

# Marine Systems & Robotics

## Cooperative Marine Robotic Systems: Theory and Practice – Part 1

Prof. Dr. Antonio Pascoal

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<http://impact.uni-bremen.de/>



JACOBS  
UNIVERSITY



National  
Technical  
University of  
Athens



University of  
Zagreb

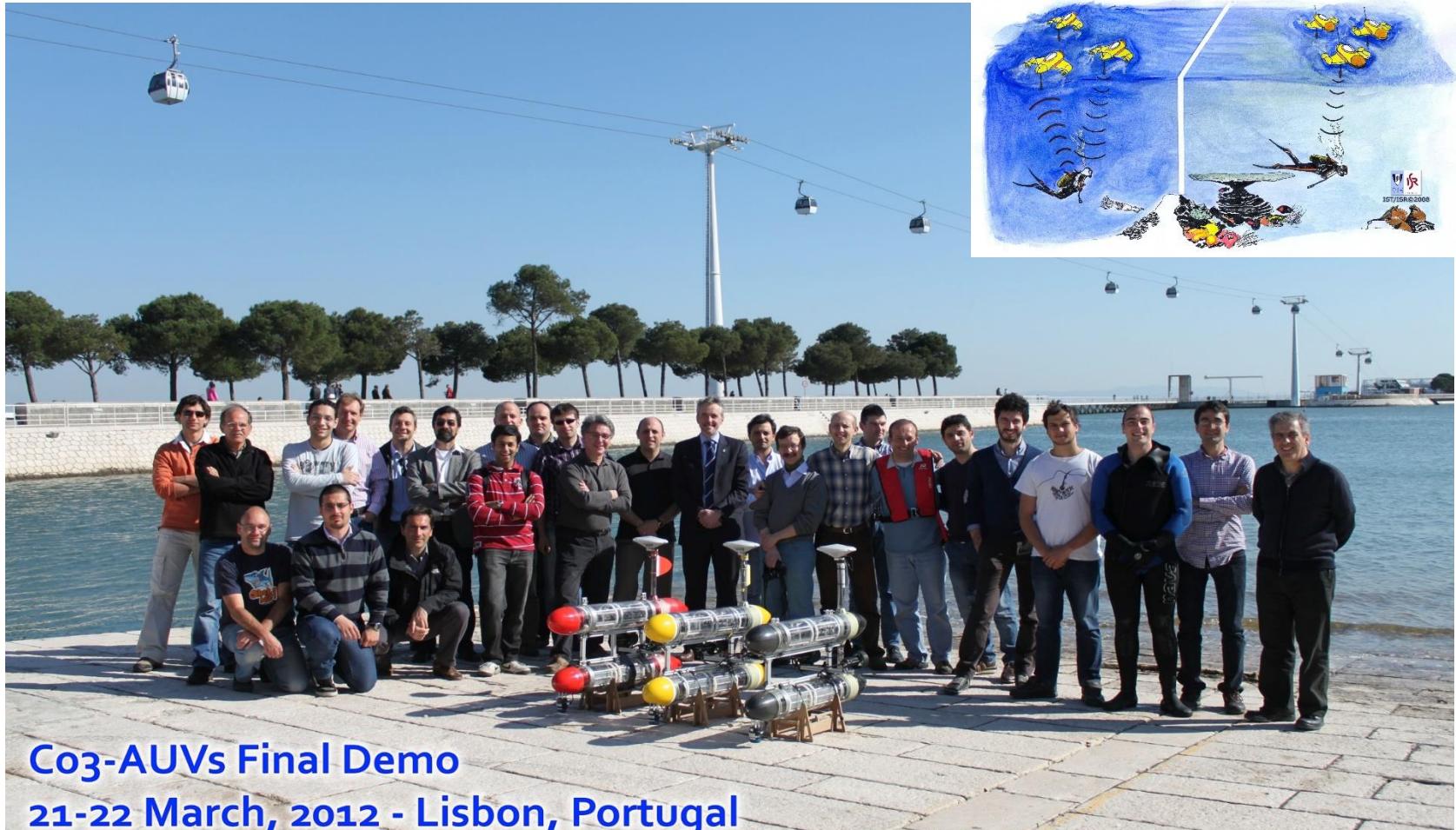


# The work of many



# EC-CO<sub>3</sub>AUVs

2009-2012



**Co3-AUVs Final Demo  
21-22 March, 2012 - Lisbon, Portugal**



FP7-ICT-2007-3 GA 231378 **CO3-AUVs**: Cooperative Cognitive Control for Autonomous Underwater Vehicles, 2009-2012

# EC-MORPH

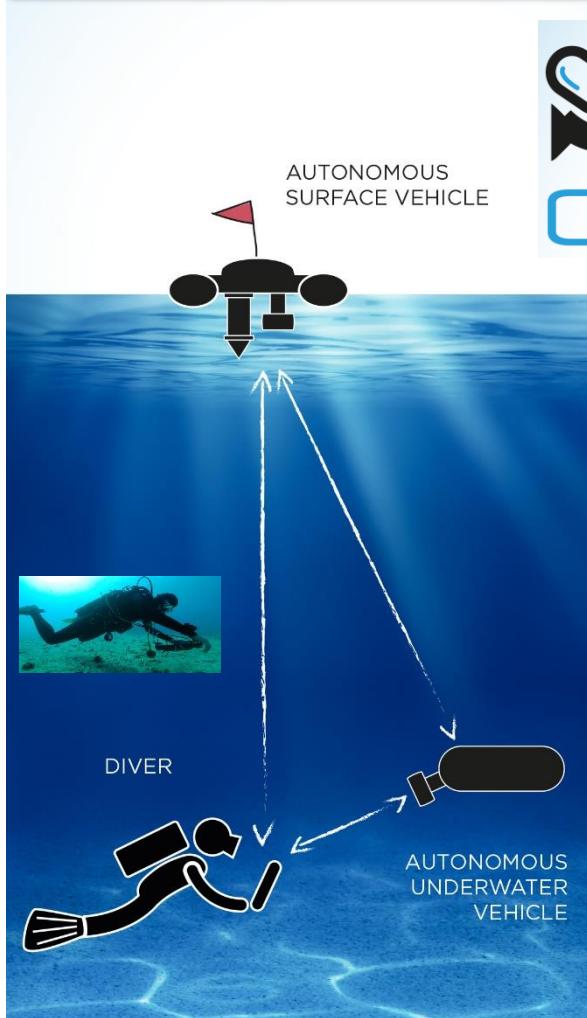
2012-2016



FP7-ICT-2011-7 GA 288704 **MORPH**: Marine Robotic System of Self-Organizing,  
Logically Linked Physical Nodes, 2012-2016

# EC-CADDY

2014-2016



FP7-ICT-2013-2 GA 611373 **CADDY**: Cognitive Autonomous Diving Buddy,  
2014-2016

# EC-WiMUST

2015-2018



H2020-ICT-2014-1/ GA 645141 **WIMUST**: Widely Scalable Mobile Underwater Sonar Technology, 2015-2018

# Marine Science, Technology, and Society - why the effort?

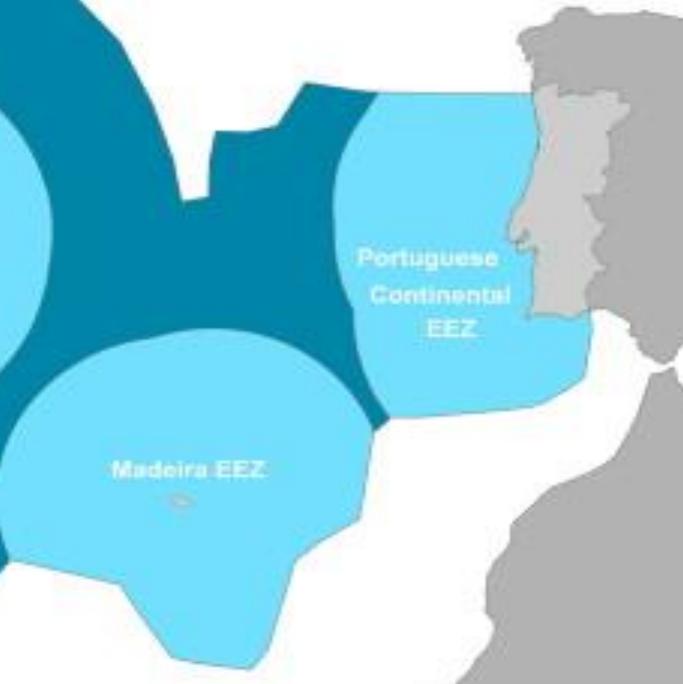
## Ocean Exploration and Exploitation (OEE)

- Fisheries and Aquaculture
- Genetic and Living Resources
- Mineral / Hydrocarbon / Oil & Gas Exploitation
- Offshore and Wave Energy Harvesting
- Environmental Monitoring
- Critical Infrastructures Inspection
- Maritime Logistics

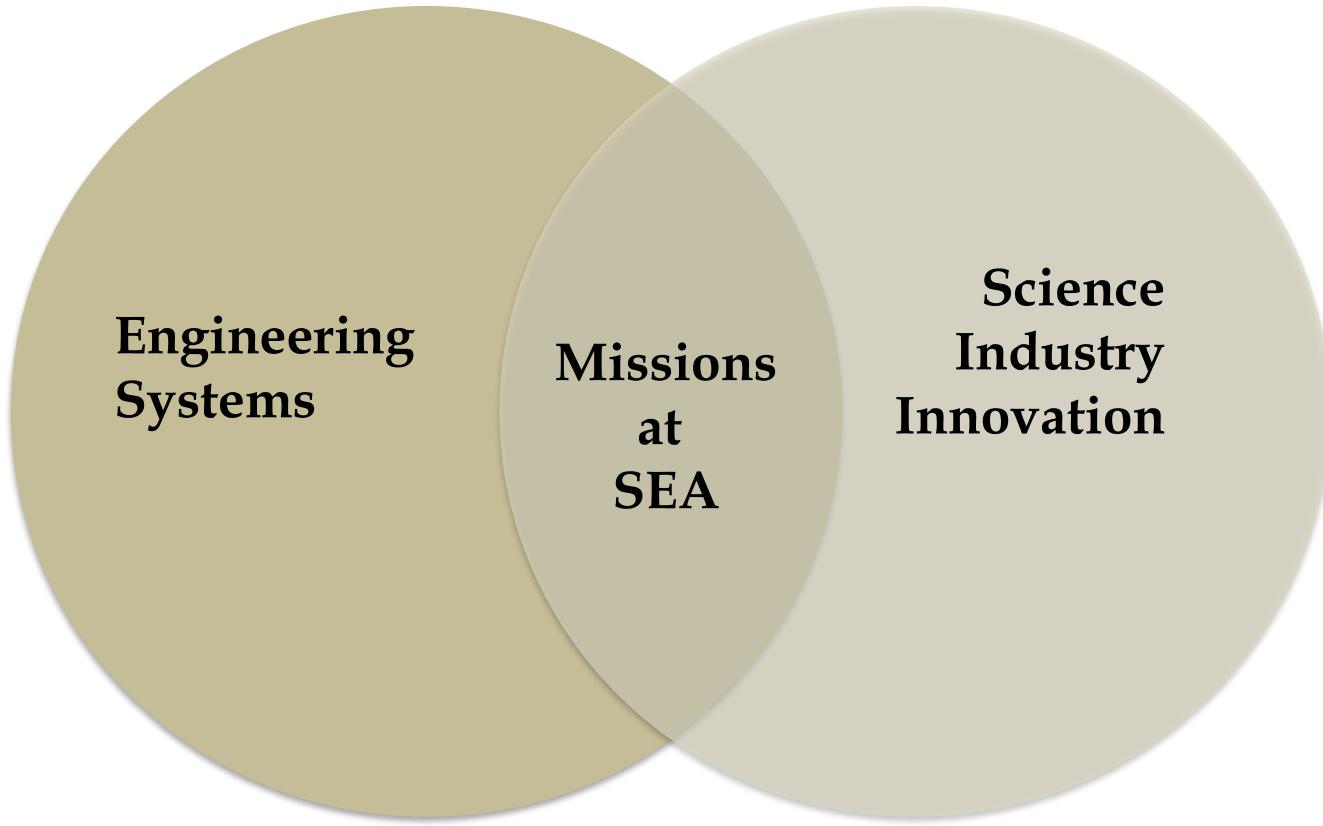


Portugal (an example)

- Exclusive Economic Zone
  - Extended Continental Shelf
- 4 million km<sup>2</sup>  
91 % of EU territory (land)



# The Pillars of Ocean Exploration and Exploitation<sup>11</sup>

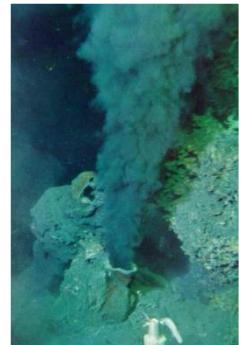
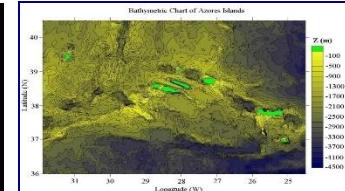
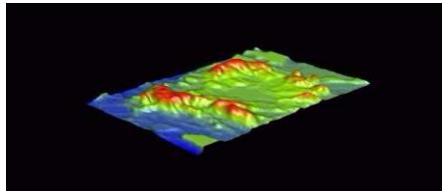
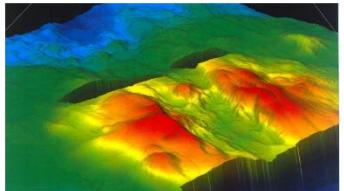
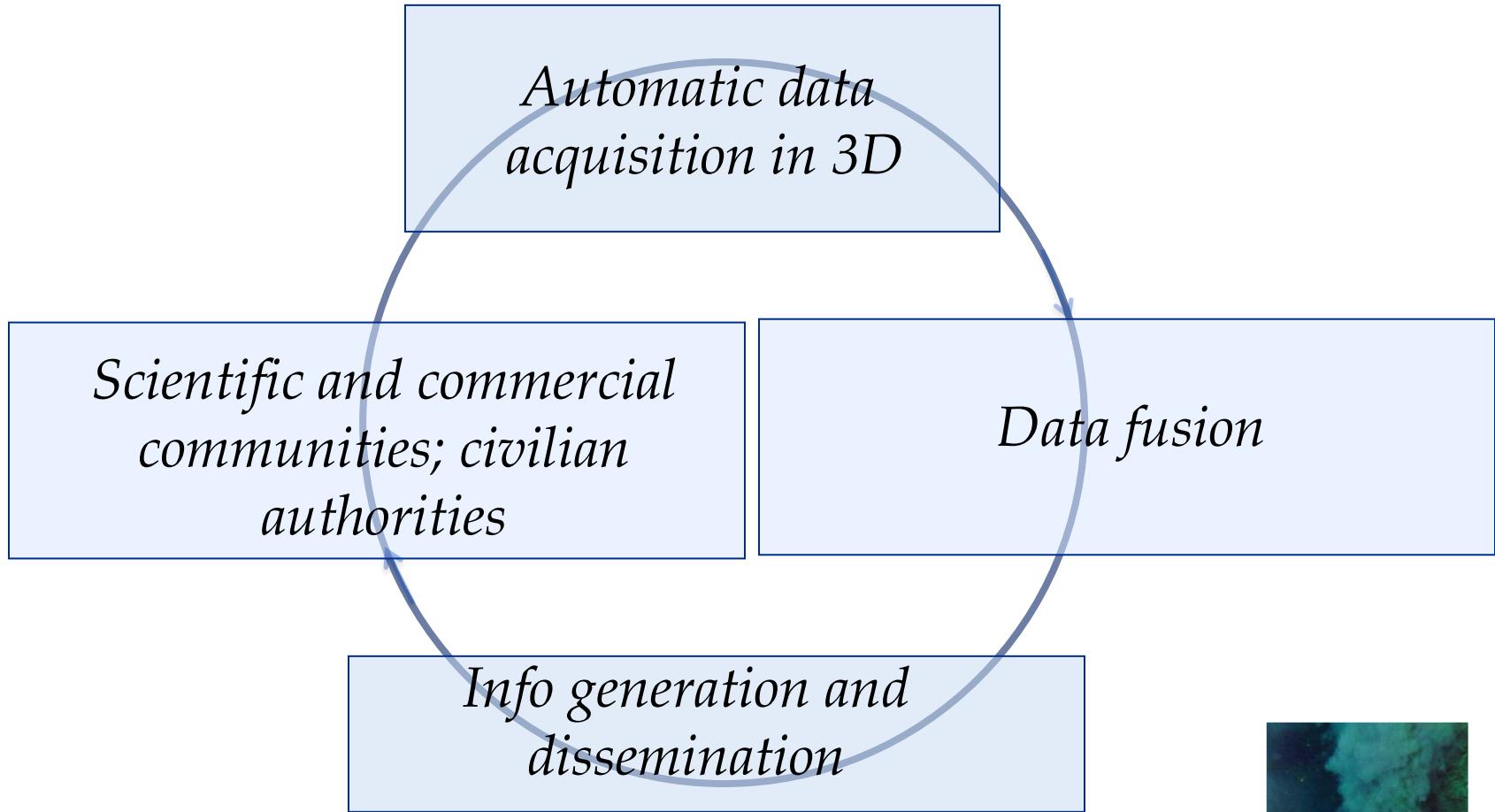


*I - Engineering Systems - Technology  
II - Science, Industry, Innovation*

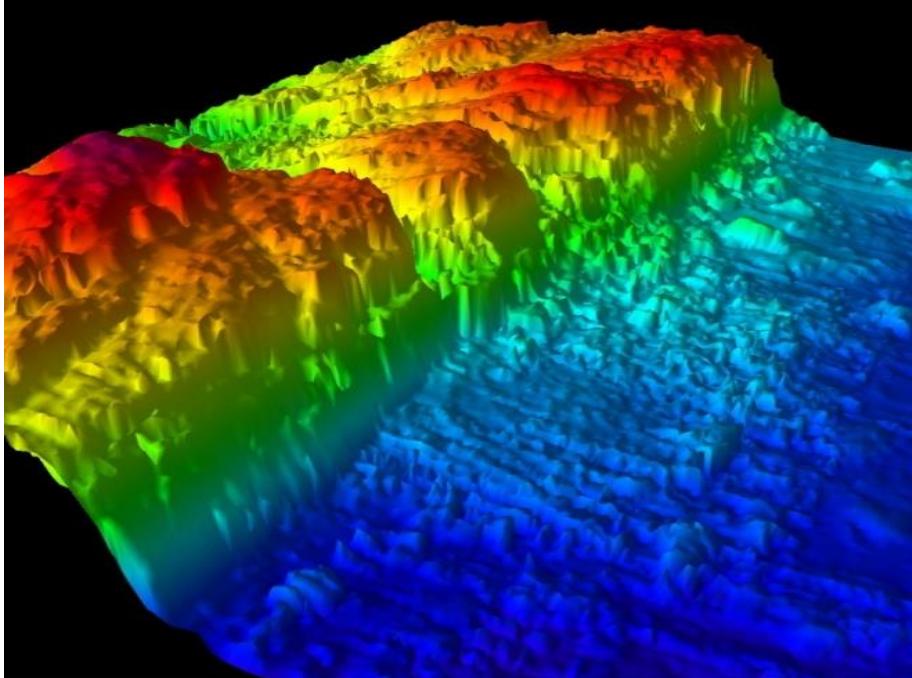
**Knowledge Transfer, Outreach Activities**



