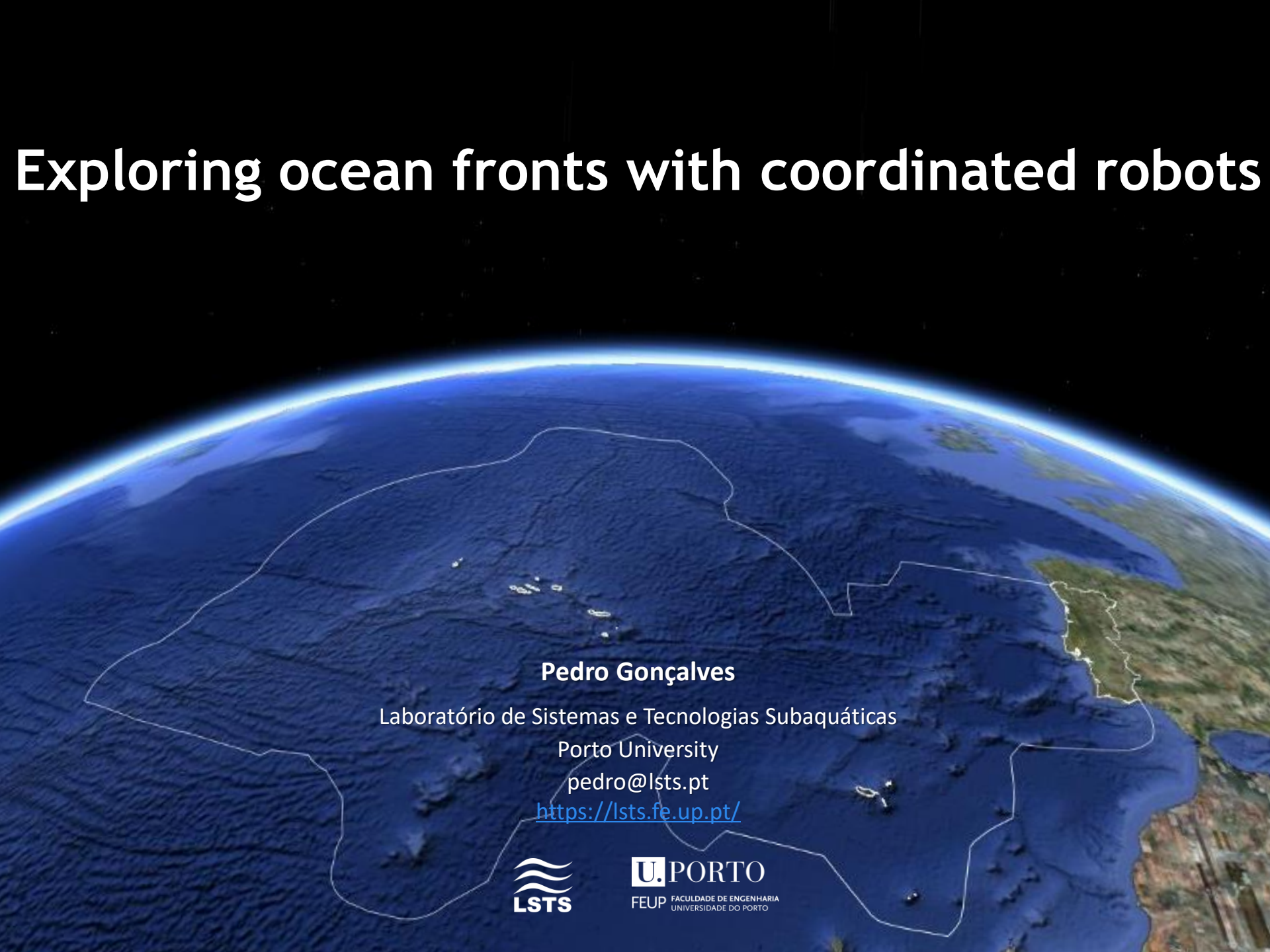
Exploring ocean fronts with coordinated robots



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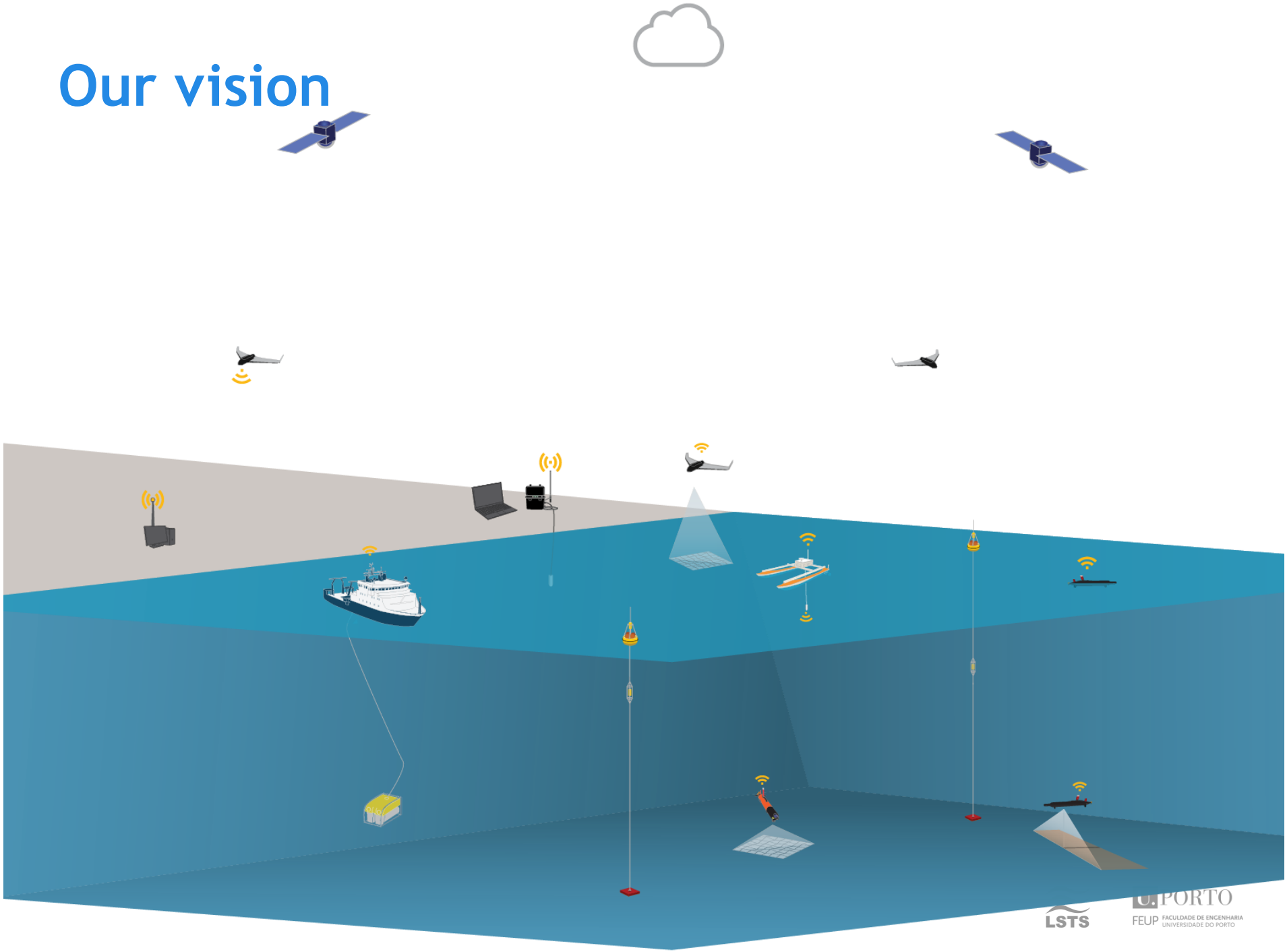
Outline

