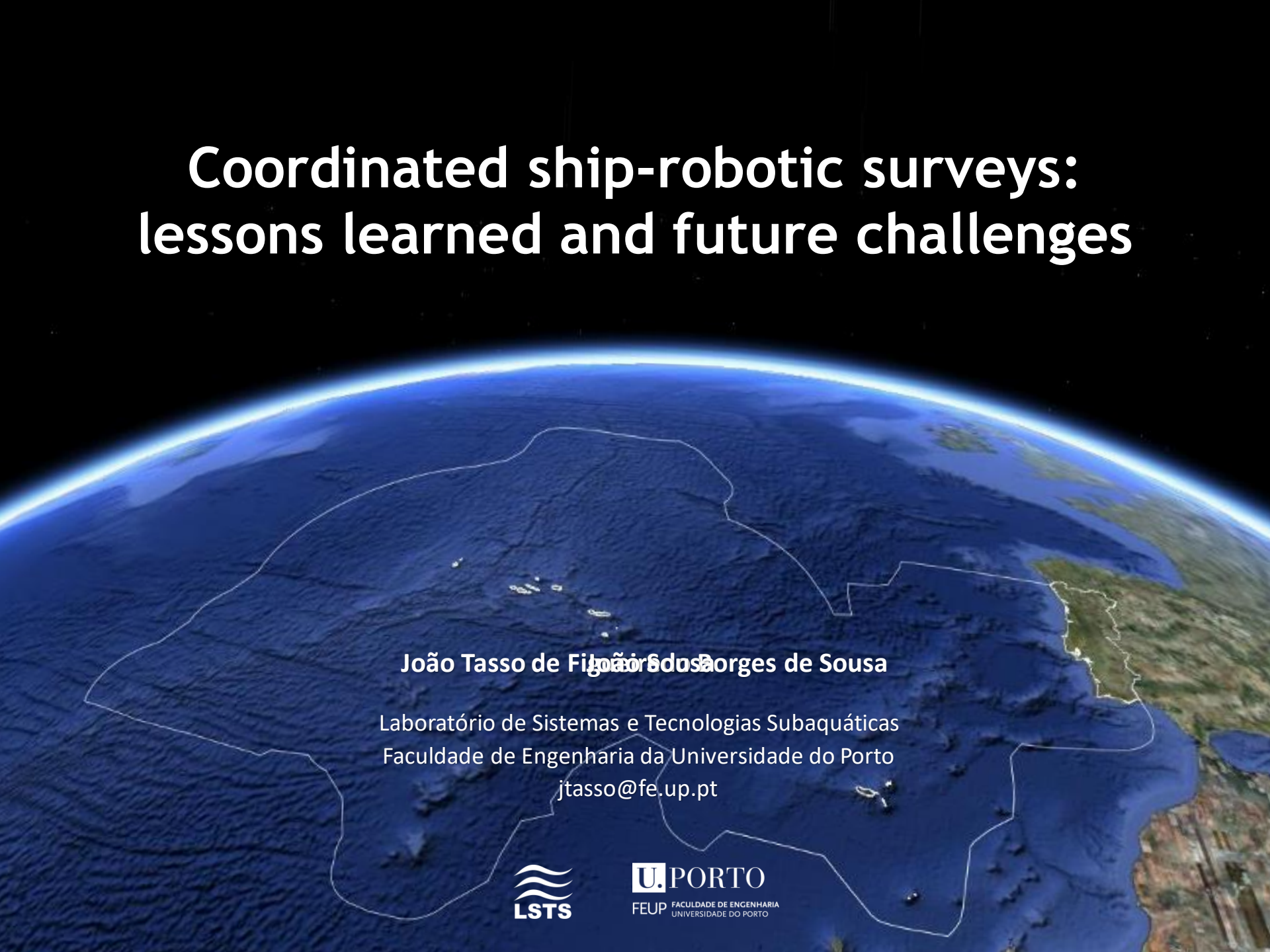
Coordinated ship-robotic surveys: lessons learned and future challenges



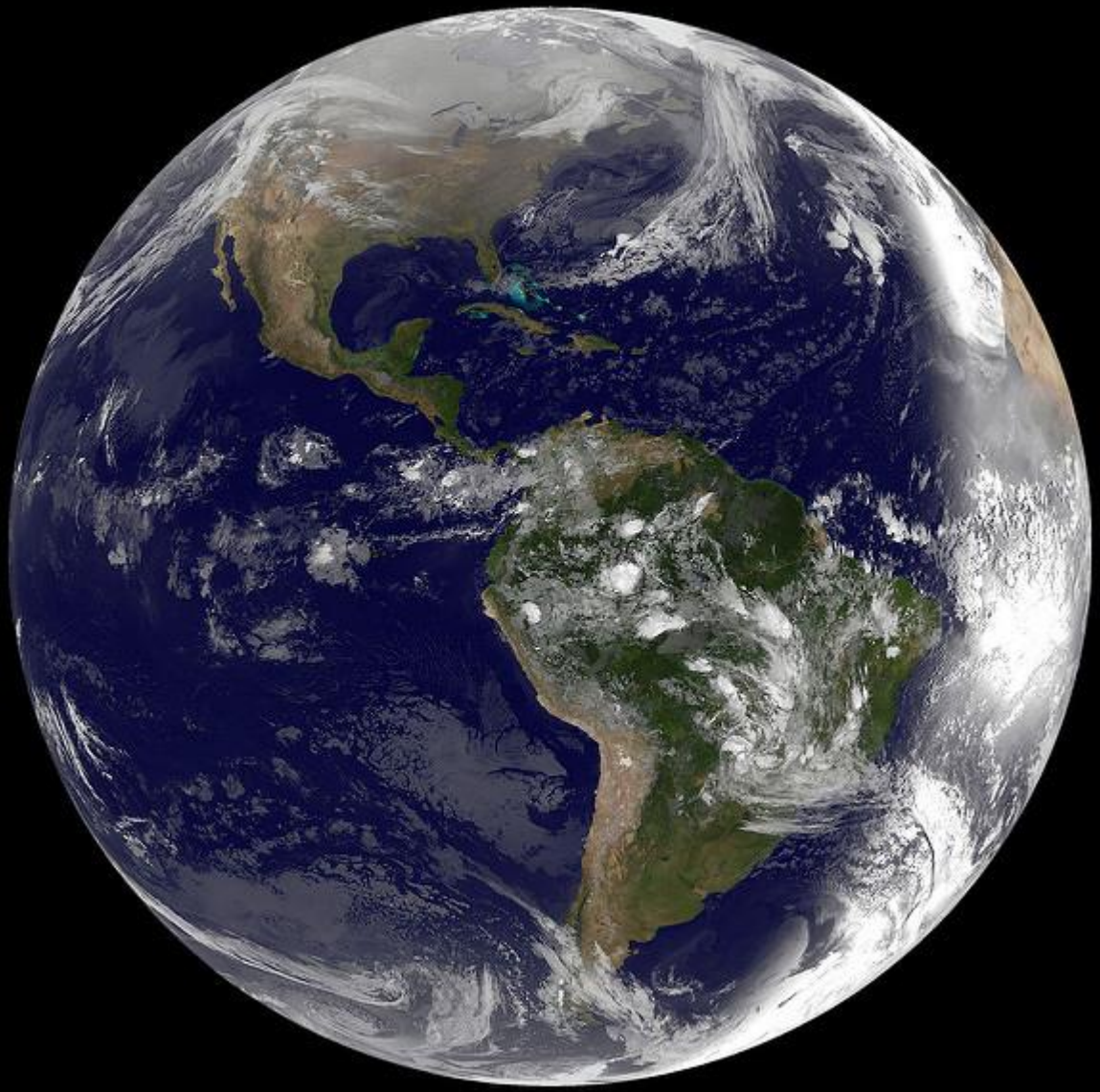
João Tasso de Figueiredo Sousa **João Sousa Borges de Sousa**

Laboratório de Sistemas e Tecnologias Subaquáticas
Faculdade de Engenharia da Universidade do Porto
jtasso@fe.up.pt

LSTS

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

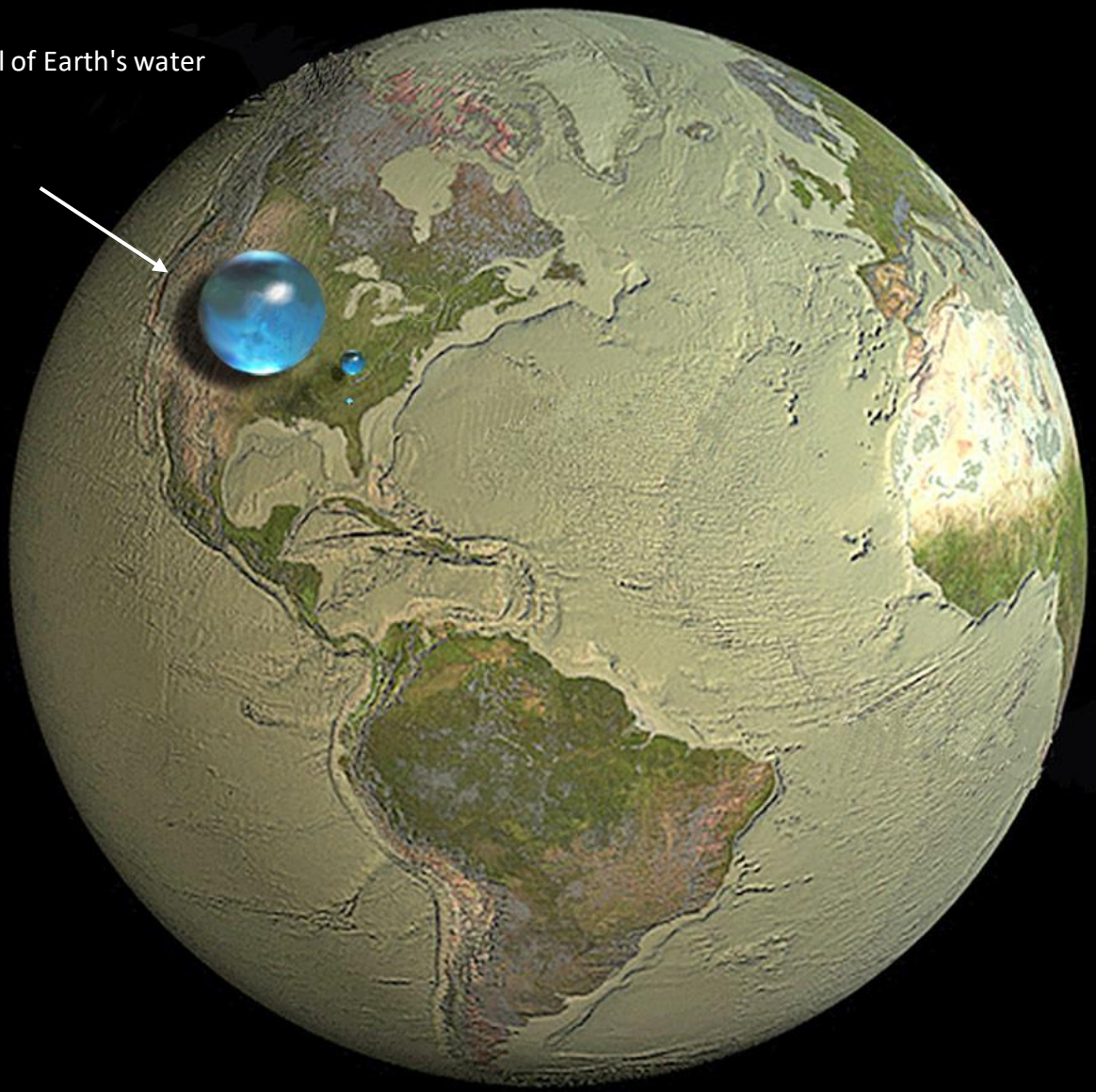
Blue planet



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

Thin blue layer

Sphere representing all of Earth's water
(860 miles diameter)



