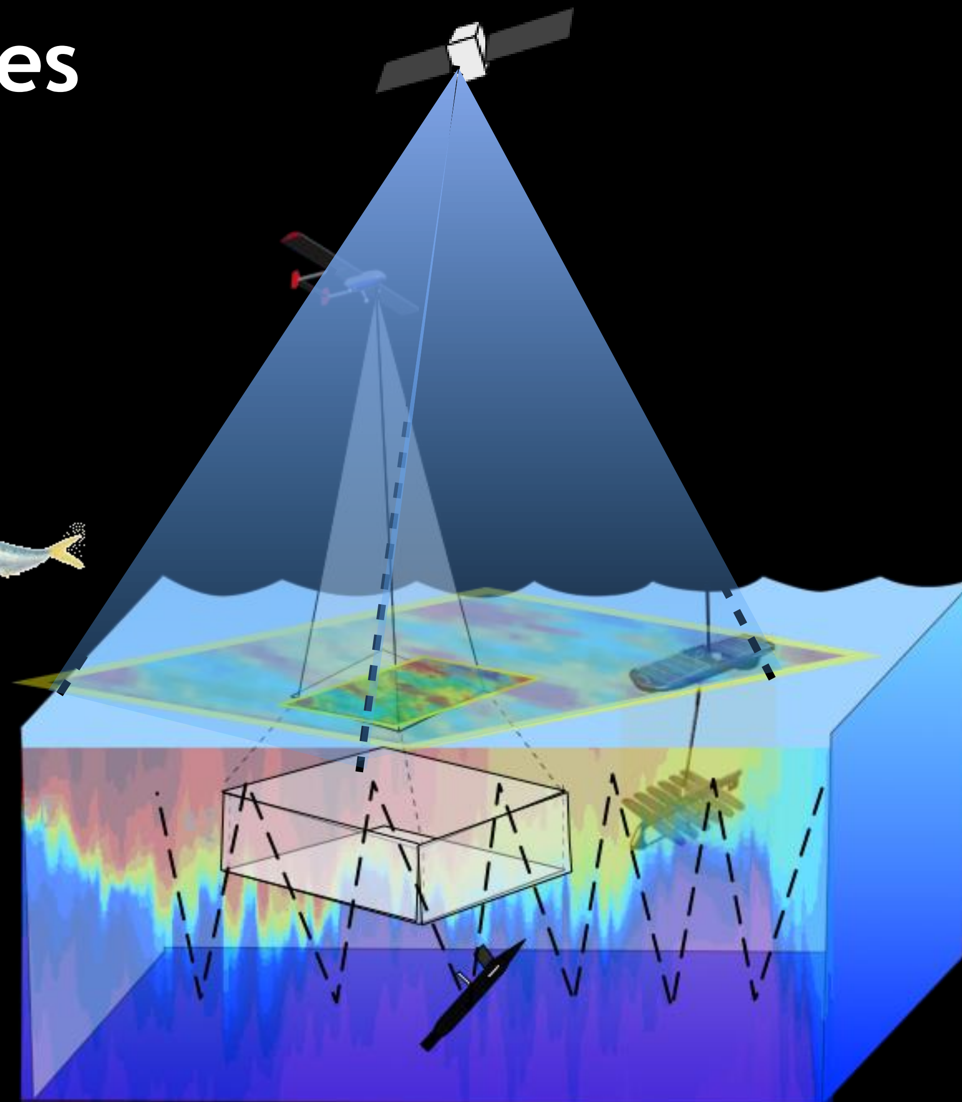
Source: https://water.usgs.gov/edu/gallery/global-water-volume.html

Observation challenges

Follow a molecule of carbon dioxide from here ....



To here on a scale of hours to months, to eventually years



Synoptic observations on large spatial scales
Persistent observations
From micro to meso-scale

Remote and challenging environment
Largely unknown
No navigation aids and no refueling stations
Communications-challenged

Courtesy of Kanna Rajan

Exploring fronts with multiple robots

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

Our team

Universidad Politécnica de Cartagena

SINTEF

NTNU

MBARI

LSTS

LAMONT-DOHERTY EARTH OBSERVATORY
THE EARTH INSTITUTE AT COLUMBIA UNIVERSITY

UAlg
UNIVERSIDADE DO ALGARVE

NASA
Ames Research Center

VE RI TAS
HARVARD

ciimar
Centro Interdisciplinar de Investigação Marinha e Ambiental

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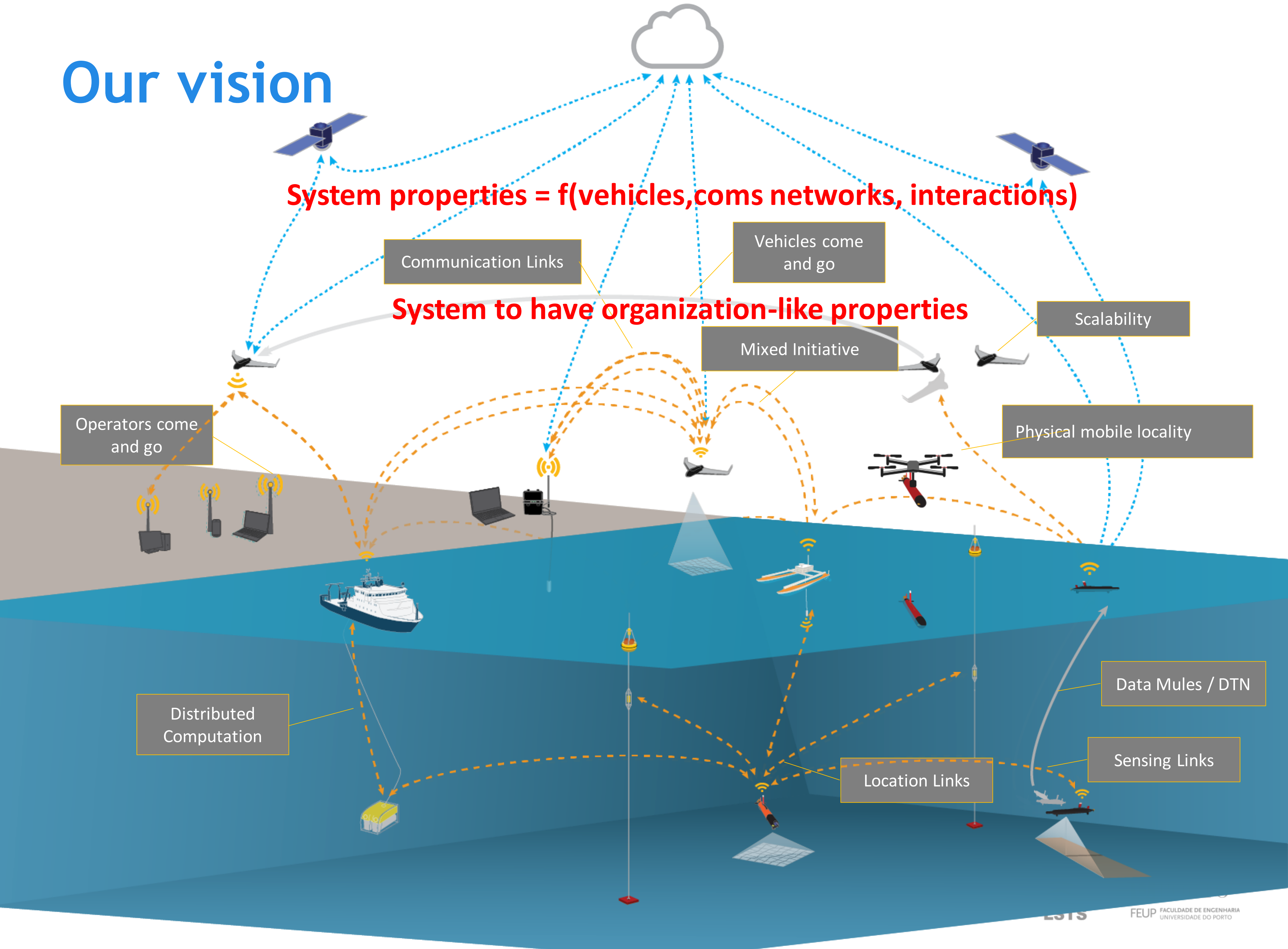
Outline

- LSTS lab
- Cruise goals and approach
- Operations
- Discussion

LSTS

LAB OVERVIEW

Our vision



System properties = f(vehicles,coms networks, interactions)
Communication Links
Vehicles come and go
System to have organization-like properties
Mixed Initiative
Scalability
Operators come and go
Physical mobile locality
Distributed Computation
Data Mules / DTN
Sensing Links
Location Links
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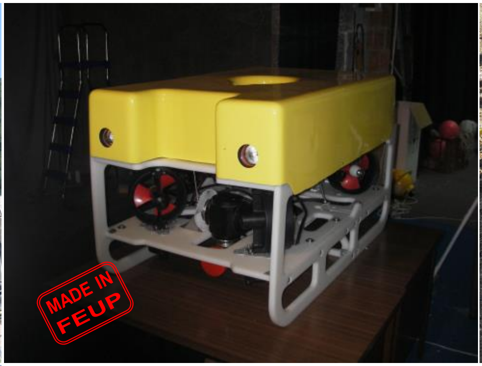
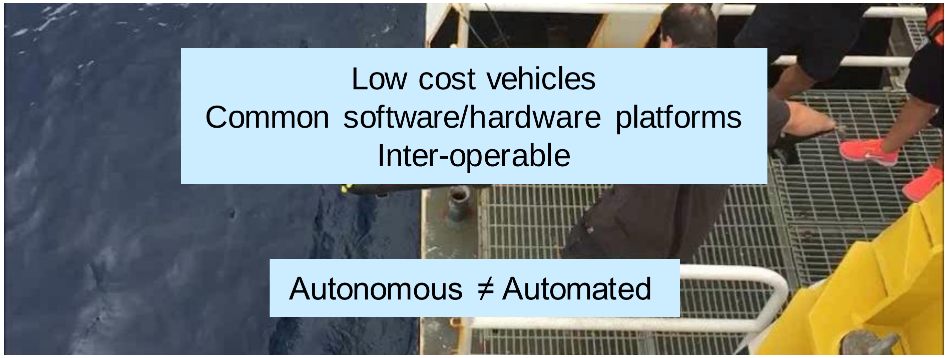
Underwater vehicles

Low cost vehicles
Common software/hardware platforms
Inter-operable

Autonomous ≠ Automated

Long endurance ASVs

- Persistent ocean operations

Wave powered surface vehicles

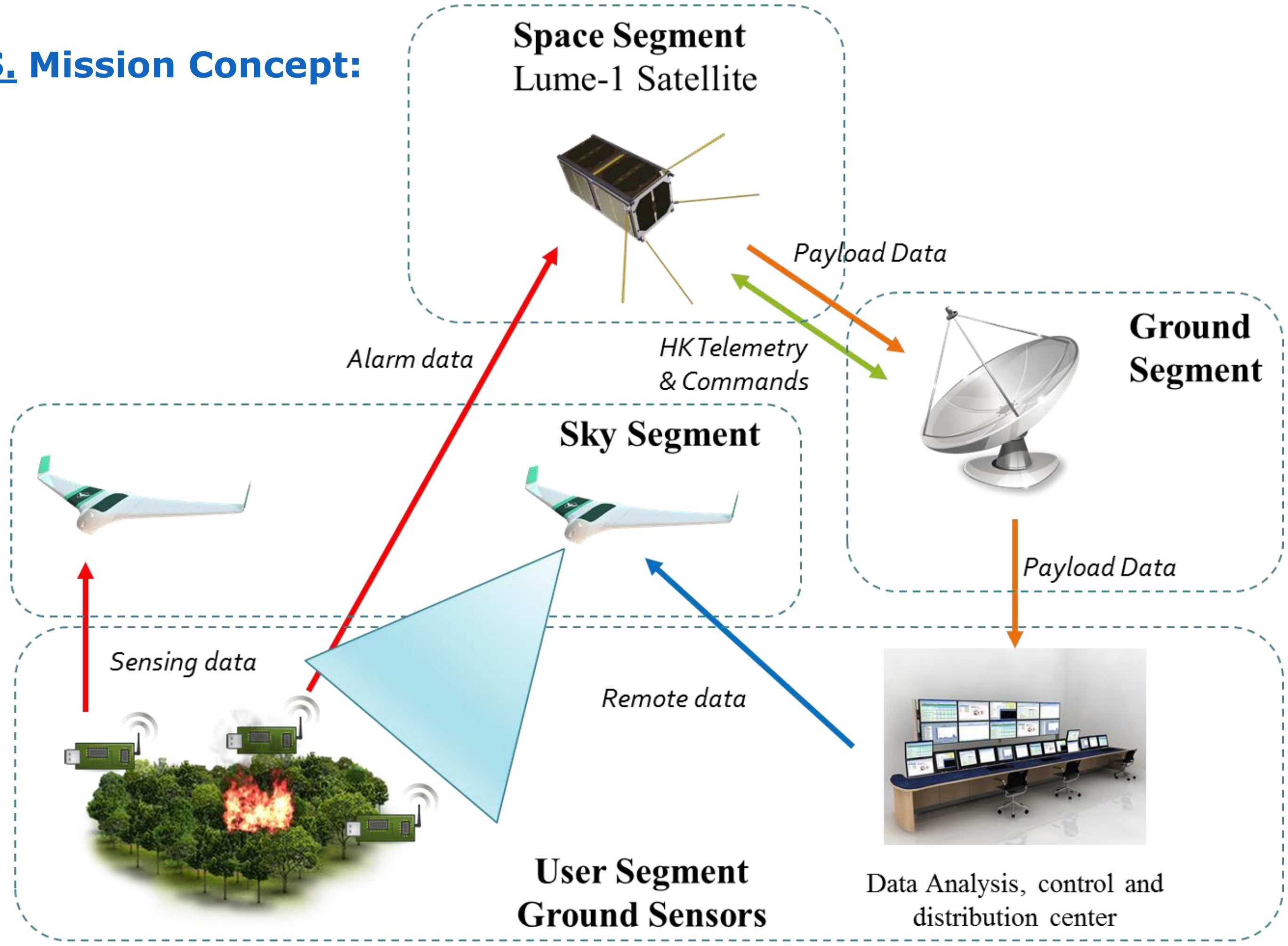
Unmanned air vehicles

*I. Prodan. S. Olaru. R. Bencatel, J. Borges de Sousa, Cristina Stoica, and Silviu-Iulian Niculescu, "**Receding horizon flight control for trajectory tracking of autonomous aerial vehicles**", Control Engineering Practice journal, Elsevier, 2013.*

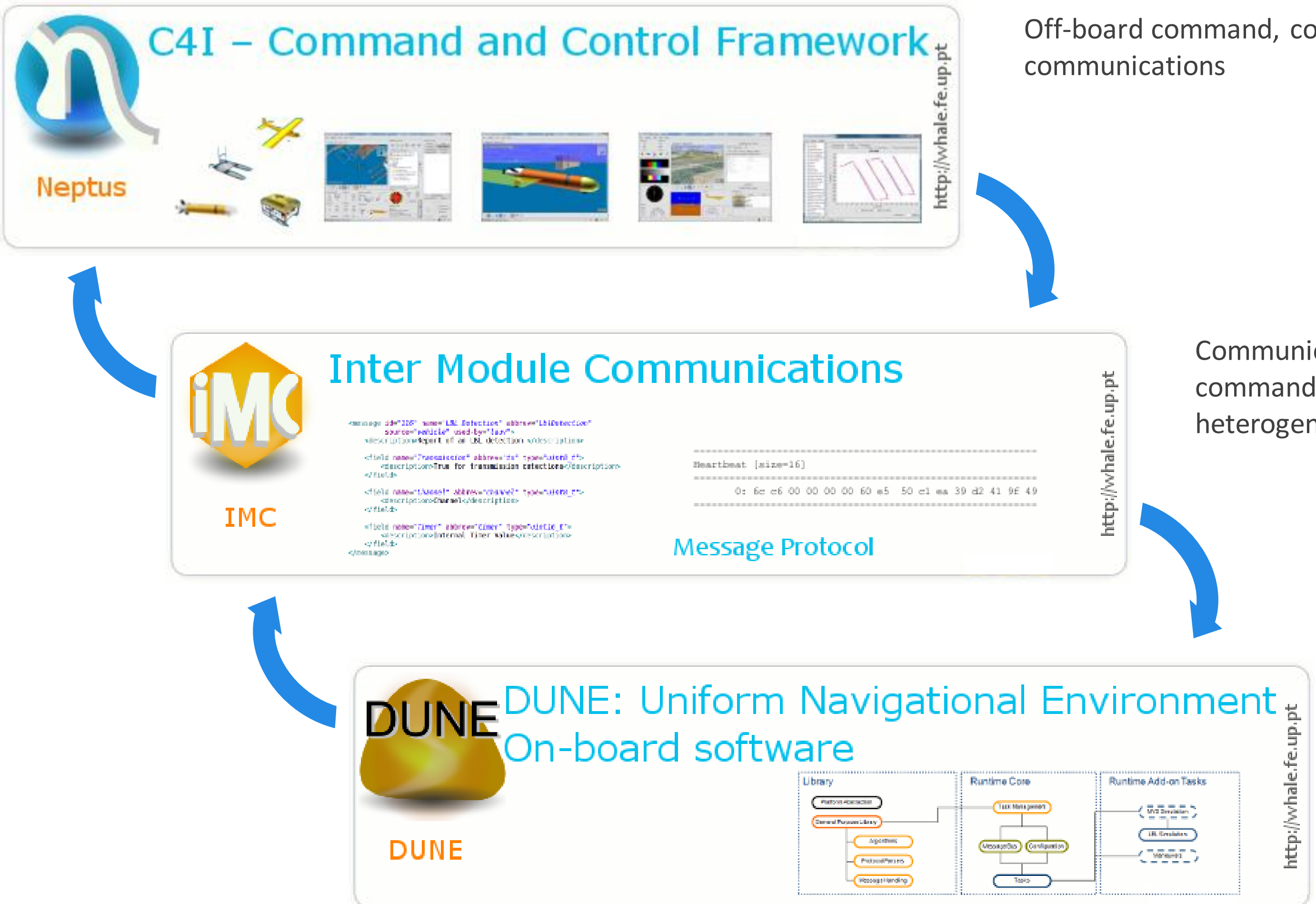
Flying modem

Space component

FIRE-RS. Mission Concept:



Open source LSTS software tool chain



Off-board command, control and communications

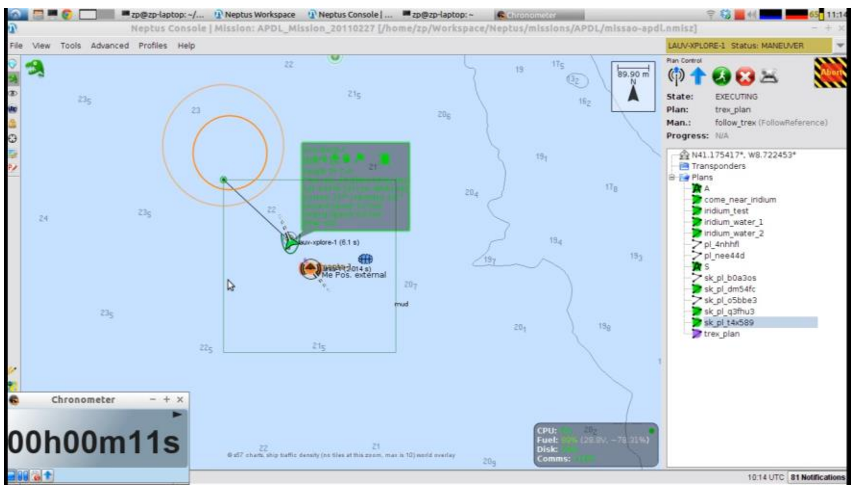
Communication protocols for command and control of heterogeneous systems