# Technology for Science, Industry, and Management



# Scientific Challenges



To study the  
Physical,  
Chemical,  
Biologic,  
and Geologic

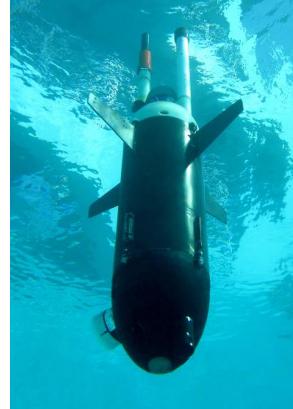
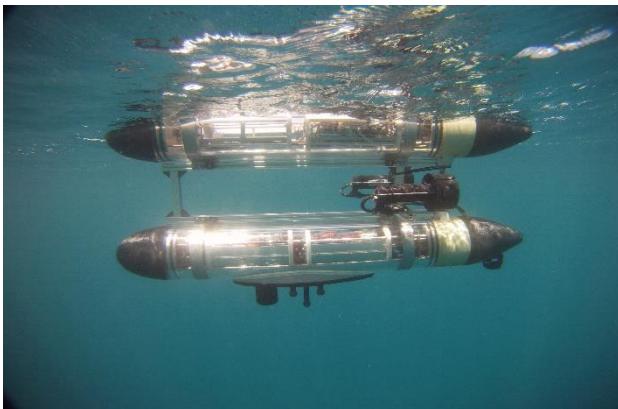
phenomena  
that occur in the ocean  
and its interfaces  
(with the atmosphere  
and the Earth's  
interior)

# Observe, Monitor, and Map

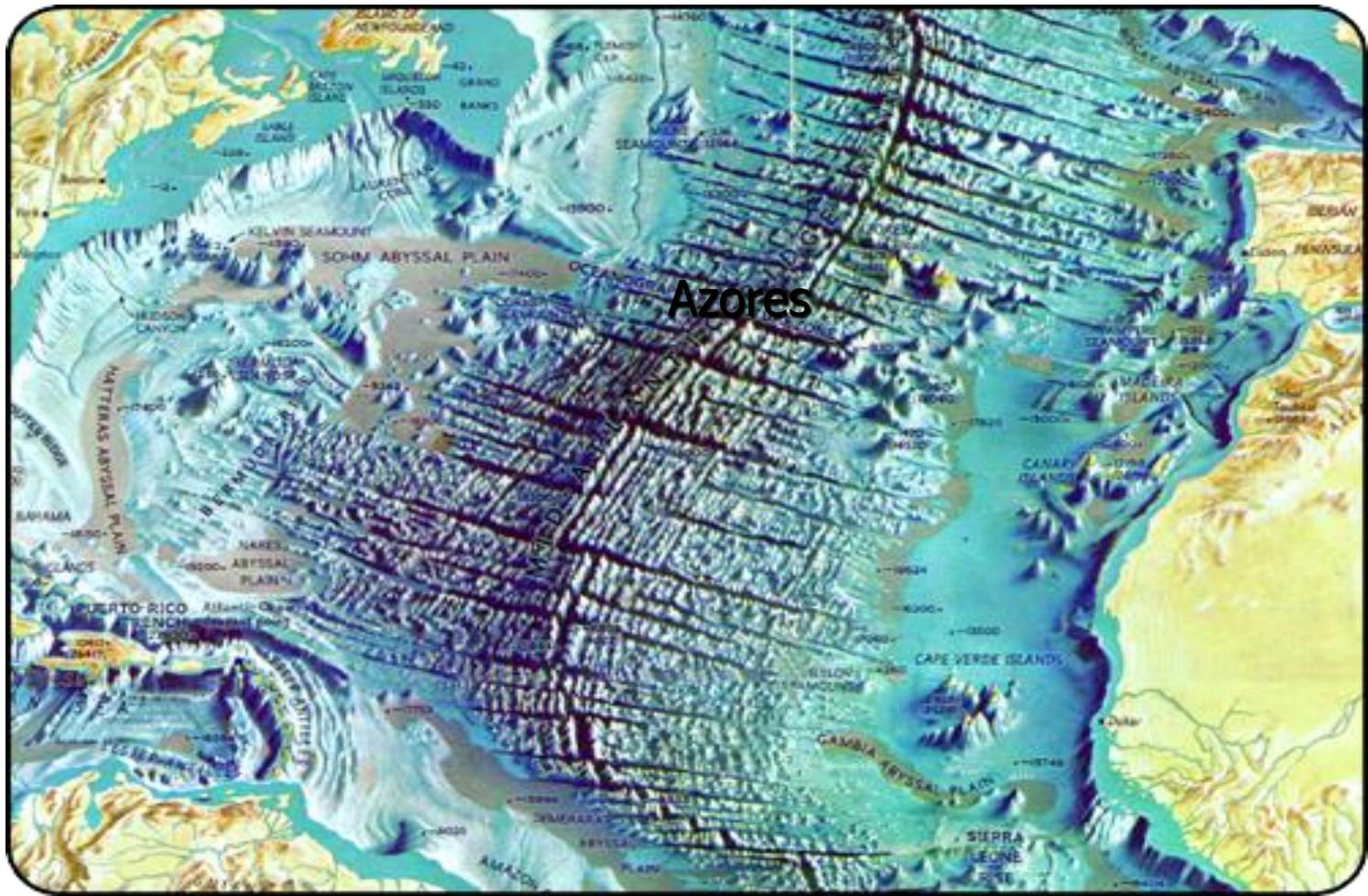


## The tools of the trade

- Technologies for ocean exploration including networked air and marine robots
- Robotic systems for the inspection of critical marine infrastructures and seabed/subbottom mapping



# The Middle Atlantic Ridge and the Azores

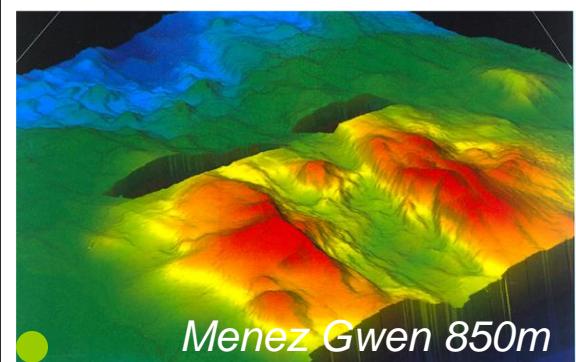
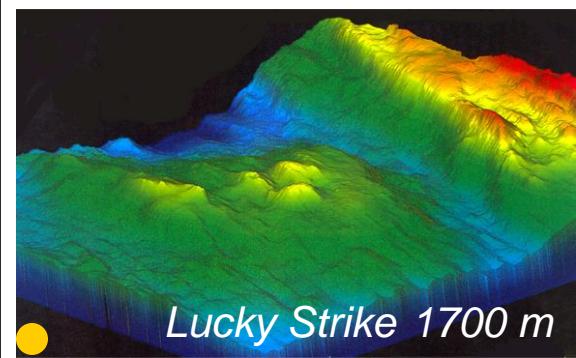
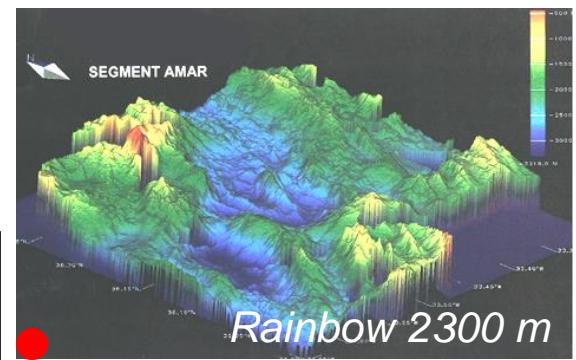
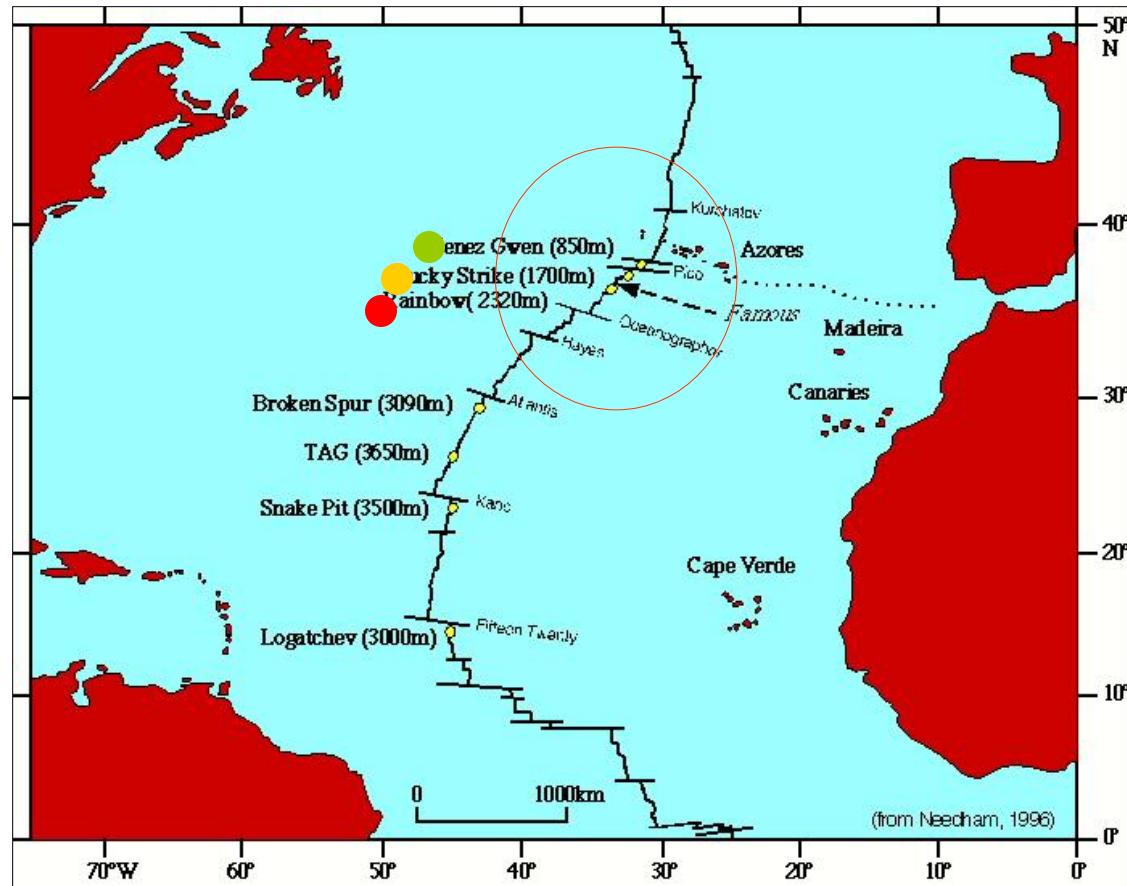


A chain of mountains at the bottom of the Atlantic ocean

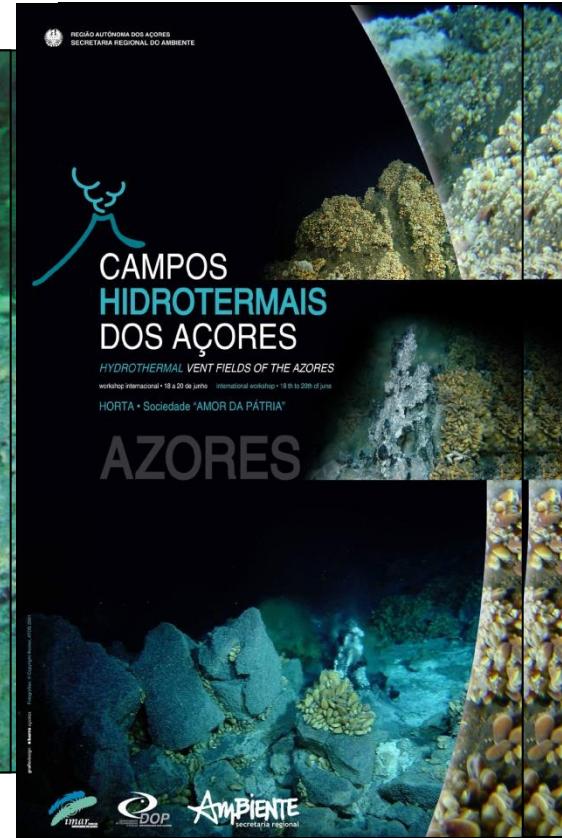
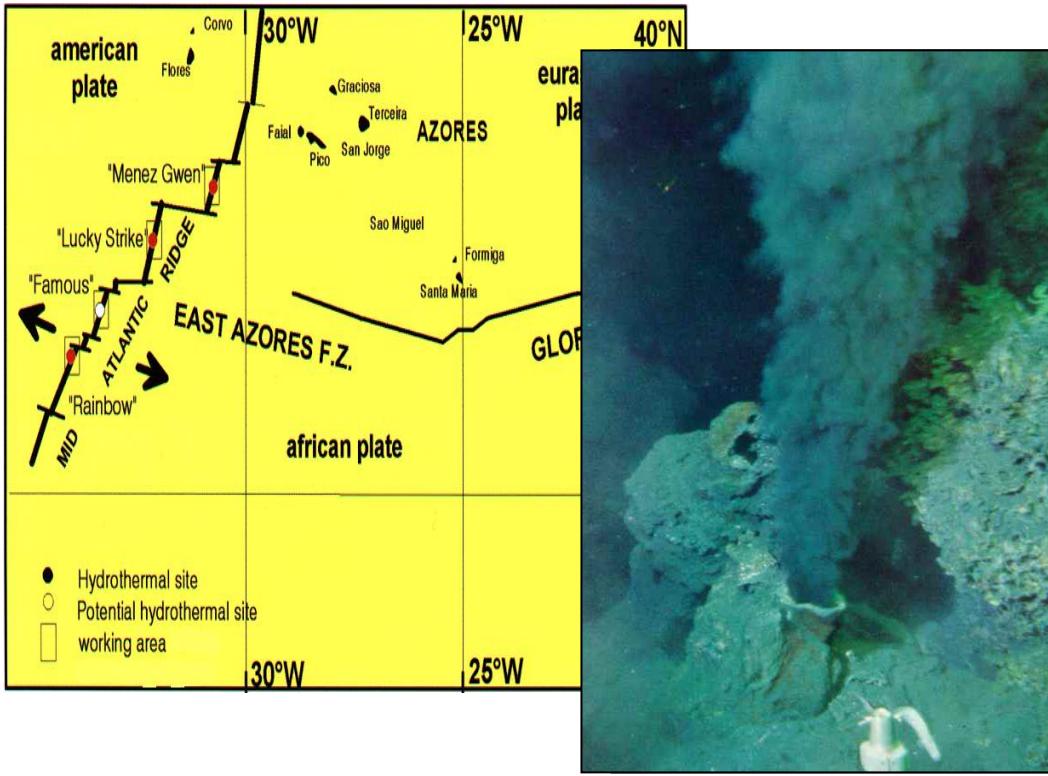


# Mission Scenario

## Underwater Hydrothermal Vents (Azores, Portugal)



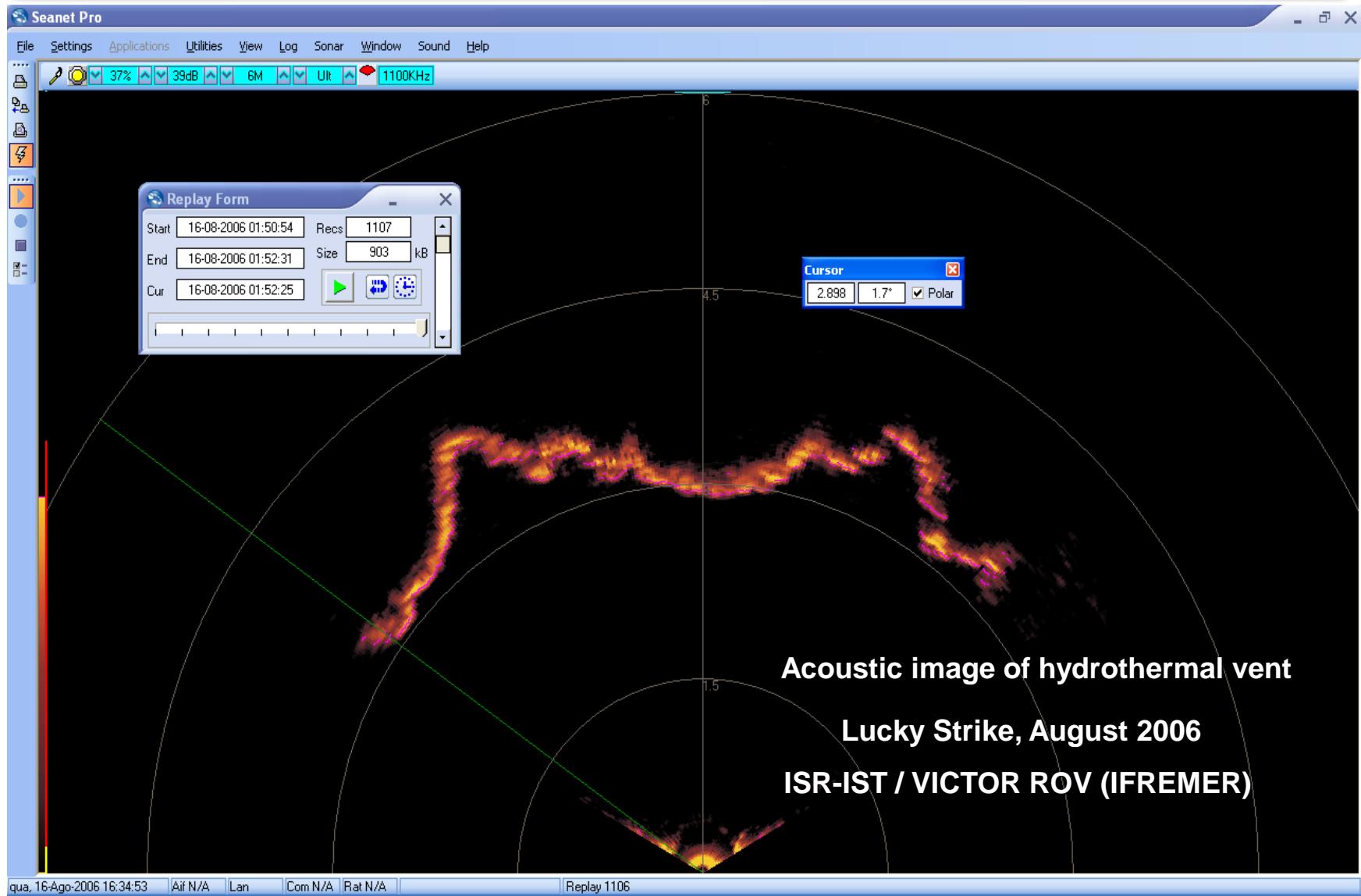
# The Azores Triple Junction (ATP)