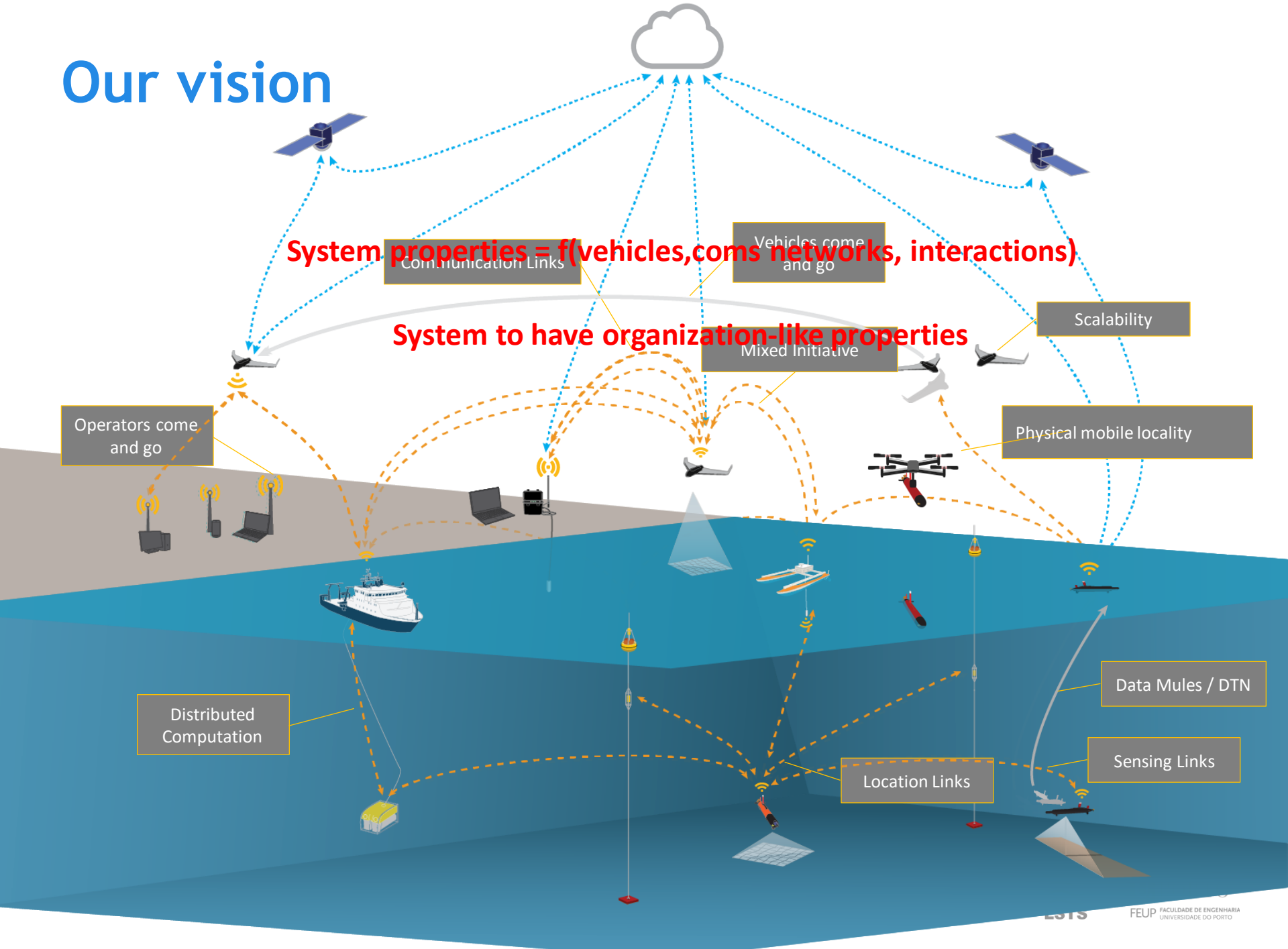
Source: https://water.usgs.gov/edu/gallery/global-water-volume.html

Outline

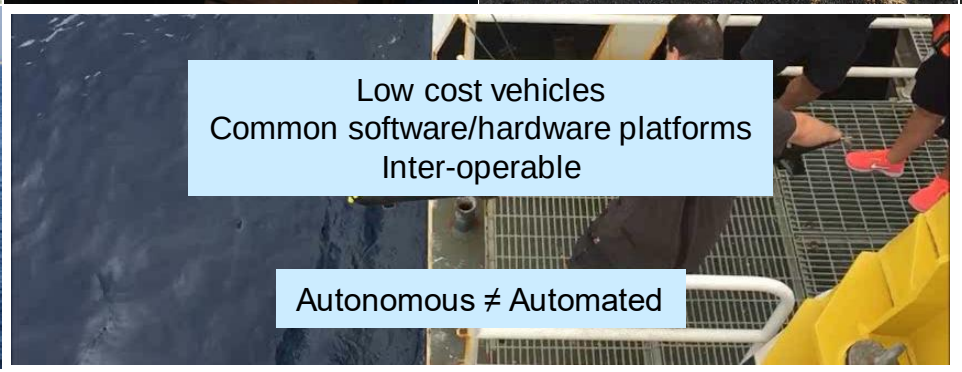
- LSTS lab
- “Exploring the STF with multiple robots”: cruise goals and approach
- Operations
- Lessons and future challenges

LAB OVERVIEW

Our vision


System properties = f(vehicles,coms networks, interactions)
System to have organization-like properties
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

Underwater vehicles



Long endurance ASVs

- Persistent ocean operations

Wave powered surface vehicles

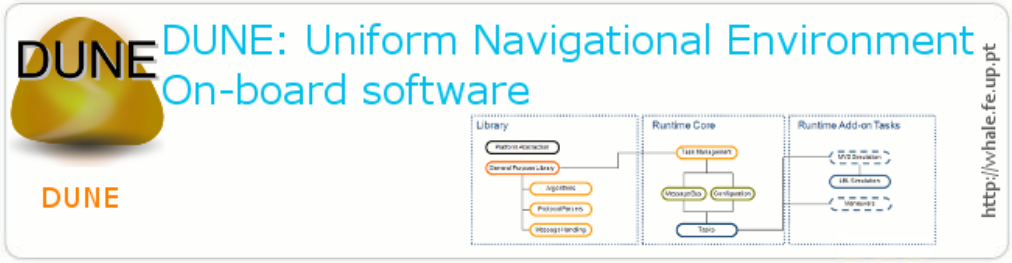
Unmanned air vehicles

*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.*

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)

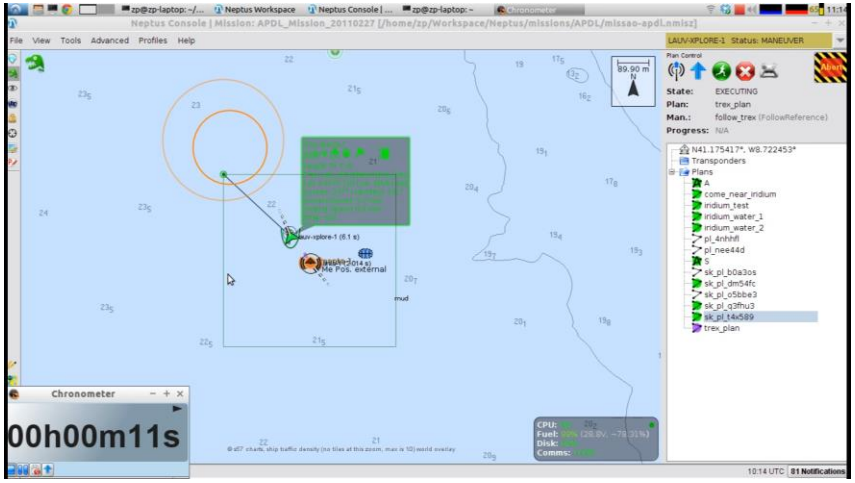
J. Pinto, P. Sousa Dias, R. Martins, J. Fortuna, E. R. B. Marques, and J. Borges de Sousa, ***The LSTS tool chain for networked vehicle systems****, Proceedings of the IEEE/MTS OCEANS'13, Bergen, June, 2013.*

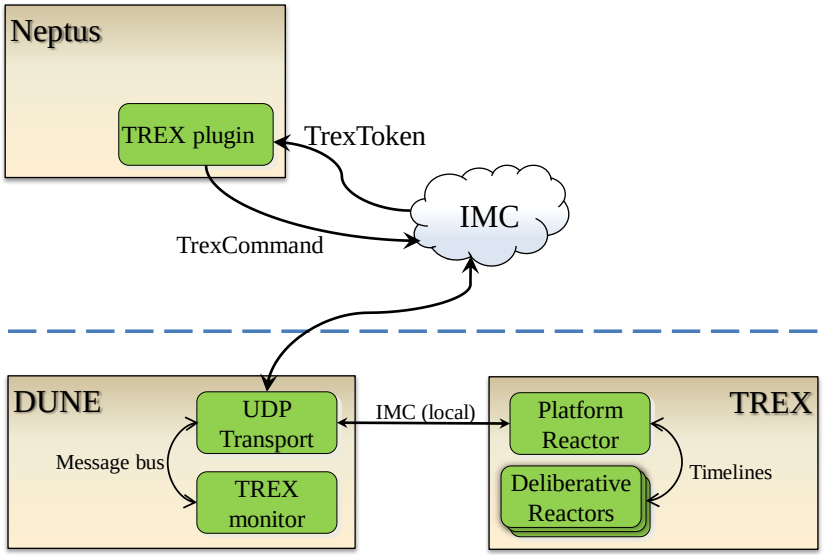
LSTS

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

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)

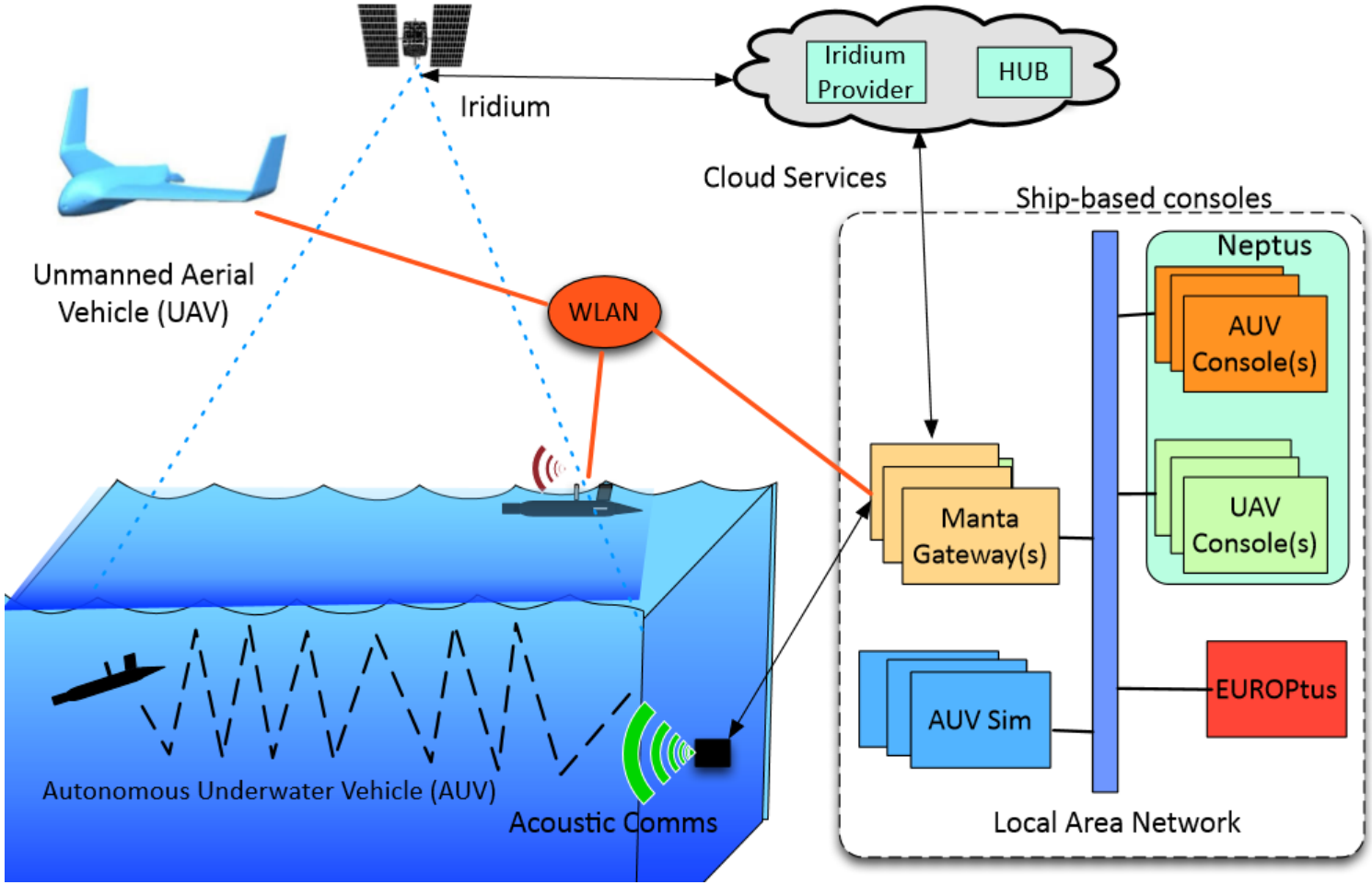




*M. Faria, J. Pinto, F. Py, J. Fortuna, H. Dias, R. Martins, F. Leira, T. Arne Johansen, J. Borges de Sousa, and K. Rajan, "**Coordinating UAVs and AUVs for oceanographic field experiments: challenges and lessons learned**", Proceedings of the 2014 IEEE International Conference on Robotics and Automation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