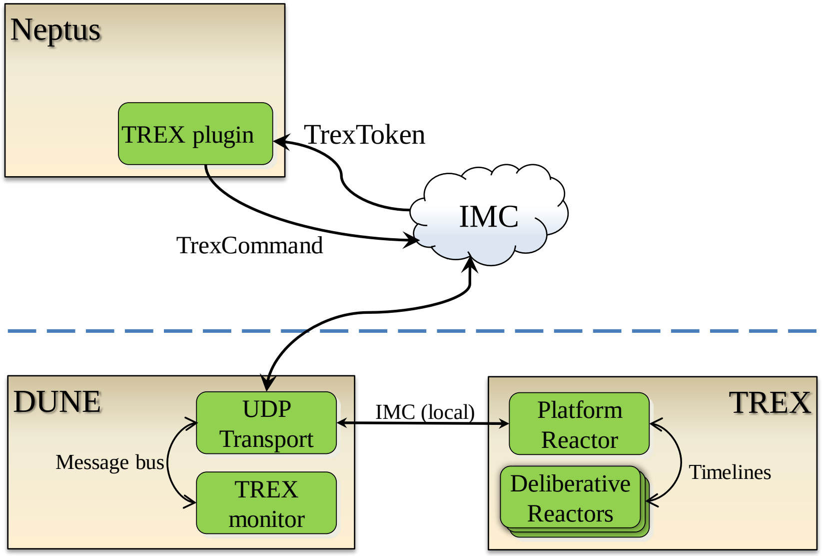
Onboard software (vehicles, buoys, data loggers)

*J. Pinto, P. Sousa Dias, R. Martins, J. Fortuna, E. R. B. Marques, and J. Borges de Sousa, **The LSTS tool chain for networked vehicle systems**, Proceedings of the IEEE/MTS OCEANS'13, Bergen, June, 2013.*

Onboard deliberation (T-REX / Europa)

- T-REX interacts with onboard DUNE
- Plans generated onboard (TREX runs on secondary CPU)
  - When new objectives are received (plan adaptation)
  - When there is an error executing some objective (replanning)

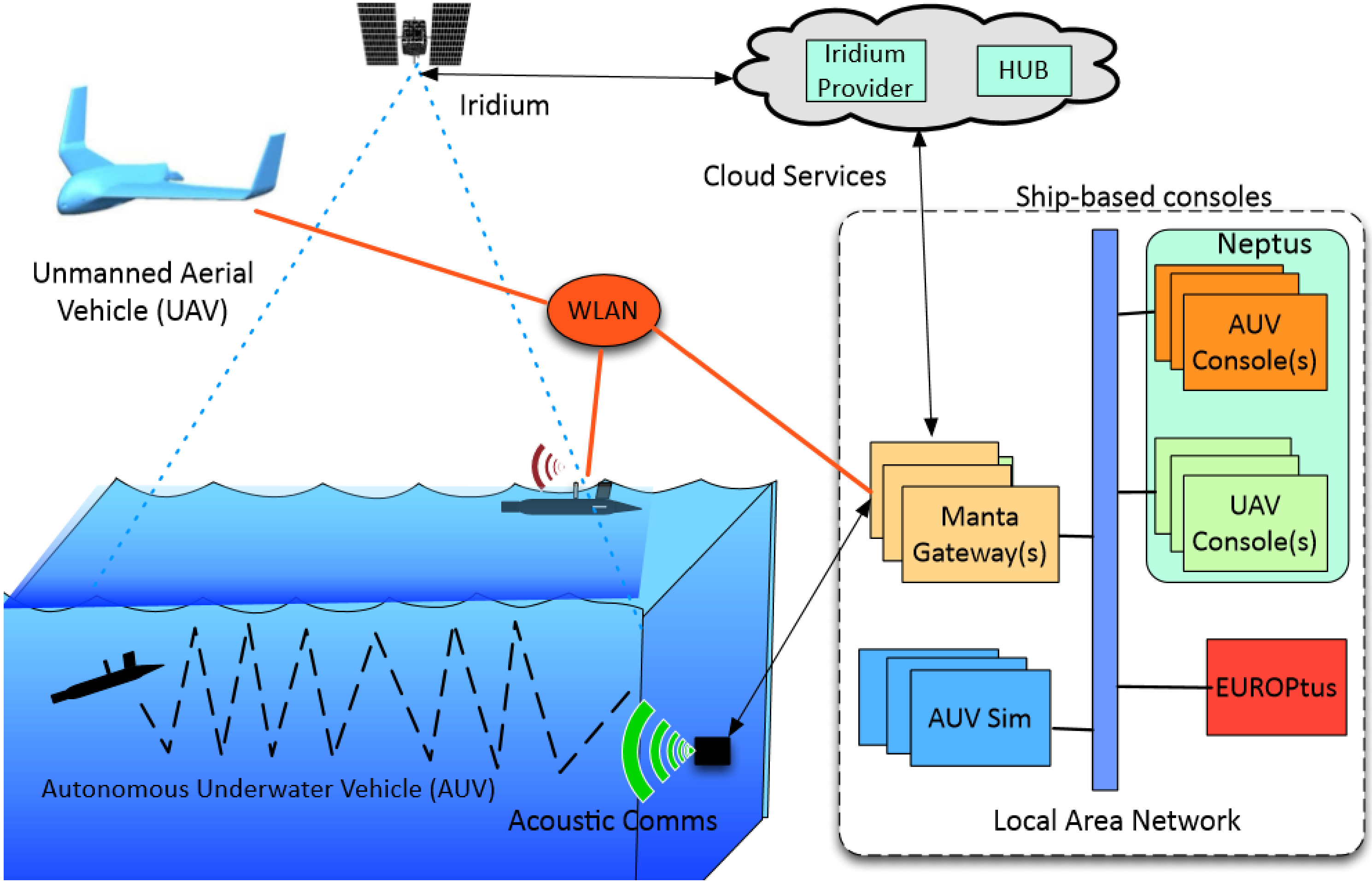




*M. Faria, J. Pinto, F. Py, J. Fortuna, H. Dias, R. Martins, F. Leira, T. Arne Johansen, J. Borges de Sousa, and K. Rajan, "**Coordinating UAVs and AUVs for oceanographic field experiments: challenges and lessons learned**", Proceedings of the 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong-Kong, May 31 – June 7, 2014.*

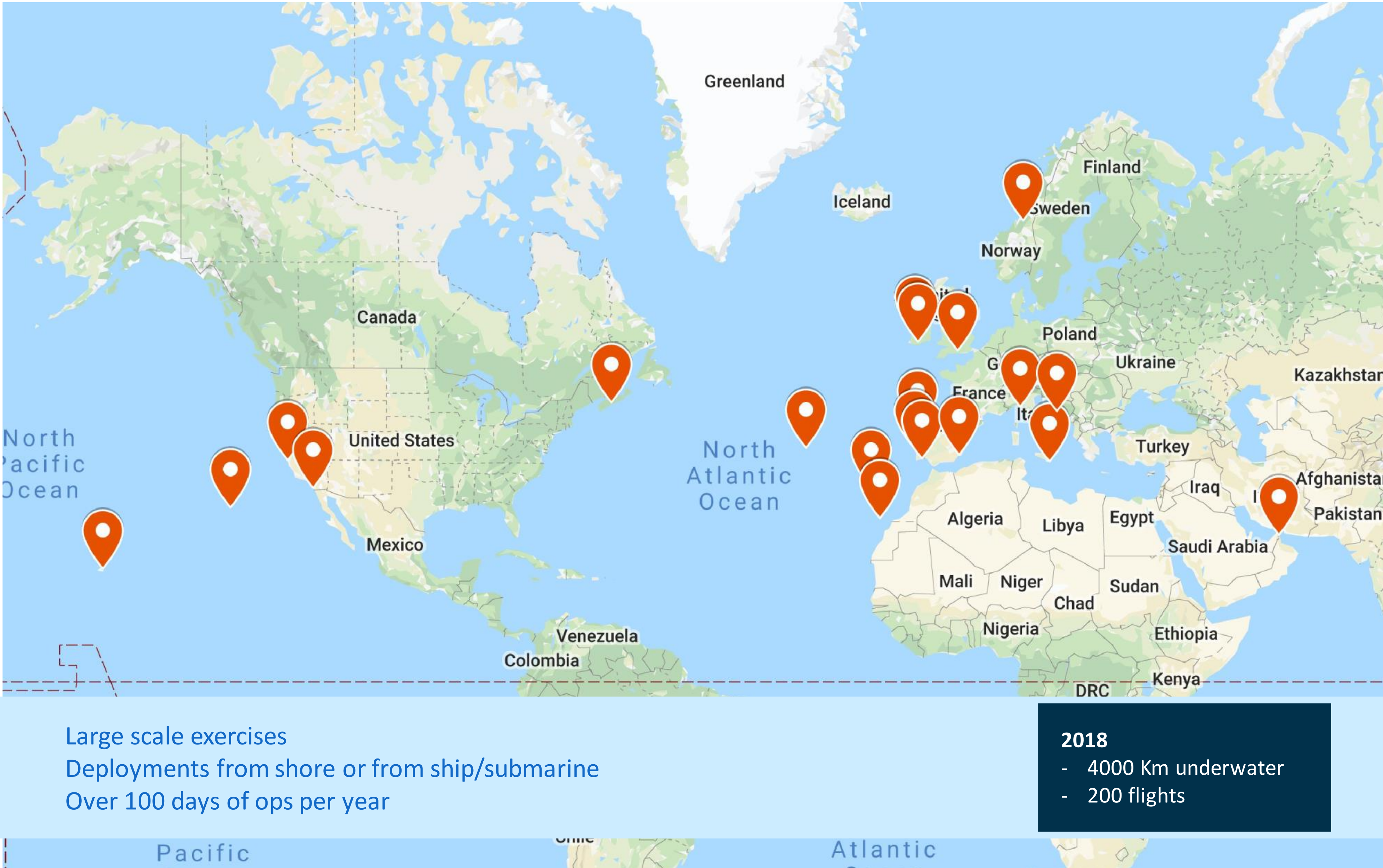
EUROPtus: mixed initiative control

- Planning and execution control for human operators and autonomous vehicles



F. Py, Pinto, J., Silva, M. A., Johansen, T. Arne, de Sousa, J. Borges, and Rajan, K., ***EUROPtus: A Mixed-initiative Controller for Multi-Vehicle Oceanographic Field Experiments****, International Symposium on Experimental Robotics, pp. 1–10, 2016.*

Operation areas



Large scale exercises
Deployments from shore or from ship/submarine
Over 100 days of ops per year

2018
- 4000 Km underwater
- 200 flights

REP (MUS) exercise

Areas

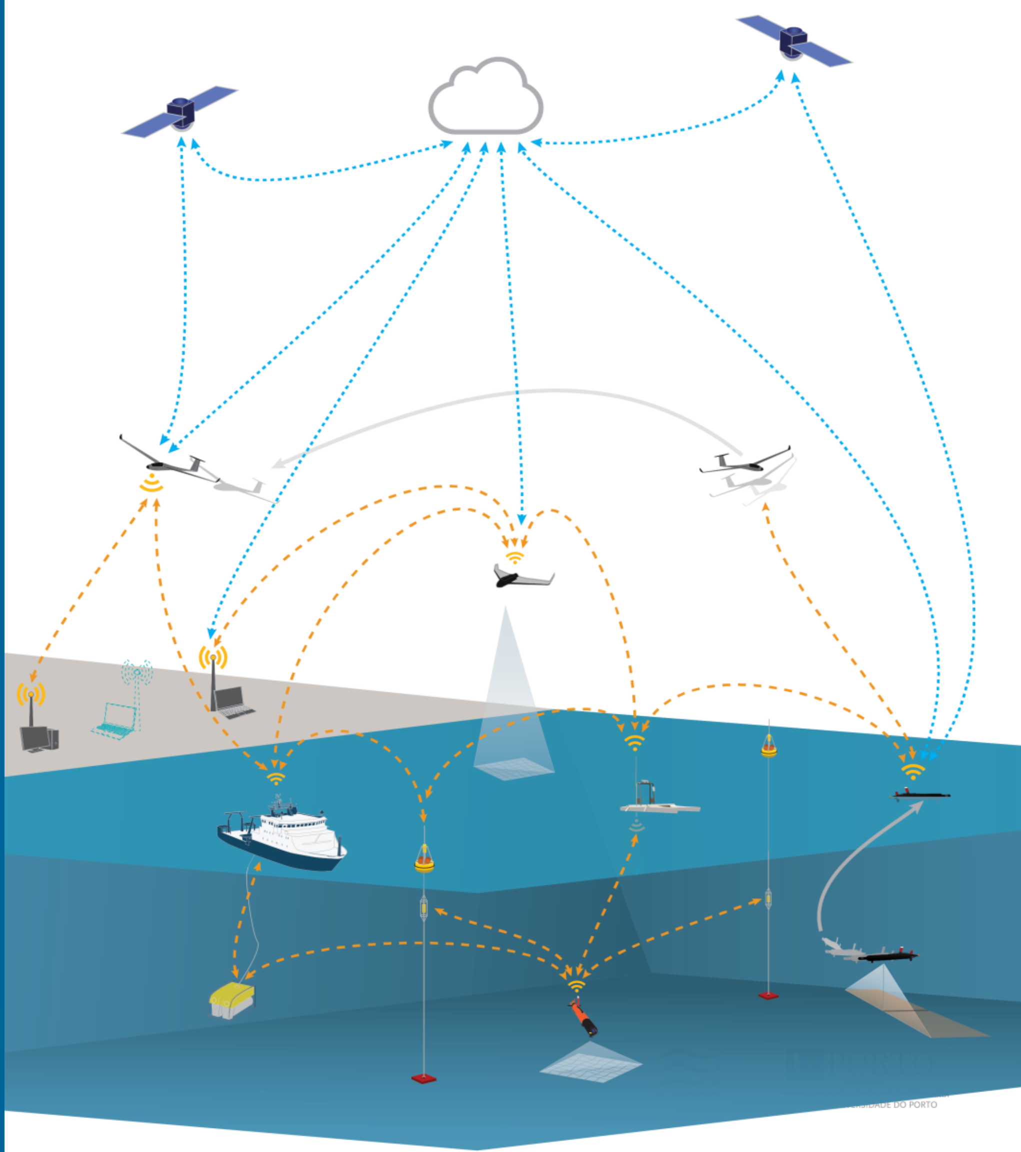
- ASW
- ISR
- Mine Warfare
- Expeditionary Hidrography
- Search and Rescue
- Standards for Underwater Communications
- Ocean Sciences

Organized by

- **Portuguese Navy**
- **Porto University**
- **Centre for Maritime Research and Experimentation**

Goals and approach

May 28–June 17, 2018

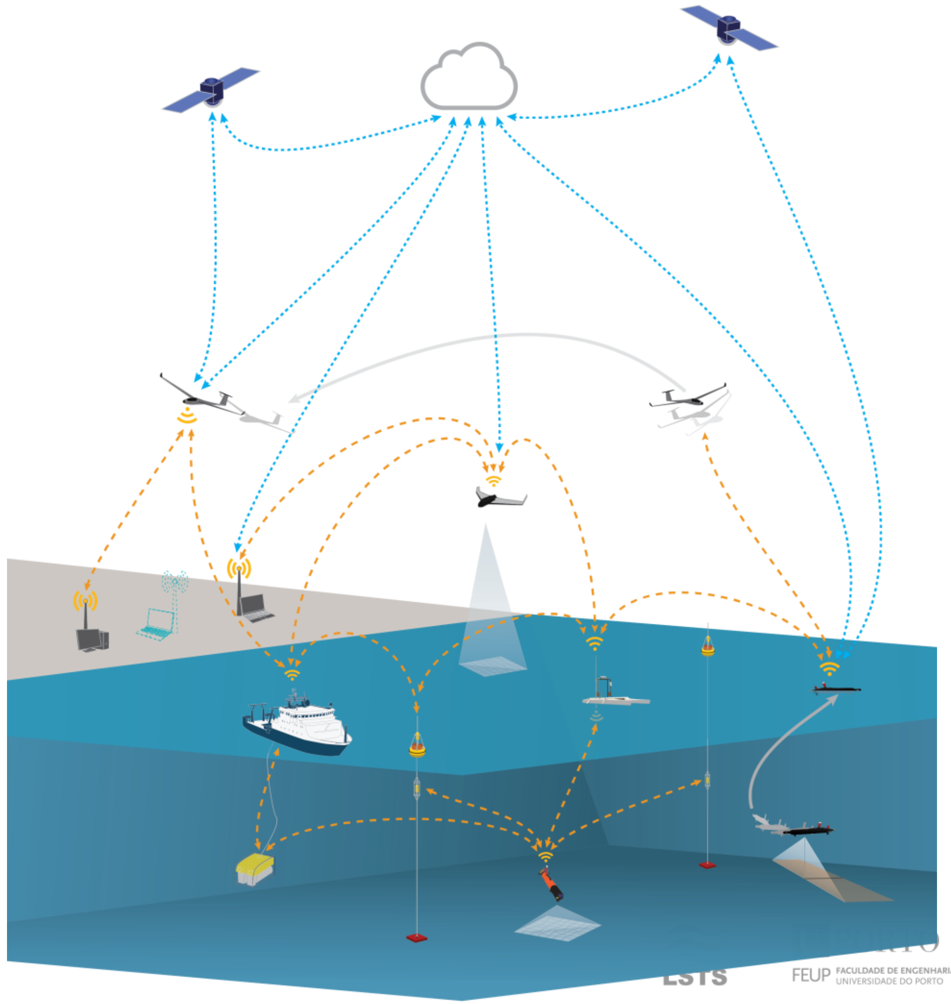


Main goal

To demonstrate a **novel multi-vehicle system capable of finding, tracking and sampling** features of the ocean with adaptive spatial-temporal resolution

- *R/V Falkor:* base, control station
- Robots distributed over wide areas
- One-operator – multiple assets
- Remote access and visualization
- Coordinate capabilities on-demand
- Scientific study of work-practice

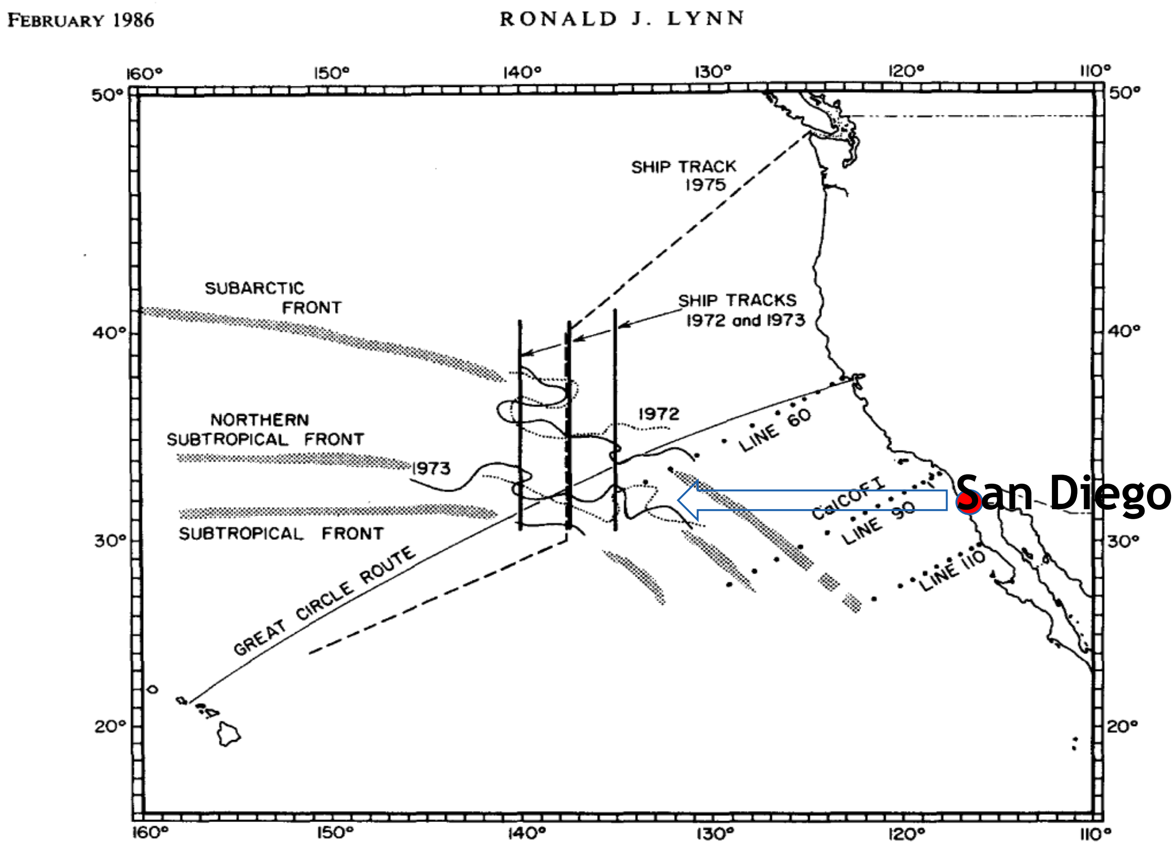
- **Target area**: North Pacific STF



Fronts are the most conspicuous, highly dynamic, and high-gradient oceanic features that can be detected & tracked with such a broad array of assets