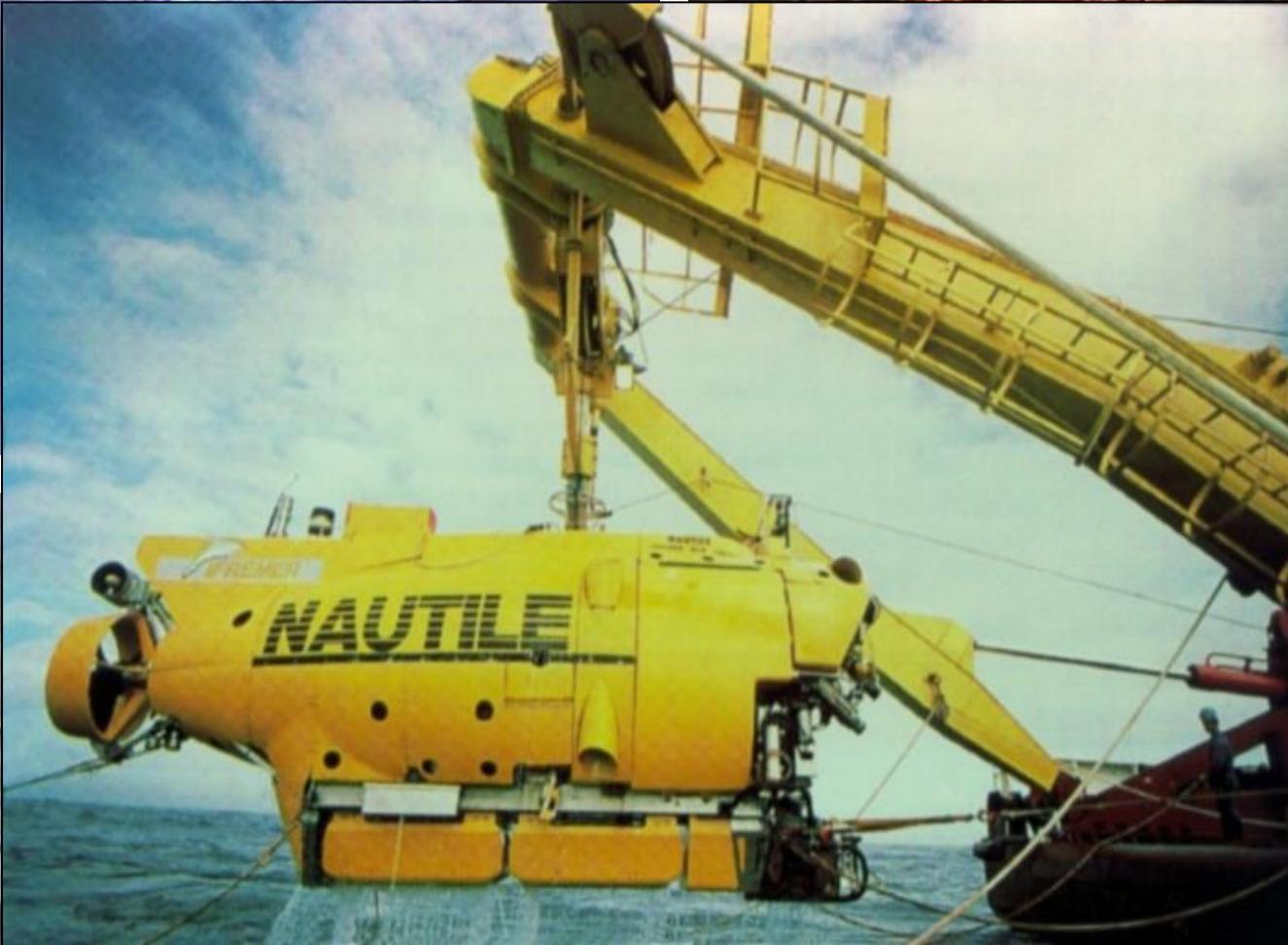
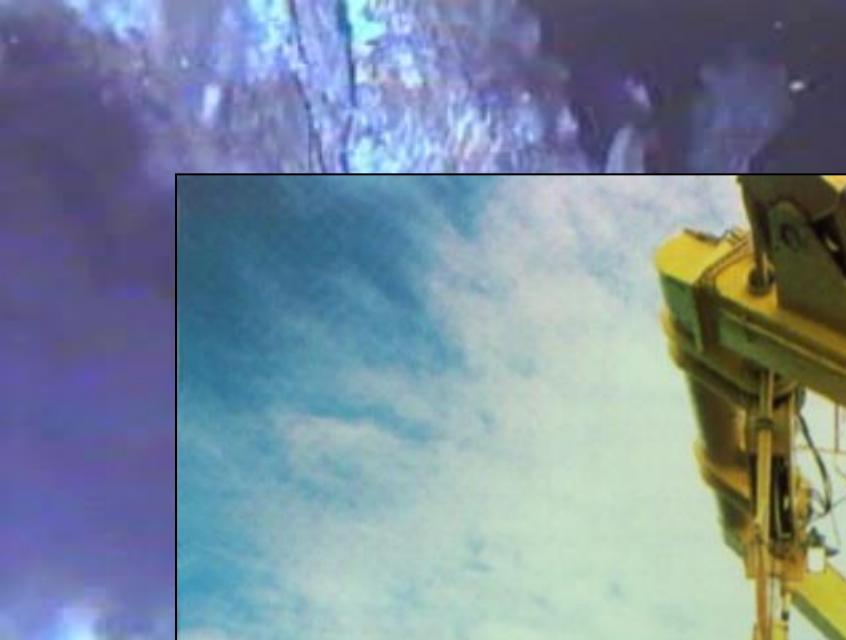
The region harbours a great variety of seamounts, active underwater volcanoes, chemosynthetic ecosystems, and “extreme” life forms (*extremophyles*)

# Underwater Hydrothermal Vents

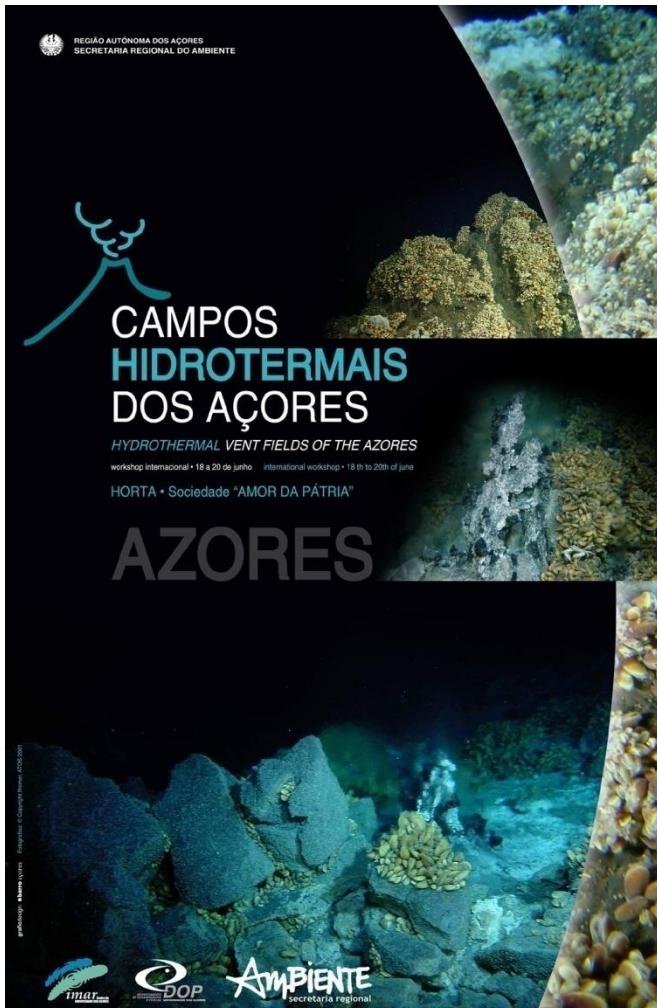
# Deep Water Hydrothermal Vents



# Underwater Hydrothermal Vents



## The Need for Technology



Vents are very hard to study:

*Large depth (pressure is high)*

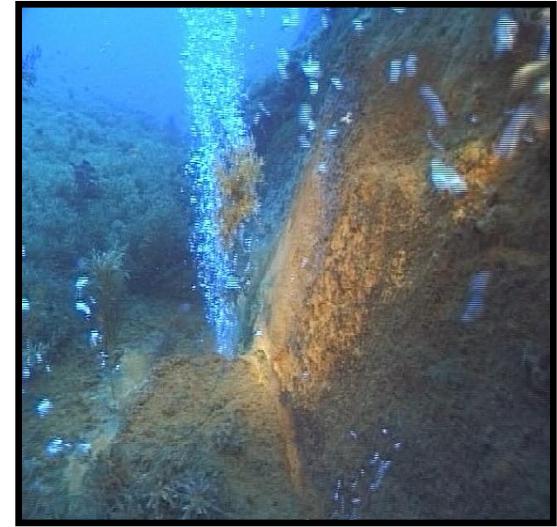
*Highly corrosive environment*

*Lack of optical visibility*

*Navigation is a challenge (lack of a GPS-like system)*

*Submersibles: place human lives at risk*

# Shallow Water Hydrothermal Vents



Hydrothermal activity at  
the D. João de Castro  
seamount  
Azores, PT

# Single Agent Operations: shallow water



No humans on board, please



Use an Autonomous Surface Vehicle to MAP the seafloor



# Mapping the seabed with an ASV

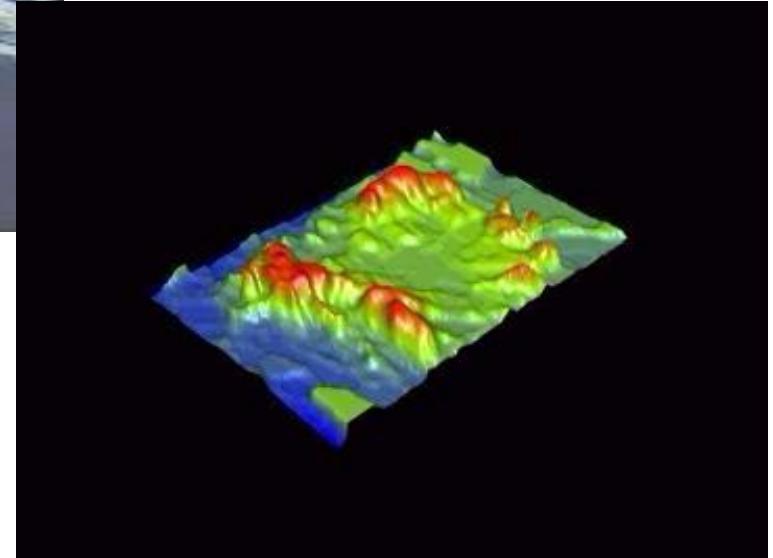


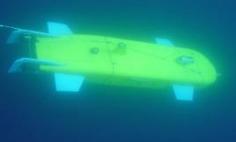
**Systems in place:**  
*Navigation, Guidance and Control for Path Following*

**Navigation: GPS**

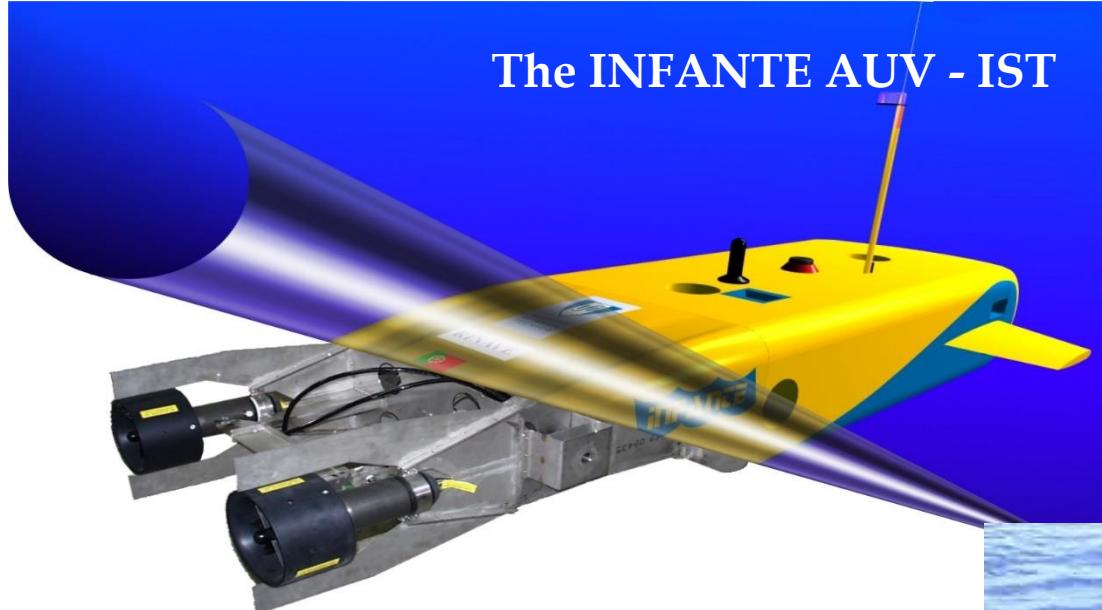
**Comms: radio**

**Path following:**  
Inner-outer loops for accurate tracking in the face of ocean currents and wind.





# Go deeper with an AUV



**Navigation:**  
Dead-reckoning  
(AHRS and Doppler unit)

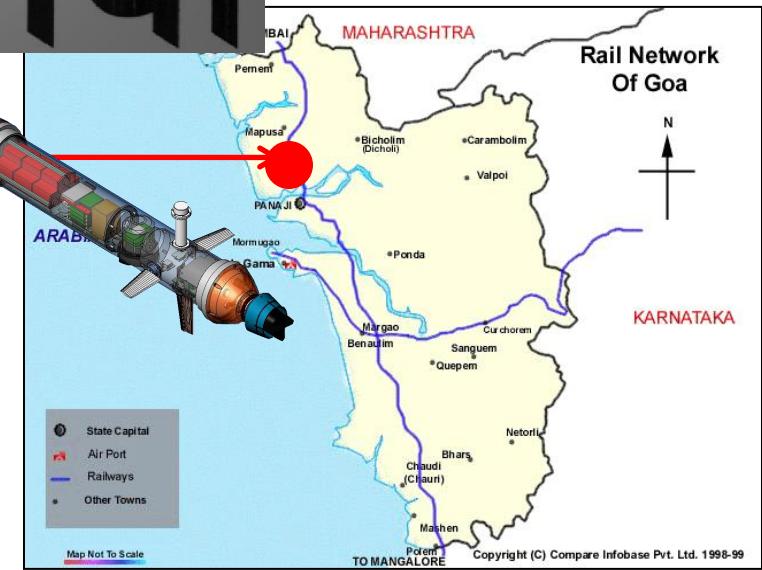
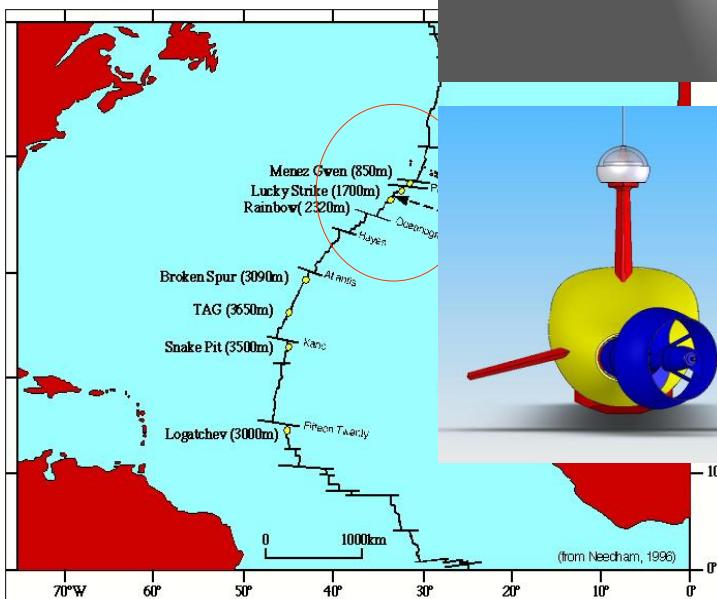
**Comms:** acoustic