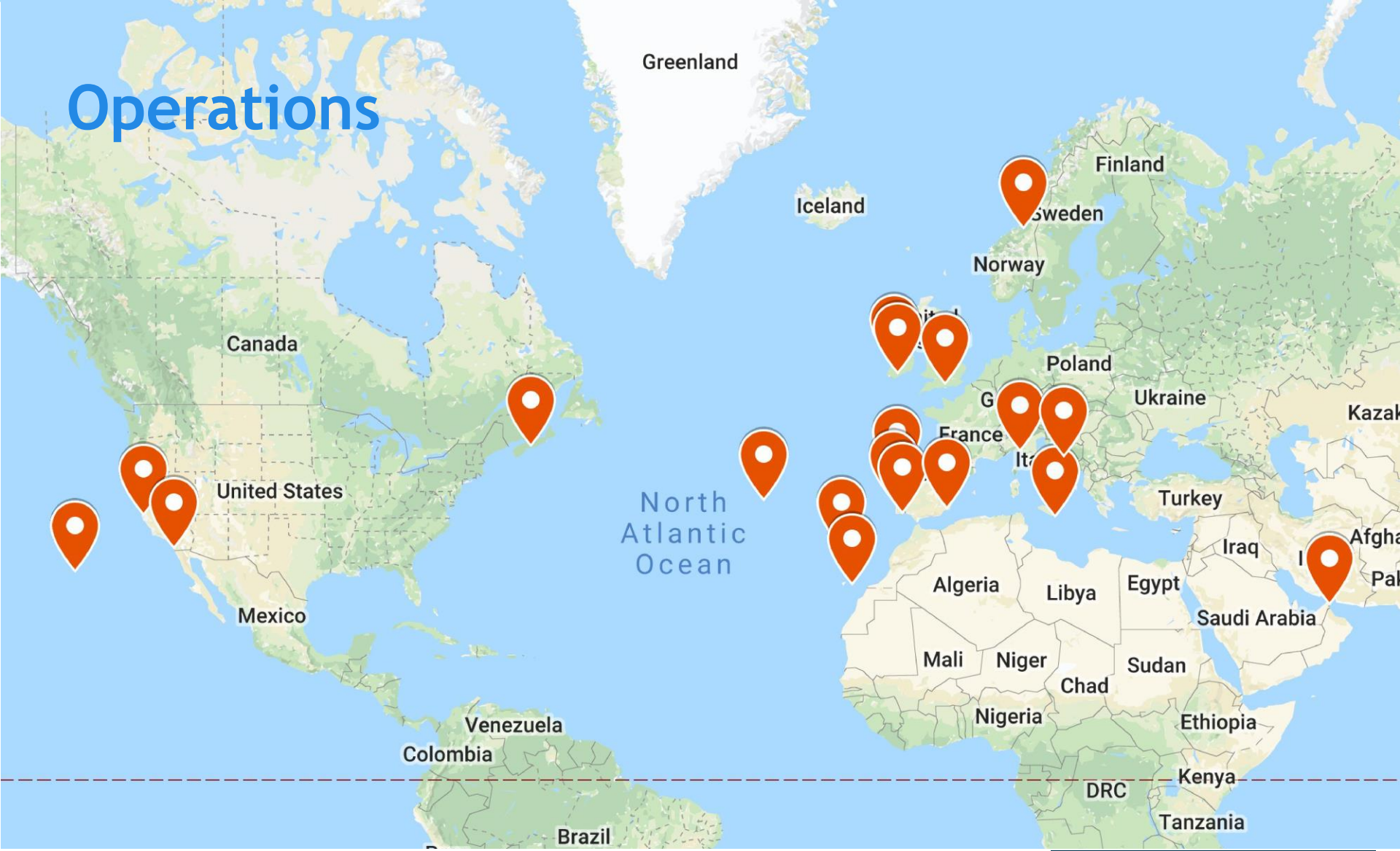
EUROPtus: mixed initiative control

- 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.*

Operations



Large scale exercises
Ops in the Pacific and Atlantic oceans, Mediterranean and Adriatic seas
Deployments from shore or from ship/submarine
Over 100 days of ops per year

2018
- 4000 Km underwater
- 200 flights

REP Atlantic annual exercise

Areas

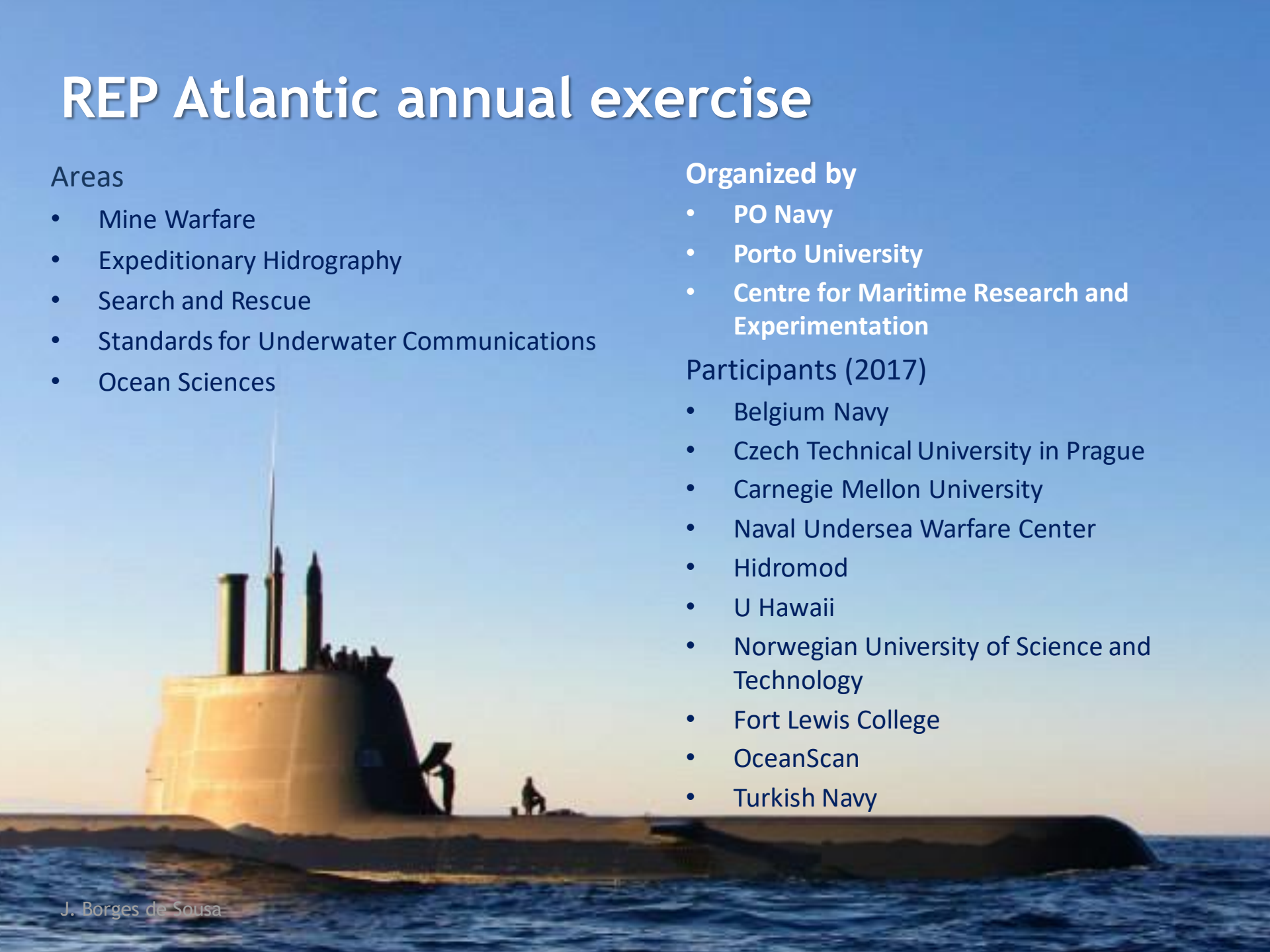
- Mine Warfare
- Expeditionary Hidrography
- Search and Rescue
- Standards for Underwater Communications
- Ocean Sciences

Organized by

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

Participants (2017)

- Belgium Navy
- Czech Technical University in Prague
- Carnegie Mellon University
- Naval Undersea Warfare Center
- Hidromod
- U Hawaii
- Norwegian University of Science and Technology
- Fort Lewis College
- OceanScan
- Turkish Navy