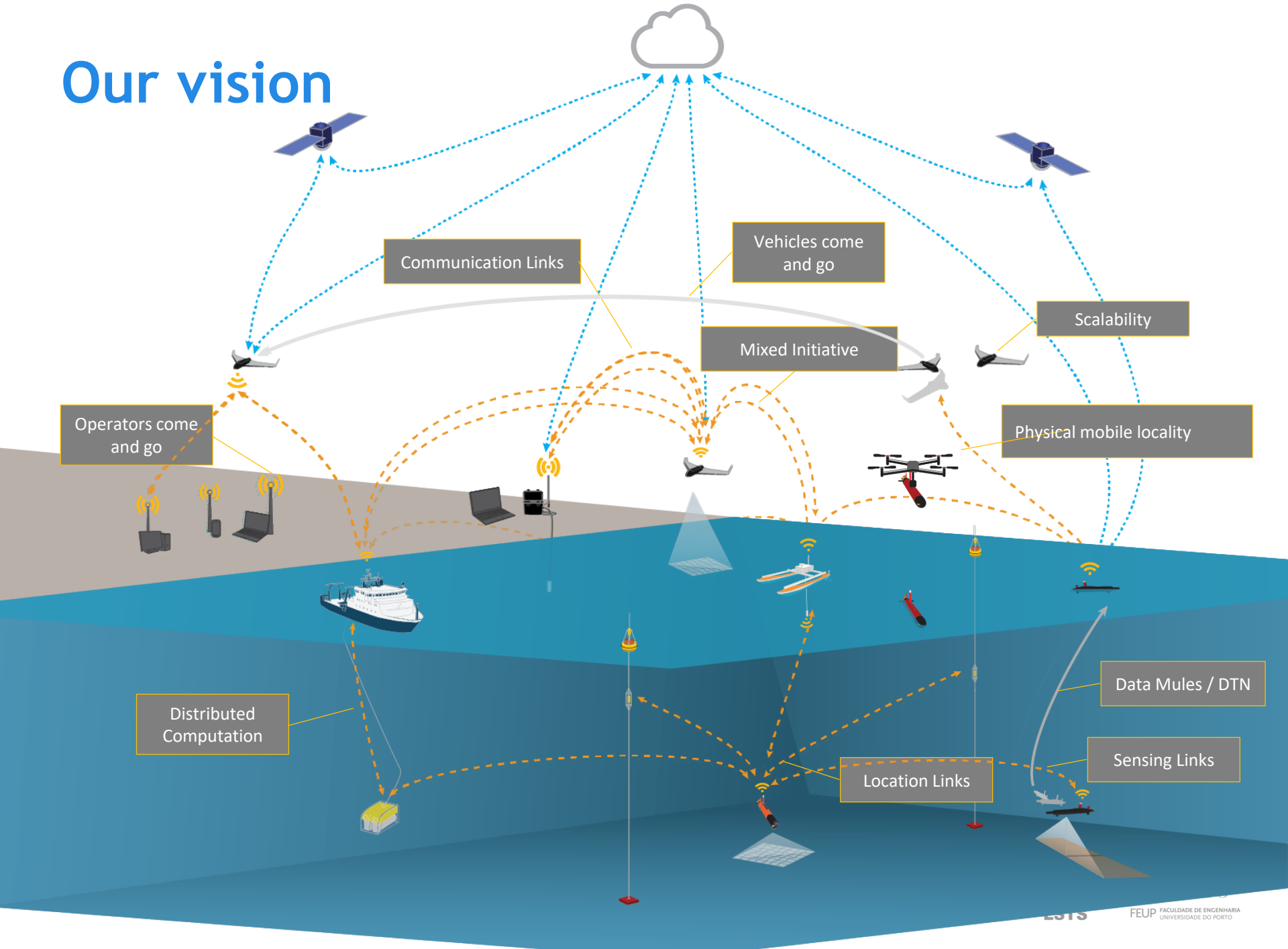
- LSTS overview
- *Exploring fronts with multiple robots* SOI cruise
- Conclusions

LAB OVERVIEW

Our vision



Our vision


Communication Links
Vehicles come and go
Scalability
Mixed Initiative
Operators come and go
Physical mobile locality
Distributed Computation
Data Mules / DTN
Sensing Links
Location Links

Vehicle systems














Low cost modular vehicles
Long endurance
Common software and hardware
Inter-operable
Flying modem
Coms with cubsats


Light autonomous underwater vehicle (LAUV)

- National innovation award (2006)
- Two versions / multiple configurations
  - Upper water column (endurance 50h+)
  - Mapping (camera, multi-beam, side-scan)
- Support for multi-vehicle operations

OceanScan
Marine Systems & Technology

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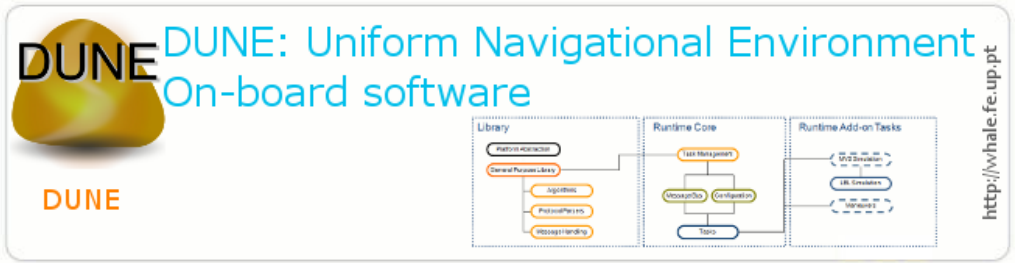
Open source LSTS software tool chain

https://lsts.fe.up.pt/toolchain

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.*

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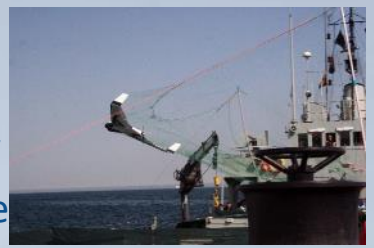
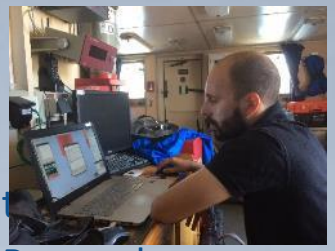
Operation areas

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

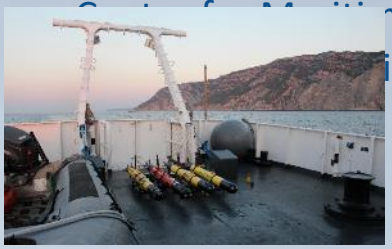
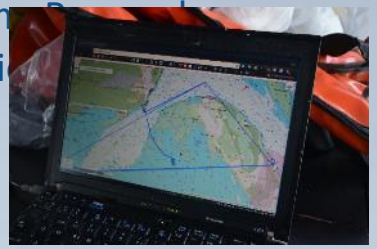
2018
- 4000 Km underwater
- 200 flights

Rapid Environmental Picture (REP) exercise

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REP(MUS) 2019 - 10th edition

REP(MUS) 2019 in numbers

- 15 days
- 7 navies
- > 10 companies
- > 800 people
- 9 ships
  - 3 oceanographic vessels
  - 1 frigate
  - 1 manned submarine
  - 1 destroyer
  - 3 patrol vessels
- > 50 AUVs, ASVs and UAVs