**Systems in place:**  
*NGC for*  
• *Path Following in 3D*  
• *Altitude Control*  
*Mapping sensor suites*

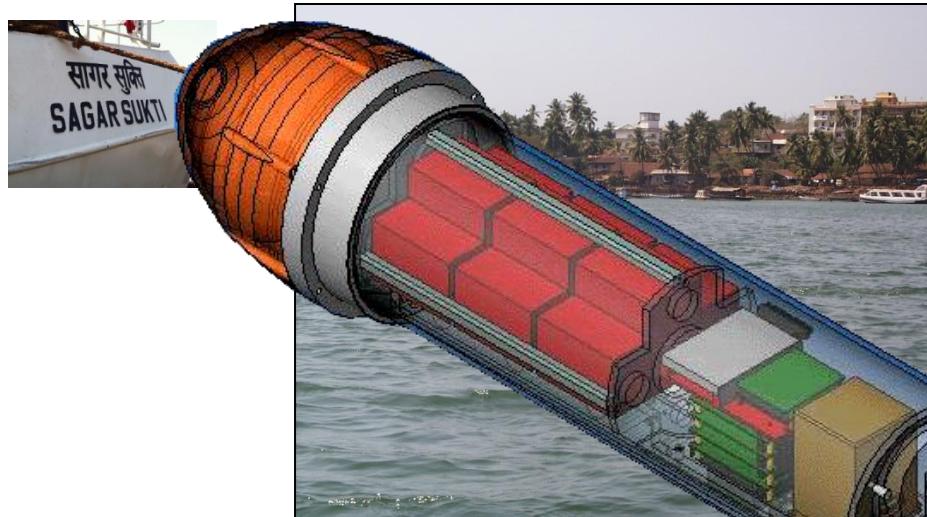


# Cooperation with Goa (NIO)

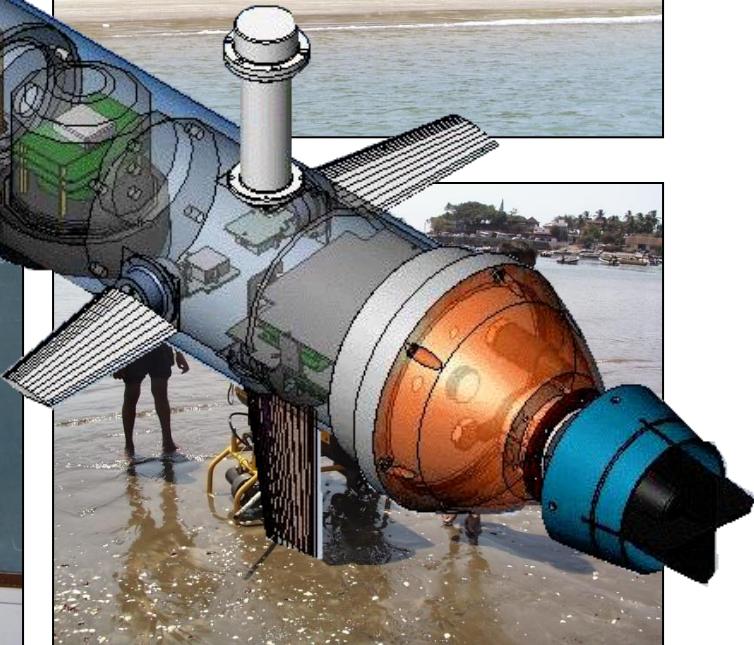
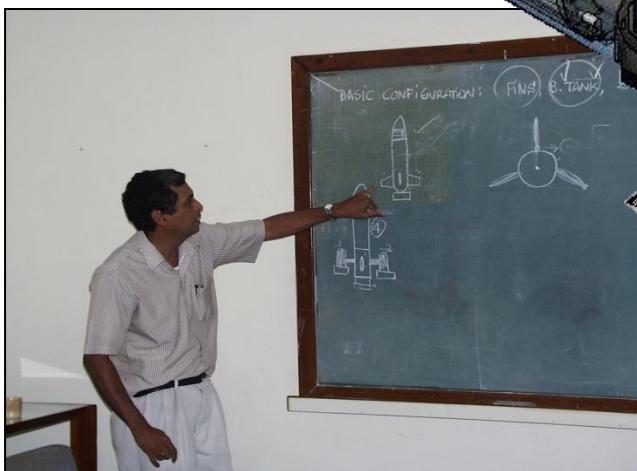
**Meeting IN-PT  
(since 1999)**



# The MAYA AUV - IST/NIO

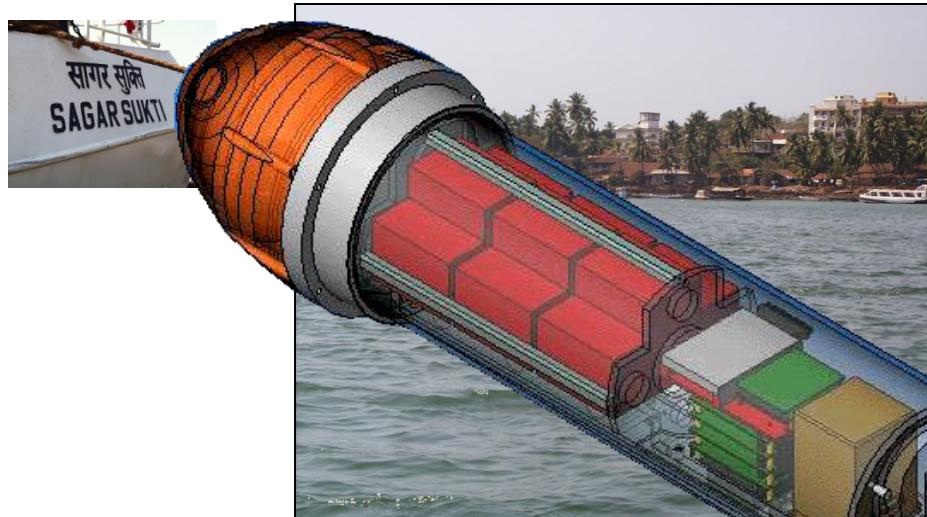


*MAYA-Sub  
work and  
tests in  
India*

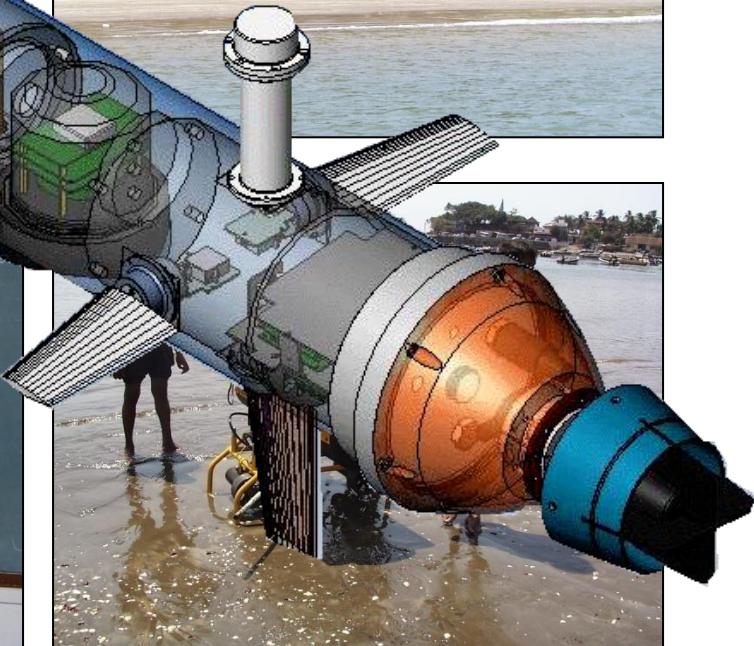
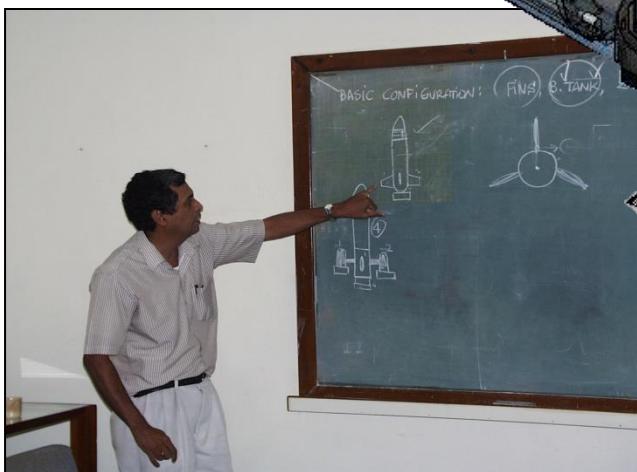


*Interchange of Researchers PT-INDIA; co-project via Web*

# The MAYA AUV - IST/NIO



*MAYA-Sub  
work and  
tests in  
India*



*Interchange of Researchers PT-INDIA; co-project via Web*

# Cooperation with India (NIO and NIOT)



*Work and tests in India*



**Maya**  
**माया**

*Amthnem, Goa*

# Cooperation with India (NIO and NIOT)



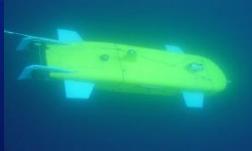
# Cooperation with India (NIO and NIOT)



India - Portugal



**Maya**  
माया



# Penetrating the Deep Sea

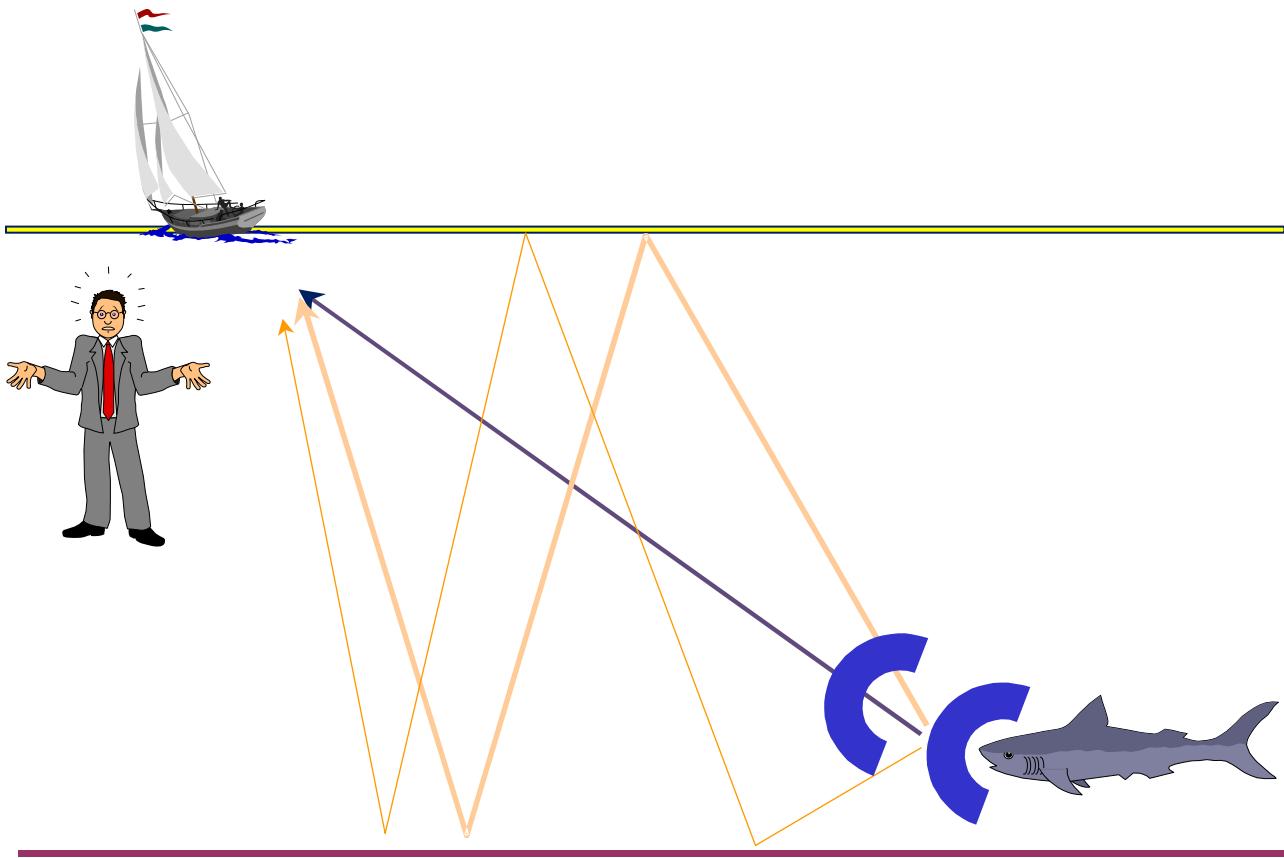
## Challenges

- Tremendous pressure
- Highly corrosive environments
- Lack of optical visibility
- Navigation is exceedingly hard (no GPS)
- Low acoustic communication bandwidth (32kb/s)



# Opening the multiple vehicle frontier

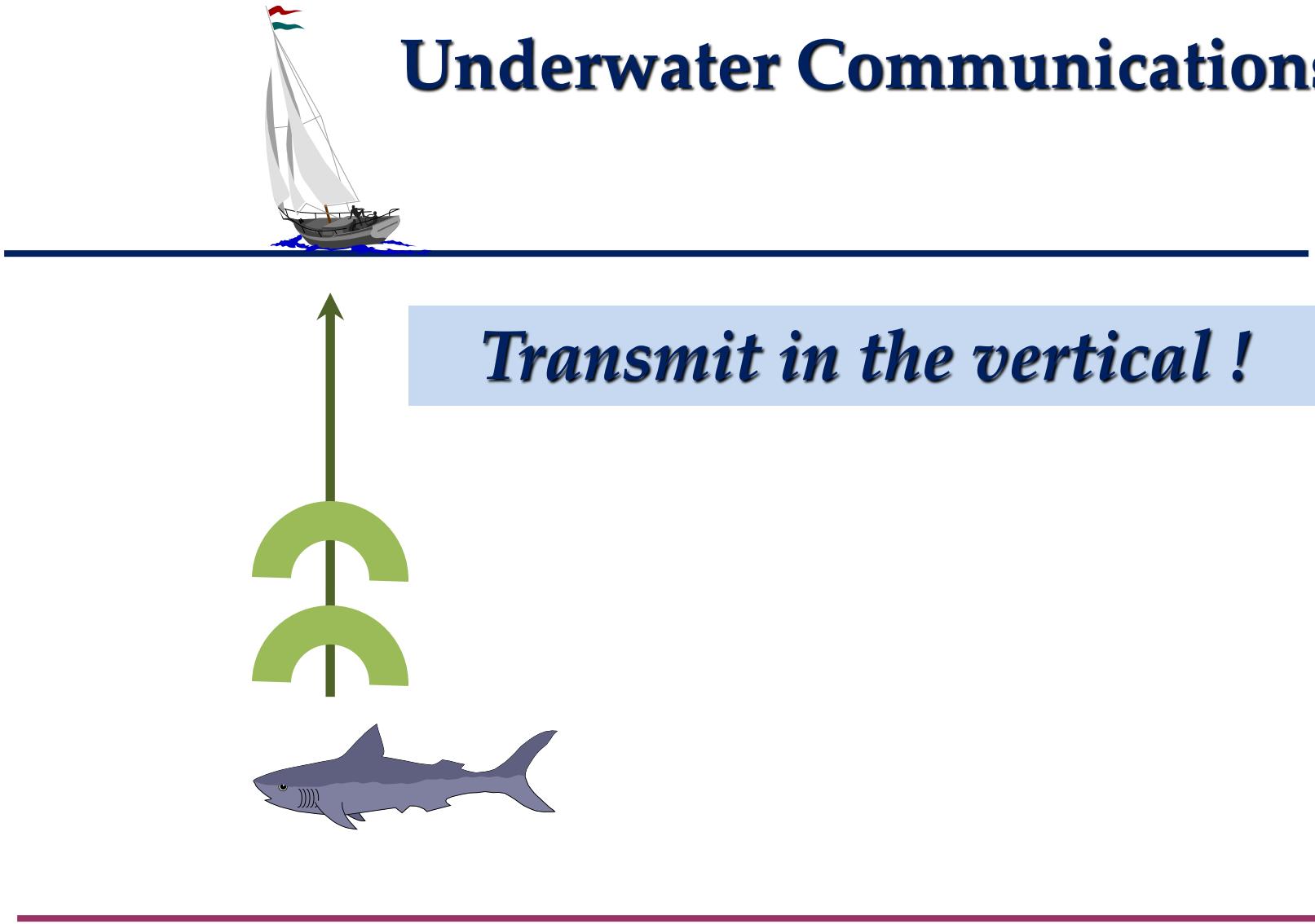
**Underwater Communications - *very hard!***



# Opening the multiple vehicle frontier

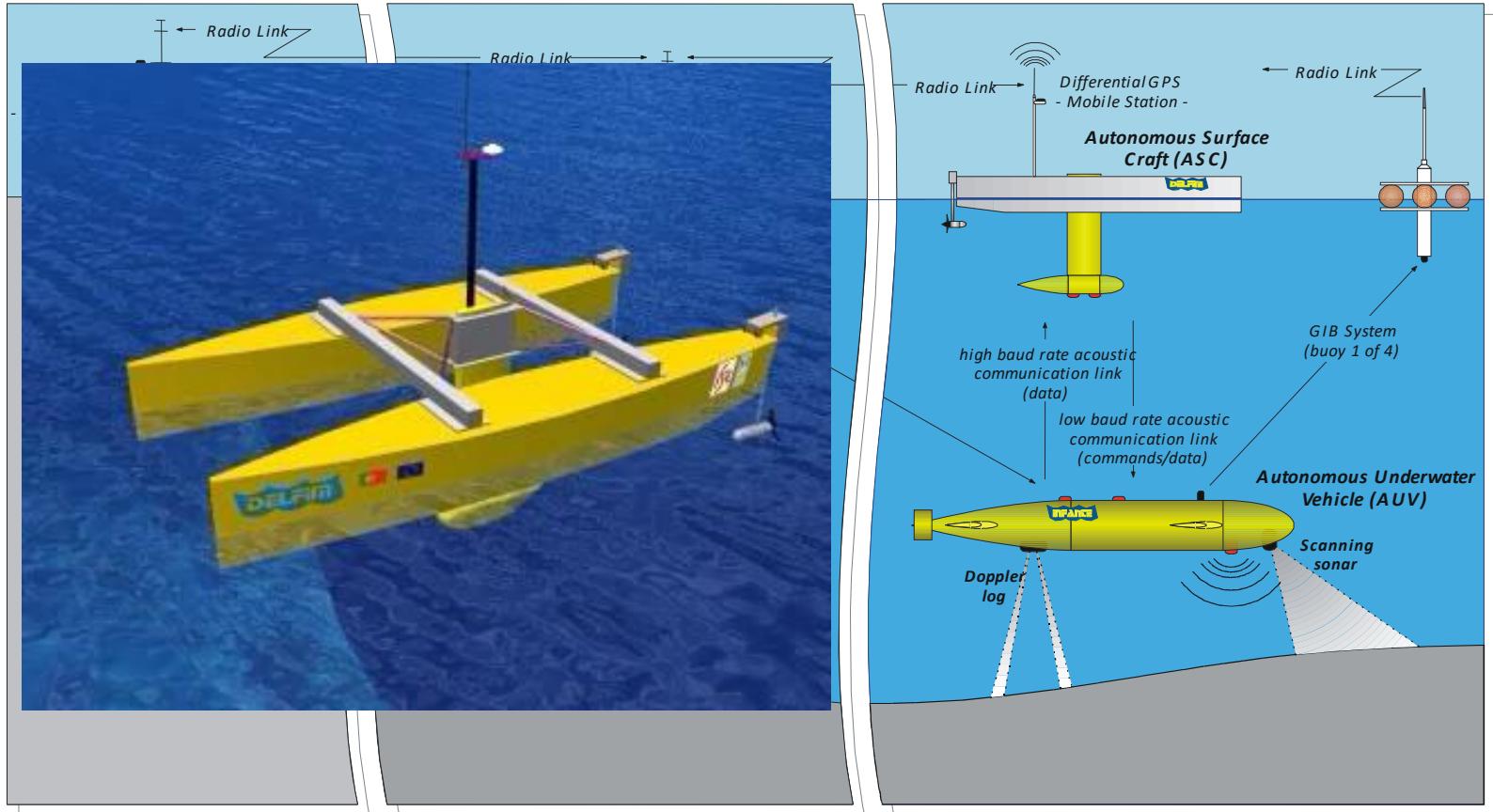
Multiple vehicle operations: the turning point