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731103

EUMarineRobots

Marine robotics research infrastructure network

https://www.eumarinerobots.eu/

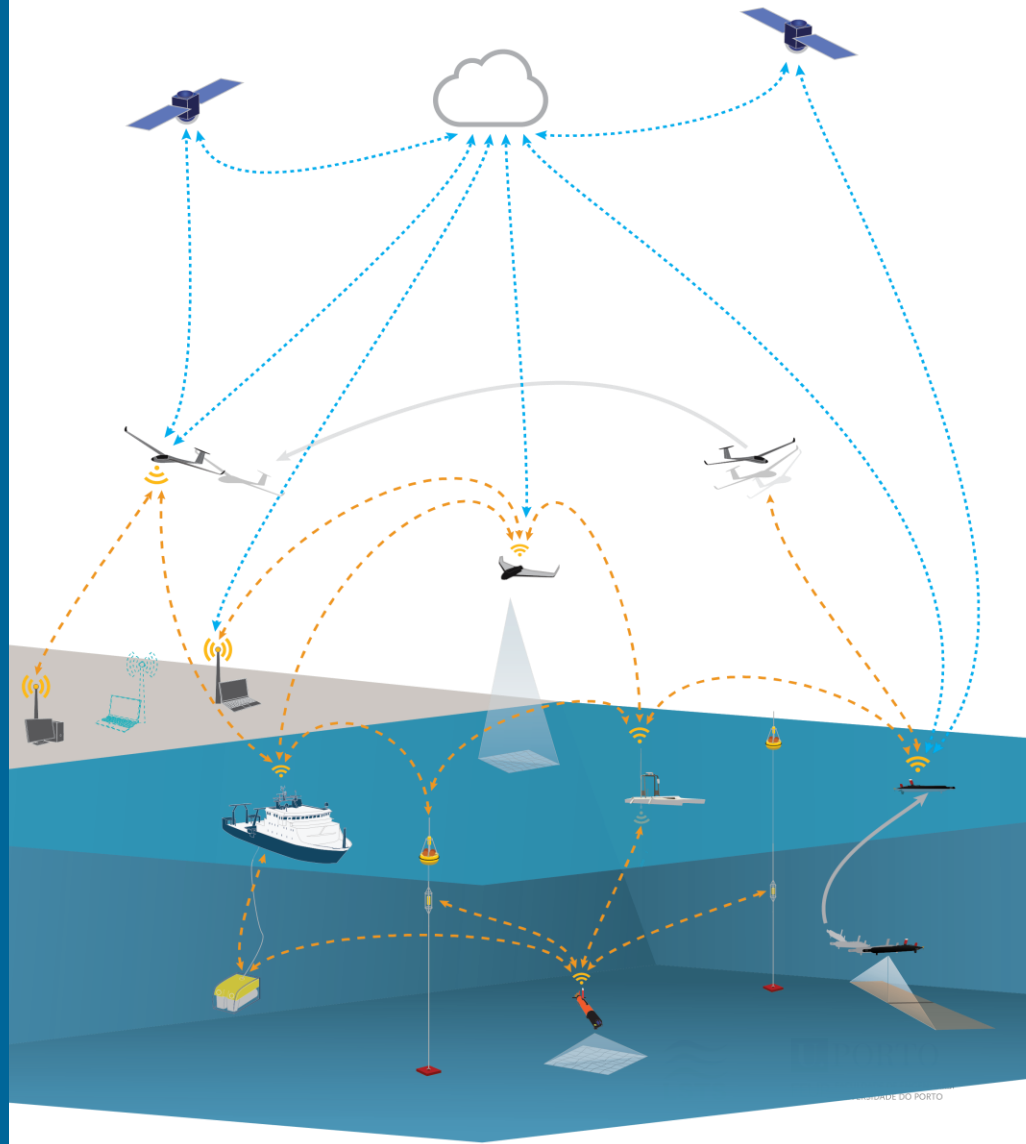
jtasso@fe.up.pt

Exploring the STF front with multiple robots

SCHMIDT OCEAN INSTITUTE

May 28–June 17, 2018

Goals and approach



Team

Universidad Politécnica de Cartagena

SINTEF

NTNU

MBARI

LSTS

LAMONT-DOHERTY EARTH OBSERVATORY

UAlg UNIVERSIDADE DO ALGARVE

Ames Research Center

HARVARD

LSTS

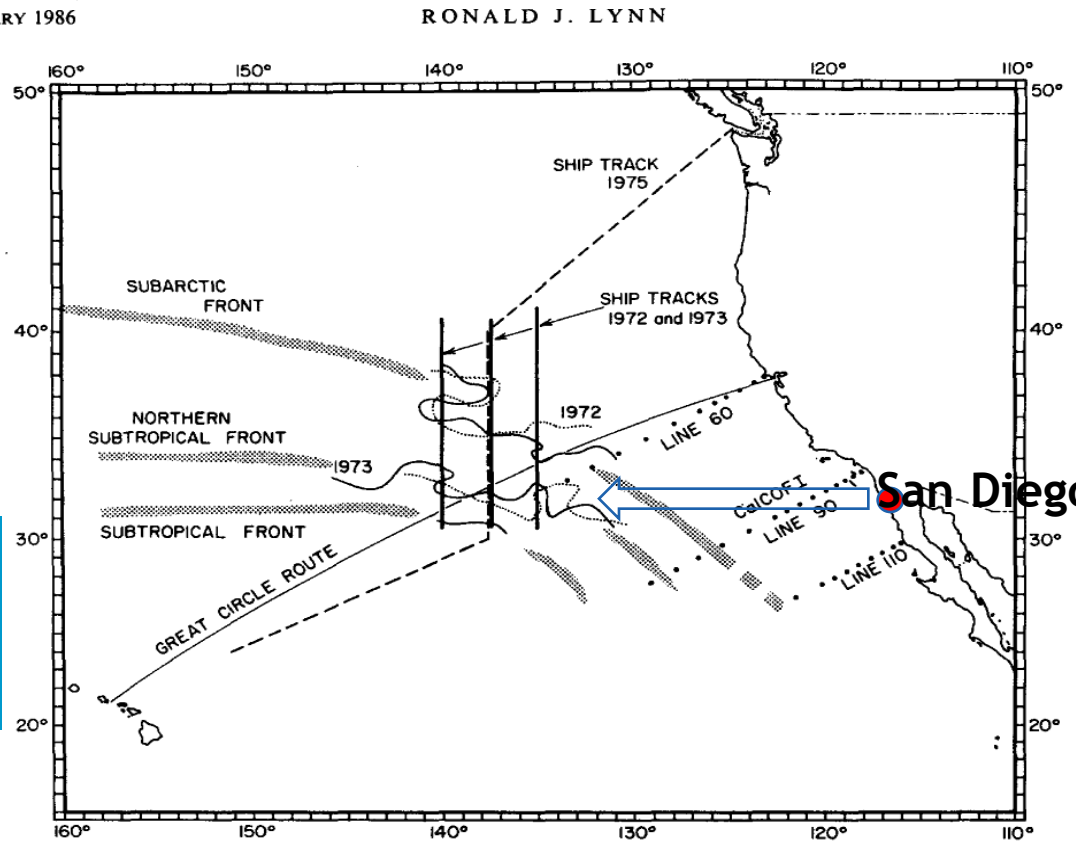
ciimar Centro Interdisciplinar de Investigação Marinha e Ambiental

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

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)

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



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.

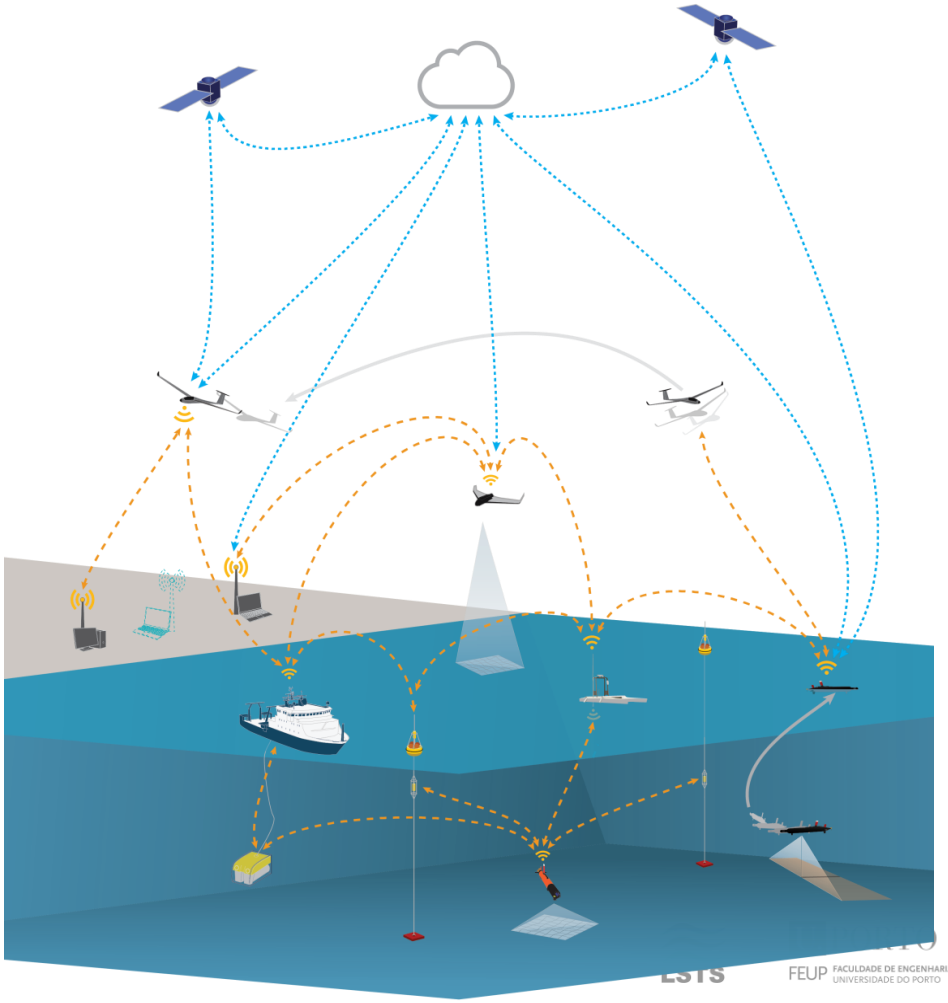
LSTS

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Main goal

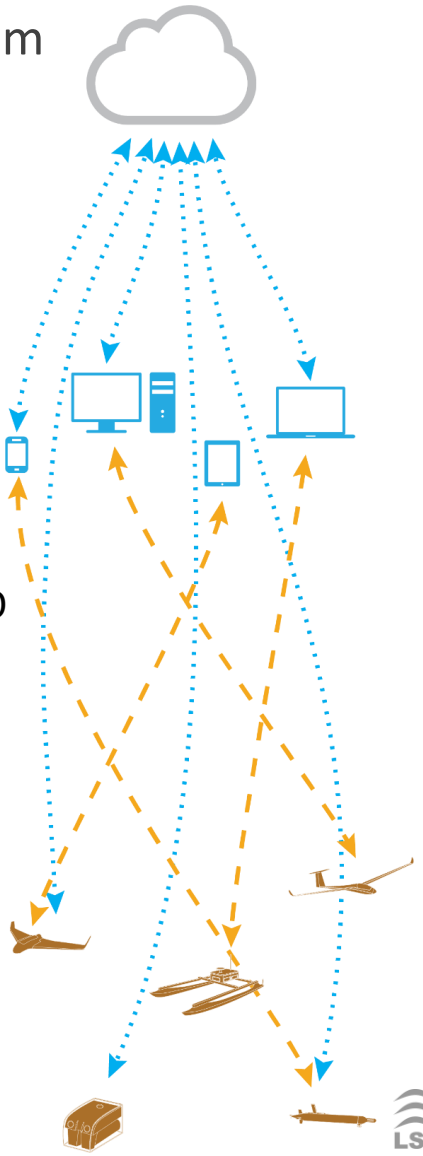
To demonstrate a novel multi-vehicle system capable of finding, tracking and sampling features of the ocean with adaptive spatial-temporal resolution

- *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



System

- R/V Falkor based networked multi-vehicle system
  - 3 VTOL UAVS (IR/mulispectral cameras, DSM)
  - 2 Quacopters
  - 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
  - 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

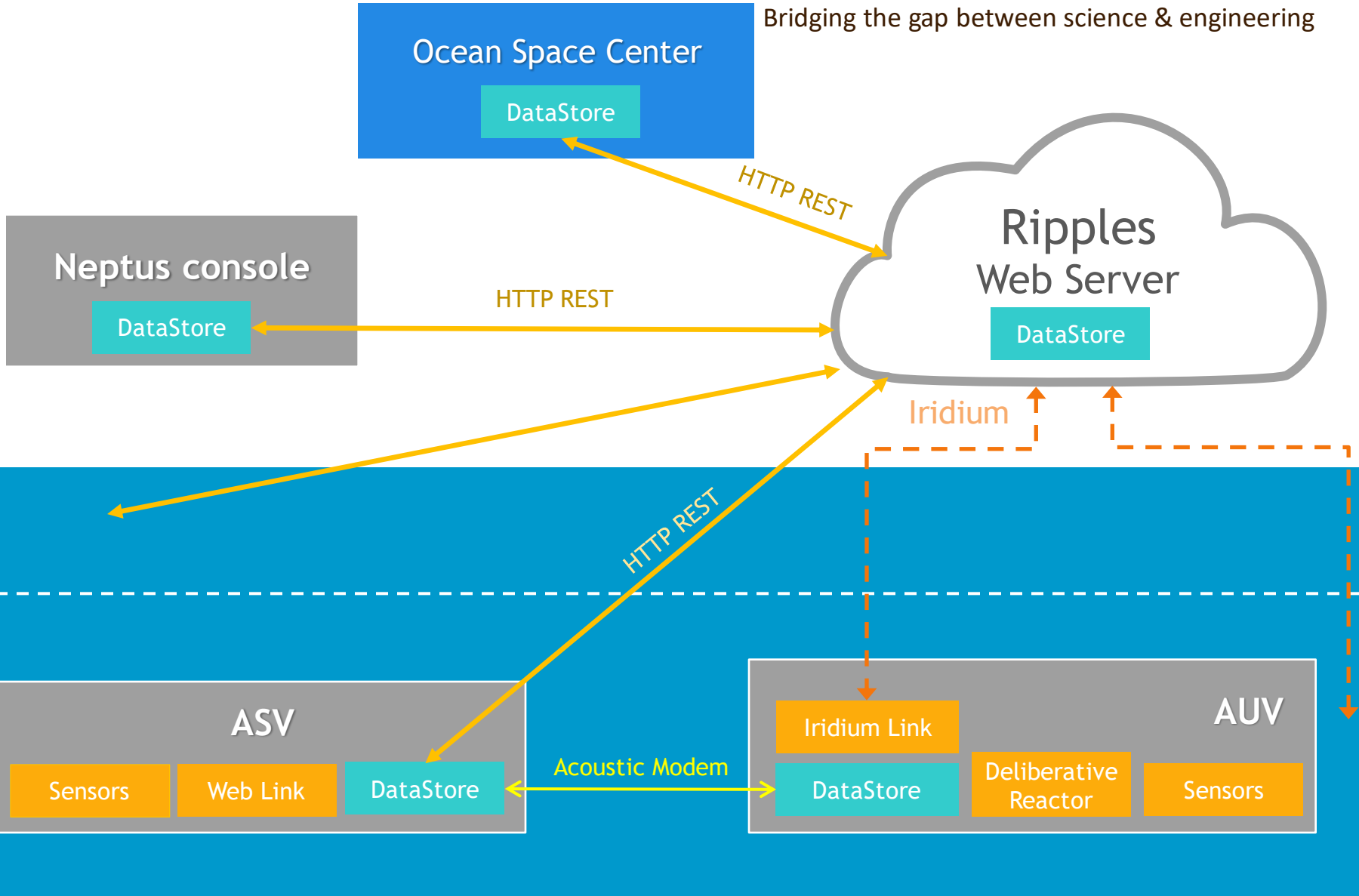
DUNE

Uniform Navigational Environment
On-board Software

LSTS

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Software and communications infrastructure