North Pacific Subtropical front

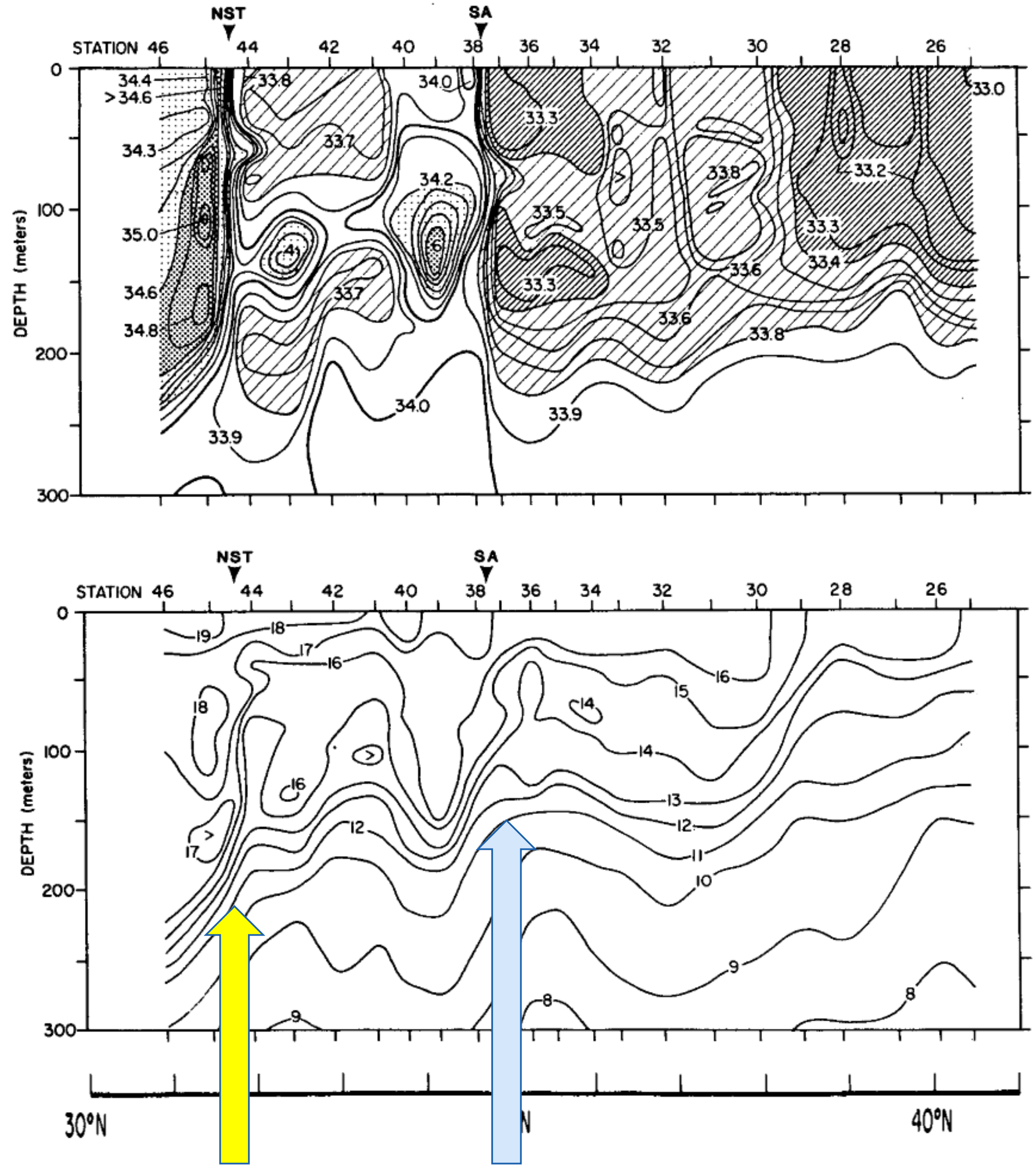
- Sharp boundary where cold fresh waters from the north meet warm salty waters from the south
  - Relatively shallow (< 300 m)
  - Strong in S, weak in SST
  - 800 Nm from San Diego
- Previous studies (70s, 80s)



Ronald J. Lynn, The Subarctic and Northern Subtropical Fronts in the Eastern North Pacific Ocean in Spring, Journal of Physical Oceanography, Volume 16 No. 2, February 1986, pp.209-222.

137.5°W section

June 1972



Salinity

Temperature

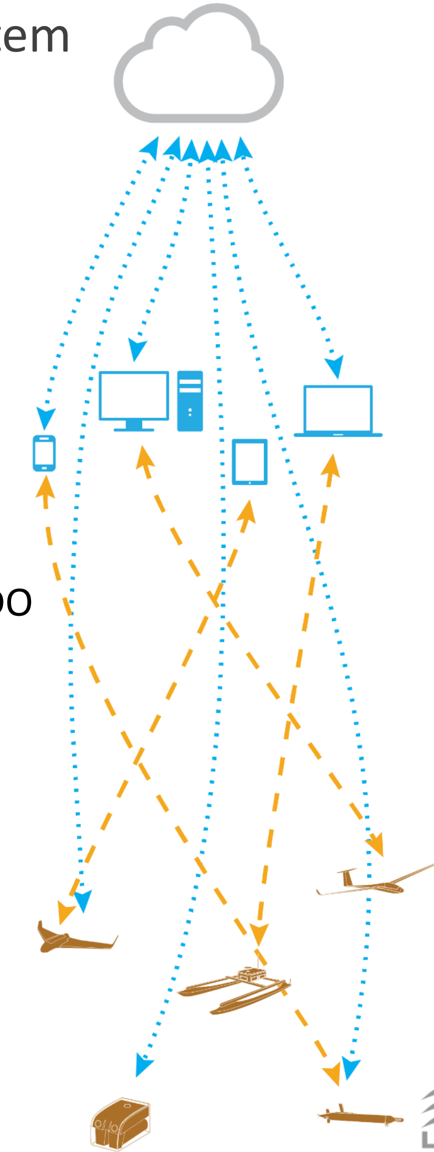
Lynn, 1986

NST = Northern Subtropical Front

SA = Subarctic Front

System

- R/V Falkor based networked multi-vehicle system
  - 3 VTOL UAVS (IR/mulispectral cameras, DSM)
  - 2 Quadcopters
  - 1 Wave glider / 2 Saildrones
  - SIL Camera/ ALF sensor
  - 1 **Eco-Mapper** AUV
  - 1 **Lauv-xplore-1:** CTD, pH and DO2
  - 1 **Lauv-xplore-2:** CTD, Chlorophyll-a and Turbidity
  - 3 **Lauv-xplore-3-5:** CTD (50h+ endurance)
  - 1 **Lauv-harald:** CTD, Chlorophyll-a, Organic Matter/DO



Ripples

Communications hub for data dissemination and situation awareness

Neptus

World Representation
Planning
Simulation
Execution
Analysis

IMC

Inter-Module Communication protocol

DUNE

Uniform Navigational Environment On-board Software

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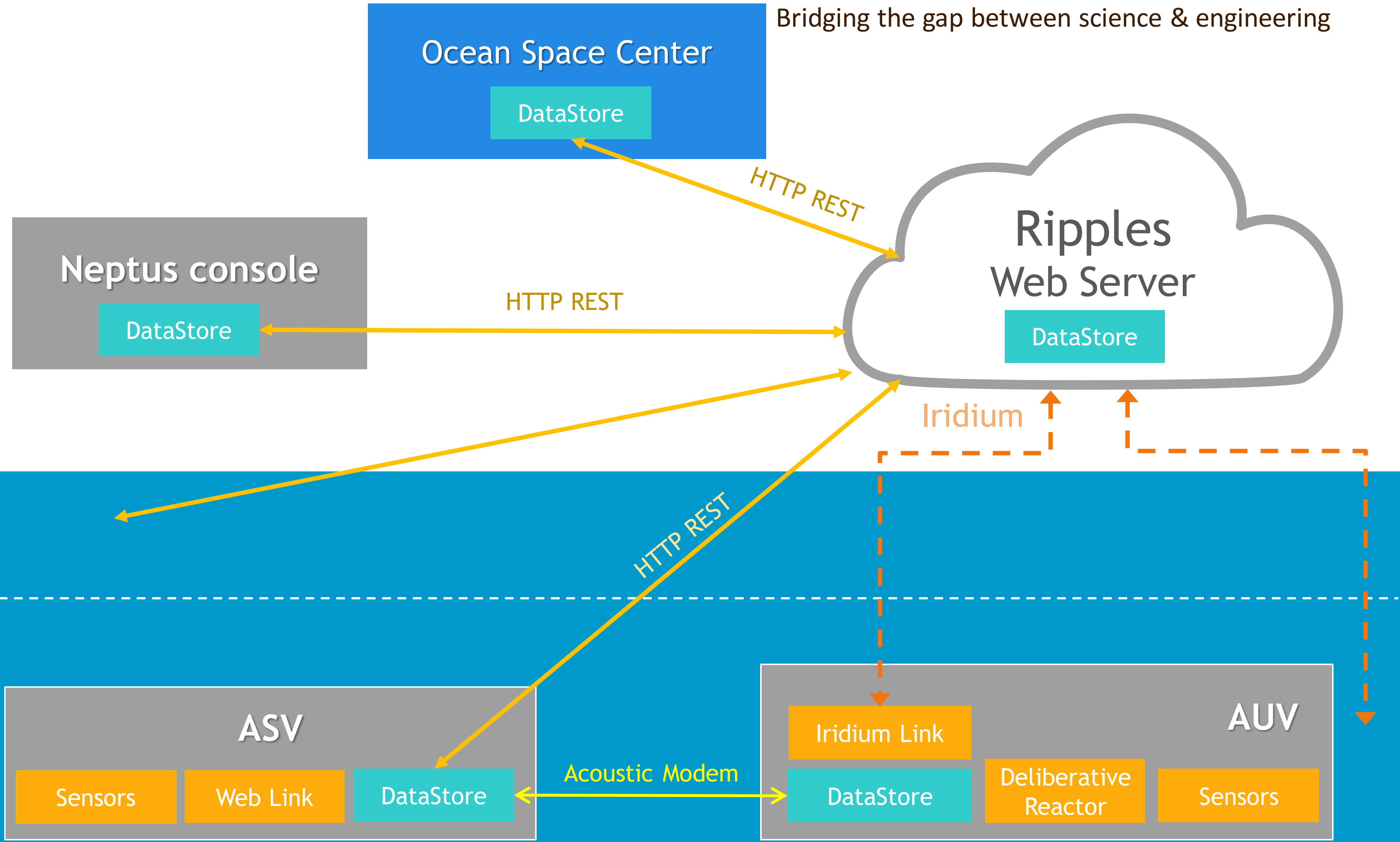
Onboard mission control center (24h/15days)

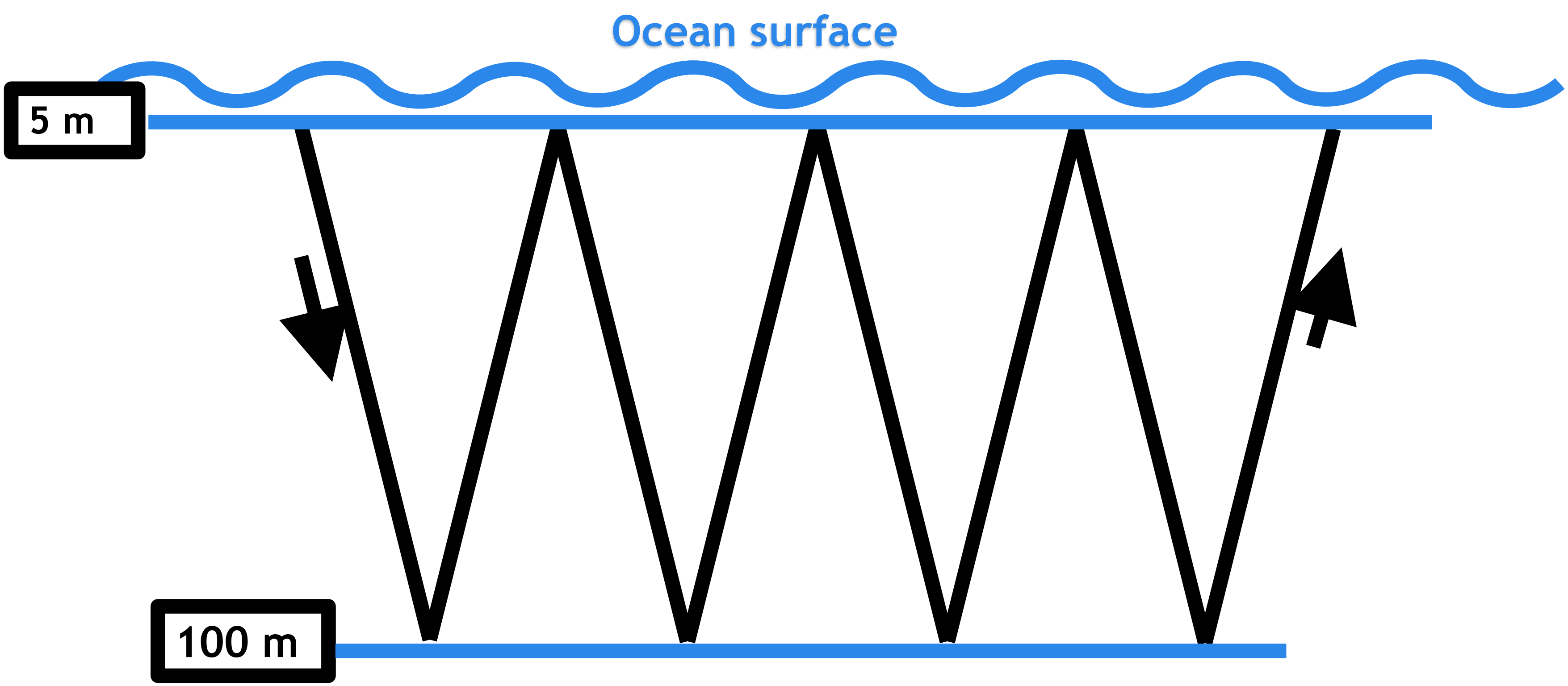
- Situational awareness, viz with multiple layers, planning & execution control
- 4 shifts per day
- Web-based access