## Underwater Communications



# Multi-vehicle operations

*The ASIMOV concept (ASIMOV project, EC – 2000) – PT, FR, UK*



*Difficulties: no reliable comms, miniaturized acoustic positioning systems, and tools for seamless implementation of Motion and Mission Control systems (ROS was not born yet!)*

# Neworked Systems : a New Era (2009 - )

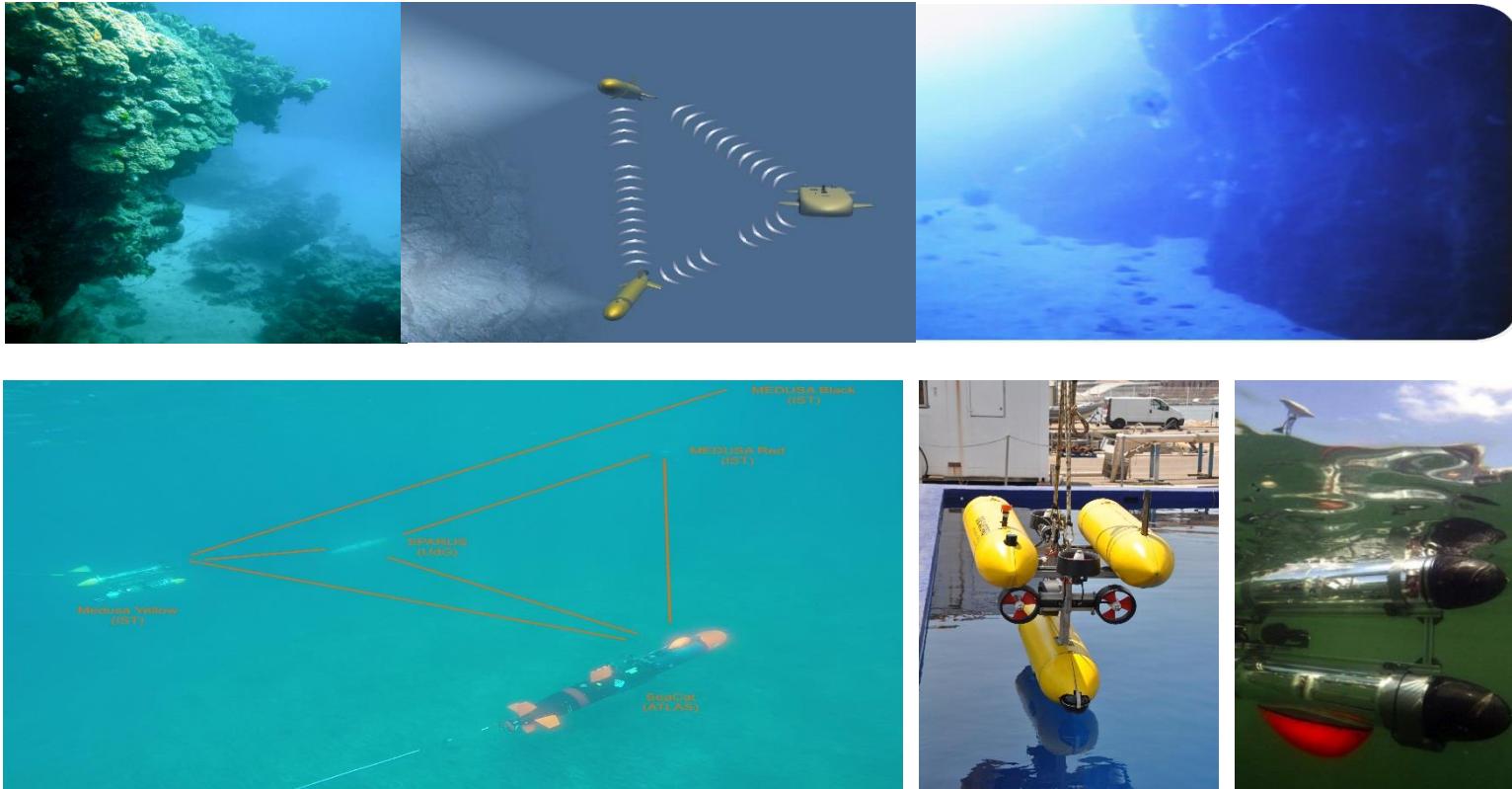


**Miniaturized USBL + Ranging Device + Acoustic Modems  
[Evologics, Germany]**

*and Control*

# MORPH / EC (2012-2016)

## Cooperative Marine Robots for Marine Habitat Mapping in Complex Underwater Environments: A New Paradigm



**ATLAS ELEKTRONIK**  
A joint company of ThyssenKrupp and EADS



Universitat  
de Girona

**ifremer**

**TÉCNICO**  
LISBOA

**JACOBS**  
UNIVERSITY

**Consiglio**  
Nazionale delle  
Ricerche

**th**  
TECHNISCHE  
UNIVERSITÄT  
ILMENAU

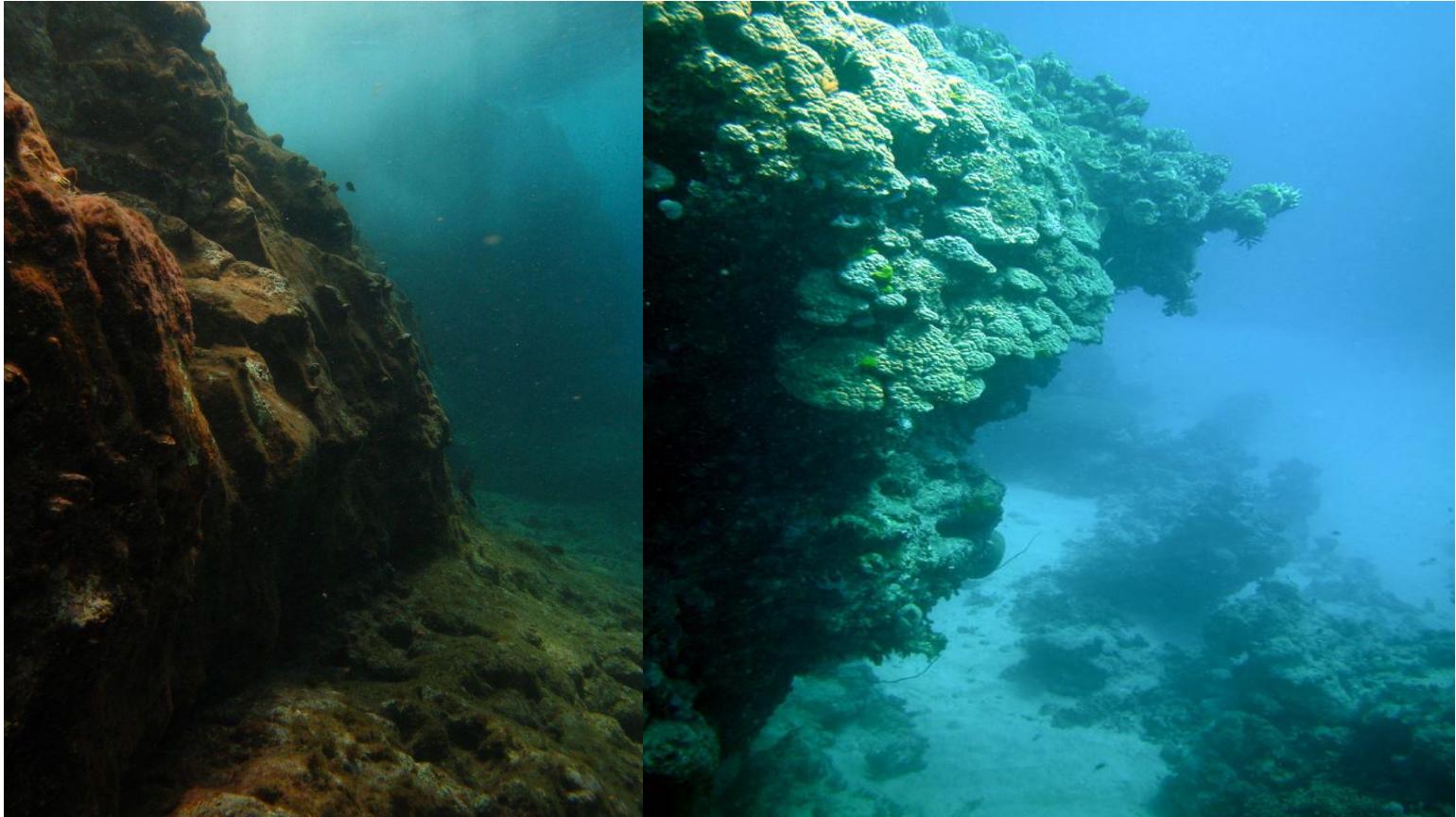
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PORTUGUÊS  
DE  
PESQUISAS  
**DOP**  
DEPARTAMENTO  
DE  
PESQUISAS  
E  
PESCA  
UNIVERSIDADE DOS AÇORES

**S&I**  
organization  
**CMRE**



# MORPH / EC (2012-2016)

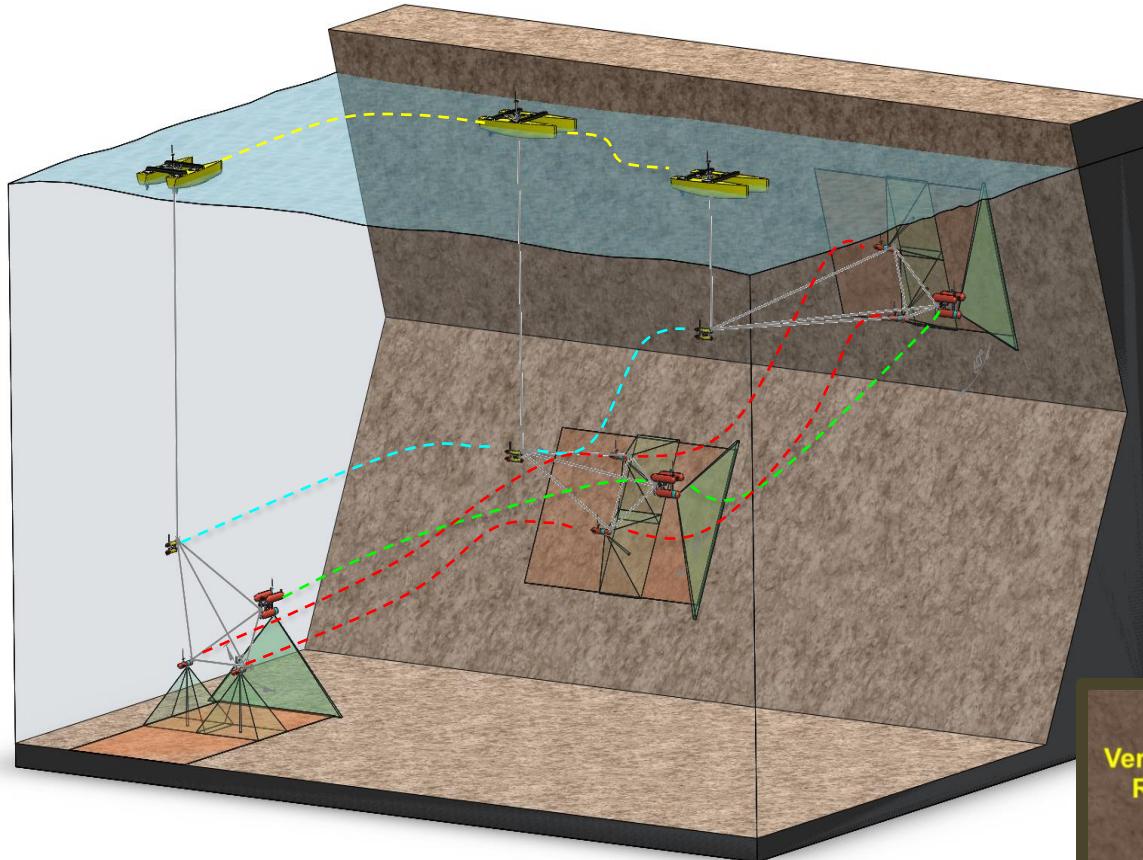
## Habitat Mapping in complex 3D environments



Underwater cliffs, canyon walls, fracture zones, seamount flanks, hydrothermal chimneys

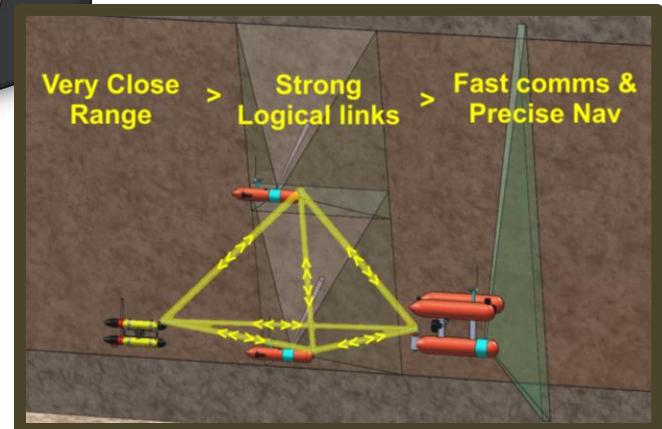
# MORPH / EC (2012-2016)