Ocean space center

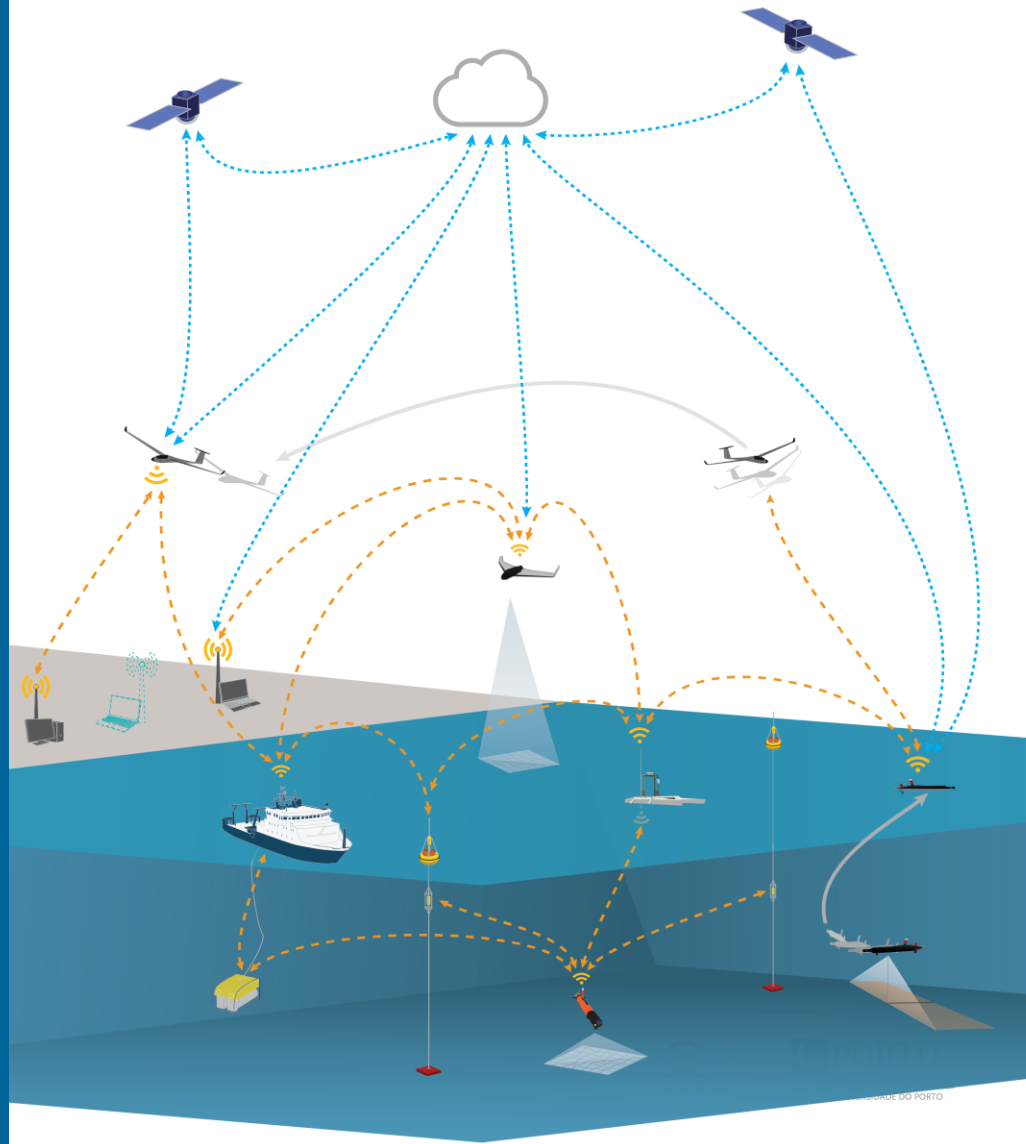
- Situational awareness, viz with multiple layers, planning & execution control

Exploring the STF front with multiple robots

SCHMIDT OCEAN INSTITUTE

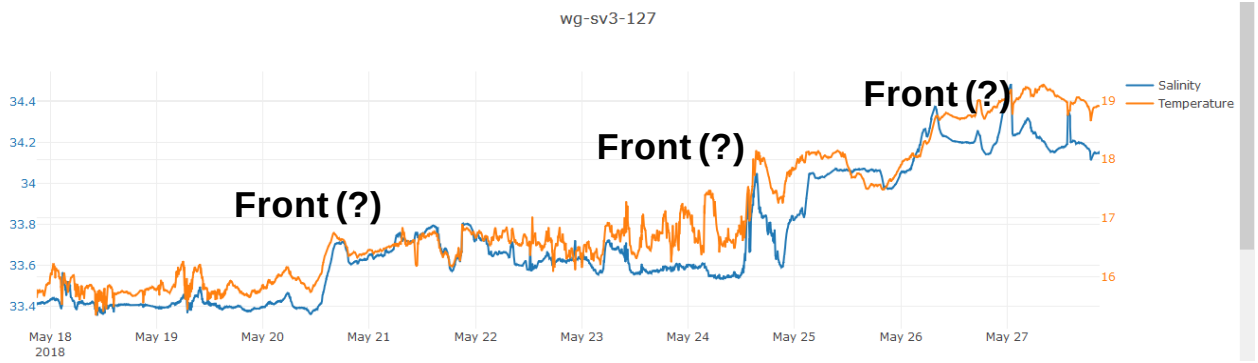
May 28–June 17, 2018

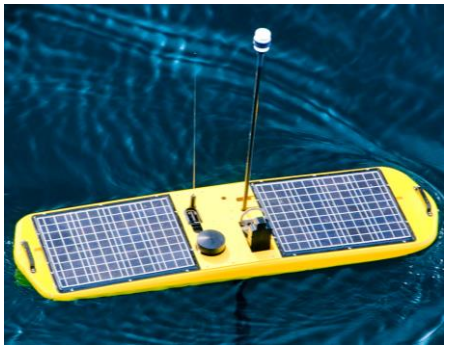
Operations

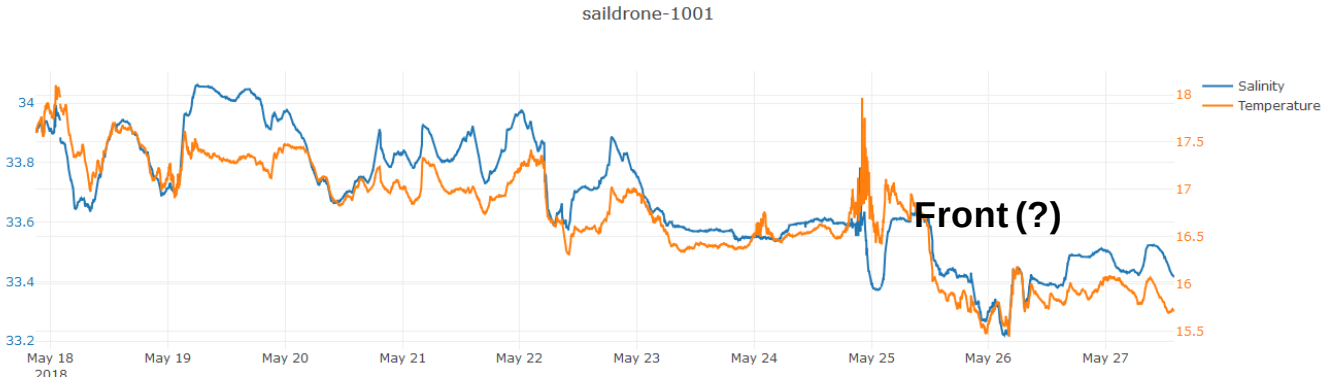


Finding the front

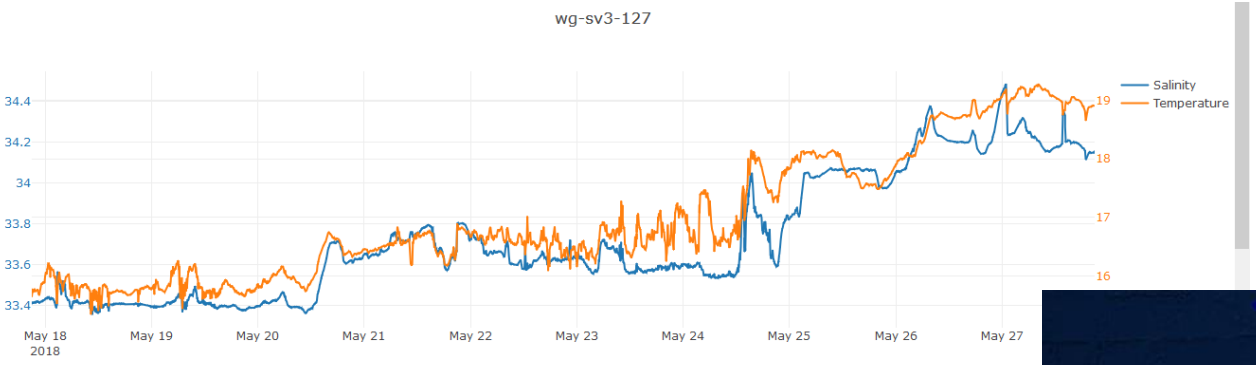
- One WaveGlider (WG) and two Saildrones (SD) deployed into the target research area ahead of the ship's arrival