Software & communications infrastructure



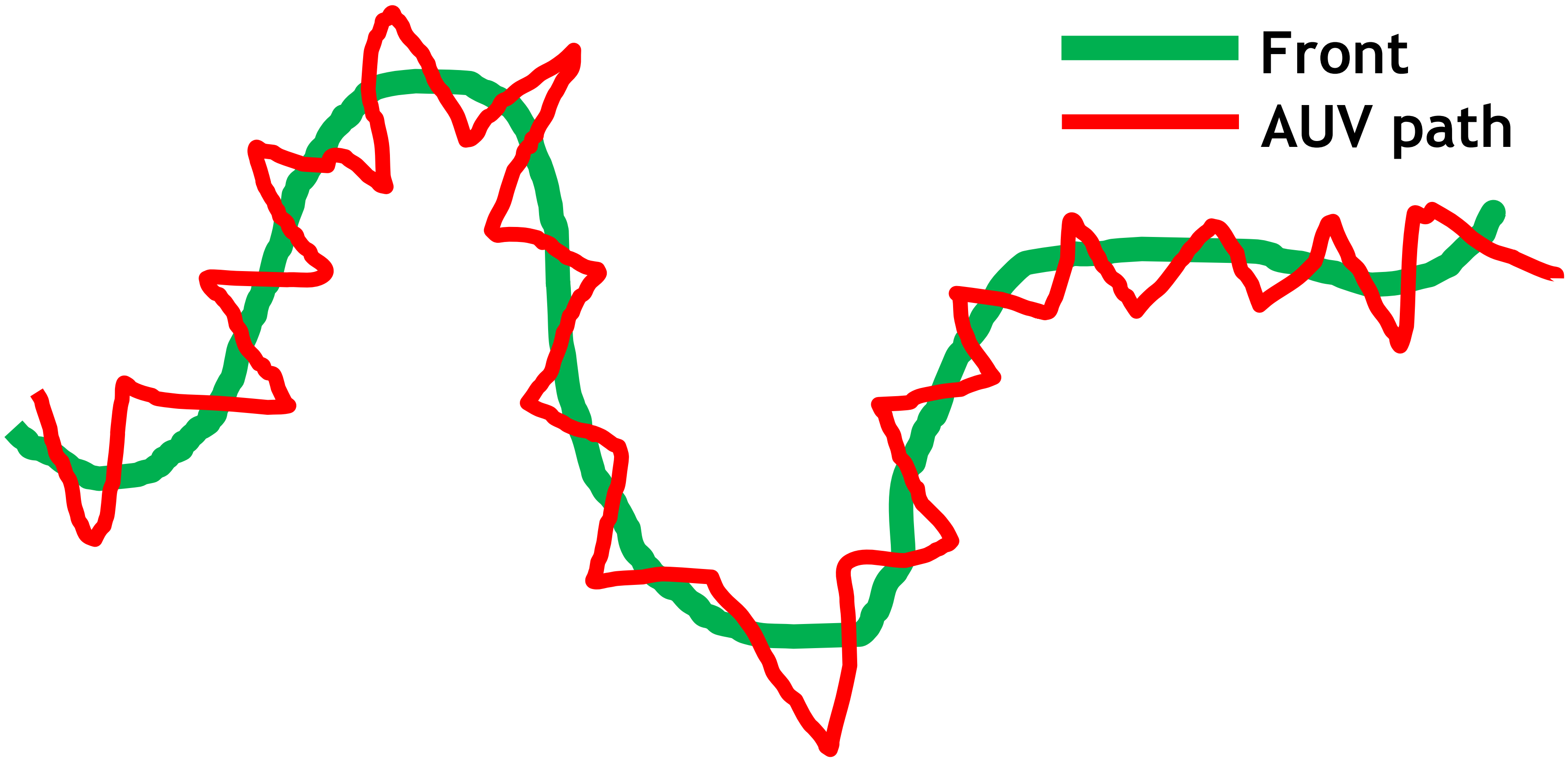
Addressing complexity: task templates

- **Task 1**: Single AUV: Yo-yo flight



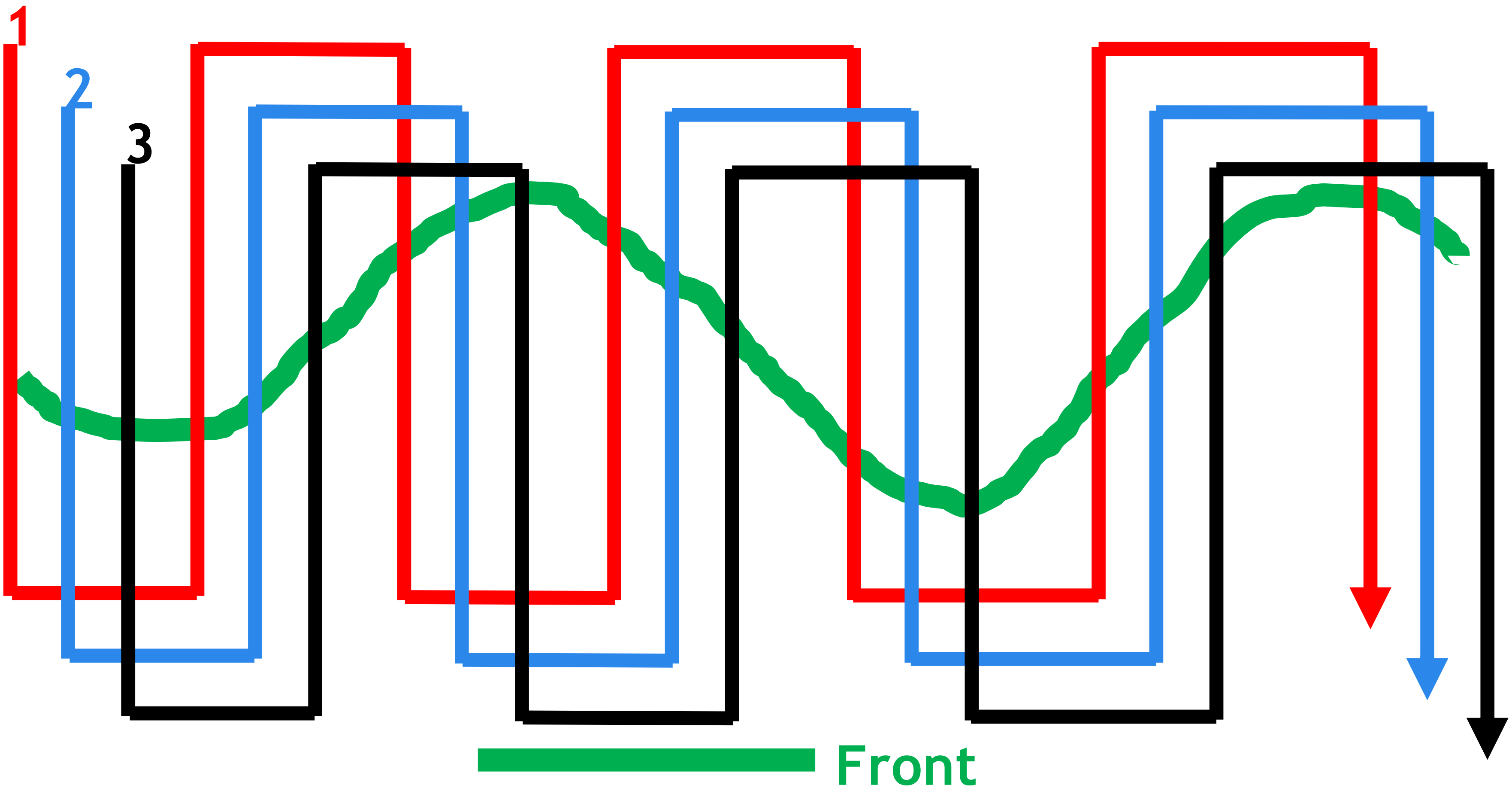
Courtesy of Igor Belkin

- **Task 5**: Single AUV: Front tracking: Zig-zag pattern (planar view)



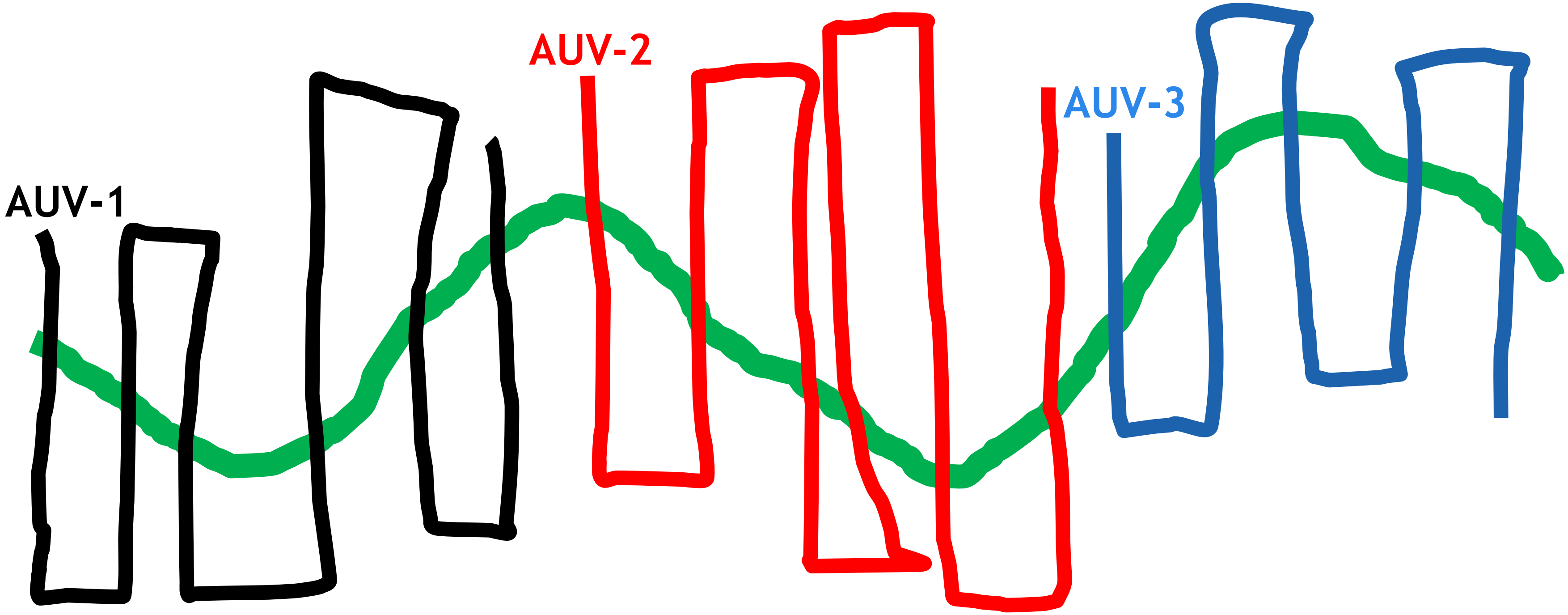
Courtesy of Igor Belkin

- **Task 7**: Multiple AUVs: Front-mapping: Radiator patterns



Courtesy of Igor Belkin

- **Task 8**: Multiple AUVs: Front mapping: Single-File Radiators (near-synchronous surveys)

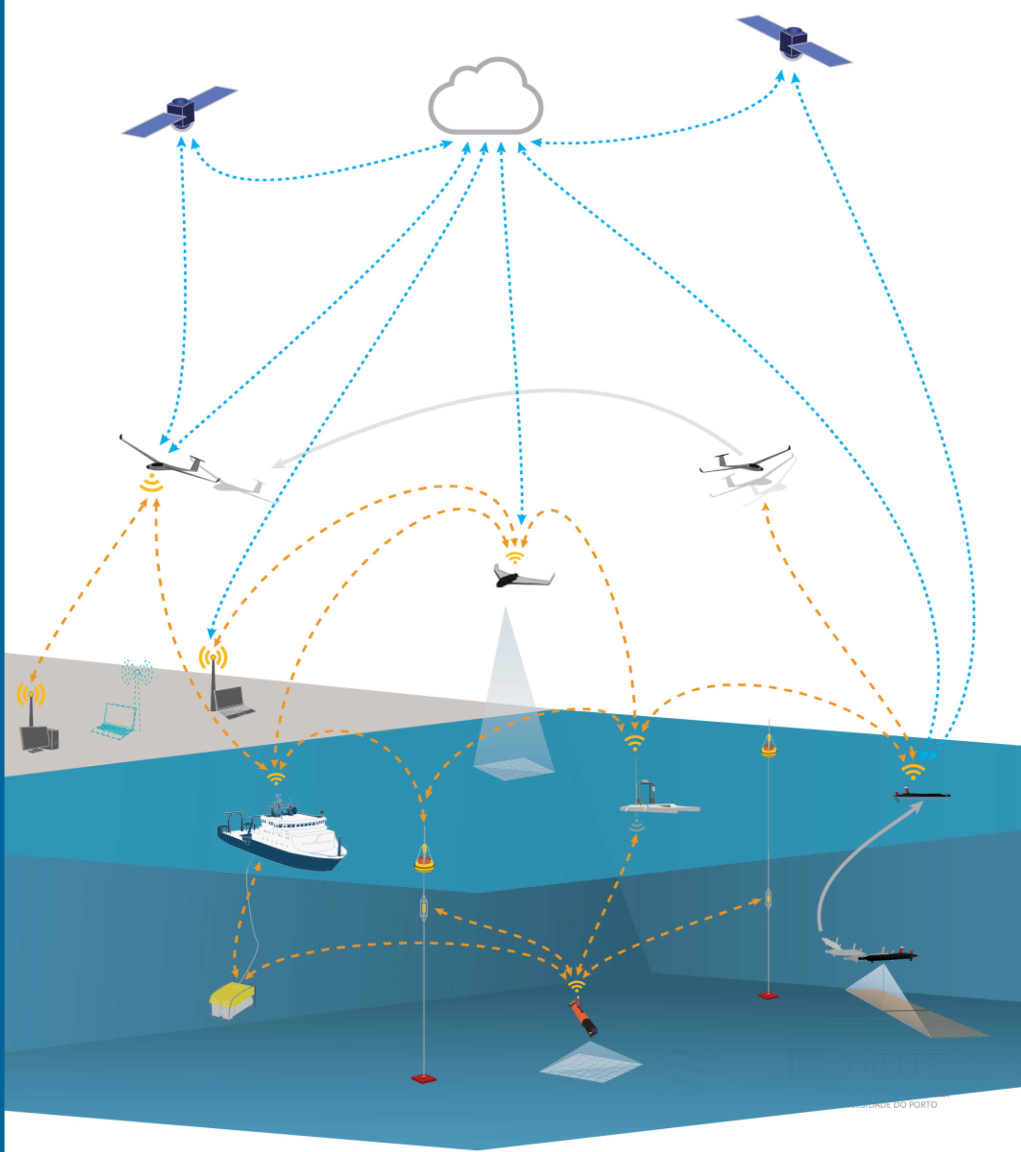


Are these the right tasks?
What about task coordination and sequencing?
What about vehicle to task allocations?
What about L/R of AUVs? And CTD casts from the ship?

Courtesy of Igor Belkin

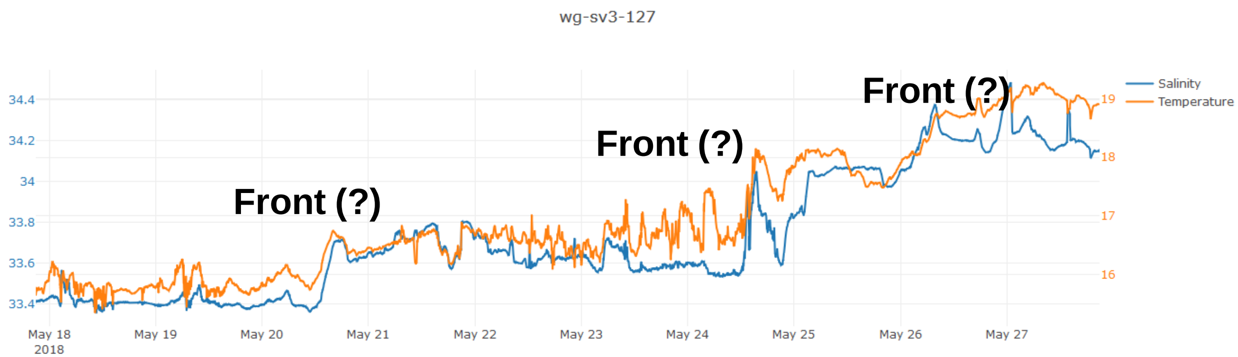
Operations

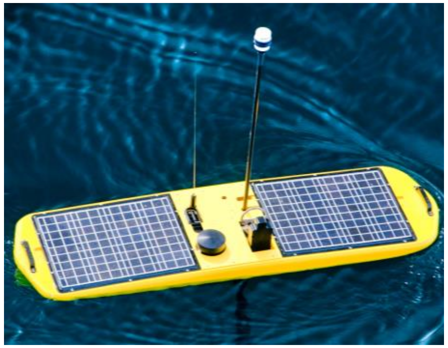
May 28–June 17, 2018

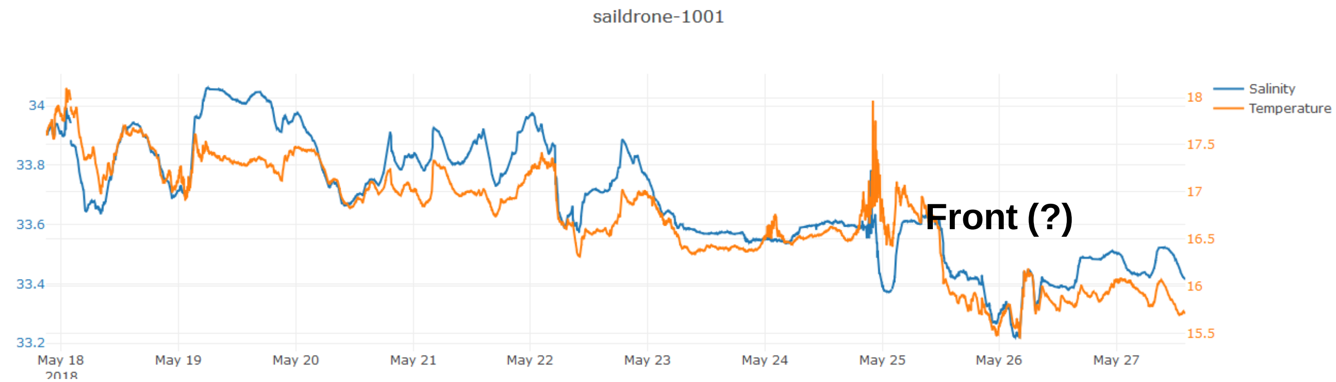


Finding the front

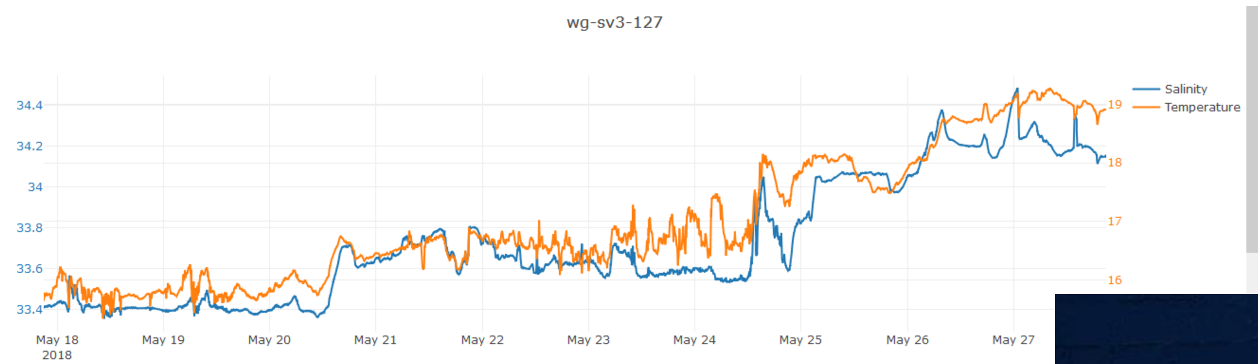
- One WaveGlider (WG) and two Saildrones (SD) deployed into the target research area ahead of the ship's arrival

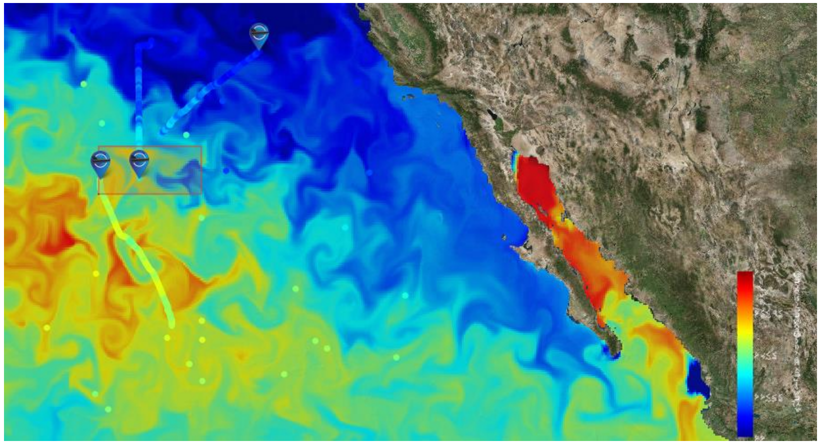


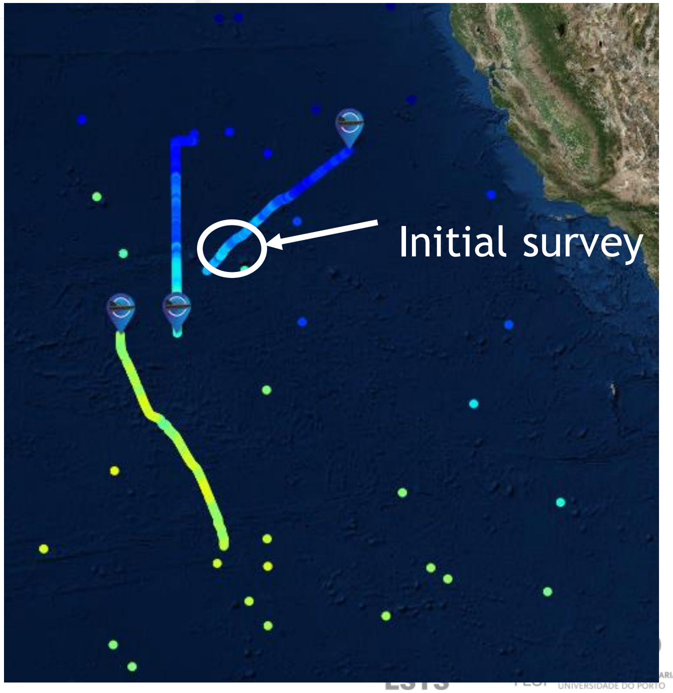




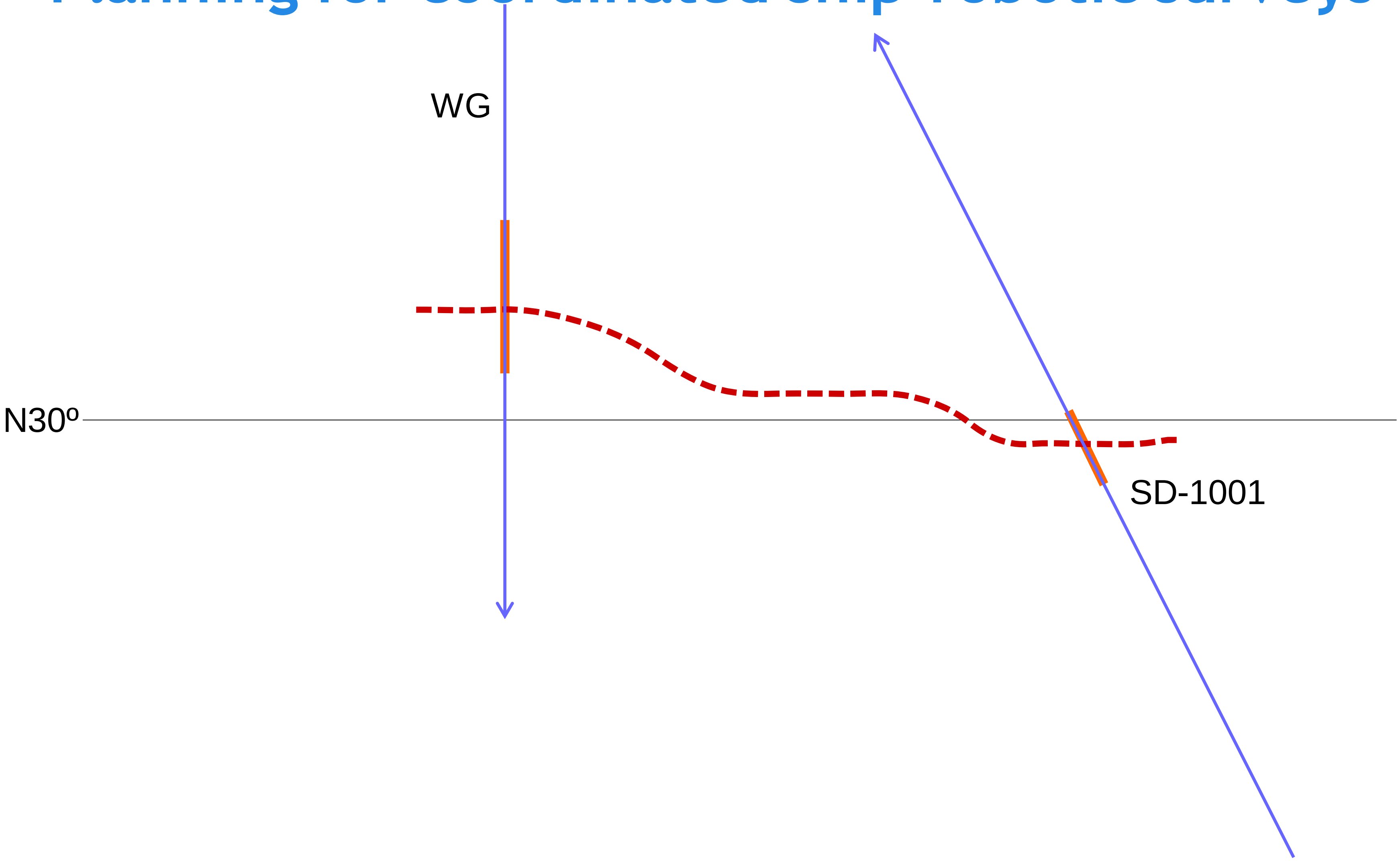
- ***Ocean space center*** ingested satellite imagery, HPC-run model outputs, and data from SD and WG and Argos floats