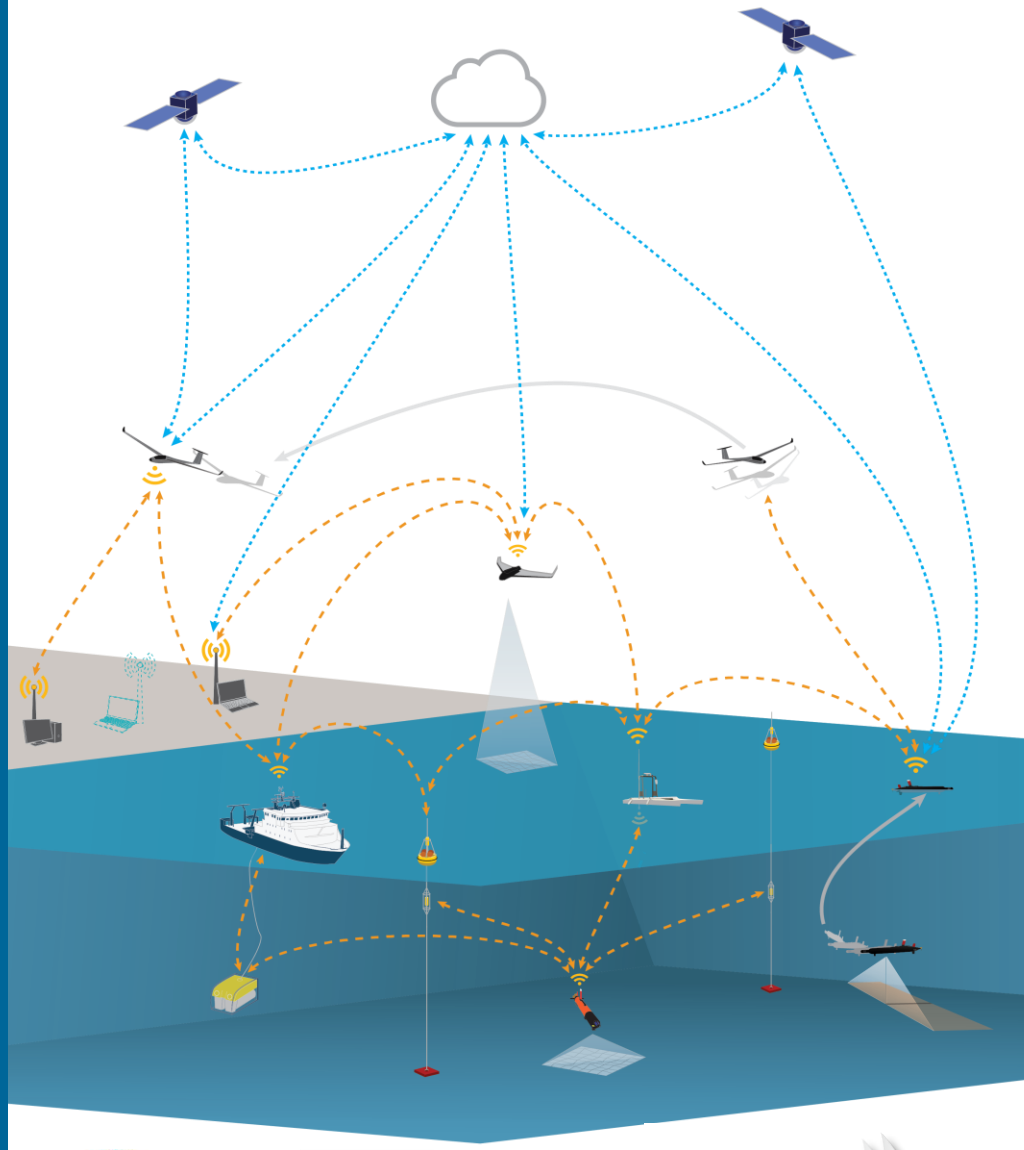
Exploring fronts with multiple robots SOI cruise

Exploring the STF front with multiple robots

SCHMIDT OCEAN INSTITUTE

May 28–June 17, 2018

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



Universidad Politécnica de Cartagena

NTNU

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UAlg UNIVERSIDADE DO ALGARVE

Marinha

LAMONT-DOHERTY EARTH OBSERVATORY

SINTEF

NASA Ames Research Center

HARVARD

MBARI

ciimar Centro Interdisciplinar de Investigação Marinha e Ambiental

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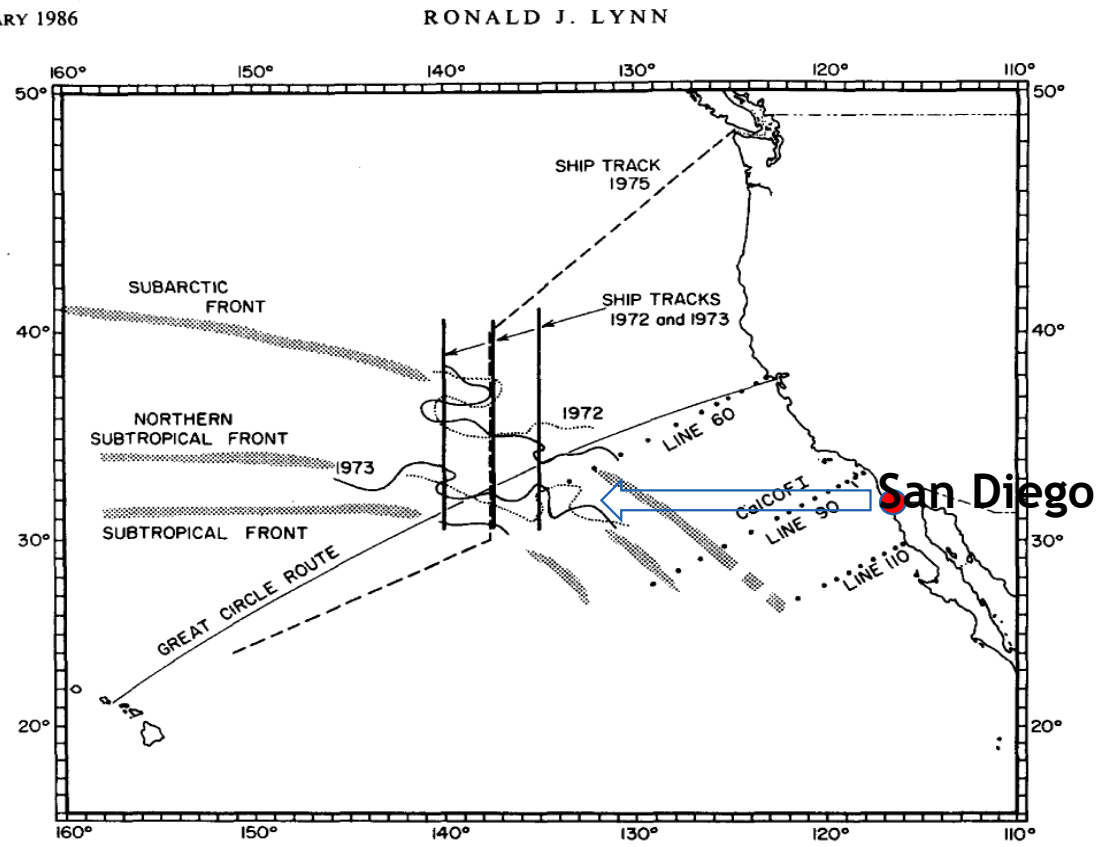
Main goal of the cruise

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

Northern Pacific Subtropical front

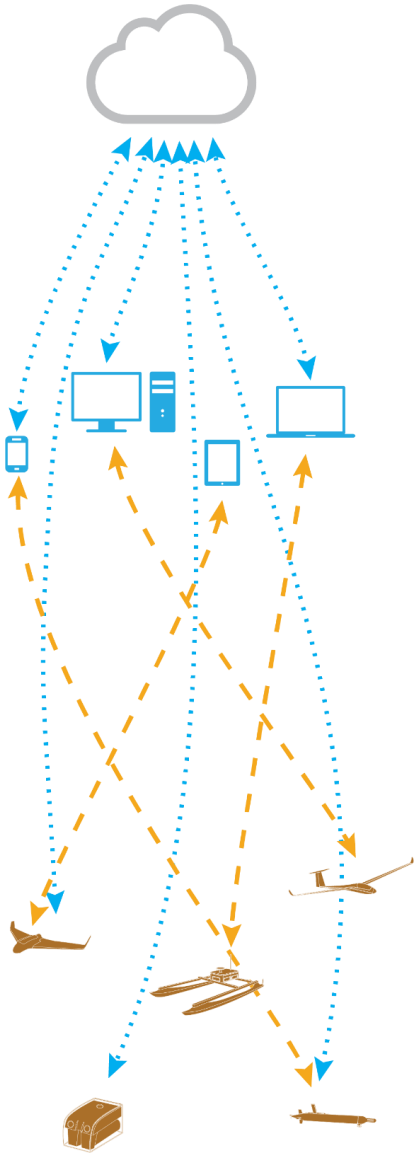
- Sharp boundary where cold fresh waters from the north meet warm salty waters from the south
  - Strong in S, weak in SST
  - Relatively shallow (< 300 m)
  - 800 Nm from San Diego
- Previous studies (70s, 80s)



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.