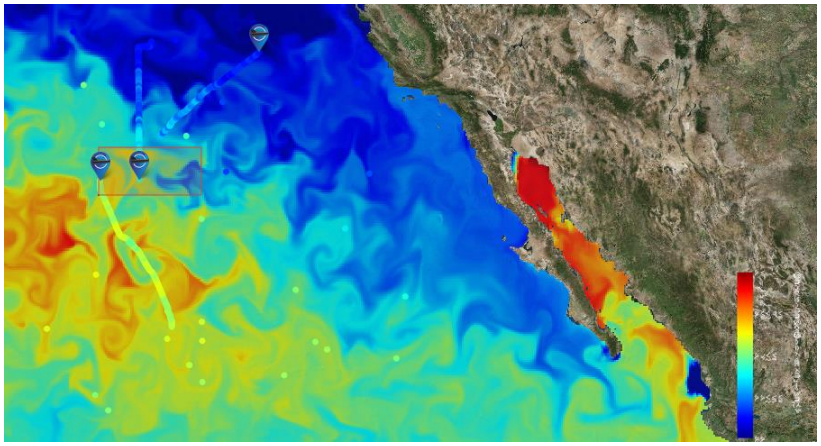


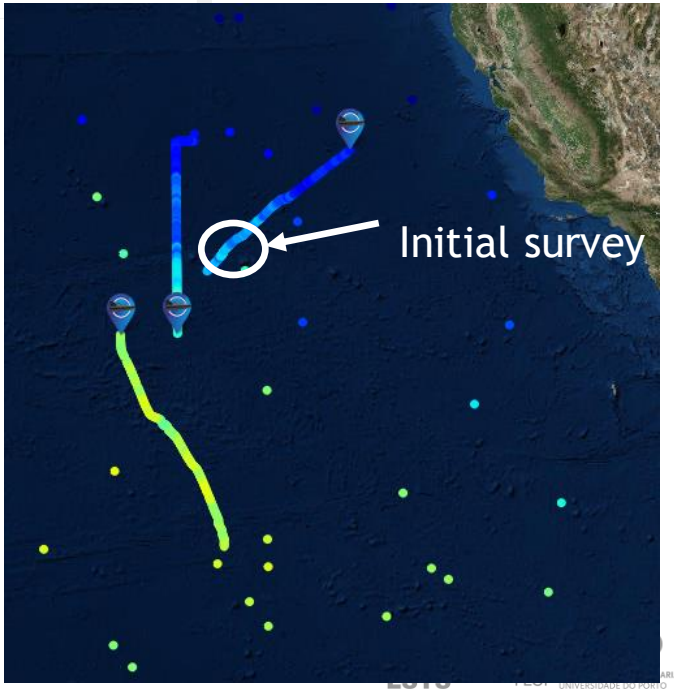




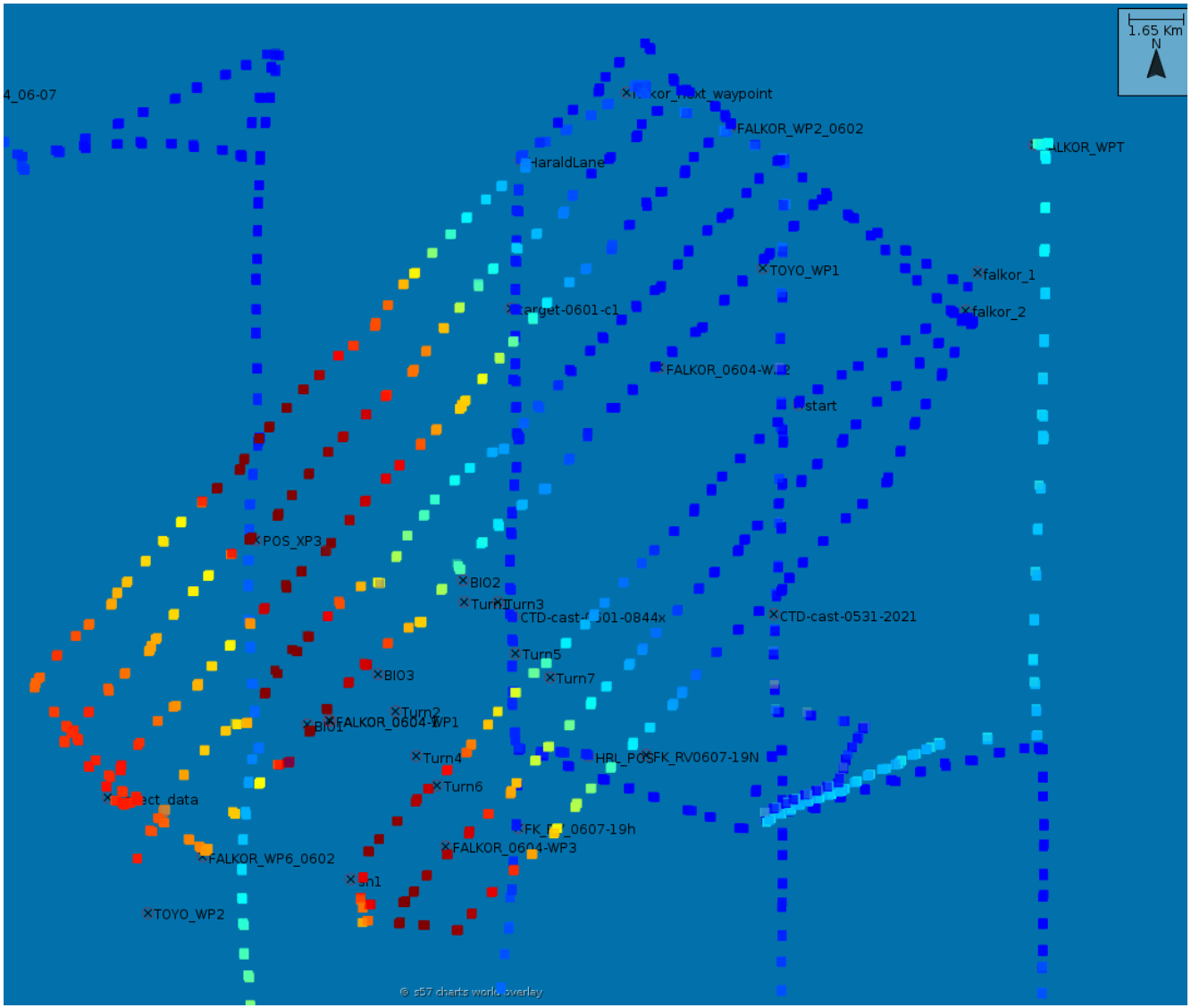
- ***Ocean space center*** ingested satellite imagery, HPC-run model outputs, and data from SD and WG and Argos floats







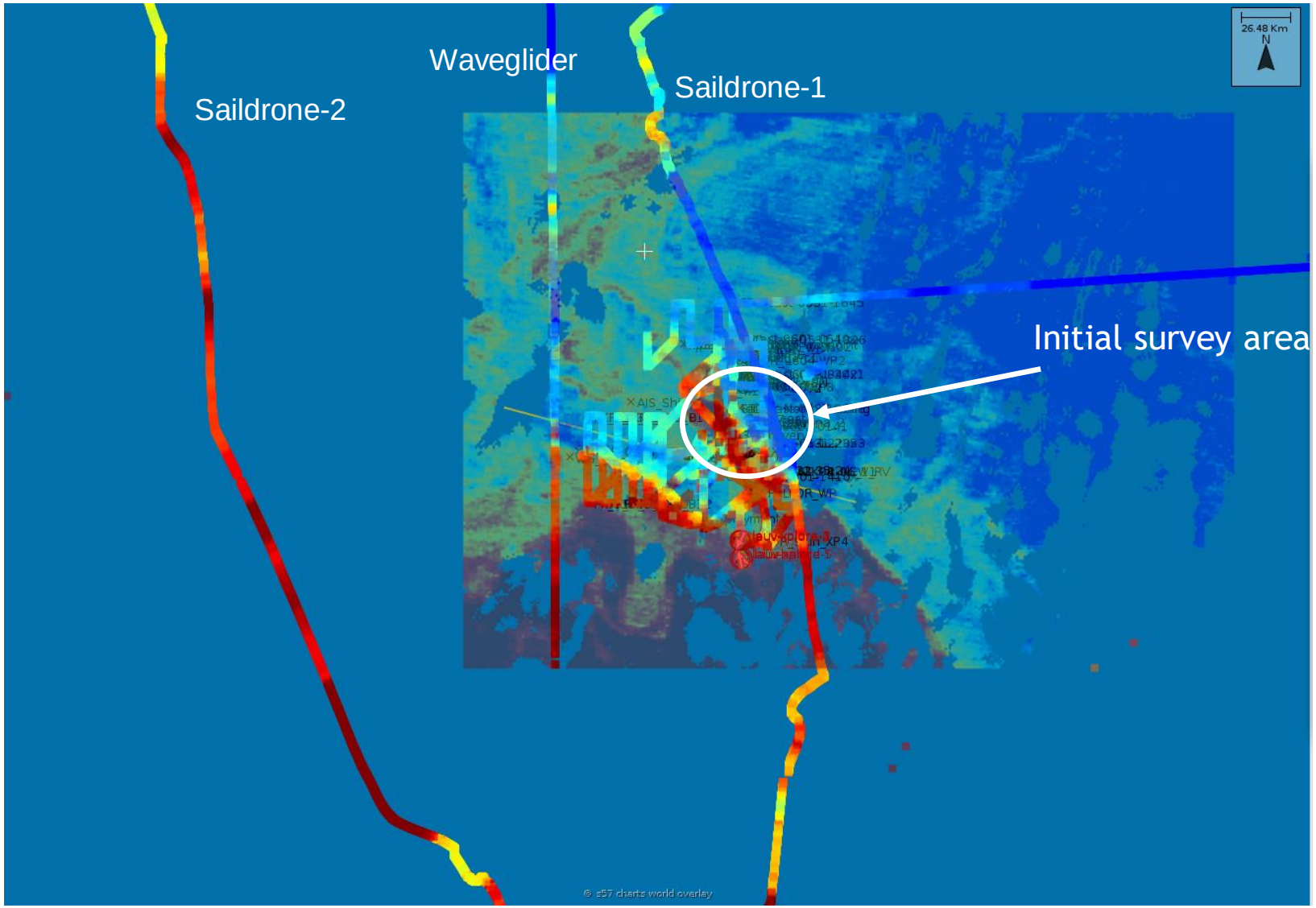
Hi-res mapping with AUVs (1Nm spacing)



LSTS

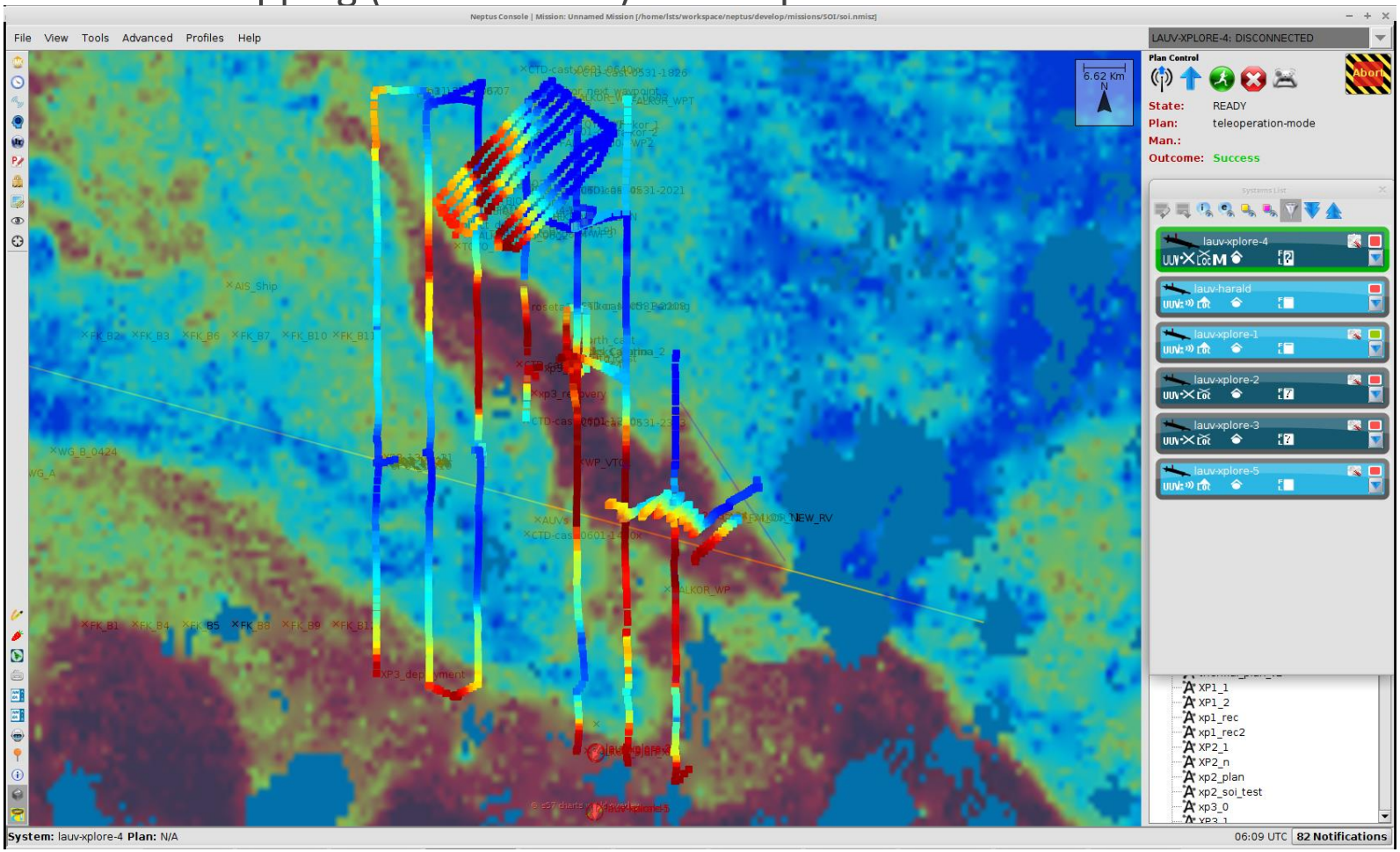
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Coordinated ship-robotic mapping



Mapping the front (AUV data + SST data)