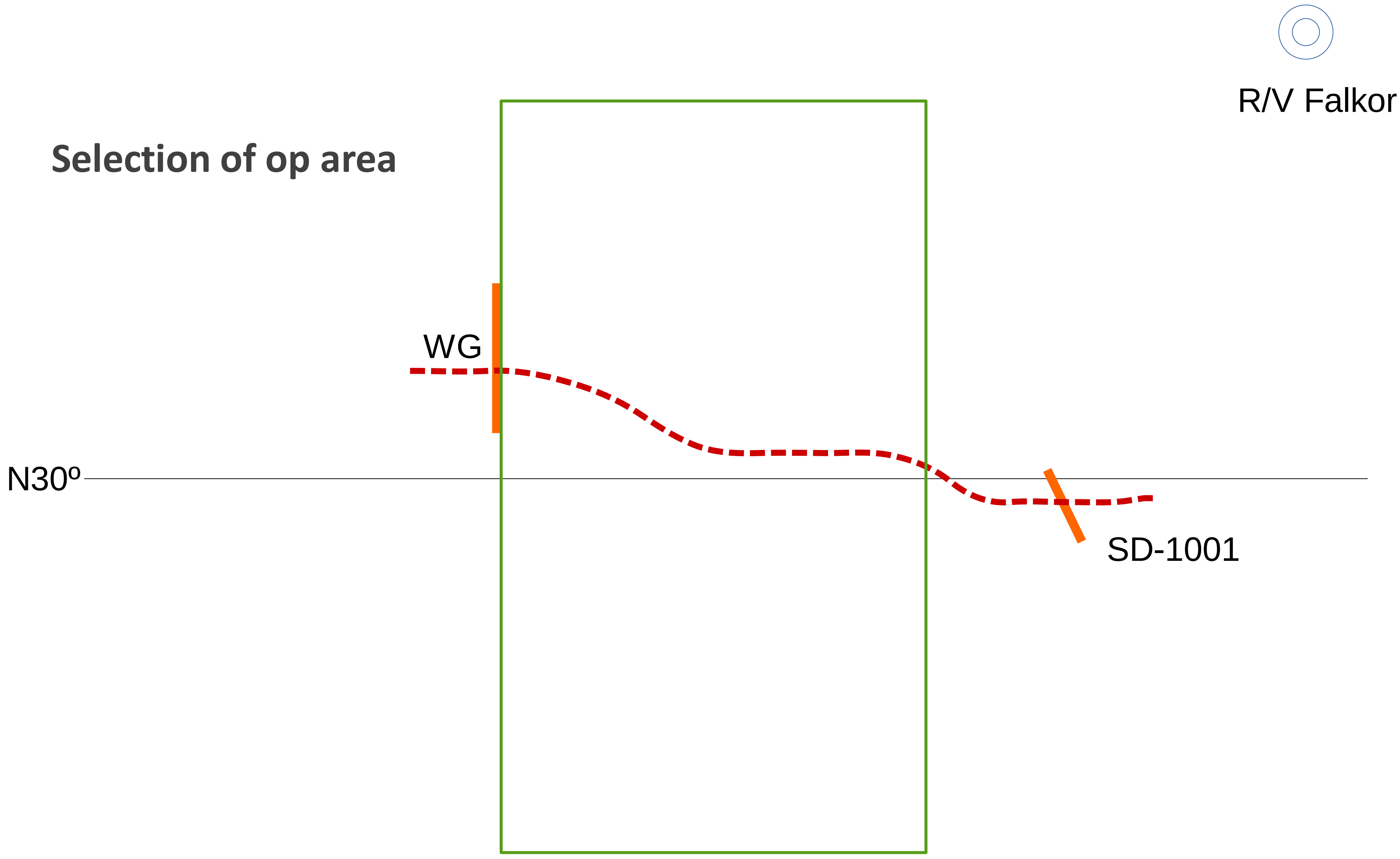


Planning for coordinated ship-robotic surveys



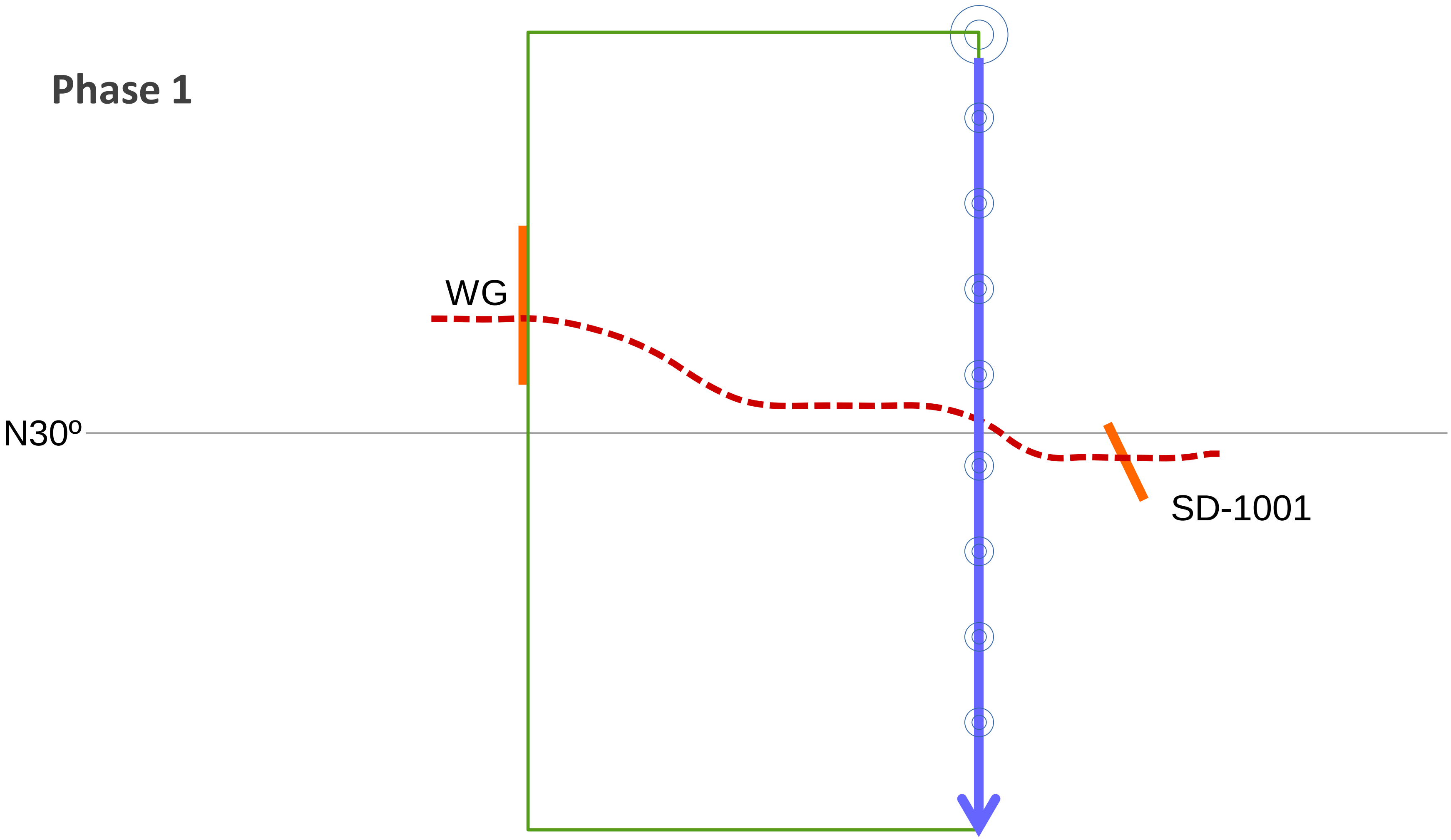
- Two ASVs crossed the front near N30º

Selection of op area



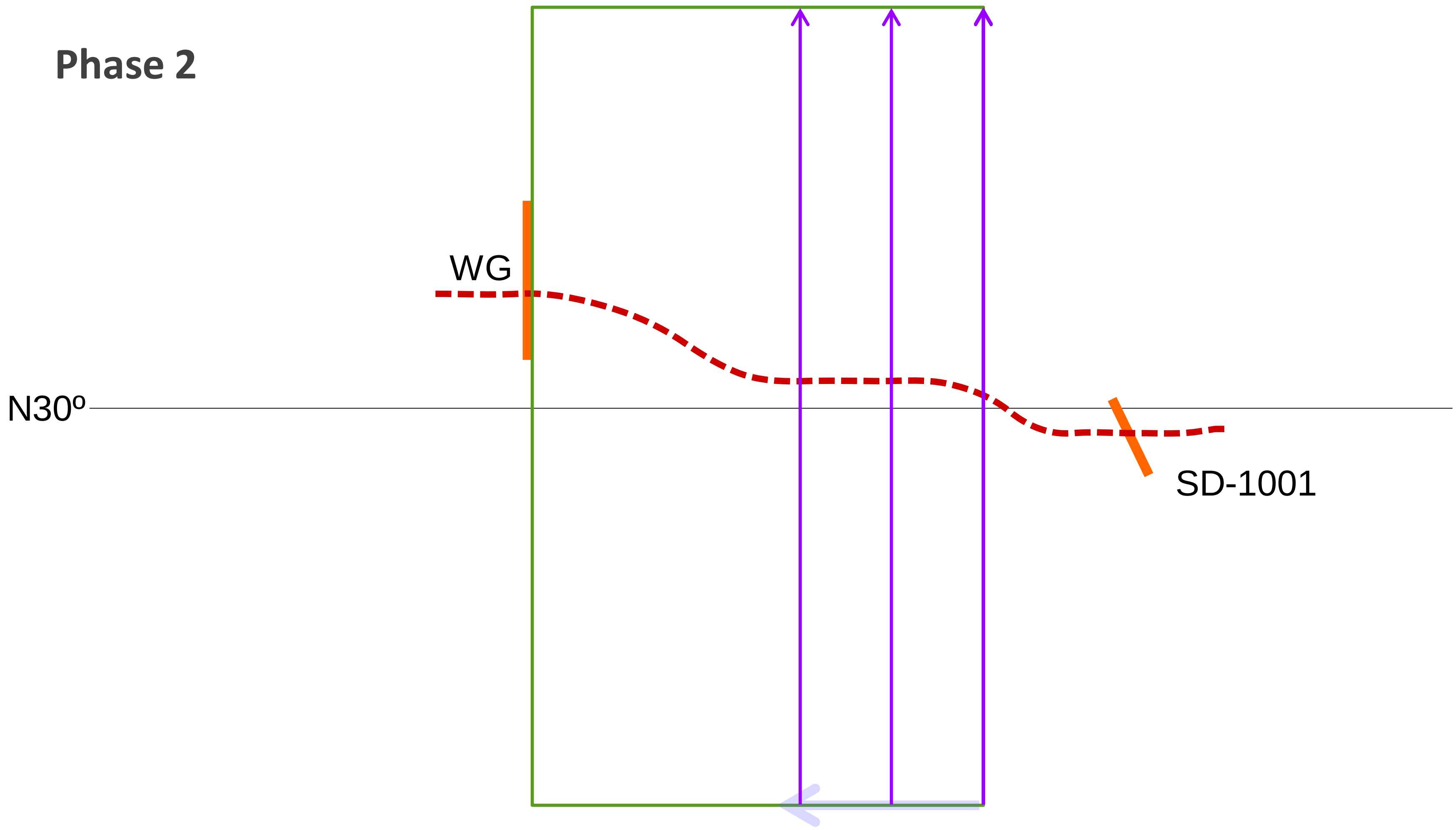
- Multi-vehicle survey area
- Corners: N29º15’ / W133º and N30º45 / W132º (165 km x 95 km)

Phase 1



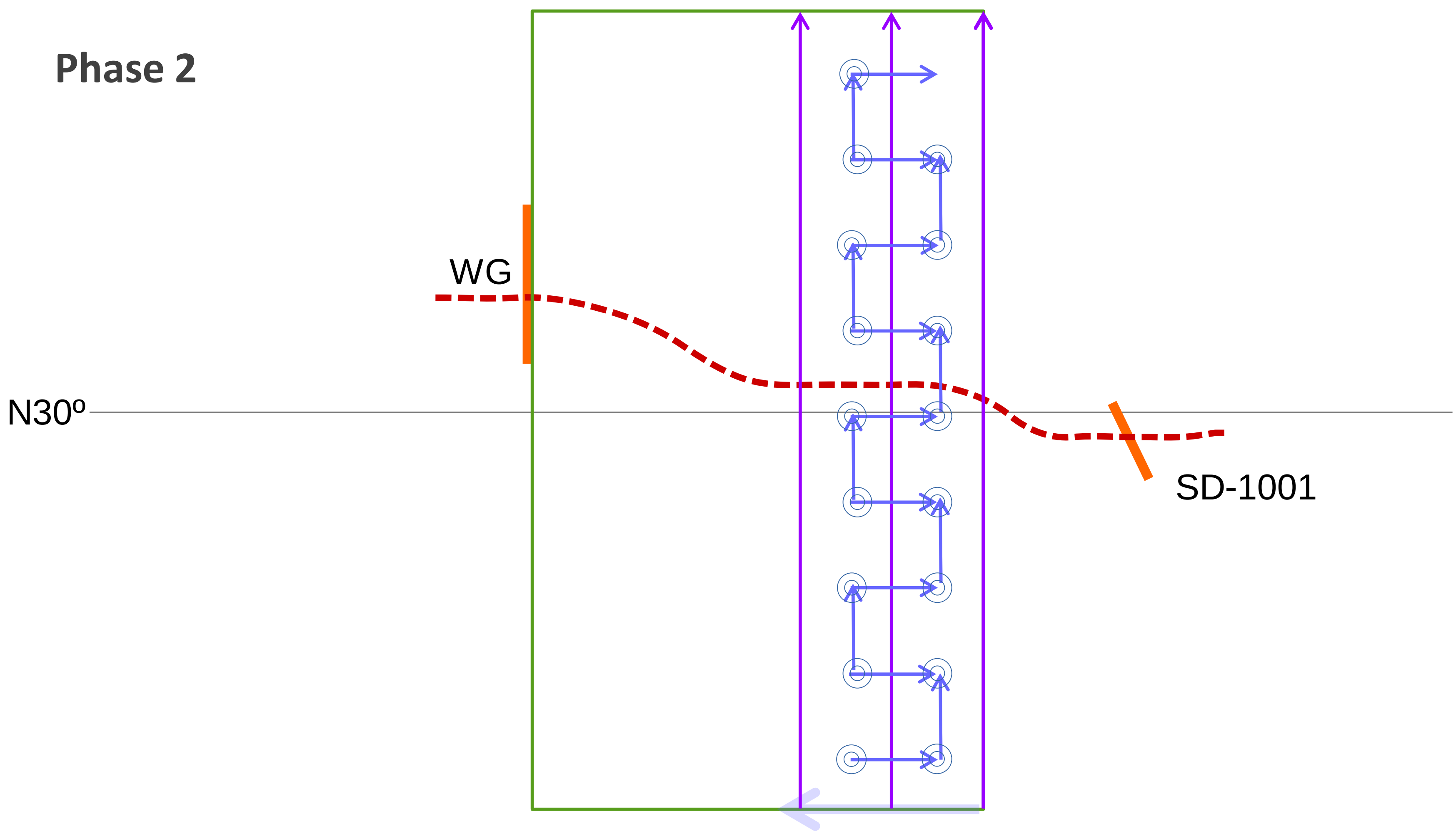
- R/V Falkor sails to nearest point in op area to perform a North → South CTD survey (165 km)

Phase 2



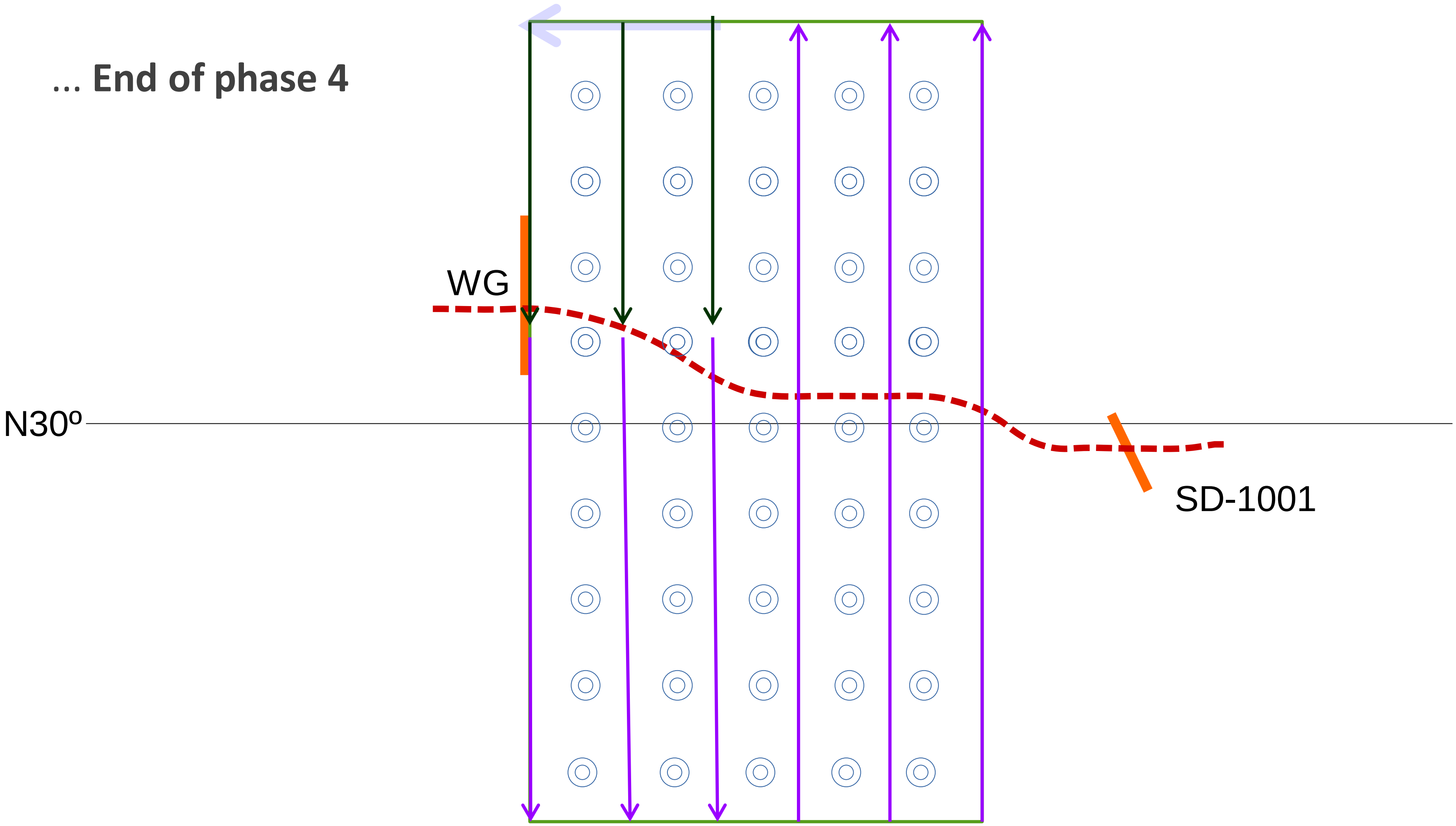
- 3 Long-range AUVs deployed for surveying south to north (165 km / 50h @ 2kn)