The EC MORPH project

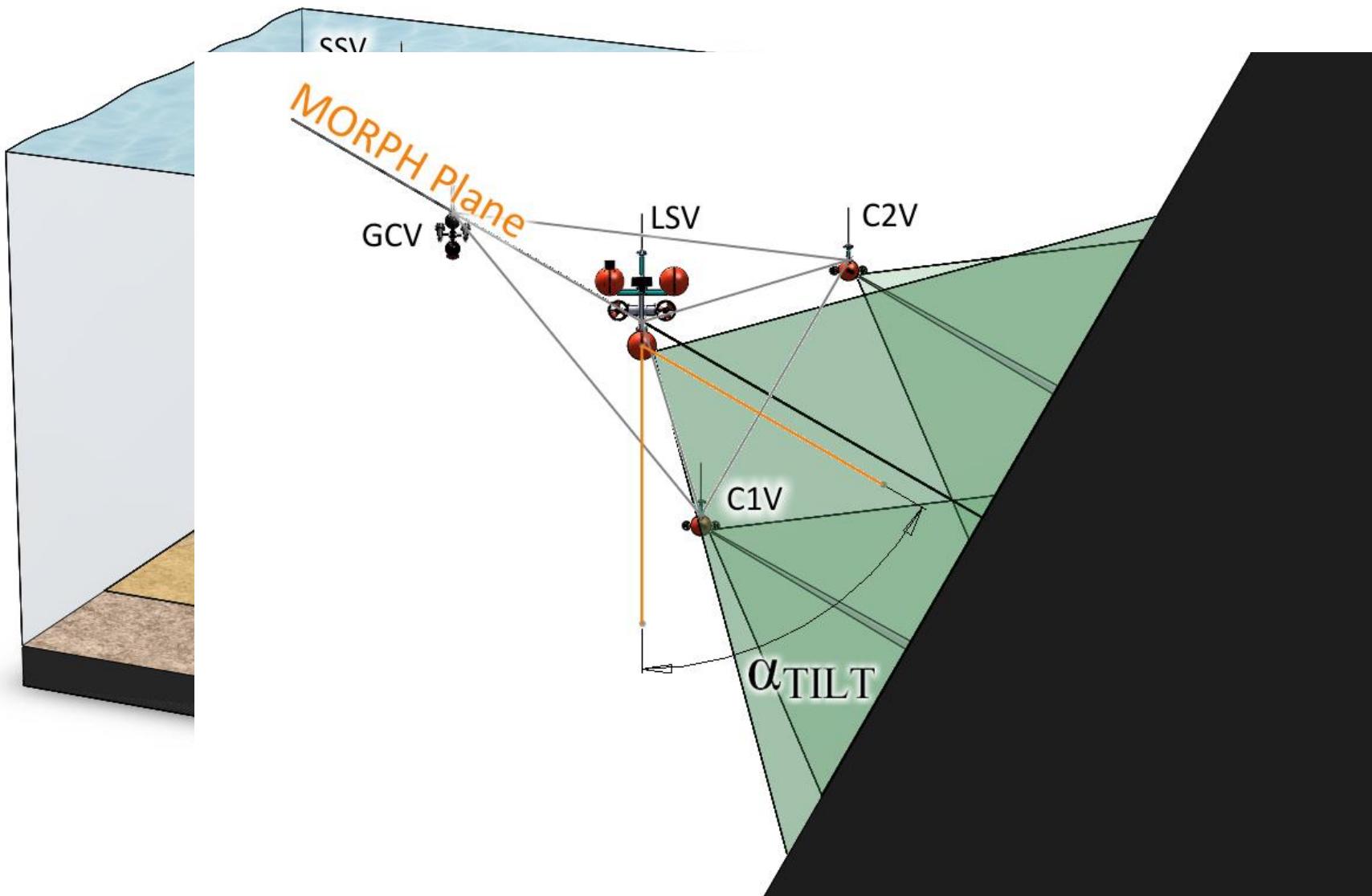


**Key MORPH concept:**  
*a self-reconfiguring robot for operations in complex 3D marine environments*

A team of agents  
operating as a  
virtual super  
marine vehicle

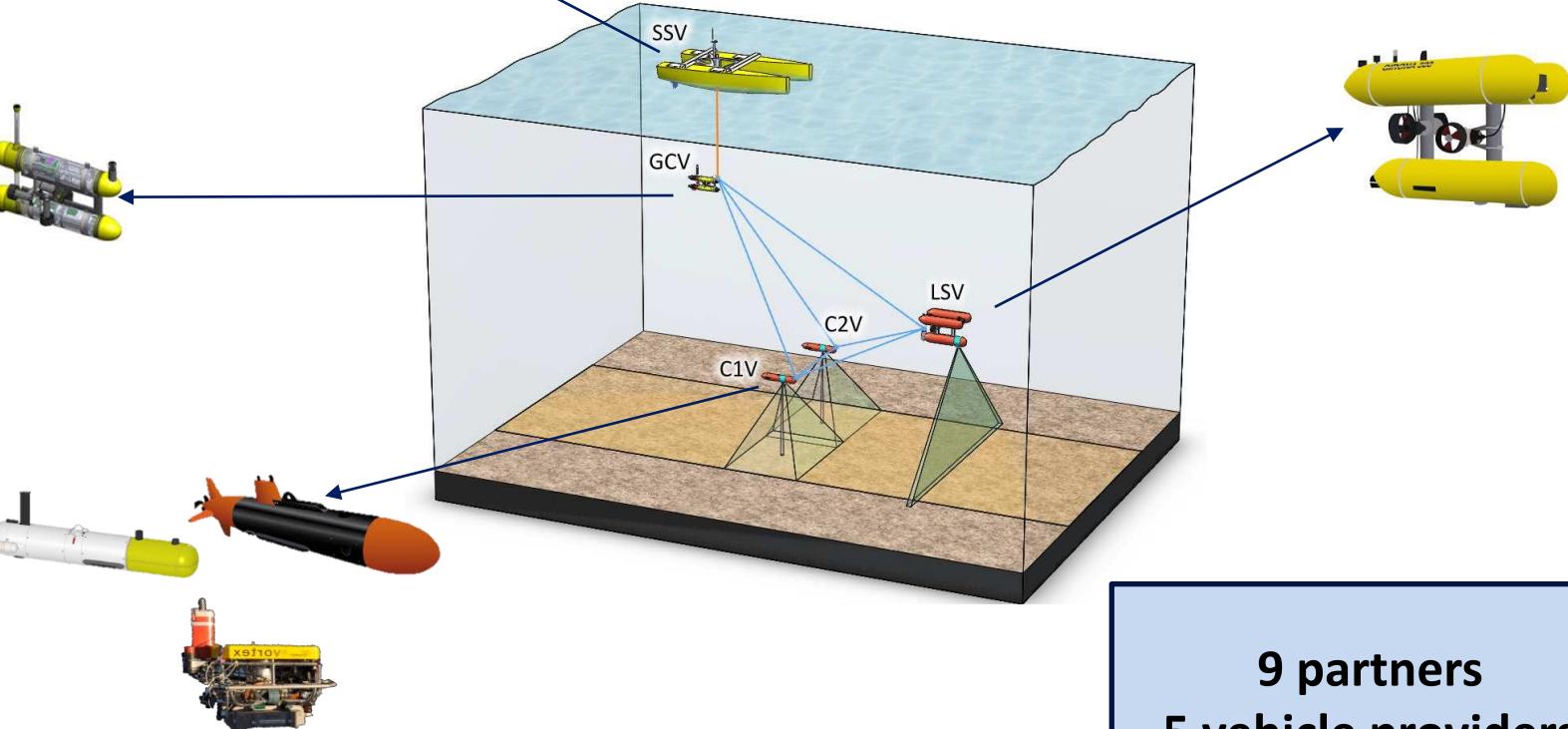


# The adaptive MORPH configuration





# MORPH Vehicles



9 partners  
5 vehicle providers



ATLAS ELEKTRONIK  
A joint company of ThyssenKrupp and EADS

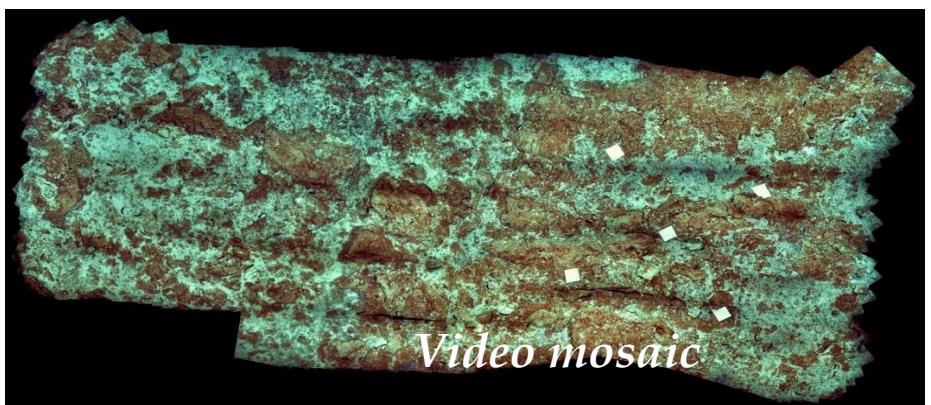
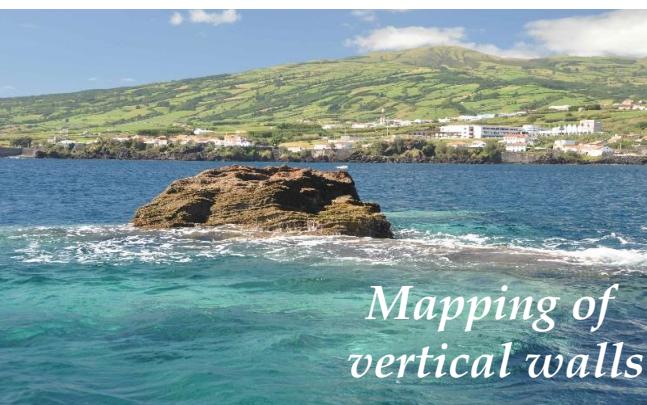


# MORPH / EC (2012-2016)

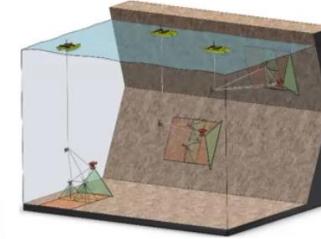
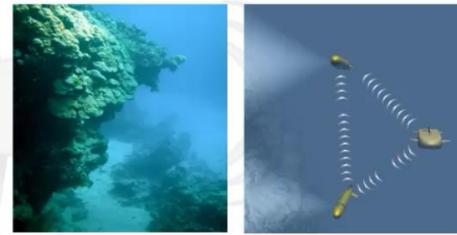
Cooperative Marine Robots for Marine Habitat Mapping  
in Complex Underwater Environments: A New Paradigm



*9 European partners*



# MORPH Azores, PT, 2014



**Marine robotics system of self-organizing  
logically linked physical nodes**

**Azores trials 2014**



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ATLAS ELEKTRONIK  
A joint company of ThyssenKrupp and EADS



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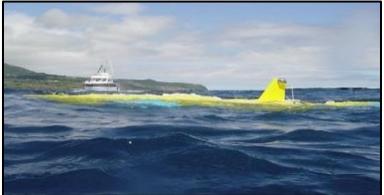
# MORPH Girona , SP, 2015



# Making it all happen: UAVs, AUVs, ASVS

*Transition from the Lab to the Real World*

through *in-house development of advanced systems and tools* (e.g. marine and air robots, software tools for operational oceanography).



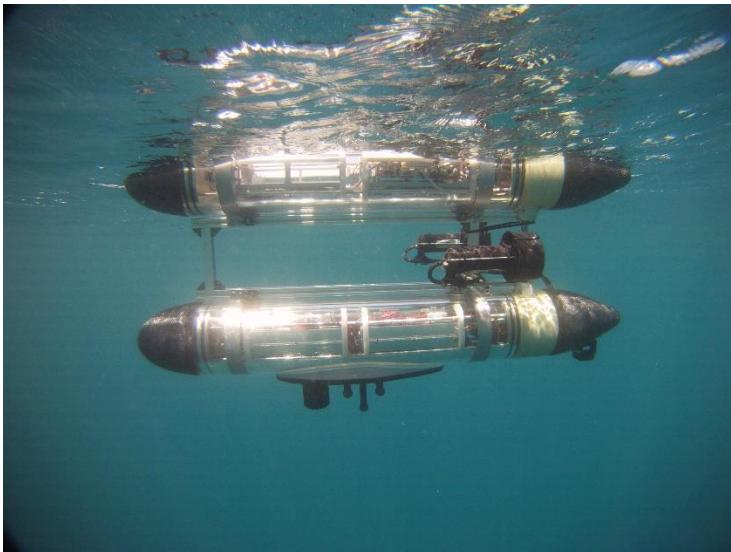
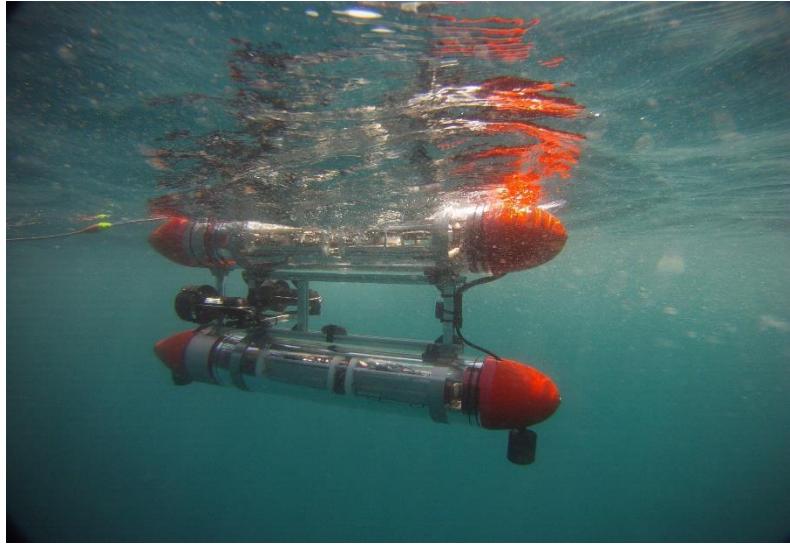
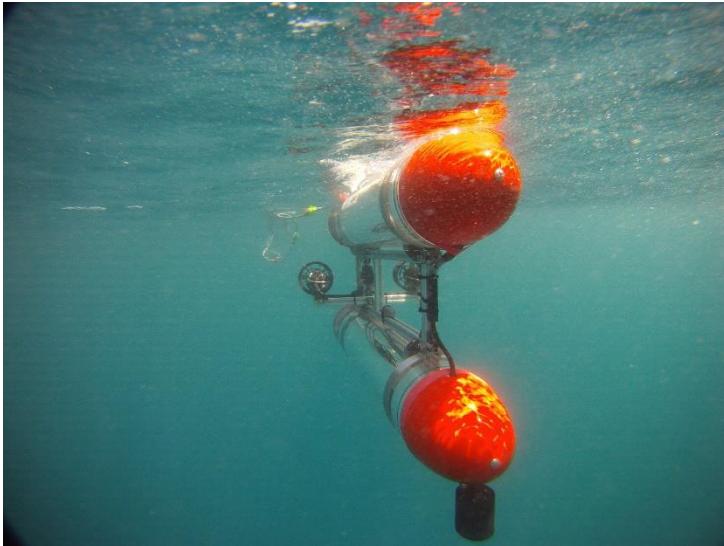
Fleet of 3 autonomous  
surface and  
4 underwater robots  
Several air vehicles



# The sea-going machines



# Labs and equipment



# The MEDUSA-class vehicles (AUV/ASV)



# Transportation and deployment



3 MEDUSAs can be transported in a van or small trailer



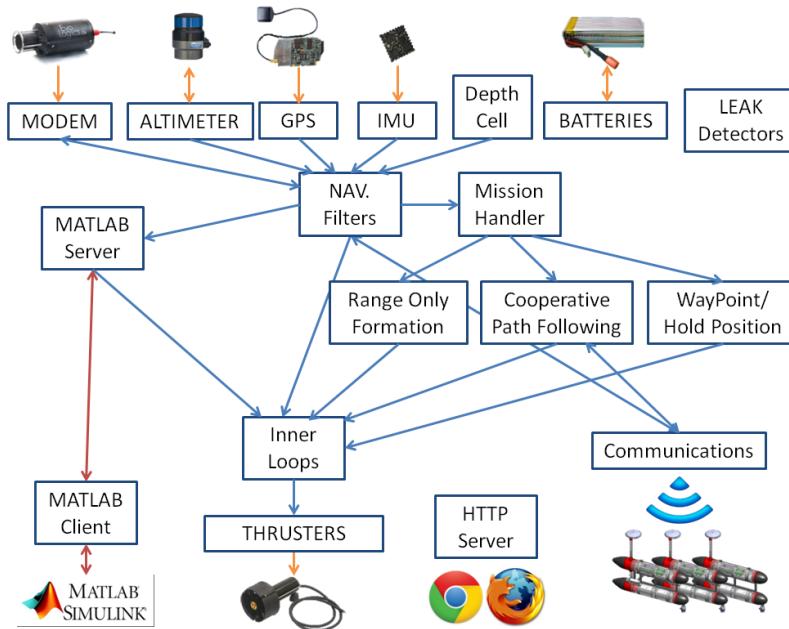
Transportation to water by a single person in a cart



The same cart can be used to deploy/recover the vehicle

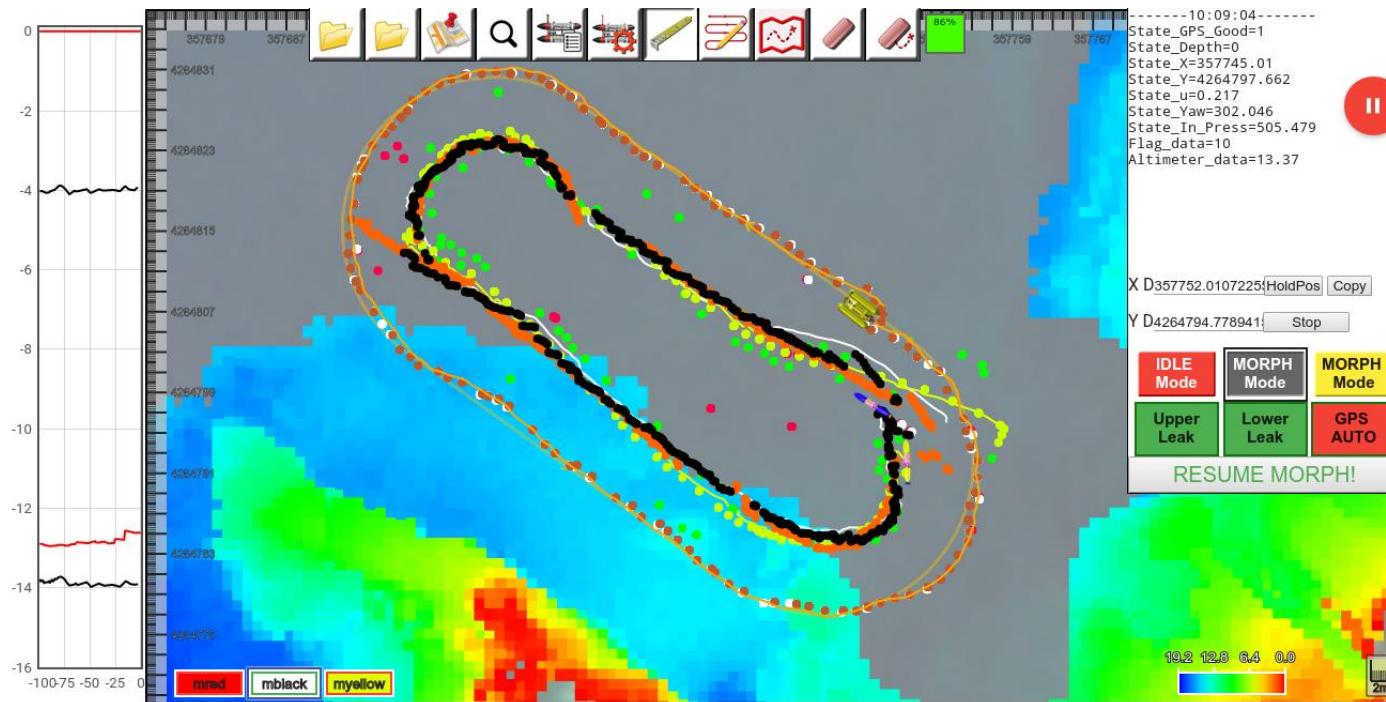
# Software architecture overview

- Built in **ROS** (Robot Operating System)
- Easy to extend: create *nodes* that *subscribe* to existing *topics* to obtain information, then *publish* to other *topics* related to lower-level features
- Lots of *packages* publicly available from the community



# Mission control console

- Browser-based: works in different OSs and browsers, adopting Google's *Material Design* guidelines – ongoing
- Enables operator to visualize vehicle positions in a map, monitor vehicle states, issue commands to vehicles
- Design/load complex missions or bathymetry data from files

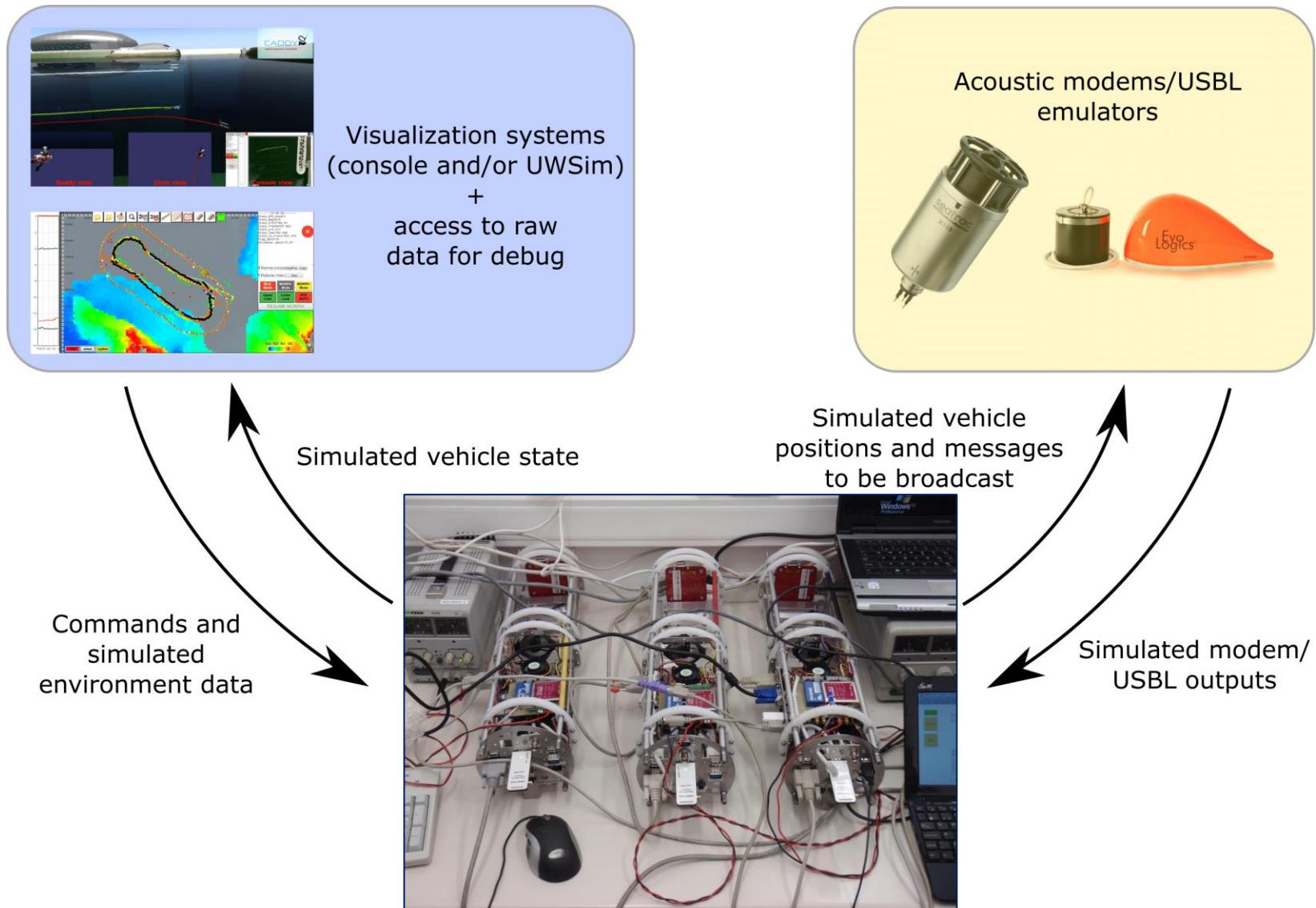


# Mission programming

- Draw missions containing complex shapes by connecting segments
- Can be exported and imported through mission files