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

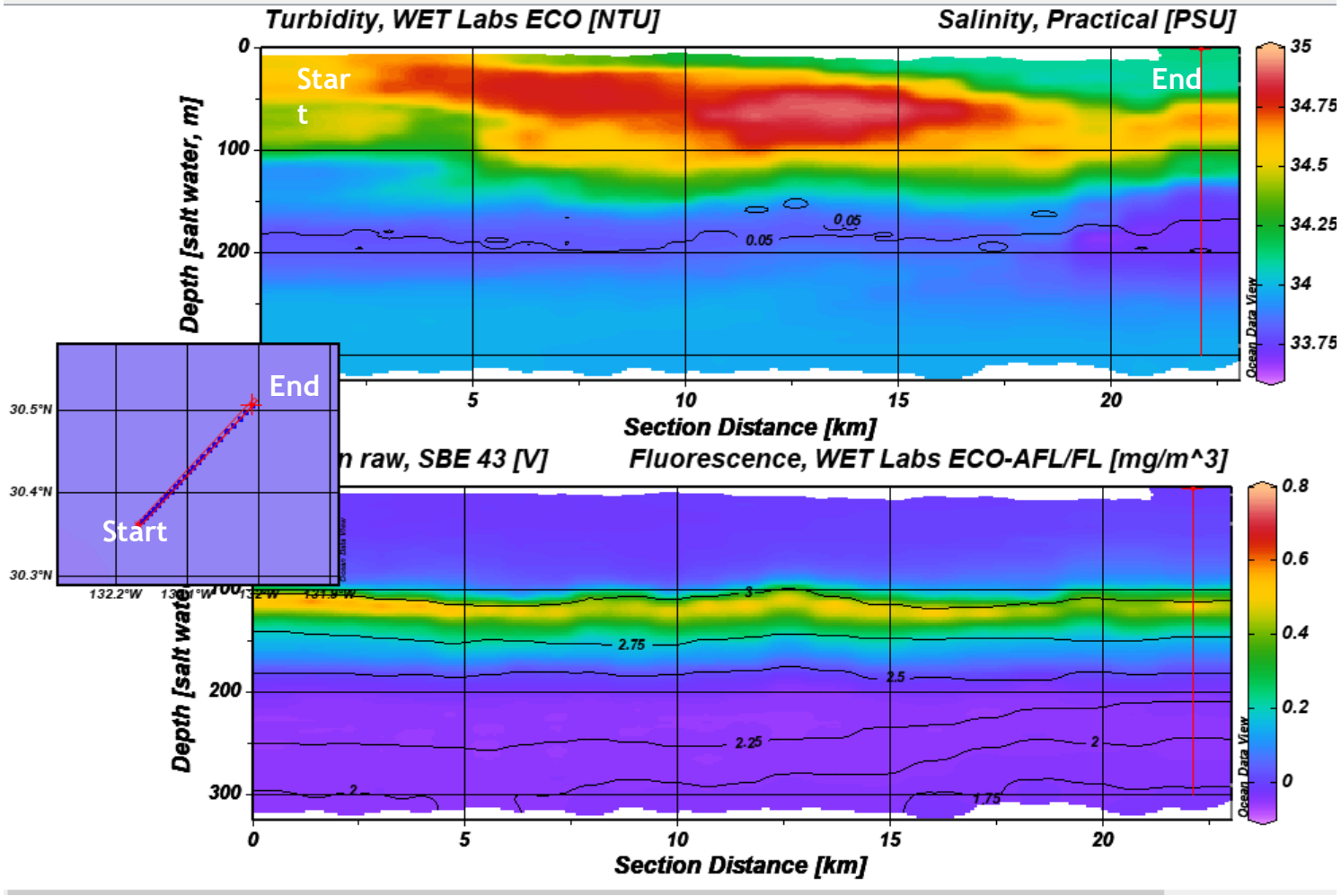


- HPC-run model helped to understand filament before SST image became available

LSTS

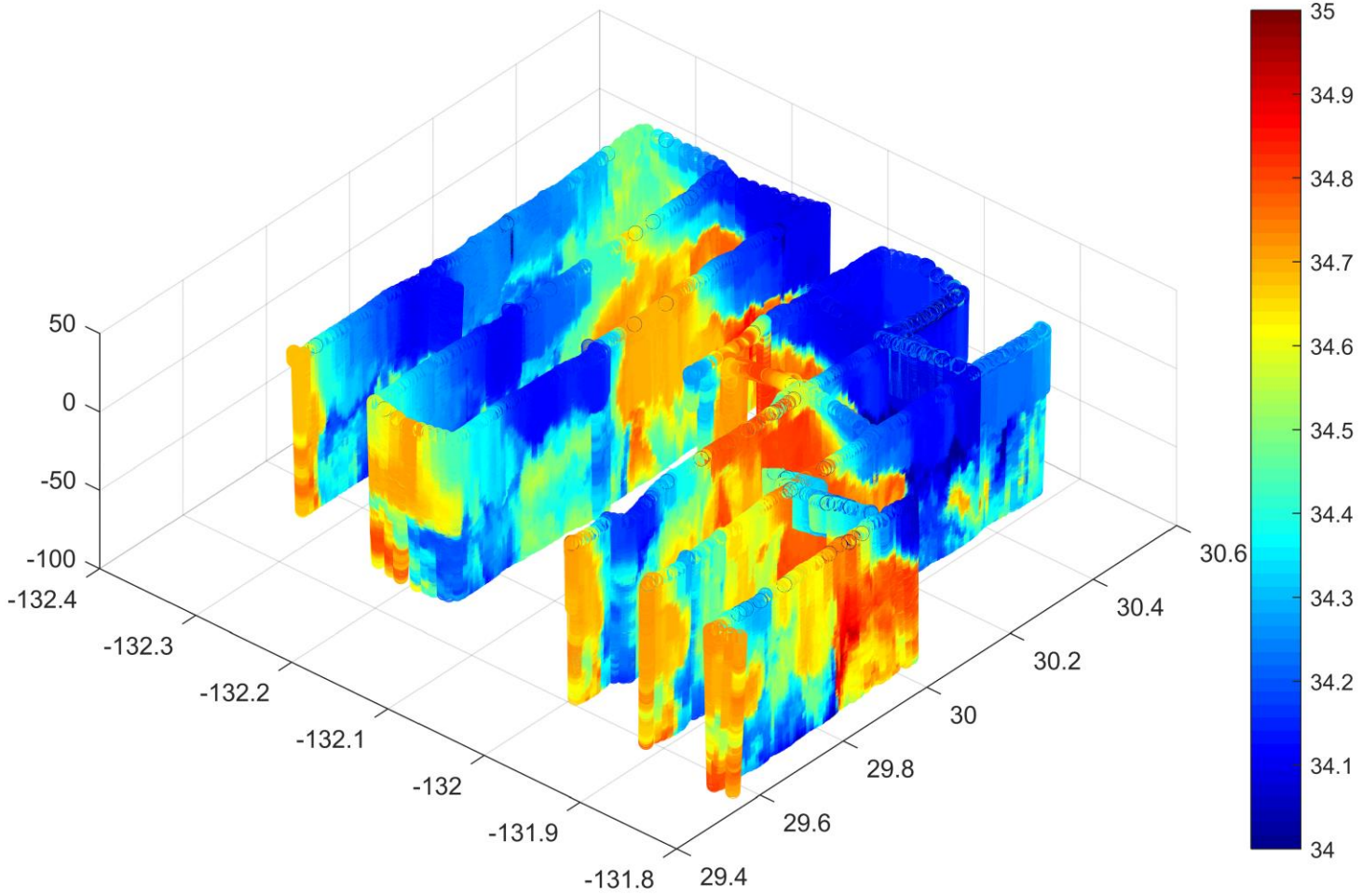
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Profiling with towed instruments