R/V Falkor based networked multi-vehicle system

- 3 VTOL UAVS (IR/multispectral cameras, DMS)
- 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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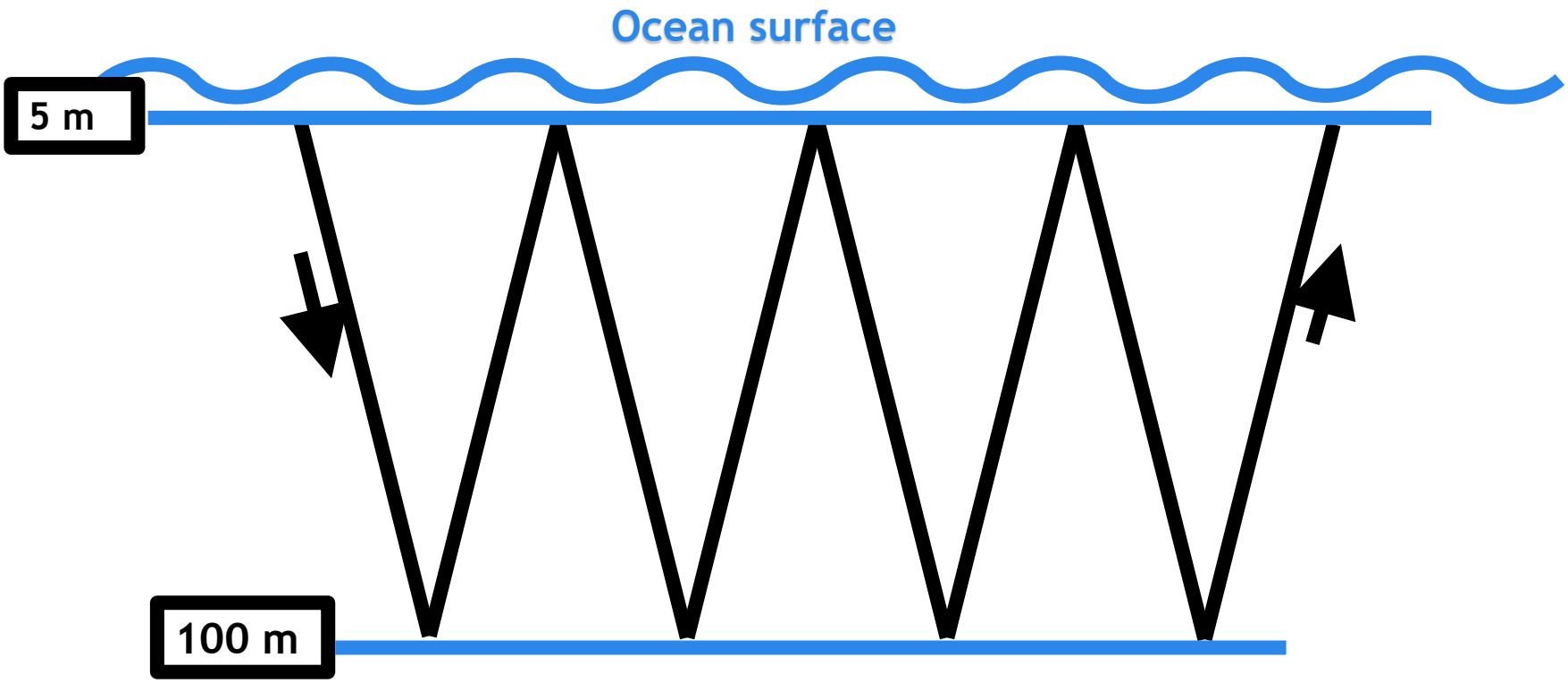
Addressing complexity: task templates