# Simulation pipeline



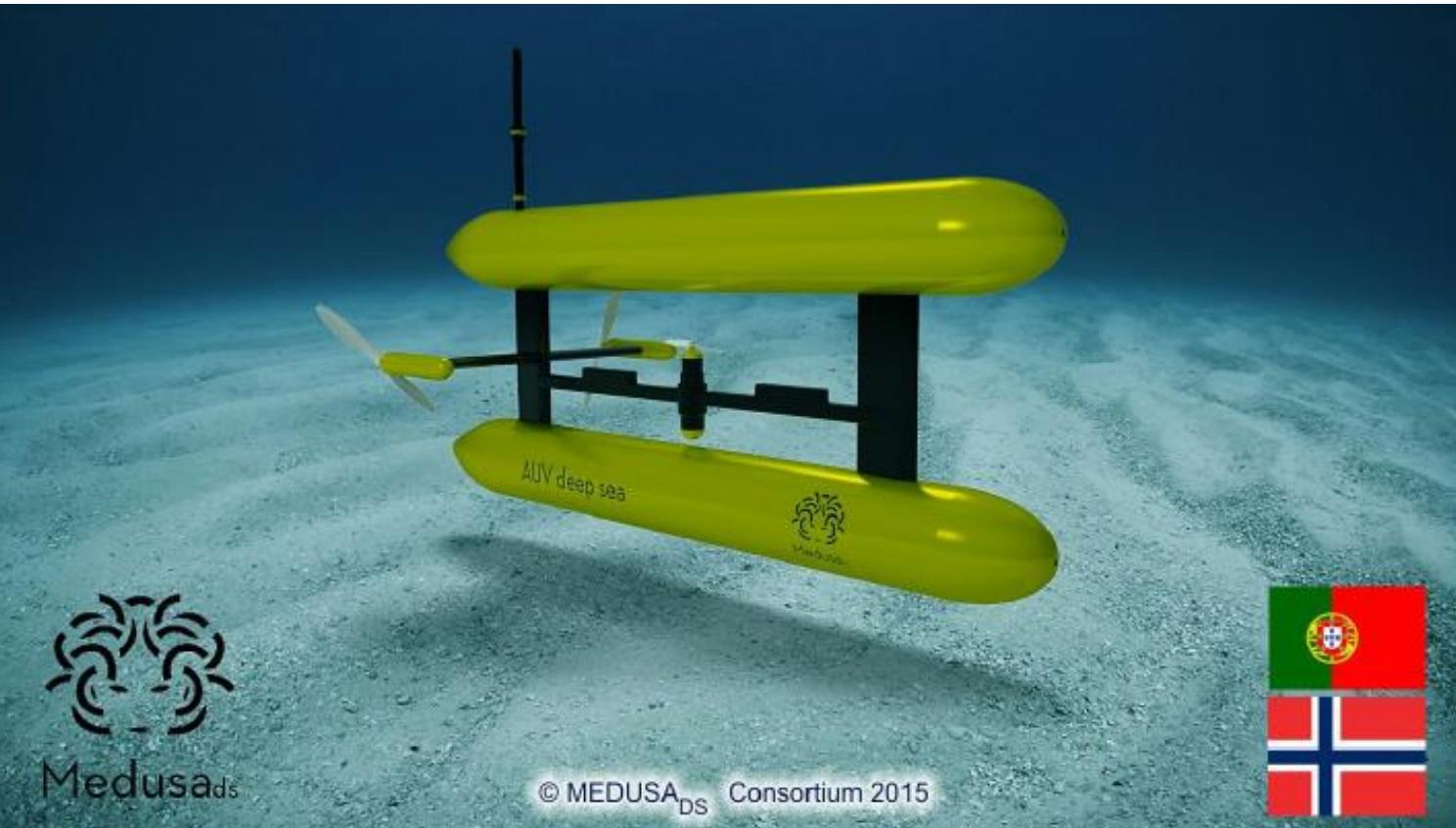


# “MEDUSA<sub>DS</sub> – OPENING THE DEEP SEA FRONTIER”

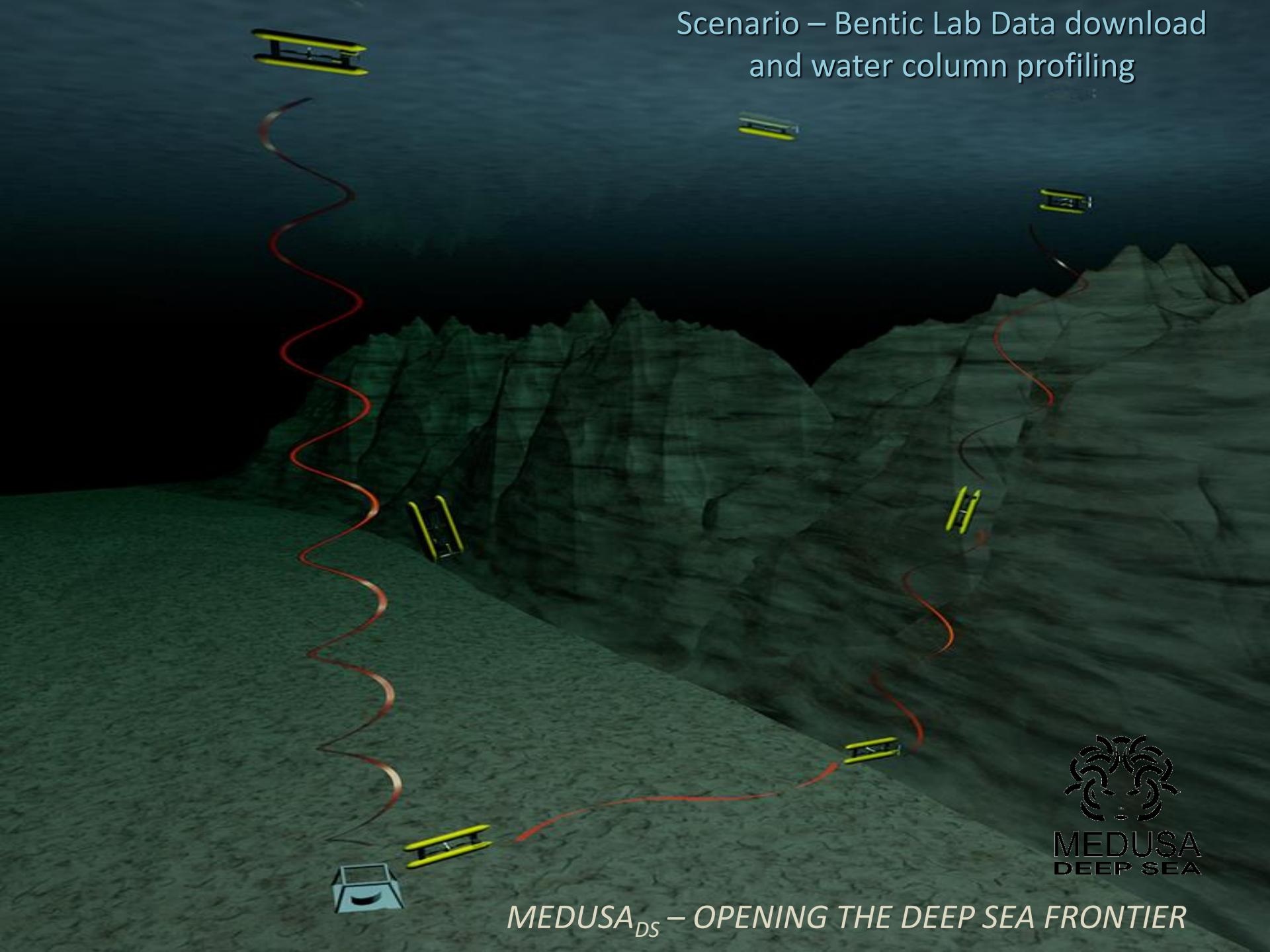
(2015-2017)



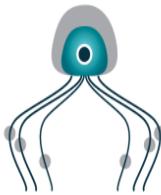
# MEDUSA<sub>DS</sub> / EC (2015-2017)



Scenario – Benthic Lab Data download  
and water column profiling

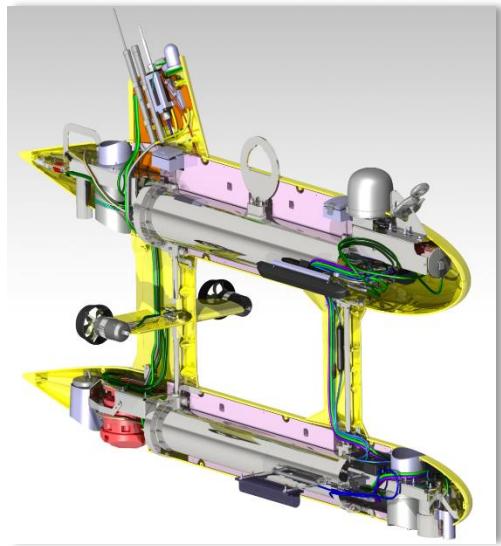


*MEDUSA<sub>DS</sub> – OPENING THE DEEP SEA FRONTIER*



MEDUSA  
DEEP SEA

OPENING THE DEEP-SEA FRONTIER



Tales of  
Housing pre



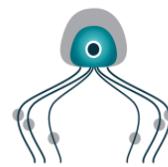
## Scenario – Benthic Lab Data download and water column profiling