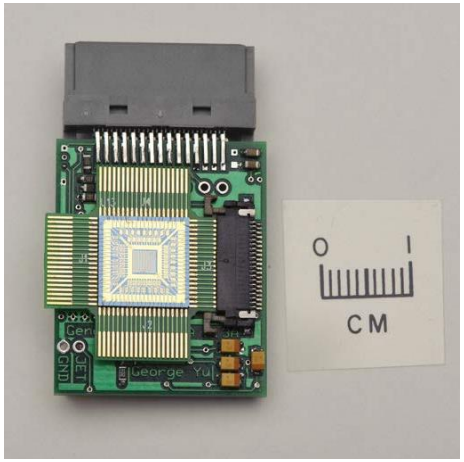


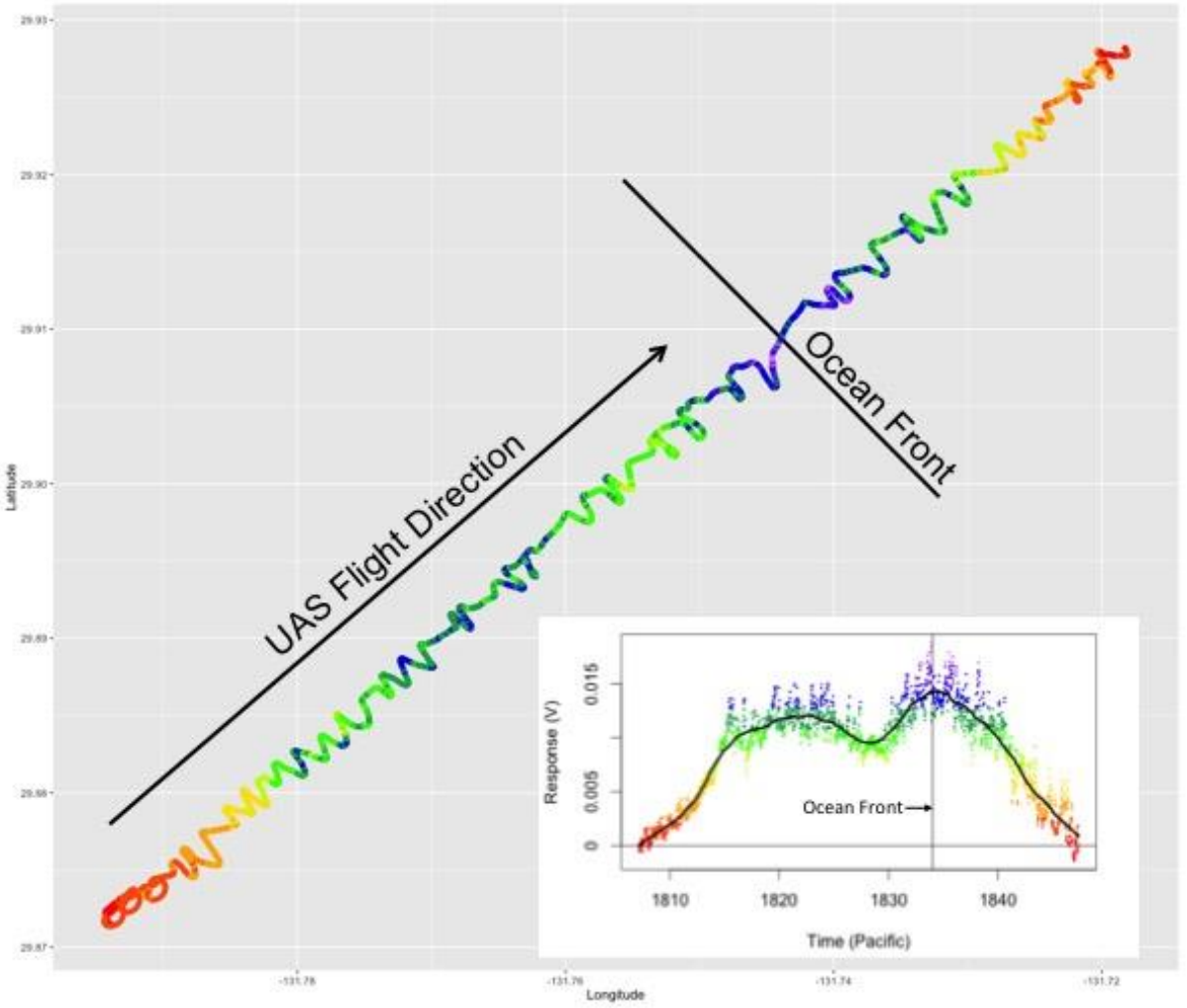
3D view of the front

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



DMS sensor data

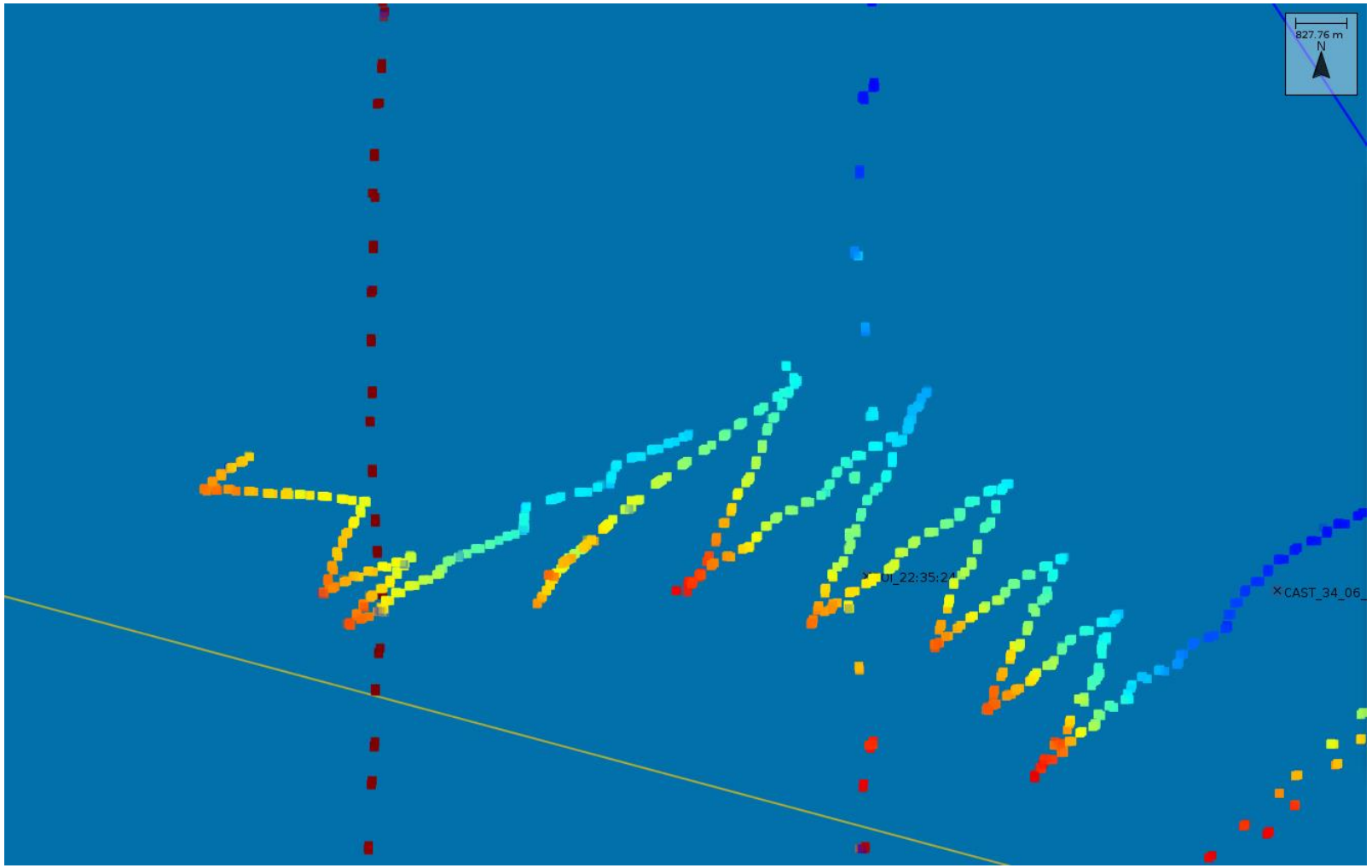




Courtesy of Ian Brosnan, NASA-Ames

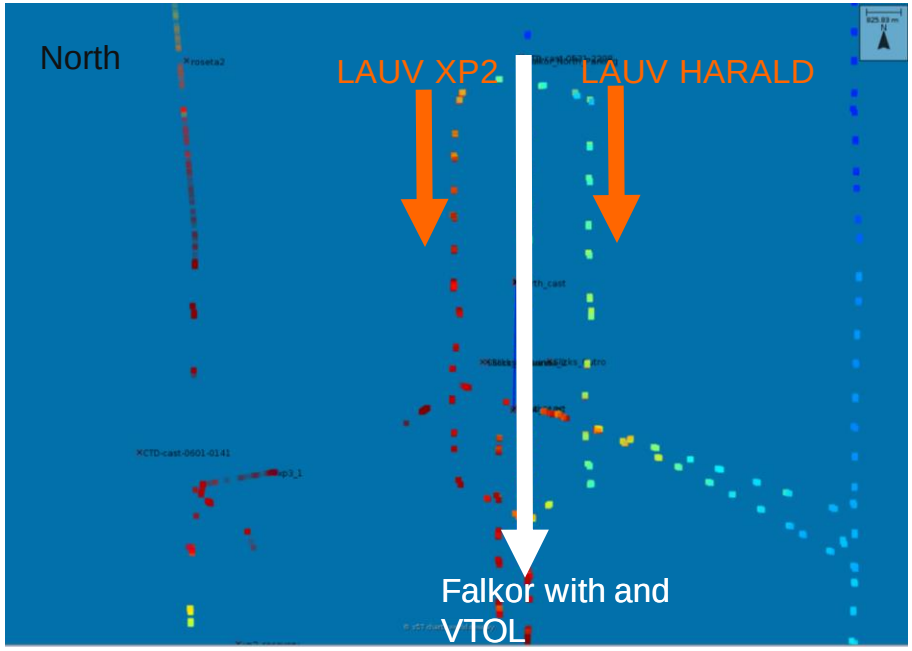
Automated front detection and tracking

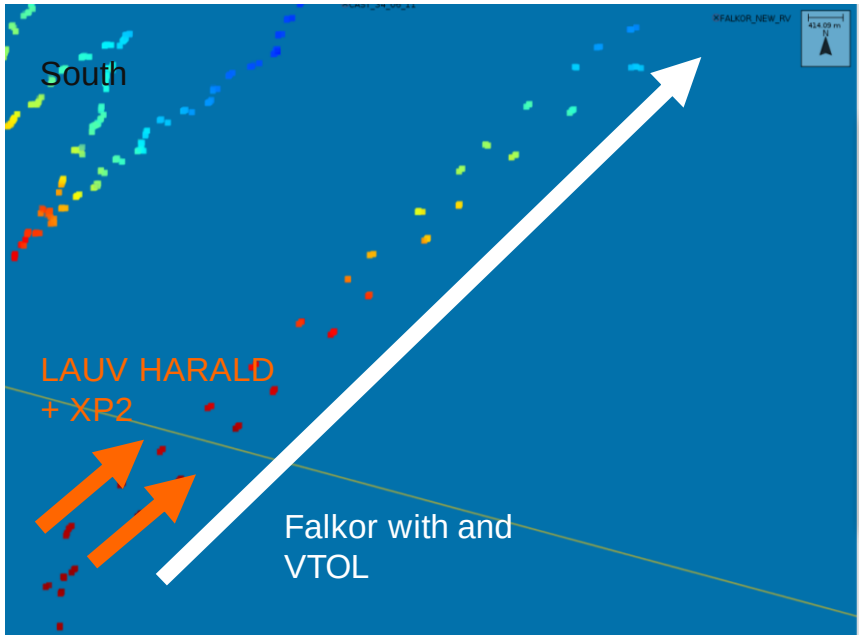
- Performed with Wave Glider, R/V Falkor and AUVs



Hi-res coordinated sampling

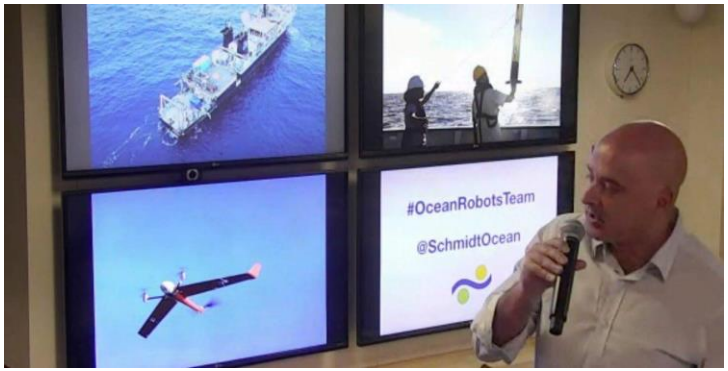
- Hi-res data sampling using AUVs with biochemical sensors coordinated with *Falkor* (ADCP, ALF, etc) and UAVs (camera and DMS sensor)





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.

On future oceanographic field operations

J. Borges de Sousa

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

LSTS

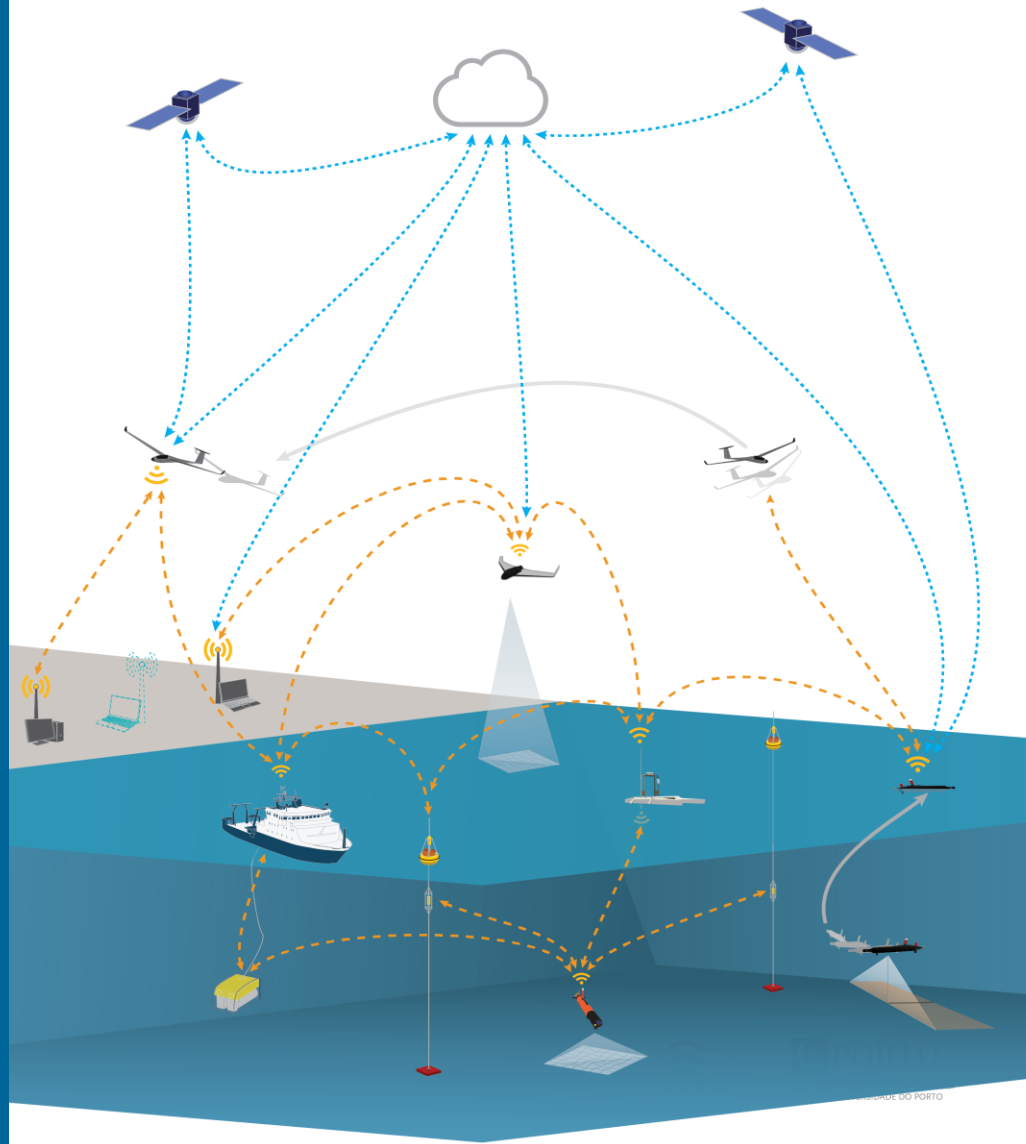
U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Exploring the STF front with multiple robots

SCHMIDT OCEAN INSTITUTE

May 28–June 17, 2018

Lessons learned and future challenges



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

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