Phase 2



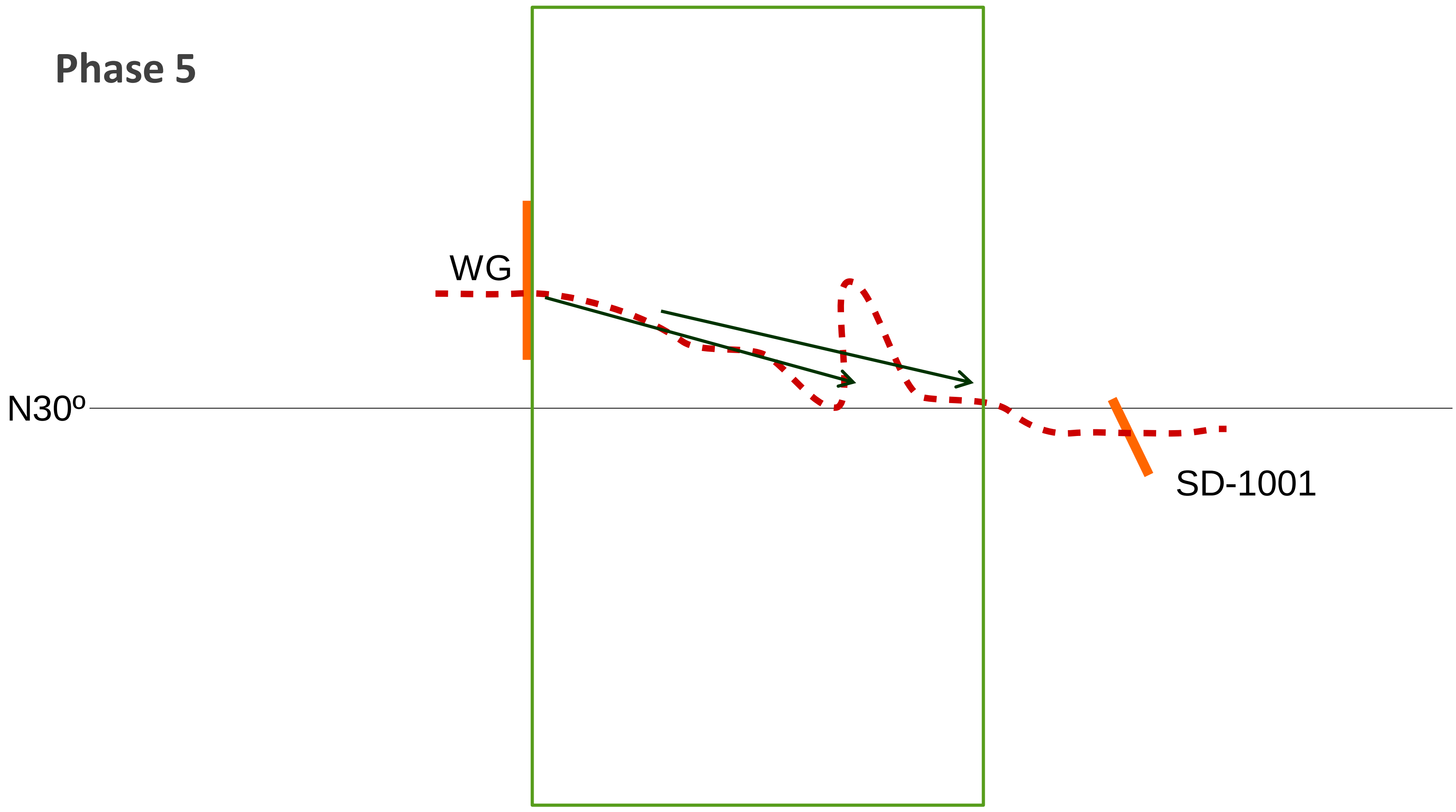
- Ship follows the AUVs while performing 18 CTD casts on the way (330 km / 50h @ 5kn)

... End of phase 4



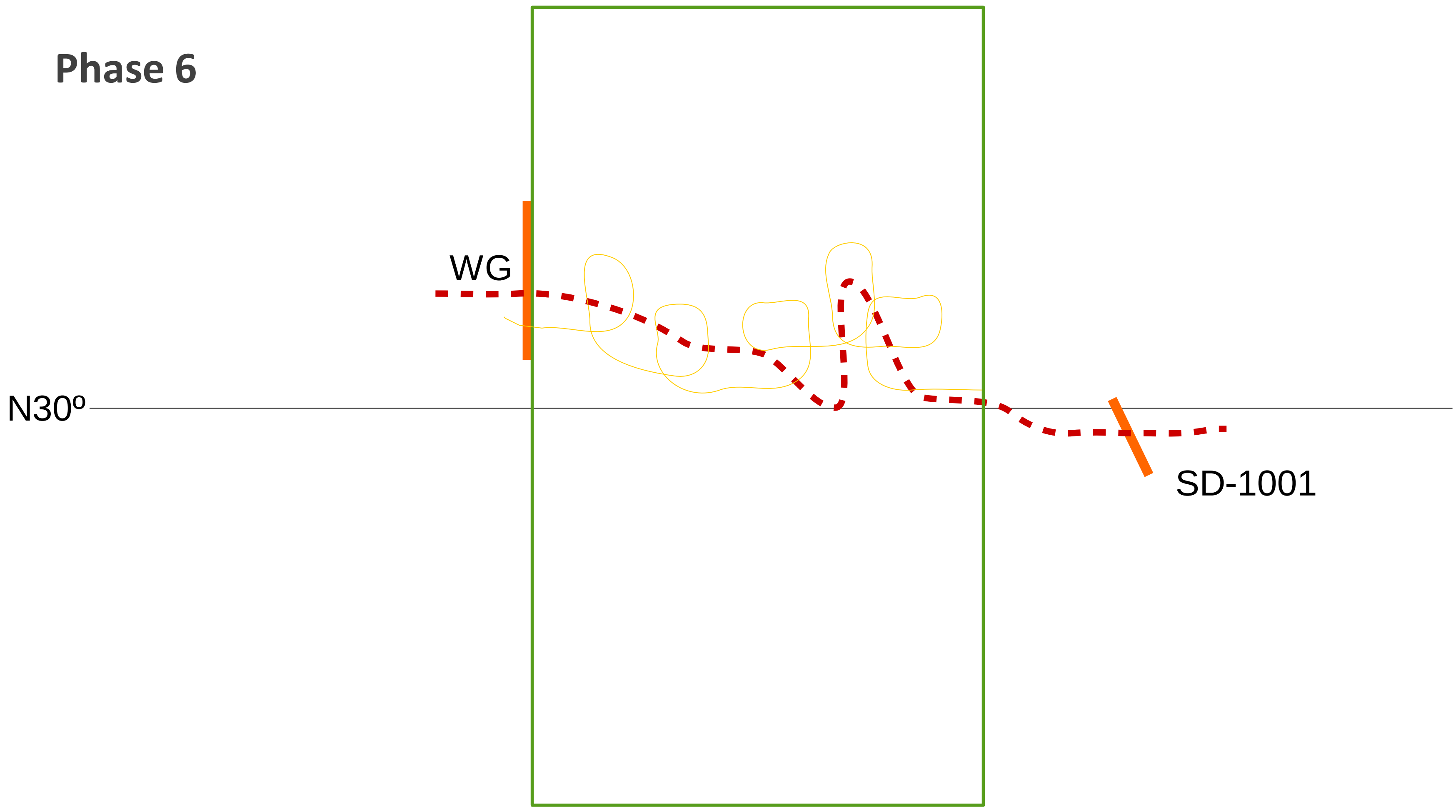
- 50 CTD casts, operated long range and short range AUVs.
- 5 NM resolution for radiator pattern

Phase 5



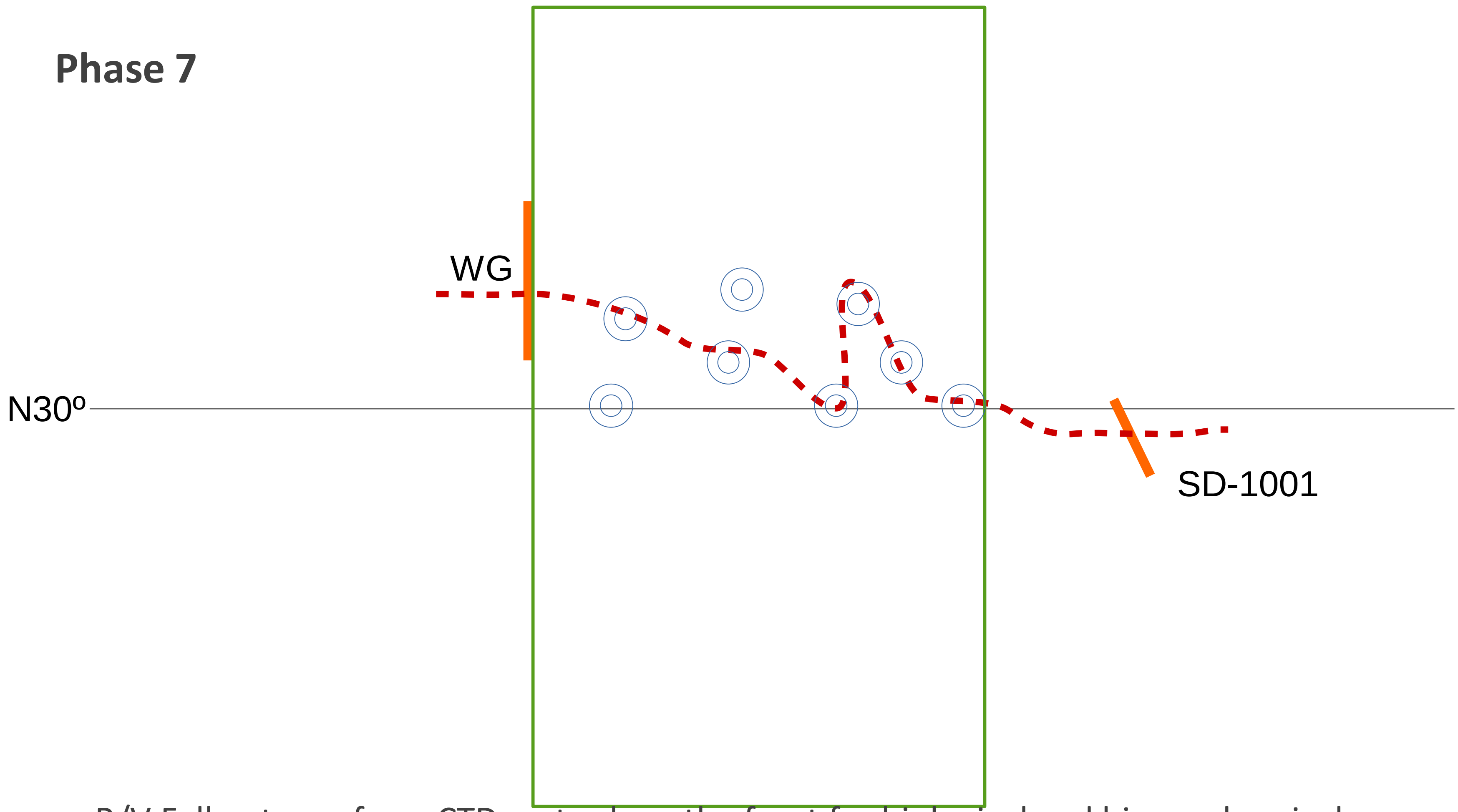
- Short range AUVs deployed along the front with biological sensors

Phase 6



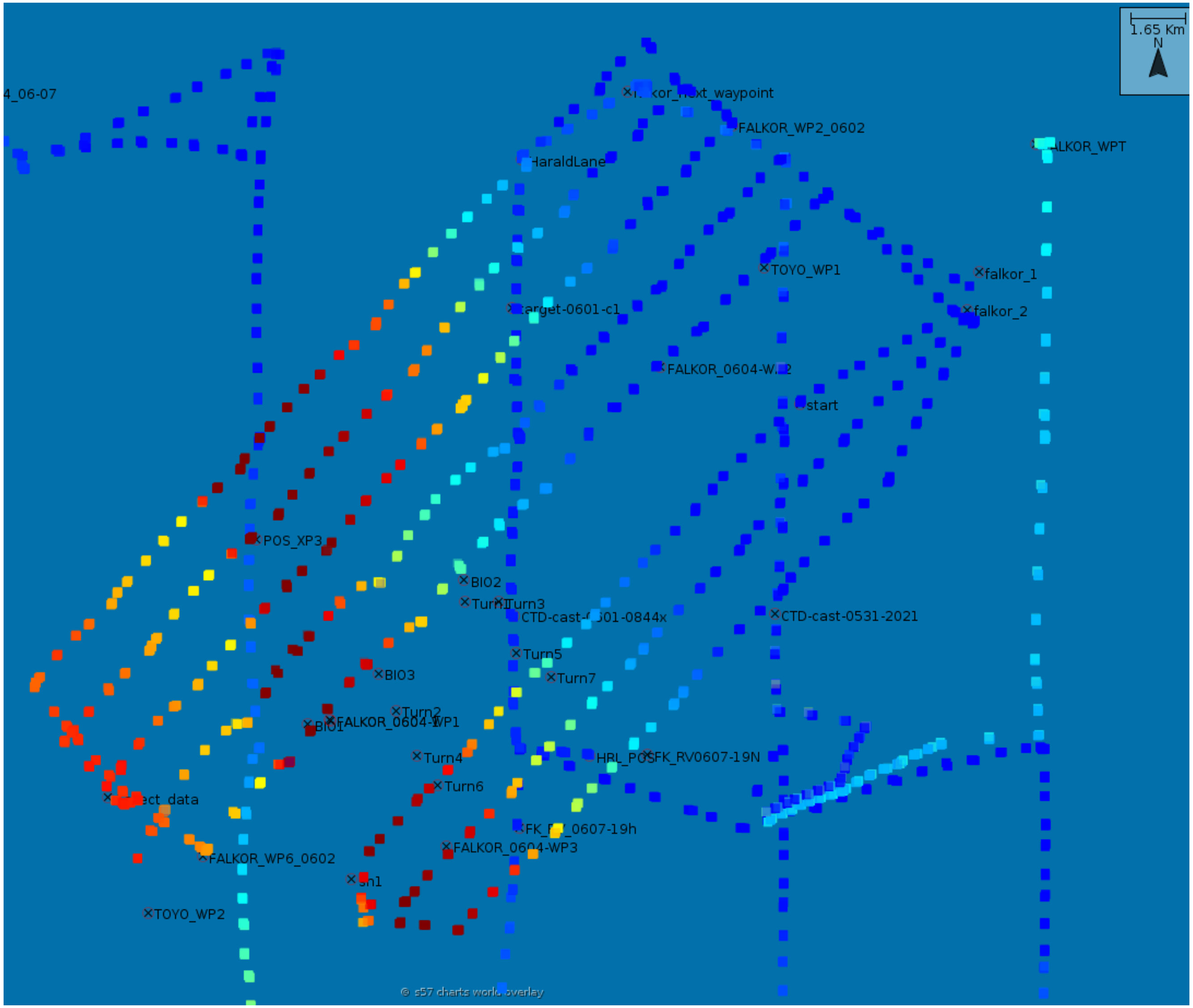
- VTOL UAV does aerial surveys with DMS / multi-spectral camera

Phase 7

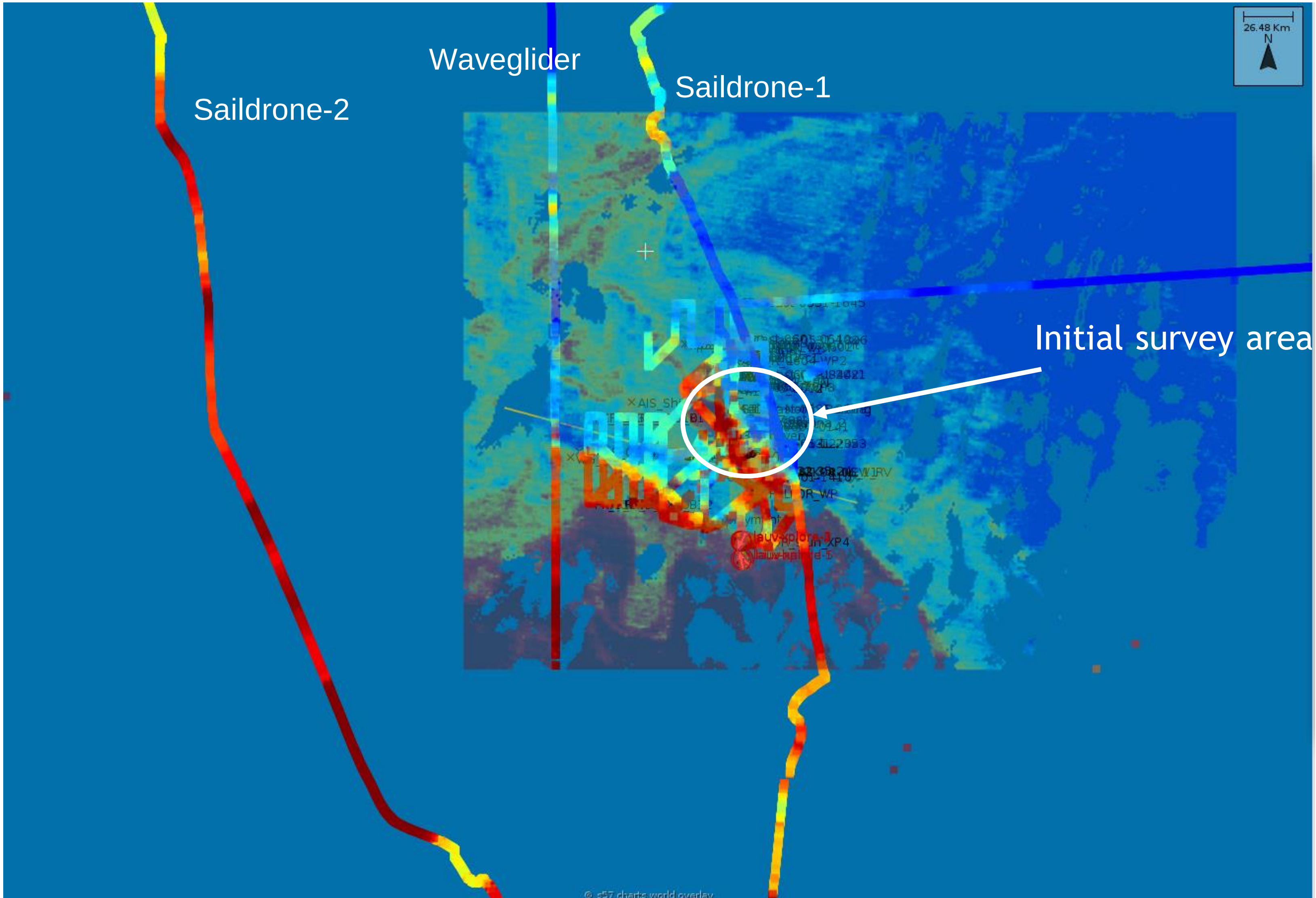


- R/V Falkor to perform CTD casts along the front for biological and biogeochemical characterization