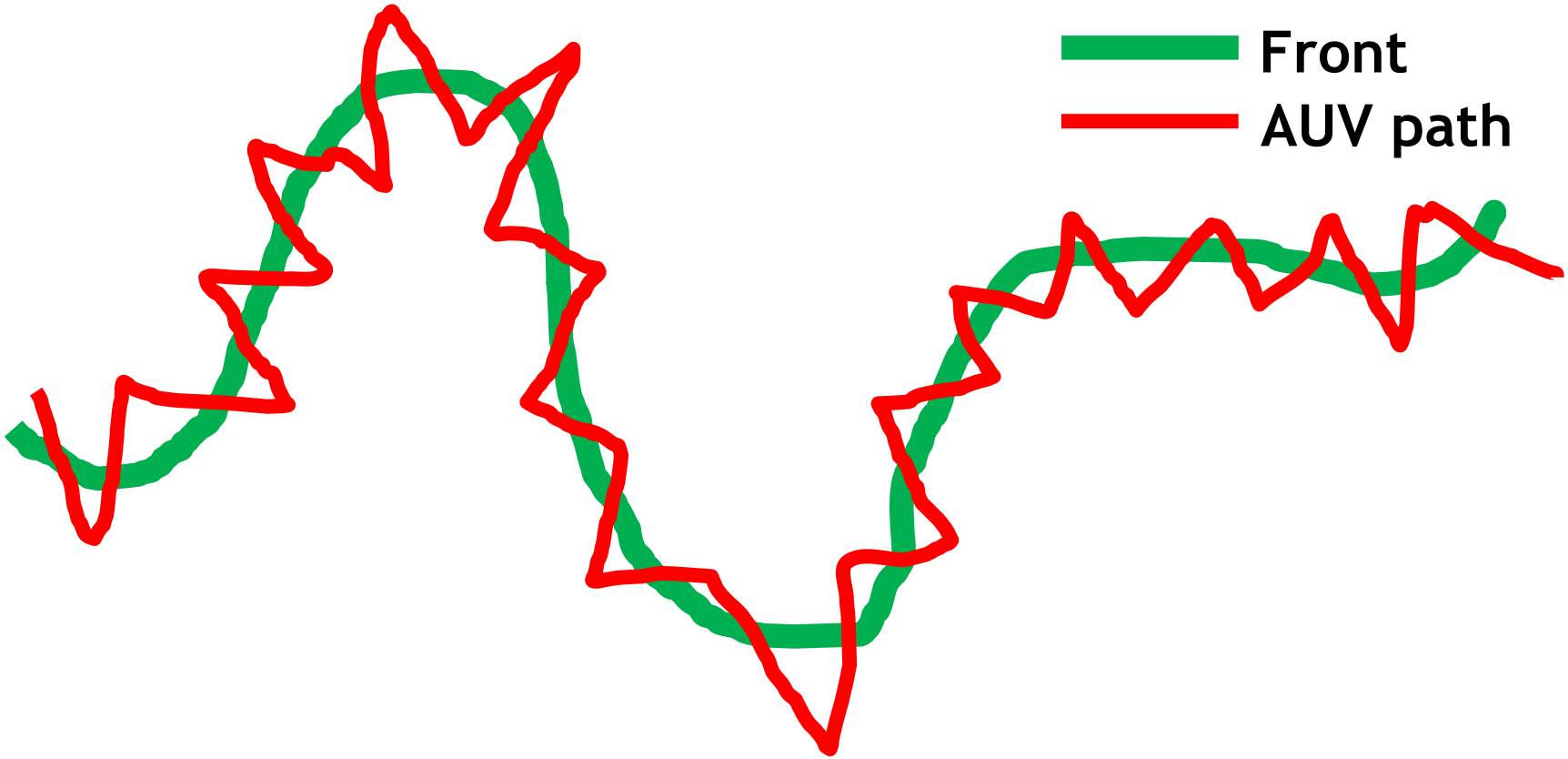
- **Task 1**: Single AUV: Yo-yo flight



Courtesy of Igor Belkin

Addressing complexity: task templates

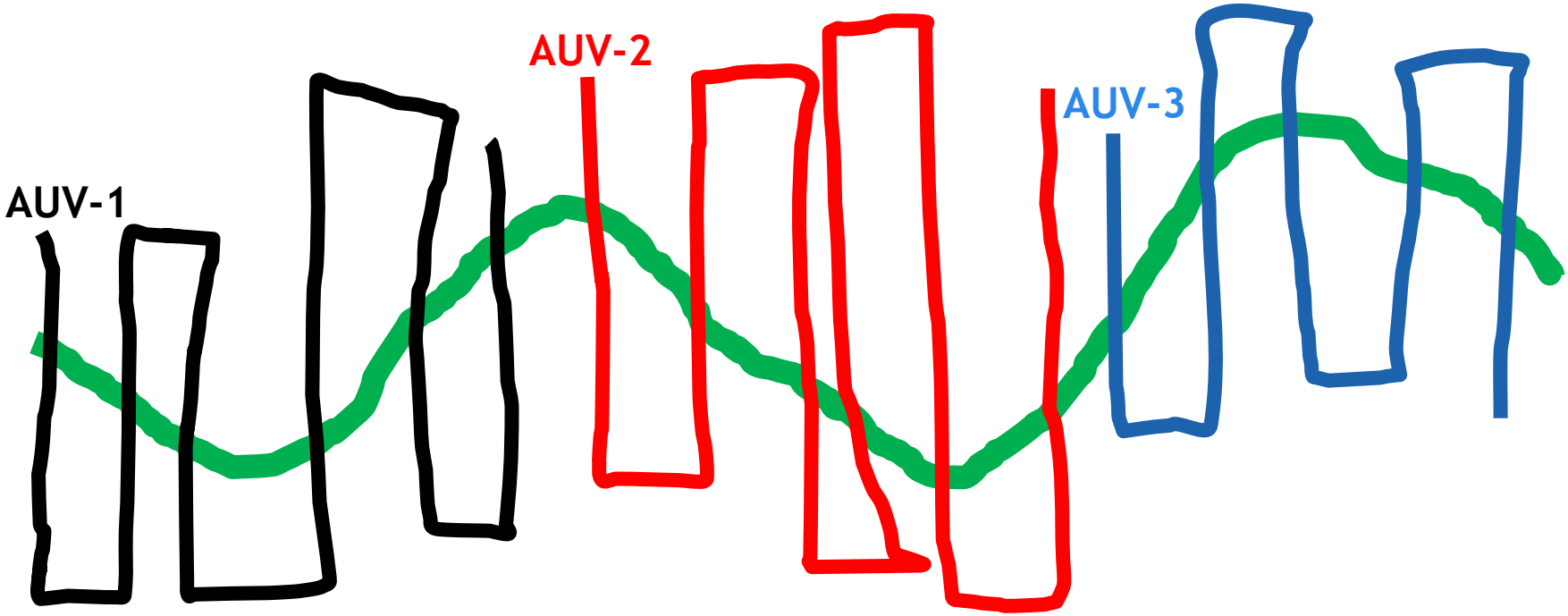
- **Task 5**: Single AUV: Front tracking: Zig-zag pattern (planar view)



Courtesy of Igor Belkin

Addressing complexity: task templates

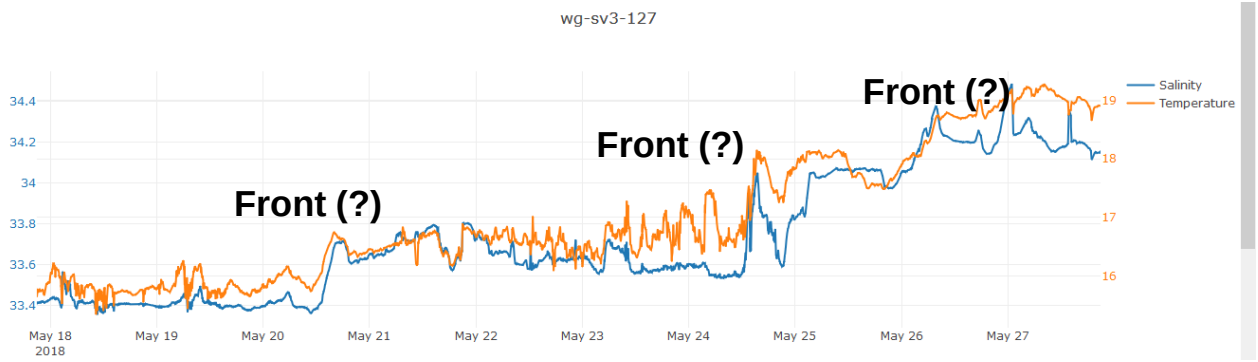
- **Task 8**: Multiple AUVs: Front mapping: Single-File Radiators (near-synchronous surveys)

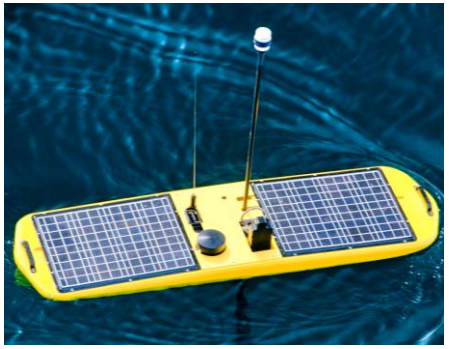


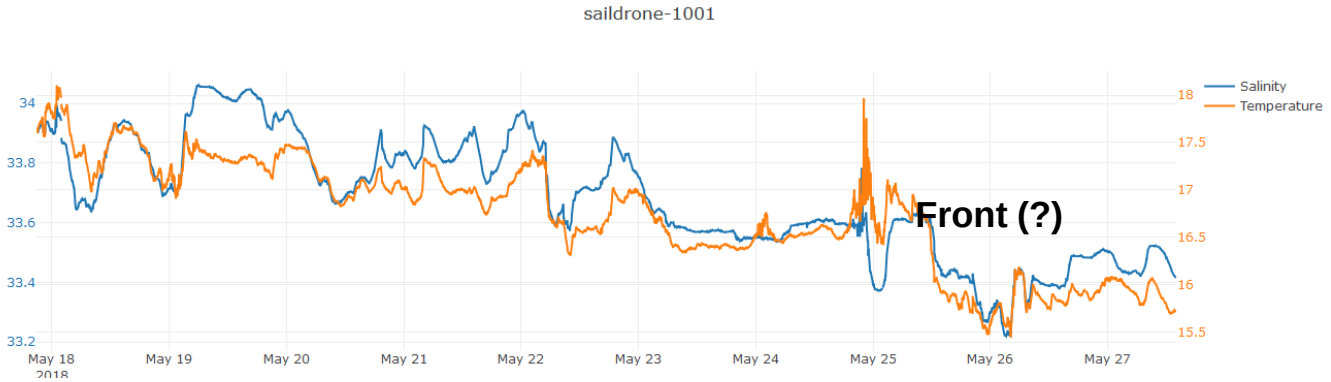
Courtesy of Igor Belkin

Finding the front

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







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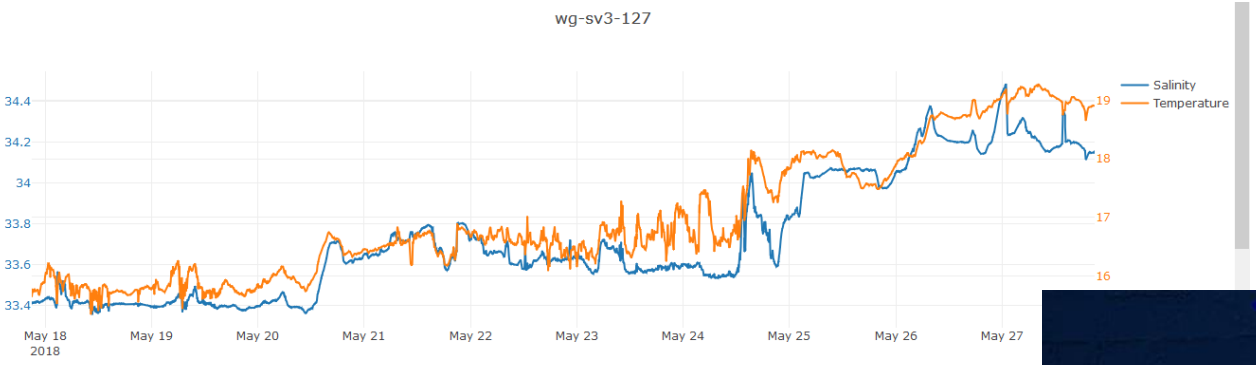
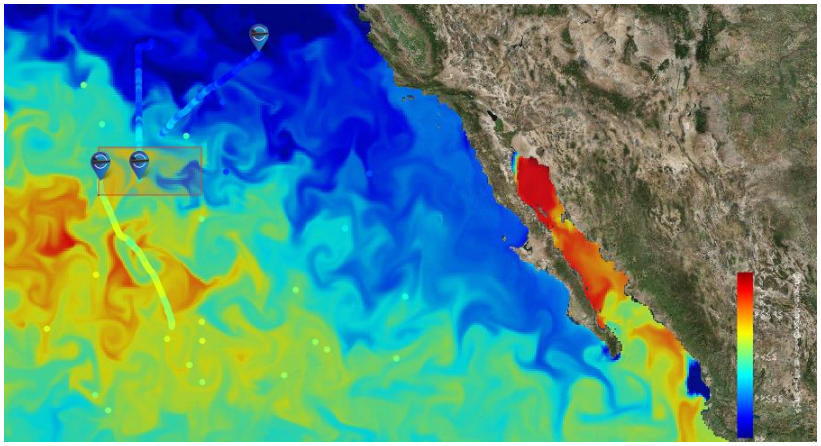
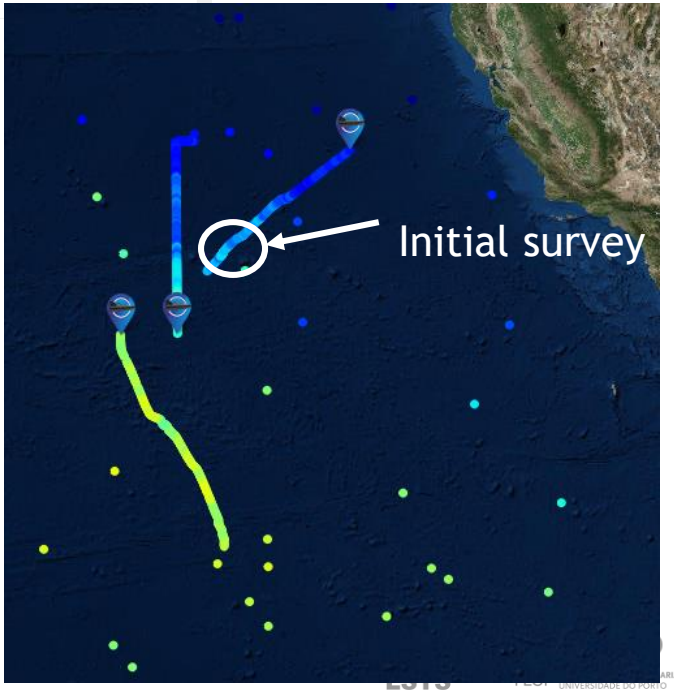
- ***Ocean space center*** ingested satellite imagery, HPC-run model outputs, and data from SD and WG and Argos floats

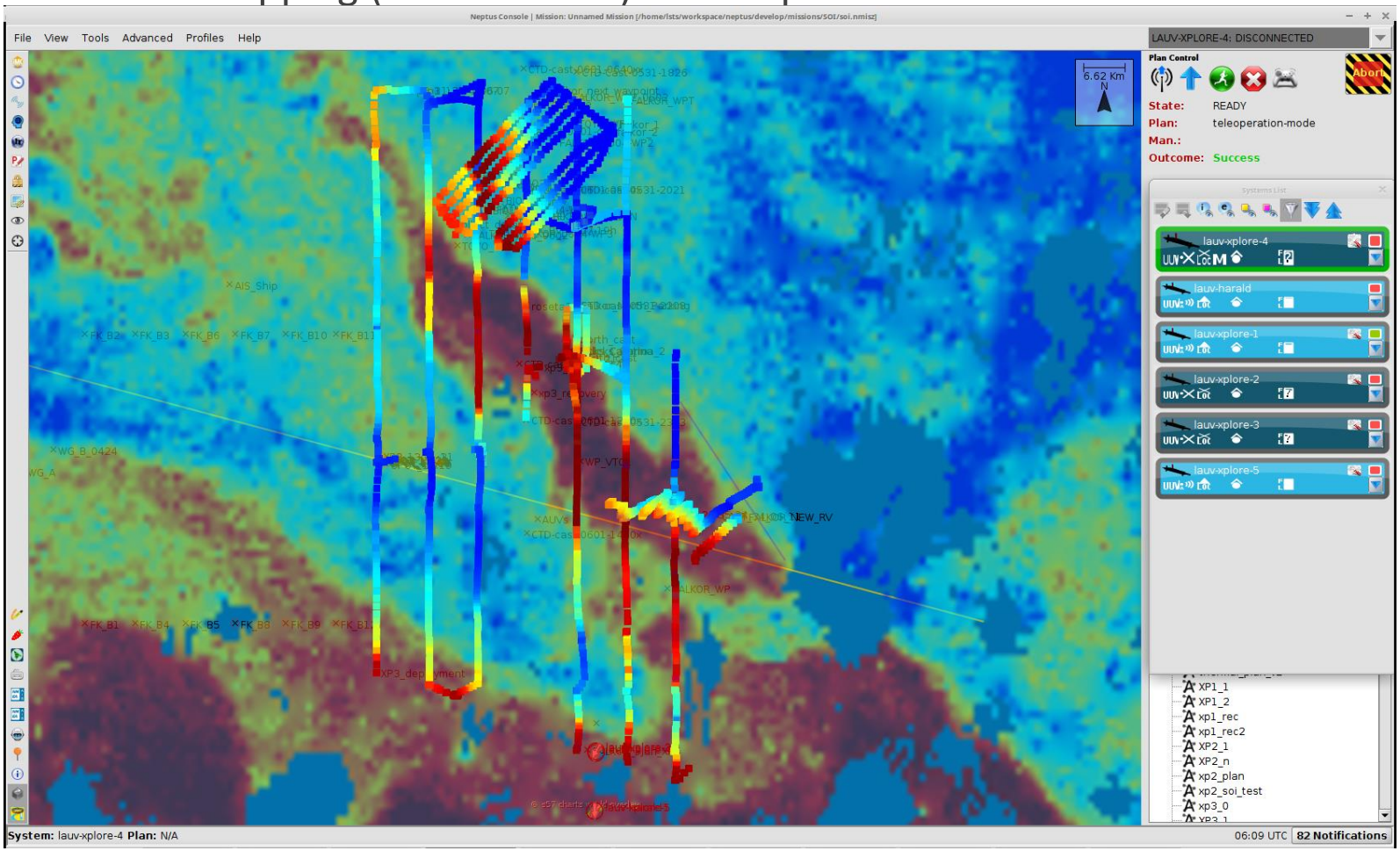






Mapping the front (AUV data + SST data)