Hi-RES mapping with AUVs (1Nm spacing)

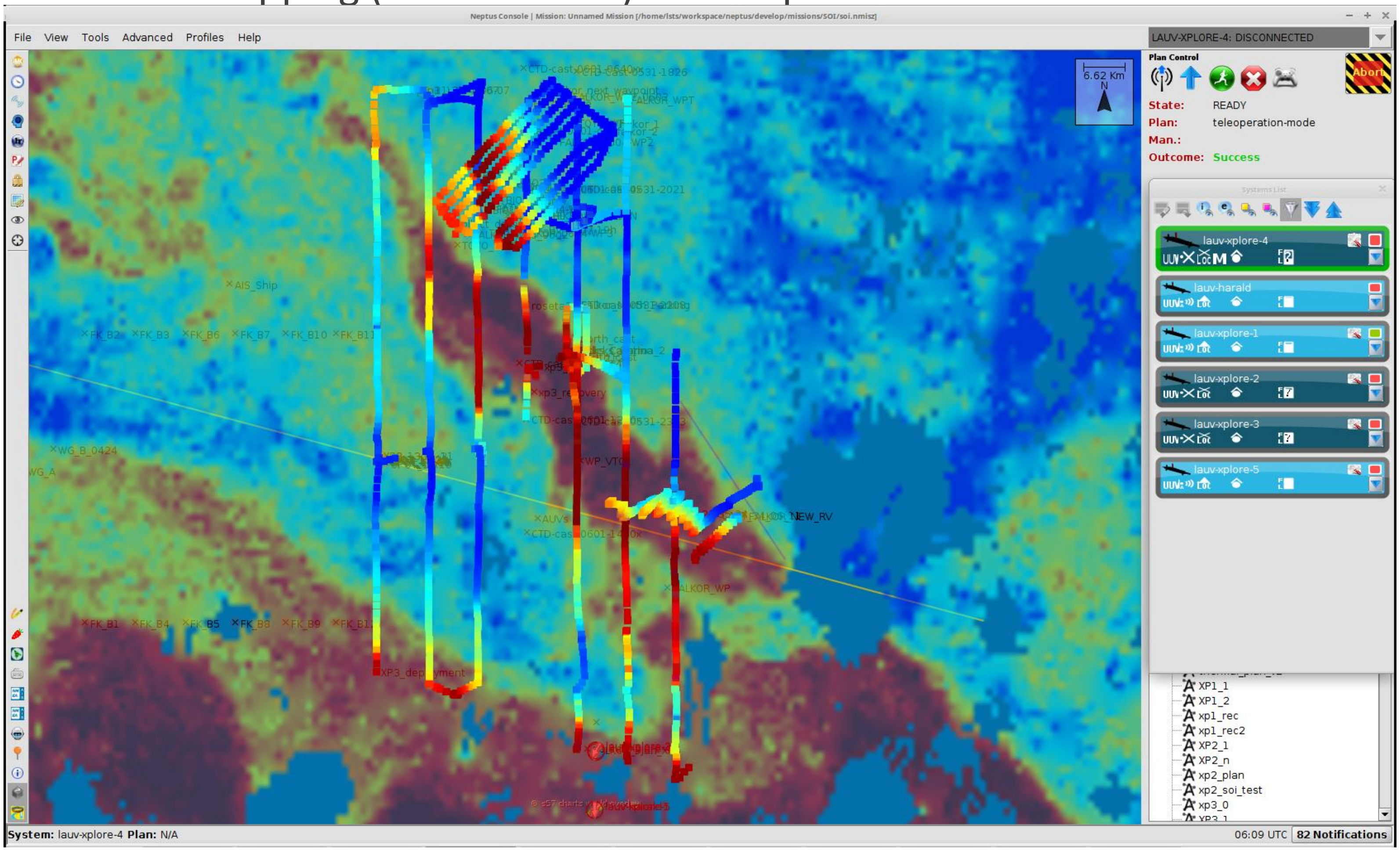


Coordinated ship-robotic mapping



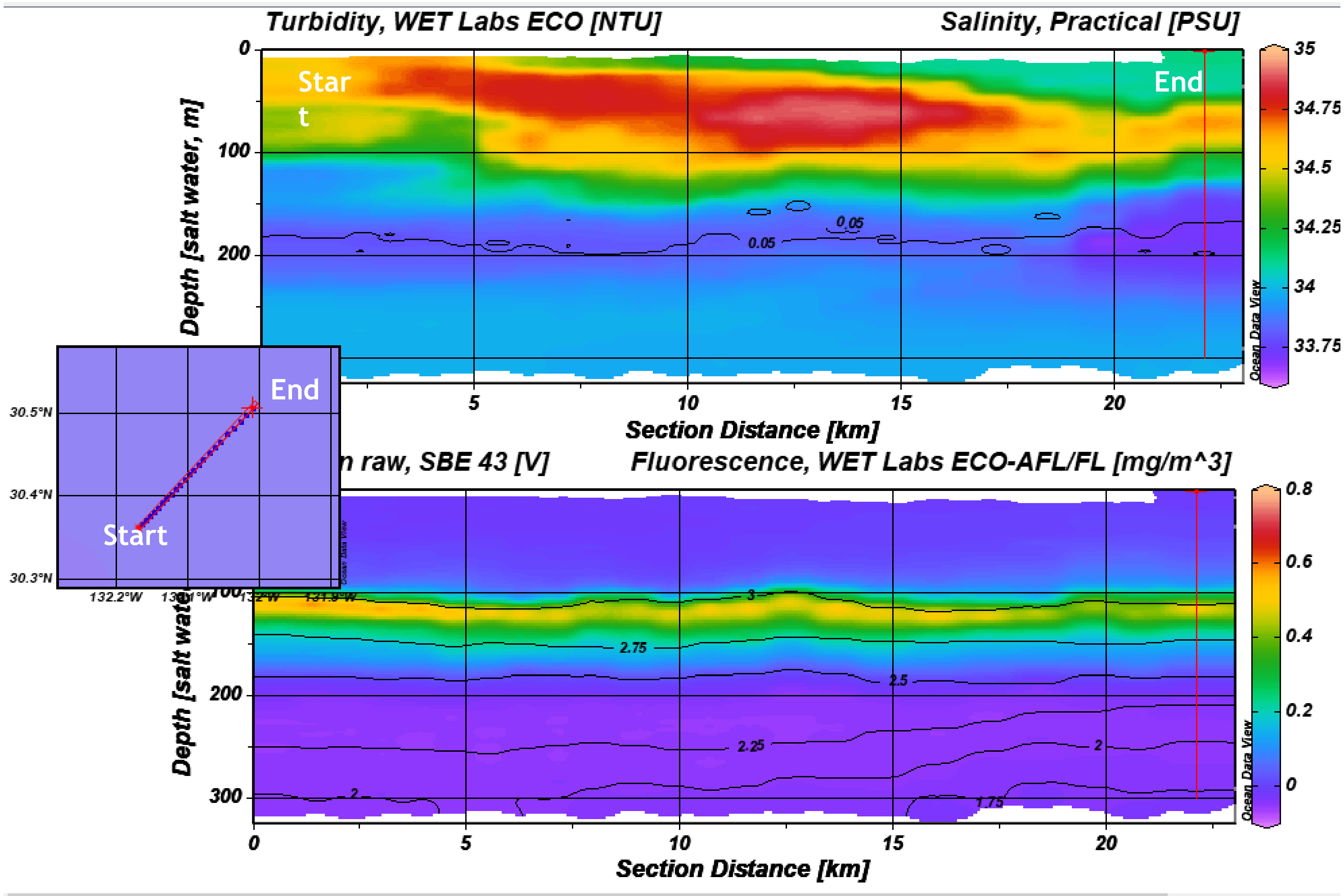
Mapping the front (AUV data + SST data)

- Mesoscale mapping (50Nmx40Nm) with unprecedented sub-mesoscale resolution



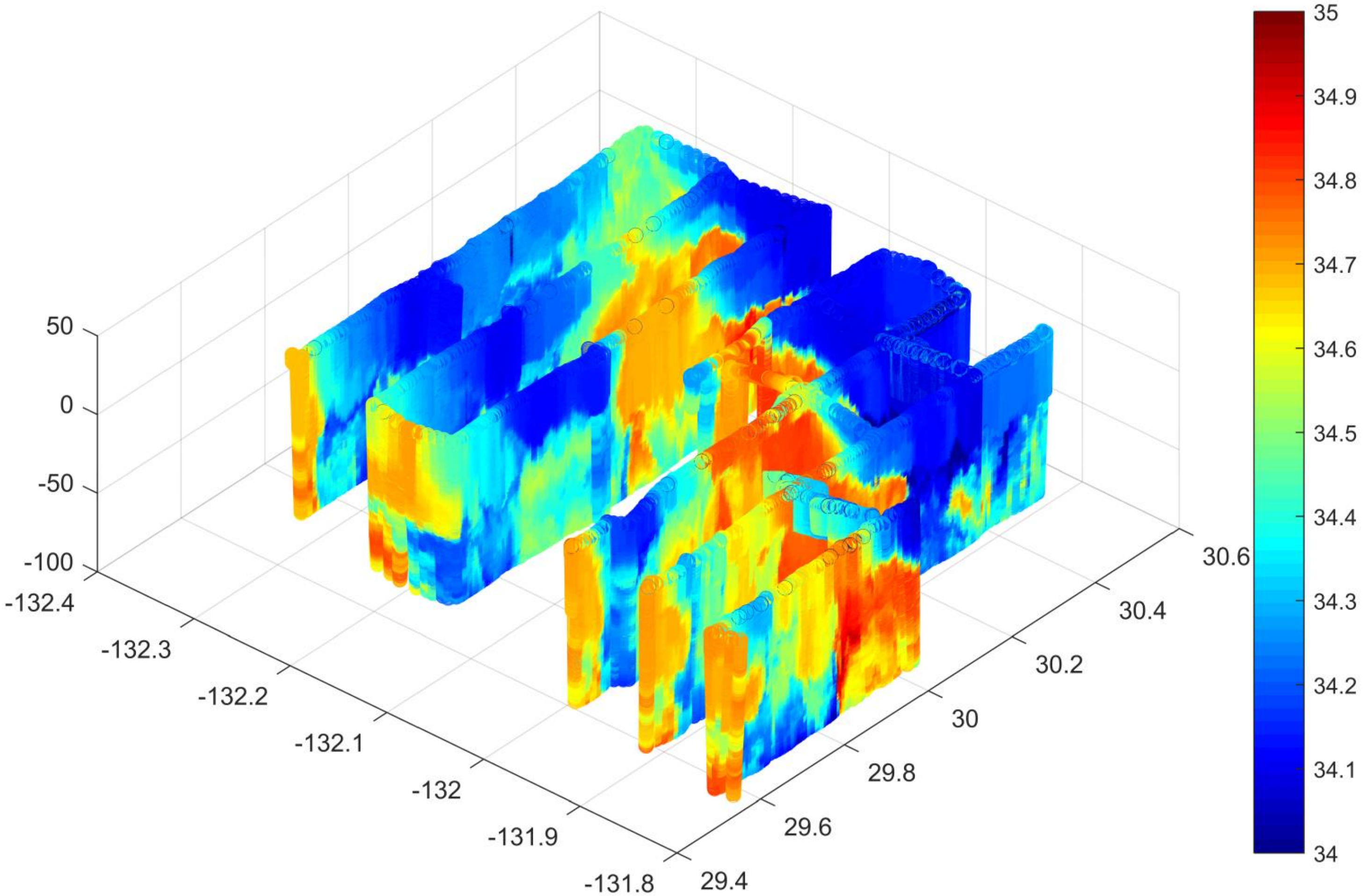
- HPC-run model helped to understand filament before SST image became available

Profiling with towed instruments



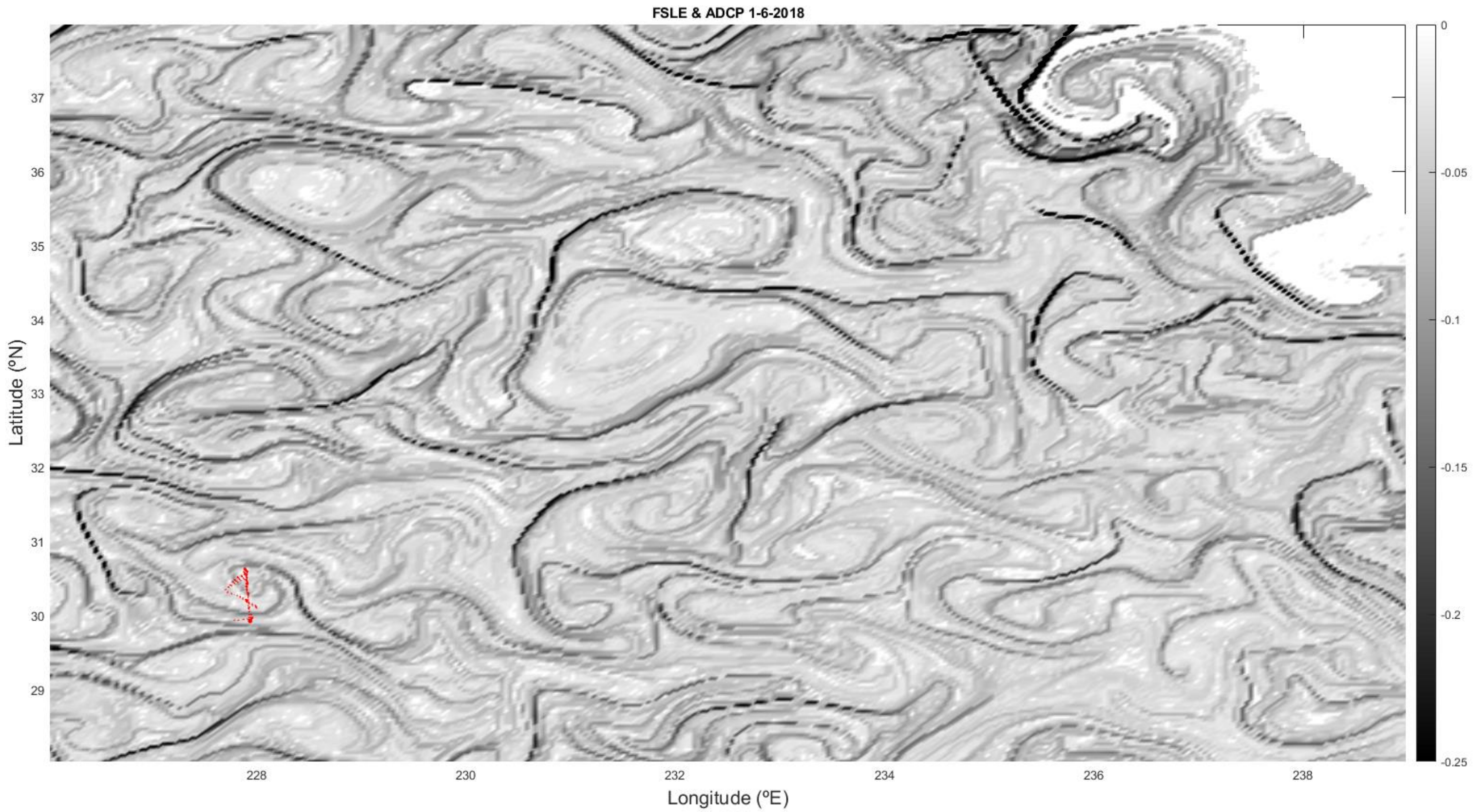
3D view of the front

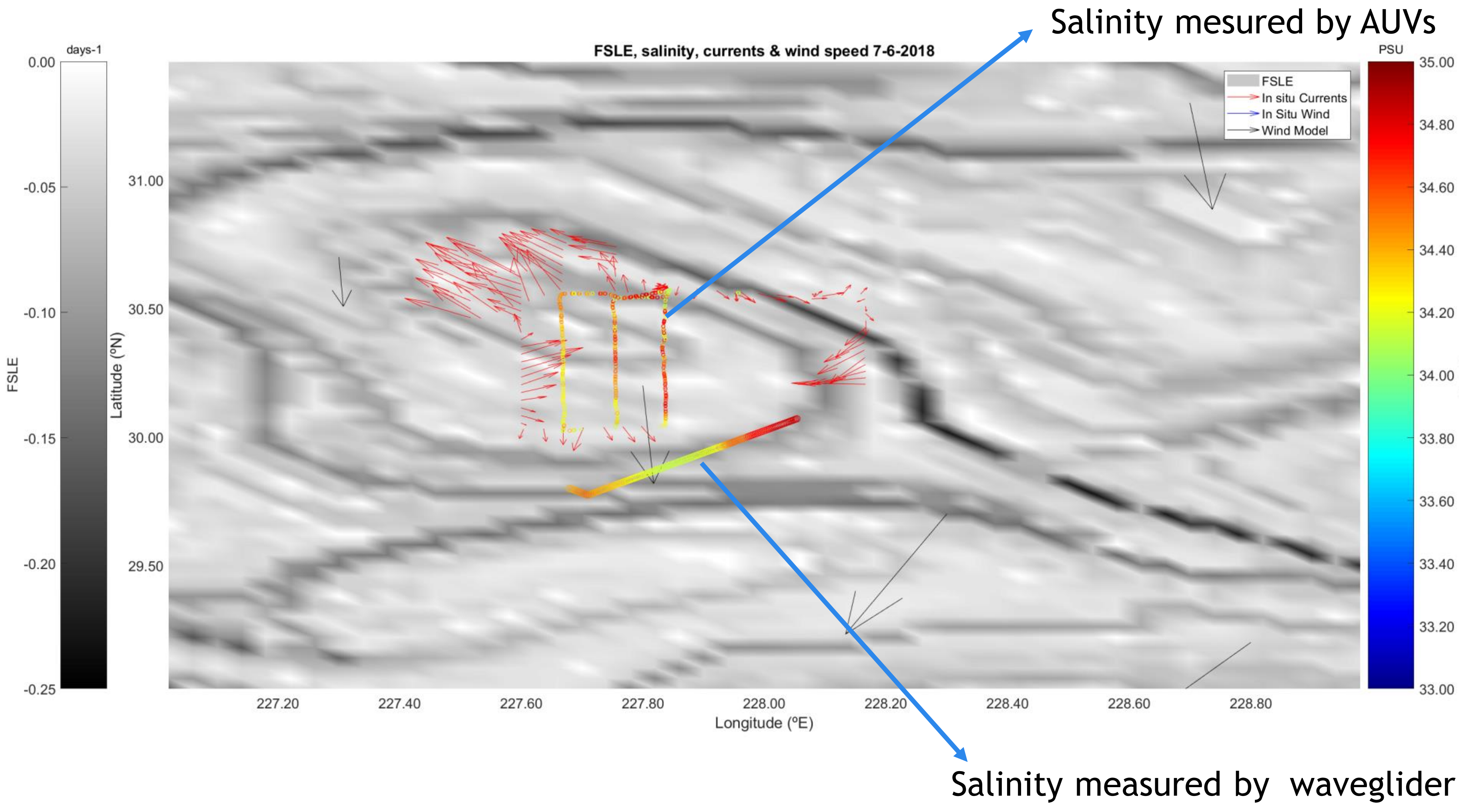
- Measurements taken by AUVs (mowing the lawn yo-yo motion pattern)



Finite-size Lyapunov exponents (FSLE)