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



- Observed a filament detaching from the front

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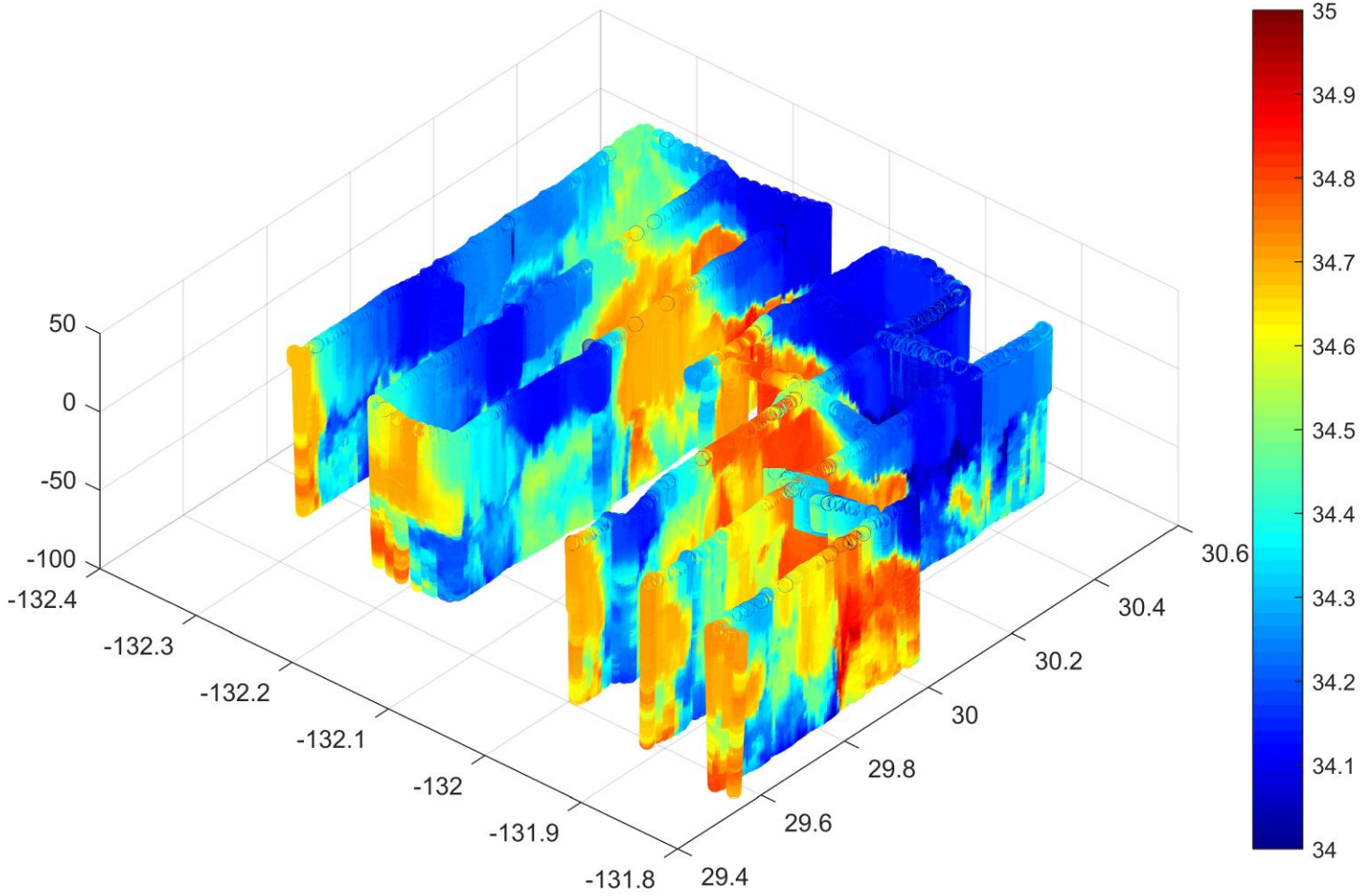
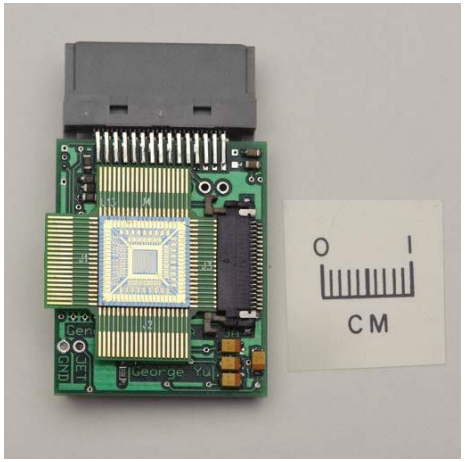
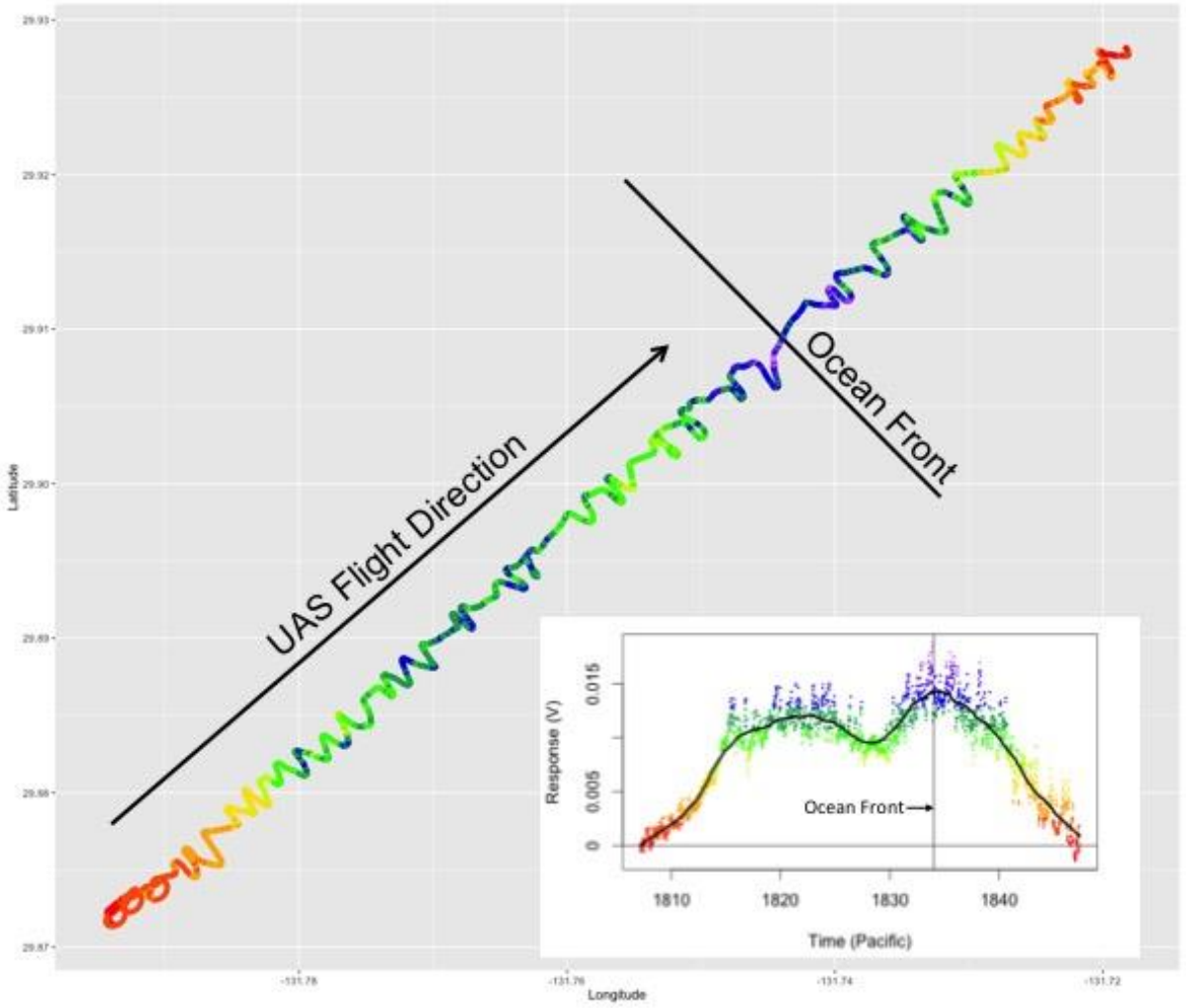
3D view of the front