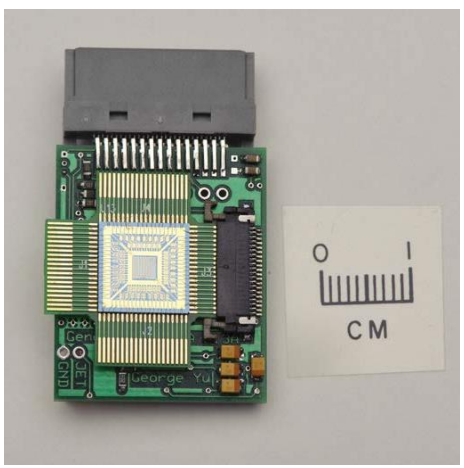
- Product derived from satellite altimetry (for the region of interest)

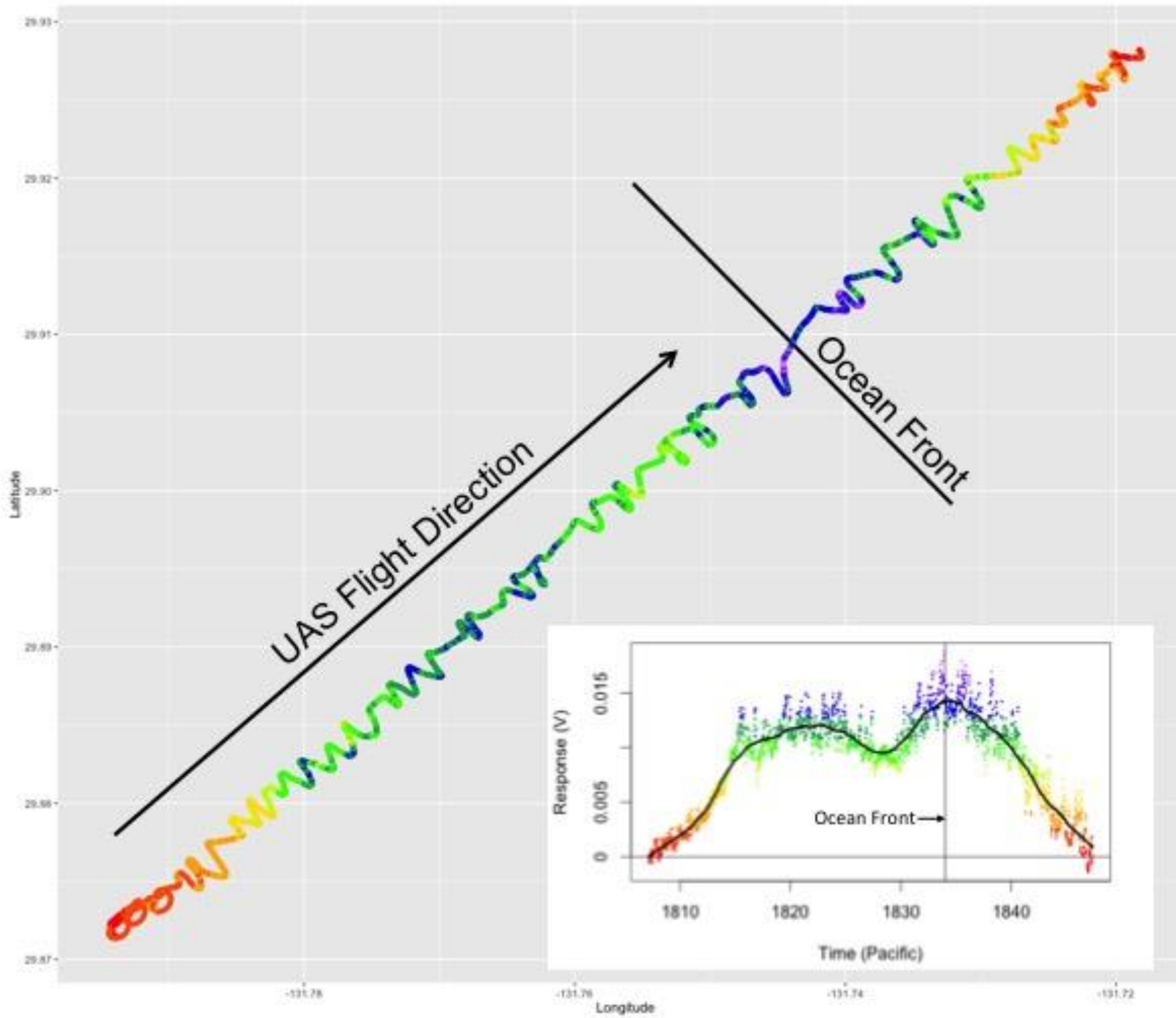




Salinity mesured by AUVs
FSLE, salinity, currents & wind speed 7-6-2018
days-1
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
FSLE
Latitude (ºN)
31.00
30.50
30.00
29.50
FSLE
In situ Currents
In Situ Wind
Wind Model
PSU
35.00
34.80
34.60
34.40
34.20
34.00
33.80
33.60
33.40
33.20
33.00
Salinity
227.20
227.40
227.60
227.80
228.00
228.20
228.40
228.60
228.80
Longitude (ºE)
Salinity measured by waveglider

DMS sensor data

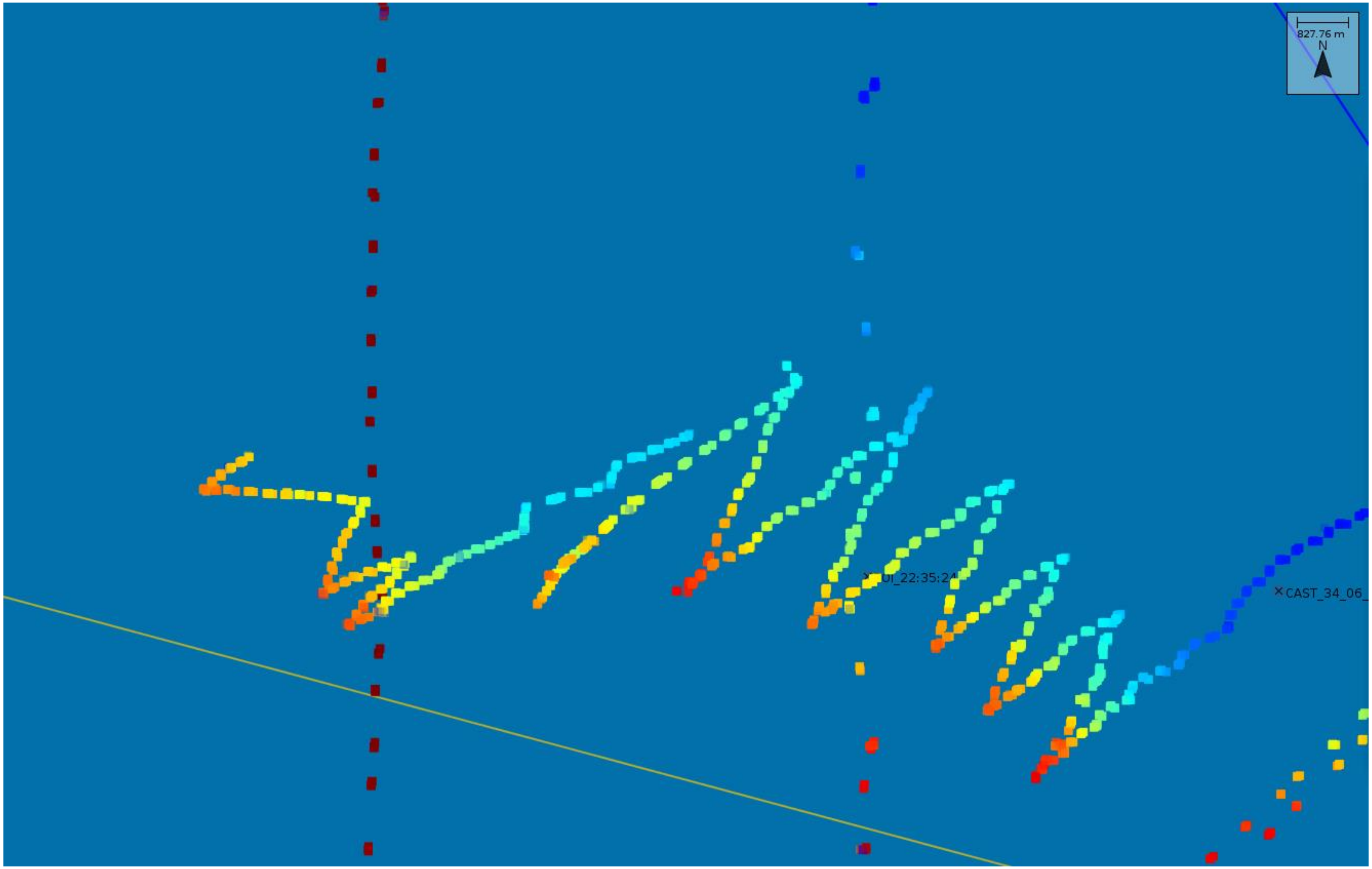




Courtesy of Ian Brosnan, NASA-Ames

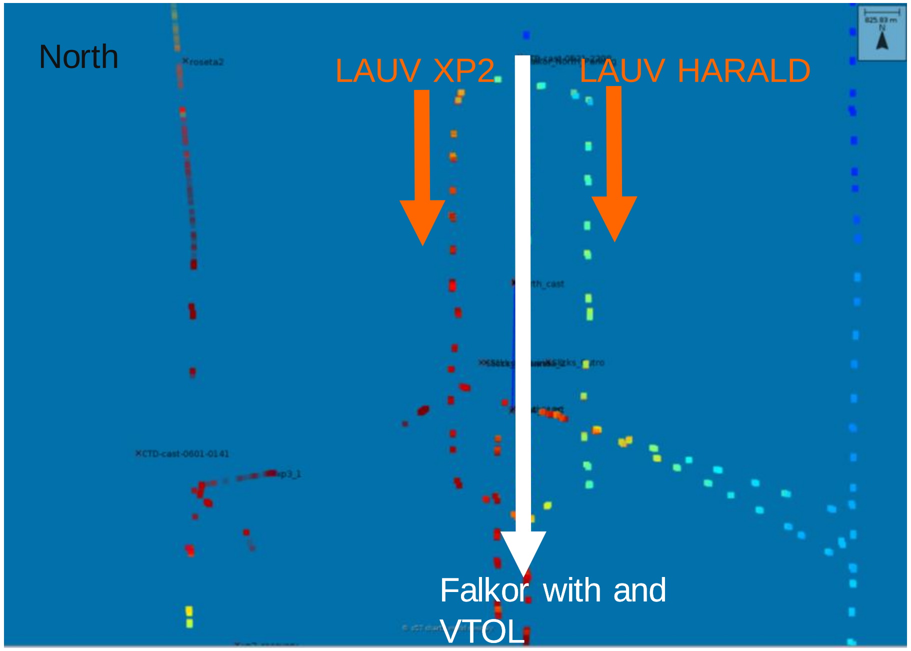
Automated front detection and tracking

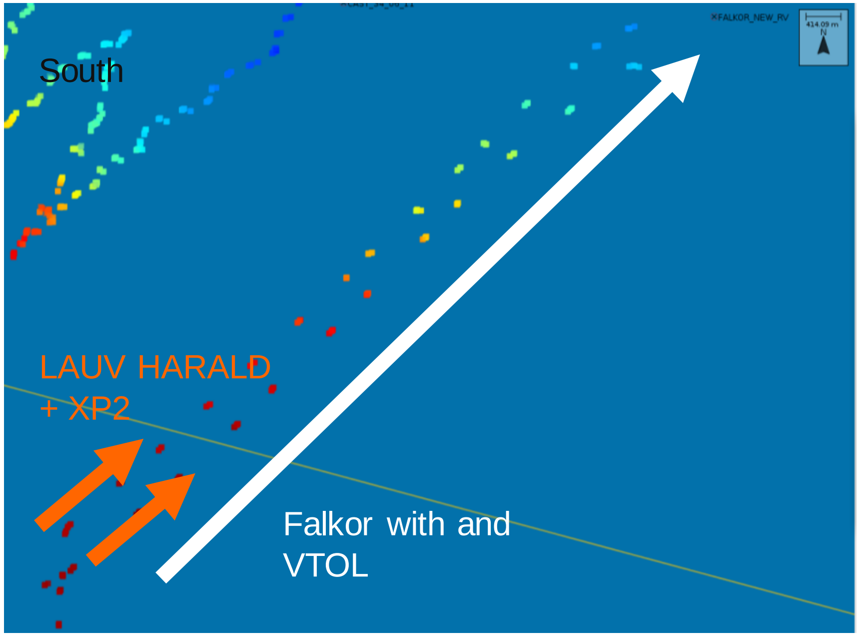
- Performed with Wave Glider, R/V Falkor and AUVs



Hi-res coordinated sampling

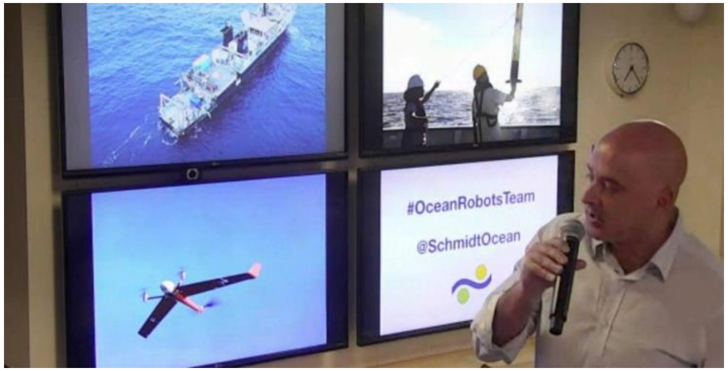
- Hi-res data sampling using AUVs with biochemical sensors coordinated with *Falkor* (ADCP, ALF, etc) and UAVs (camera and DMS sensor)





Ship to shore engagement

- Outreach sessions
  - Countries: Portugal, Spain, Cape Verde, Mozambique, Norway, USA, Italy
  - Audience: 3400+ people directly reached
  - # of schools: over 20
- Celebrated World Oceans day with dedicated live sessions
- Connected live with António Costa, Portugal’s PM, while visiting the MIT



Few indicators

- AUV operations
  - 600+ h, 1000+ Nm
  - Persistent day/night ops
  - 2 minor problems (2 servos)

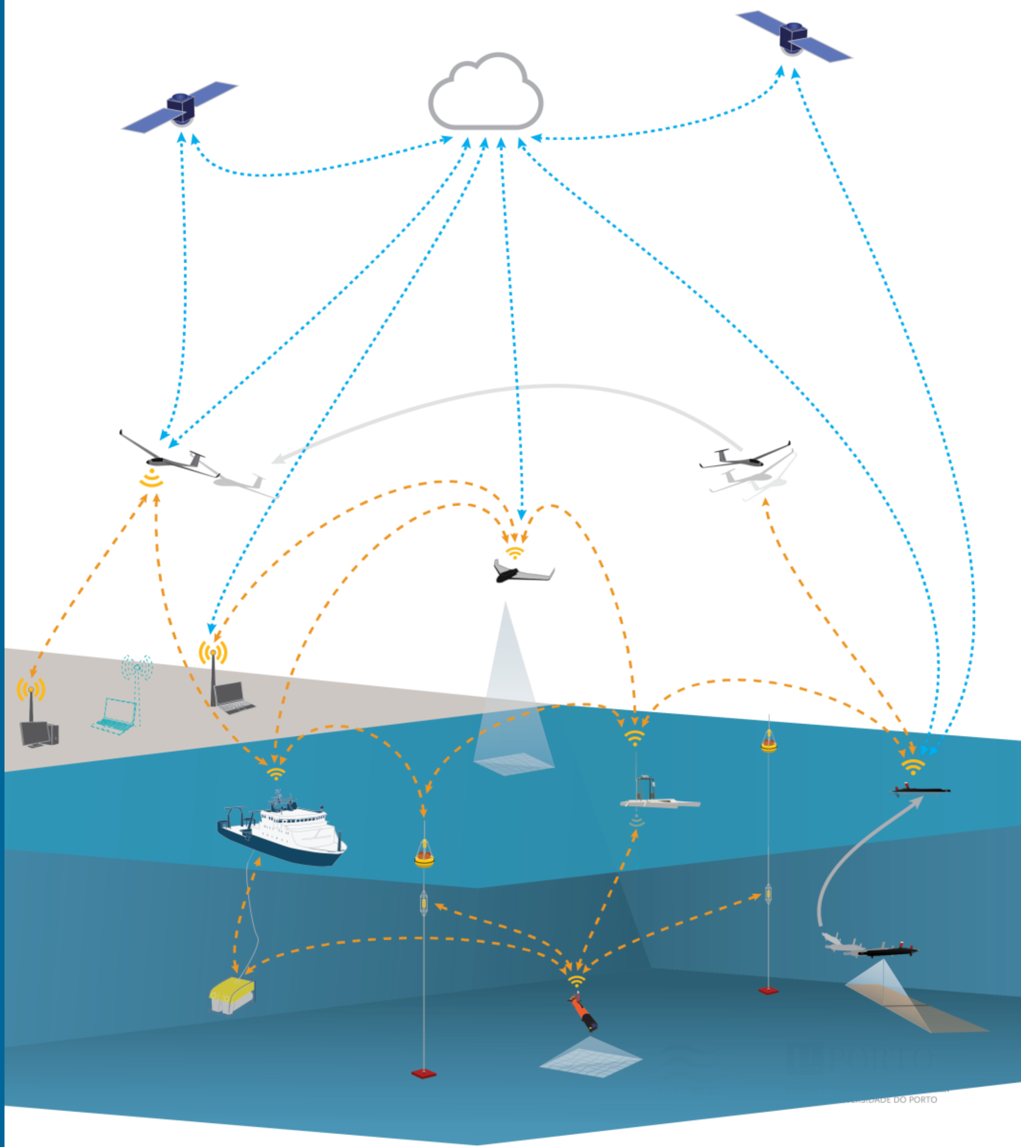
- UAV operations
  - 3 different cameras (IR, multi-spectral, GoPro), DMS gas sensor, comms relay
  - Flight durations: up to 55mins; max altitude 1000m

- Ocean space center (*Ripples* and *Neptus*)
  - 4 daily shifts / 2 operators per shift.
  - Ingested all incoming data for unprecedented situational awareness and multiple assets mission control.

- HPC
  - ROMS model for study area
  - Model outputs used to evaluate short term forecast of the mapped filament.

Discussion

May 28–June 17, 2018



Conclusions

- Successfully demonstrated a novel approach to observe the ocean with persistent networked vehicle systems
    - The North Pacific Subtropical Front was located precisely as predicted.
    - Easternmost segment of the North Pacific STF was studied in unprecedented detail.
    - For the first time ever, a mesoscale filament of a major open-ocean front was mapped with sub-mesoscale resolution using largely multiple AUVs.
    - Enabled researchers to code and deploy new algorithms on the fly

- Armada-like organization
    - Footprint(Coordinated ship-robotic systems) >> Footprint(Ship)
    - Hi-RES coordinated multi-domain ship-robotic surveys

- Systems and technologies demonstrated this cruise are applicable to other frontal regions, as well as to other phenomena of the world Ocean

On future oceanographic field operations

“Systems that go beyond the footprint of what a ship can do … they can be 20 miles this way and 20 miles that way …”

Lessons

- Multi-purpose ship
  - Oceanographic vessel
  - Mobile L/R offshore base
  - Mobile computing node
  - Mobile communications node
- Oceans space center
  - Contributed to bridge the science-engineering gap
  - Remote supervision and control
- Persistence/adaptation/spatial coverage
  - Persistence does not mean spatial coverage or speed
  - Rapid exploration and adaptation requires speed
  - Speed(ship) >> Speed(AUVs/ASVs)
  - Cost(ship time) >>> Cost(AUV/ASV time)
- May need
  - ASVs with AUV LR capabilities to decouple ship ops from AUV ops
  - Evolve the role of the ships

What's next?

- Autonomous organizations for persistent operations in remote environments
  - Ship or land based operations
  - Autonomous launch and recovery of AUVs and UAVs
  - Fixed and mobile recharging stations
  - Mobile computing stations
  - Mobile computation
  - Upload code and controllers on the fly
- Scalable systems – 10s, 100s, 1000s, …
- Still bridging the gap between science and technology
- Learn from experimentation
- But, we need the human in the loop

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