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



DMS sensor data

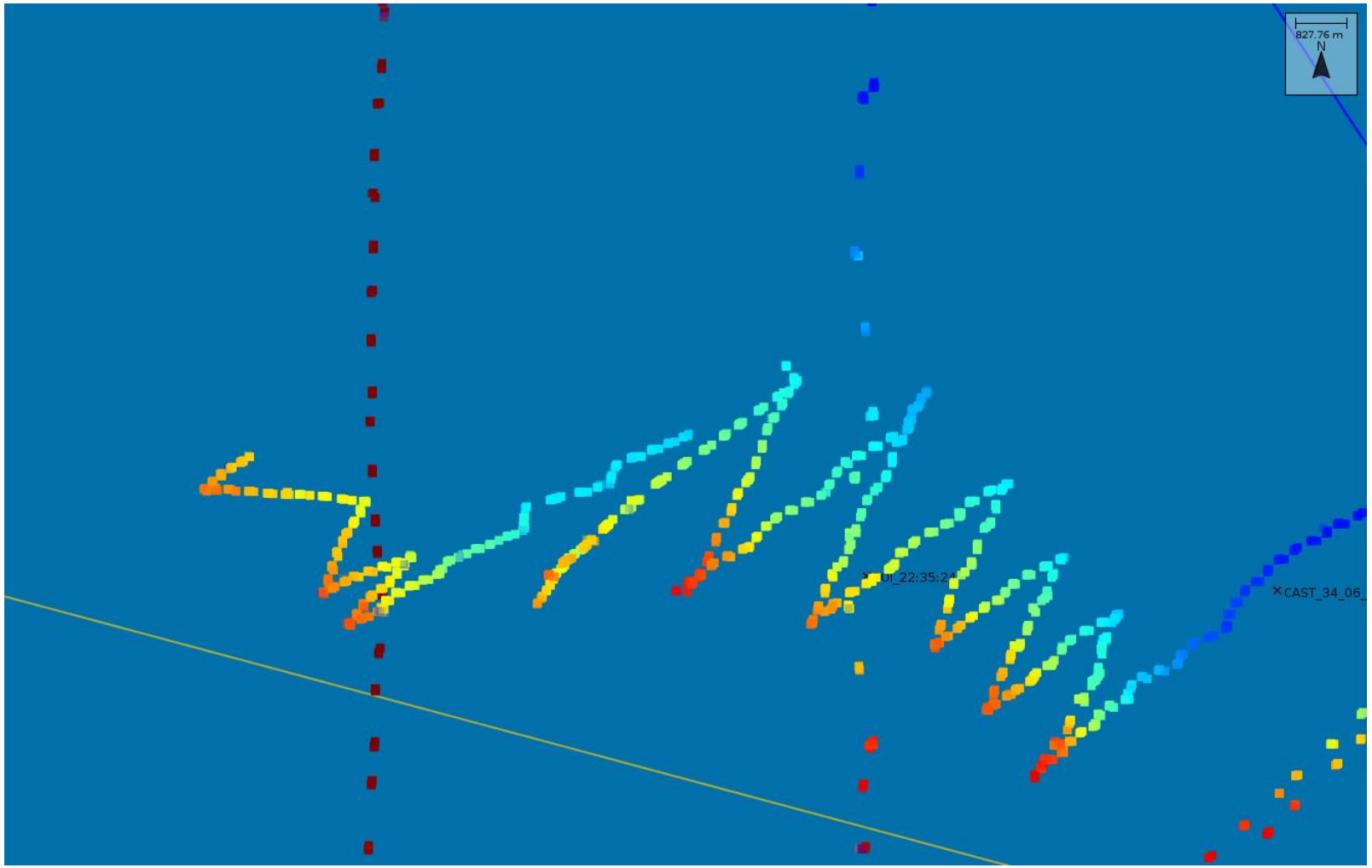




Courtesy of Ian Brosnan, NASA-Ames

Automated front detection and tracking

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



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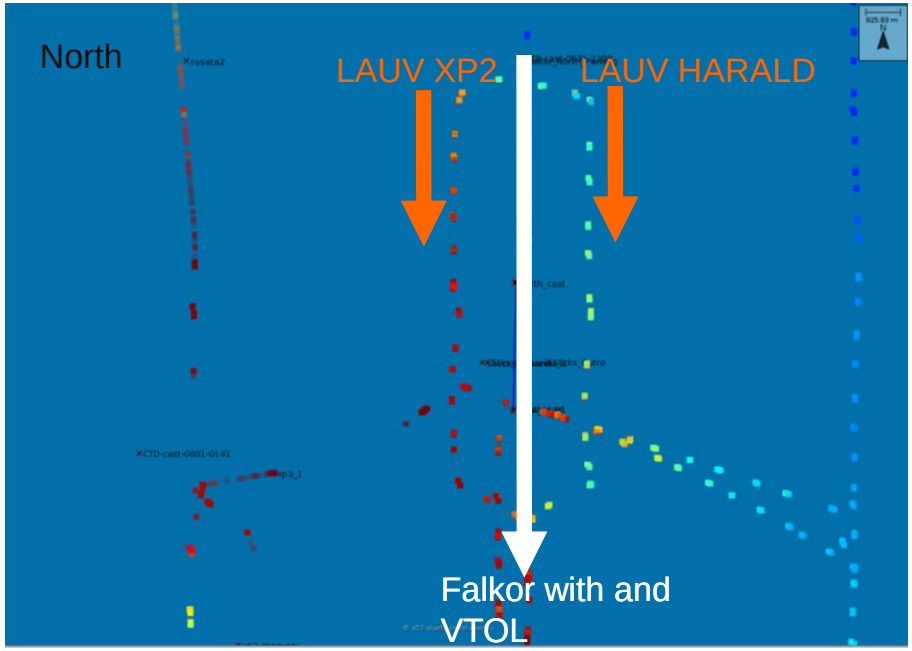
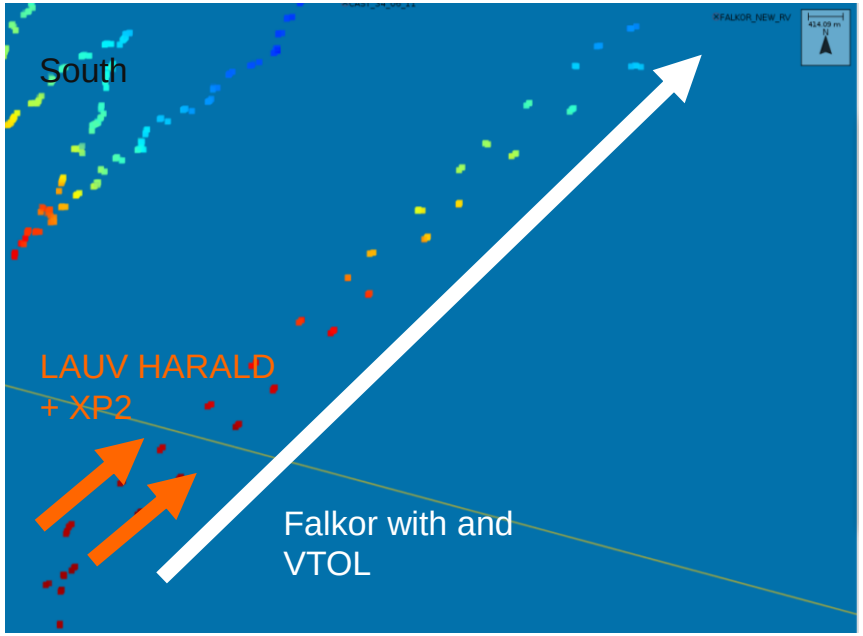
Hi-res coordinated sampling

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





Conclusions

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 …"

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In summary

- Successfully demonstrated a novel approach to observe the ocean with persistent networked vehicle systems
  - The front was located precisely as predicted.
  - Easternmost segment of the front 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.

- Operations
  - AUVs: 600+ h, 1000+ Nm; Persistent day/night ops
  - UAVs: Cameras (IR, multi-spectral), DMS gas sensor, comms relay / Flight time: up to 55mins
  - Ocean space center: 4 daily shifts / 2 operators per shift
  - Coordinated ship-robotic surveys

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

Thank you.

OCEANS 2021

MTS/IEEE-OES Porto Portugal

“Opening the Ocean Frontier: A New Age of Discoveries”

Ocean science and technology for the benefit of humankind.

https://www.oceansconference.org/porto-2021/