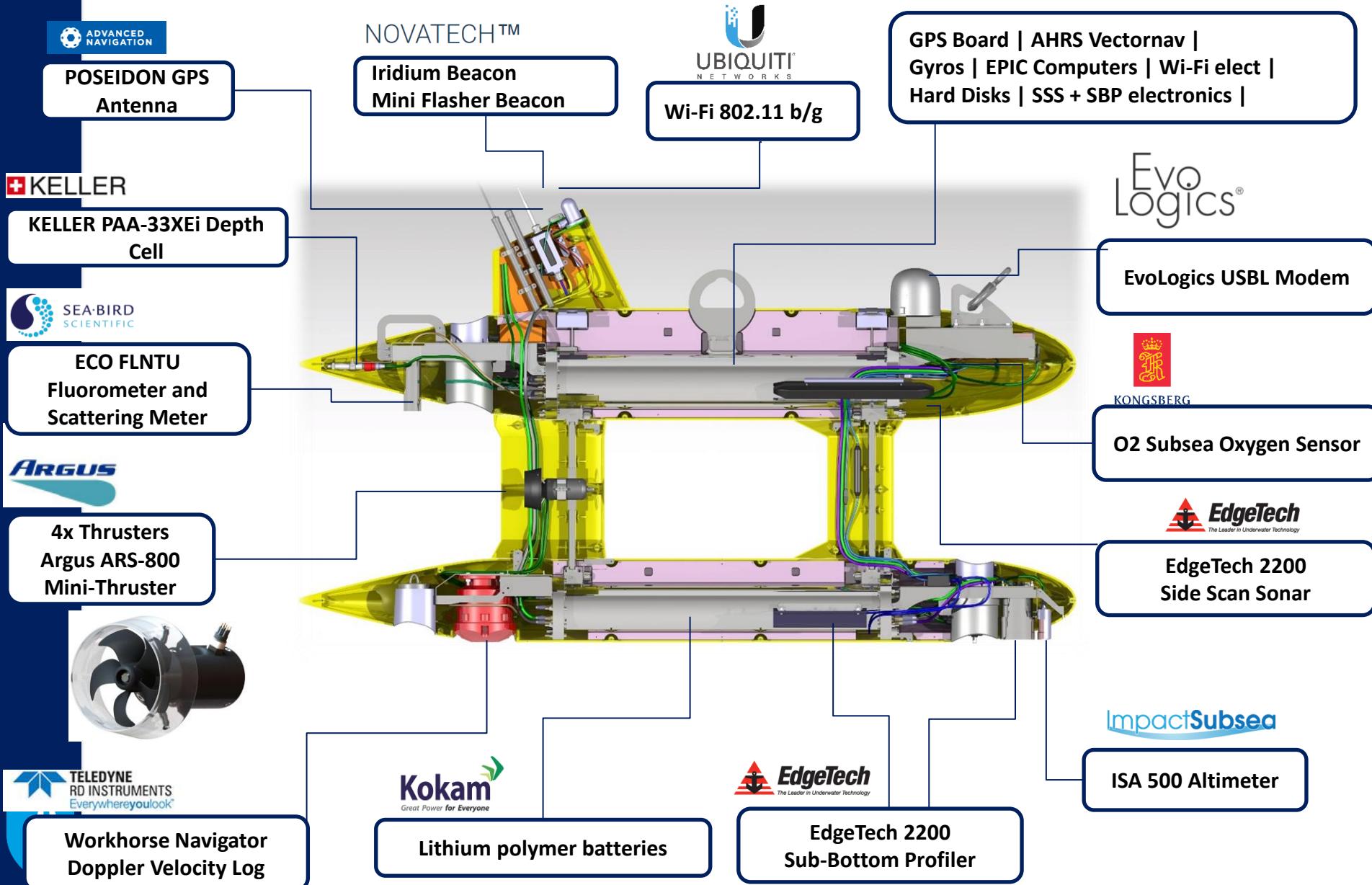
MEDUSA  
DEEP SEA

*MEDUSA<sub>DS</sub> – OPENING THE DEEP SEA FRONTIER*

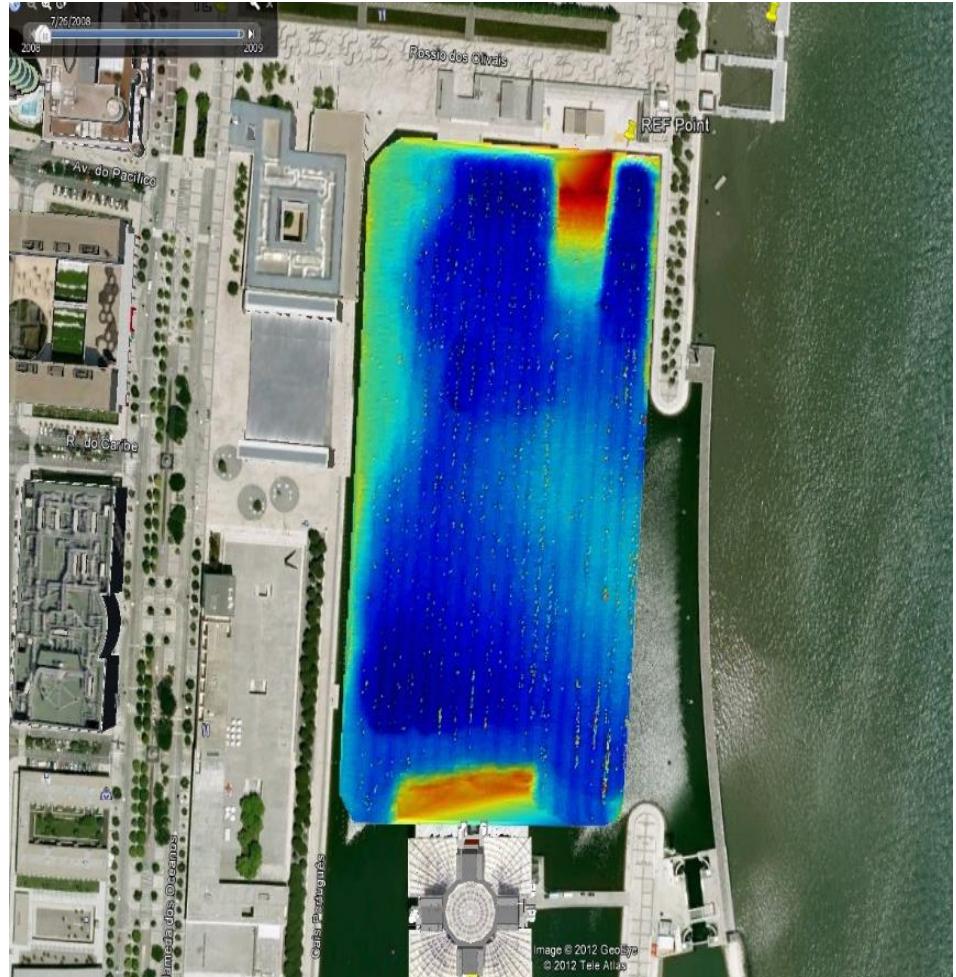
# System Breakdown



MEDUSA  
DEEP SEA



# Test Facilities

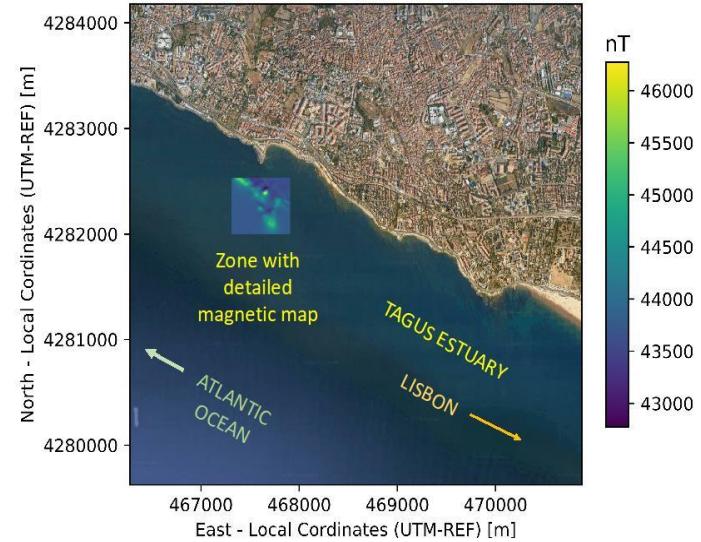


EXPO'98 Site, Lisbon, PT

# Test Facilities



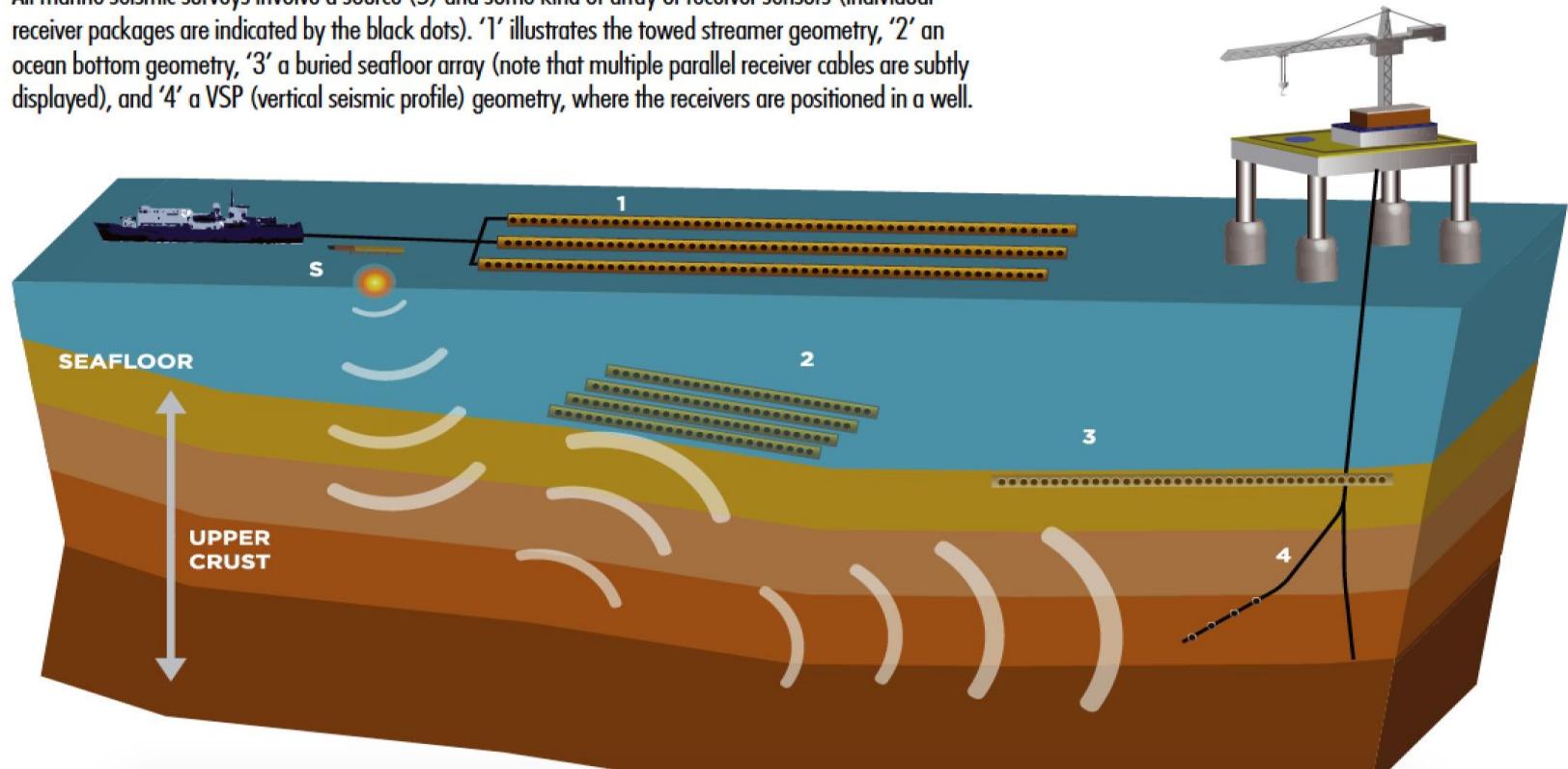
S. Pedro do Estoril - Prior Total Magnetic Field Map



Tagus River, Portugal

# Probing under the seabed : the EC WiMUST project

All marine seismic surveys involve a source (S) and some kind of array or receiver sensors (individual receiver packages are indicated by the black dots). '1' illustrates the towed streamer geometry, '2' an ocean bottom geometry, '3' a buried seafloor array (note that multiple parallel receiver cables are subtly displayed), and '4' a VSP (vertical seismic profile) geometry, where the receivers are positioned in a well.



S-acoustic source

1-Towed receiver geometry (hydrophones)

2- Ocean bottom geometry

3- Buried seafloor array

4- Vertical seismic profiler

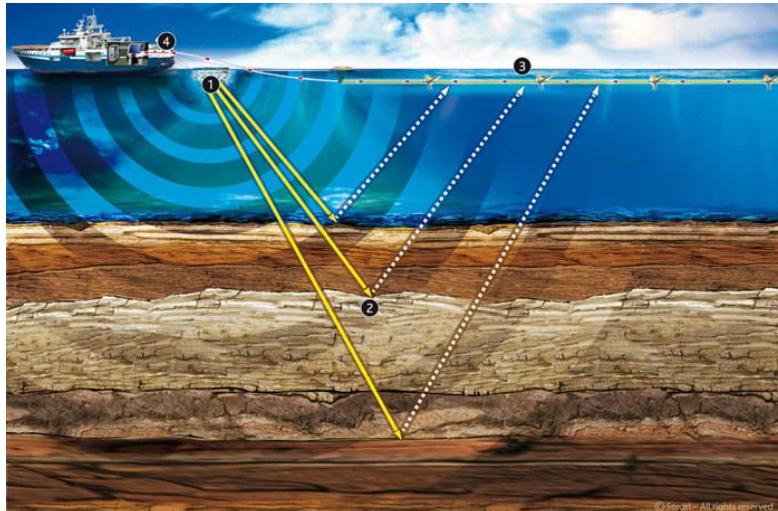


**WiMUST**

Widely scalable Mobile  
Underwater Sonar Technology

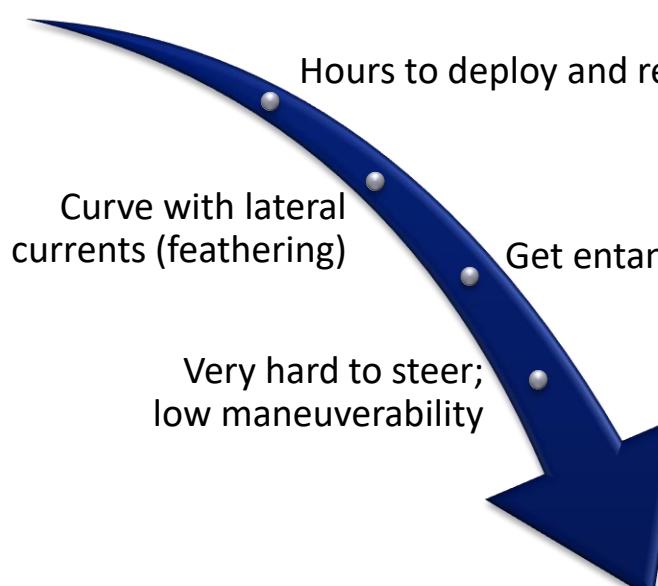
# Marine seismic surveys

- Vessel tows **acoustic sources** and long cables (**streamers**) up to 10km long, equipped with **hydrophones**, very close to the surface
- Acoustic sources shoot, waves reflect/refract off geological features on and beneath the seabed, hydrophones pick up these reflections
- Processing allows for inference of geophysical features



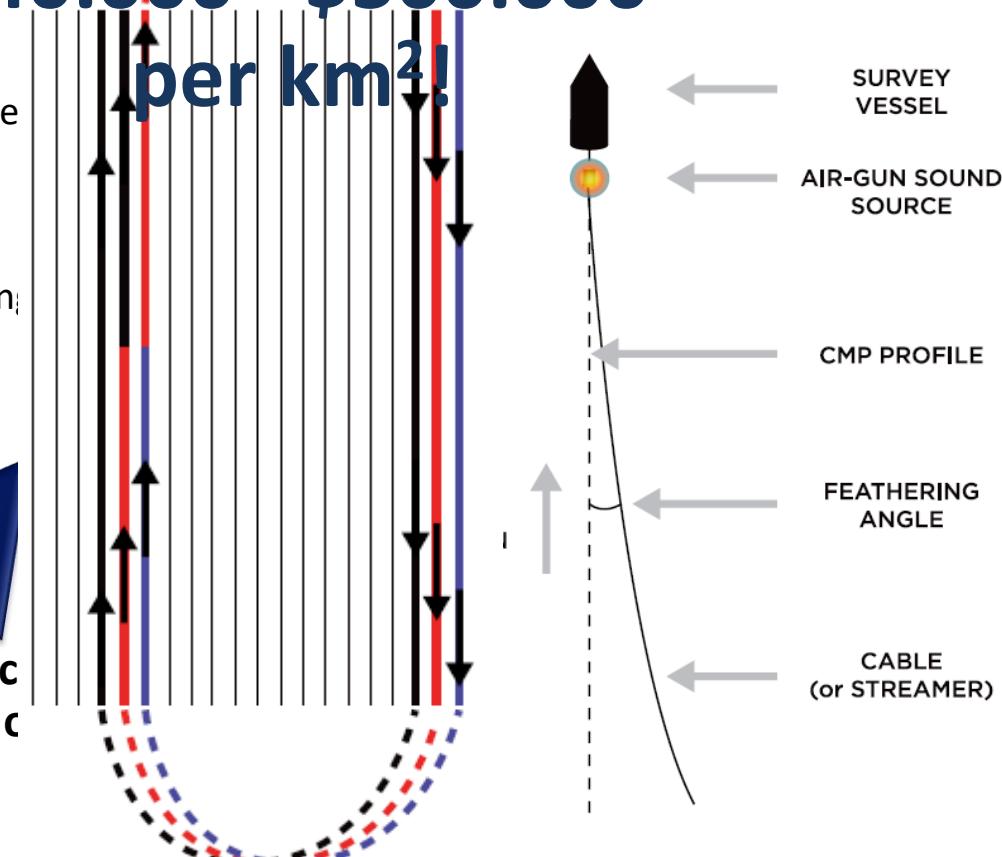
# Marine seismic surveys

Very long streamers

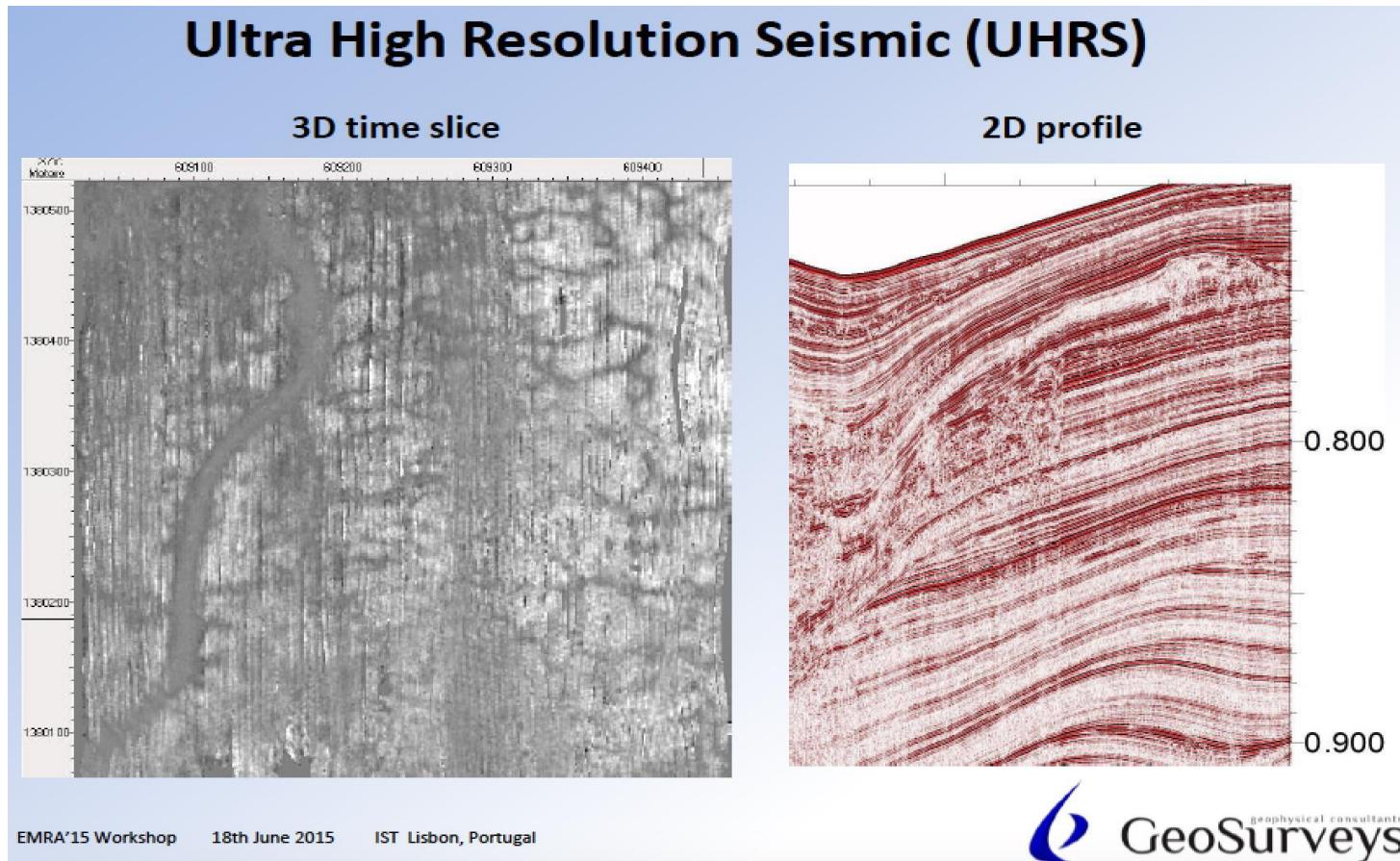


Low produ  
expensive c

3D seismic surveys:  
\$40.000 - \$500.000  
per km<sup>2</sup>!

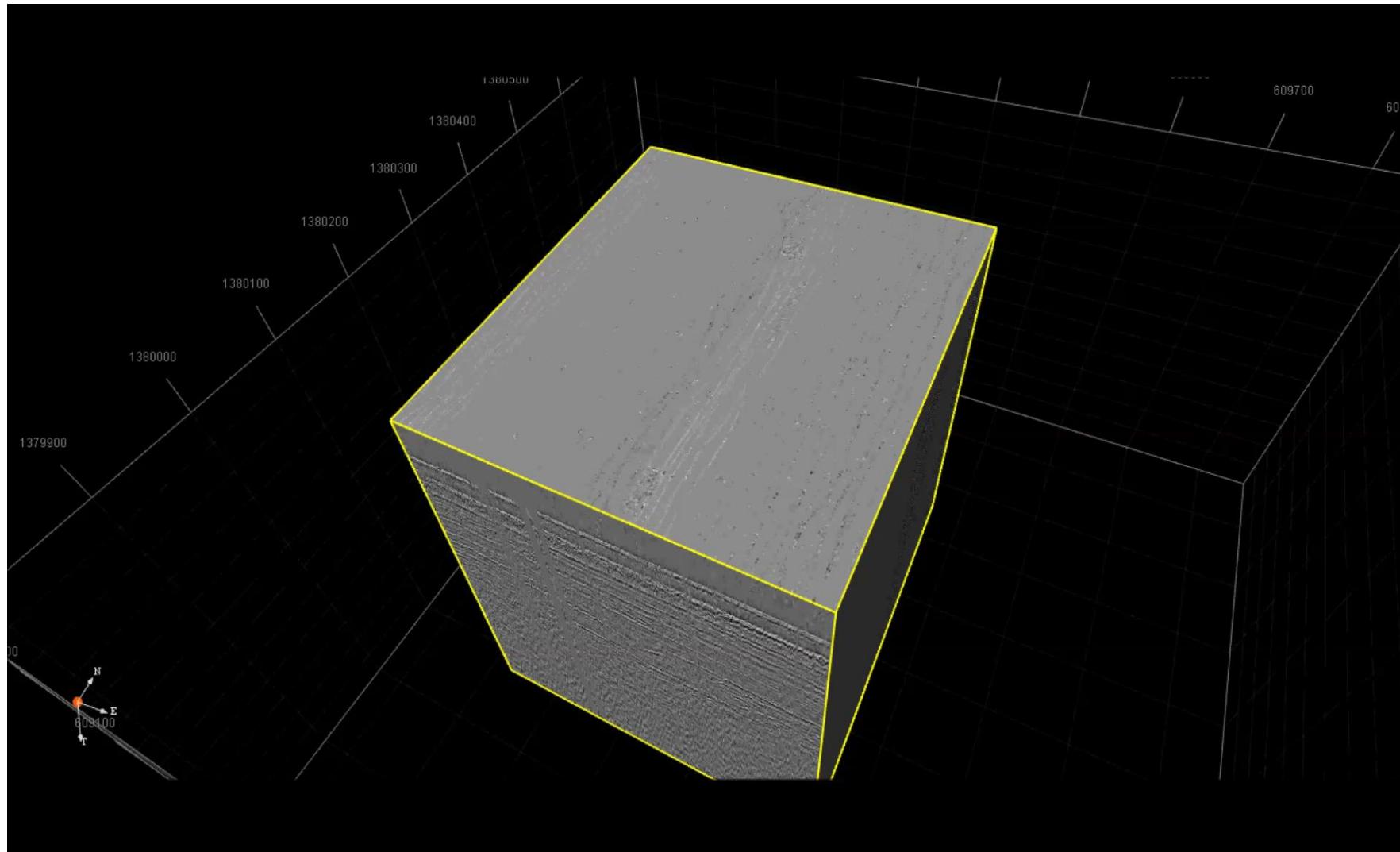


# Ultra high resolution Seismic Surveys in 2D and 3D



Key applications: design of foundations for overwater and subsea structures and anchors; assessment of burial performance for pipelines and cables – marine windfarms

# Ultra High Resolution Seismic (UHRS) surveys

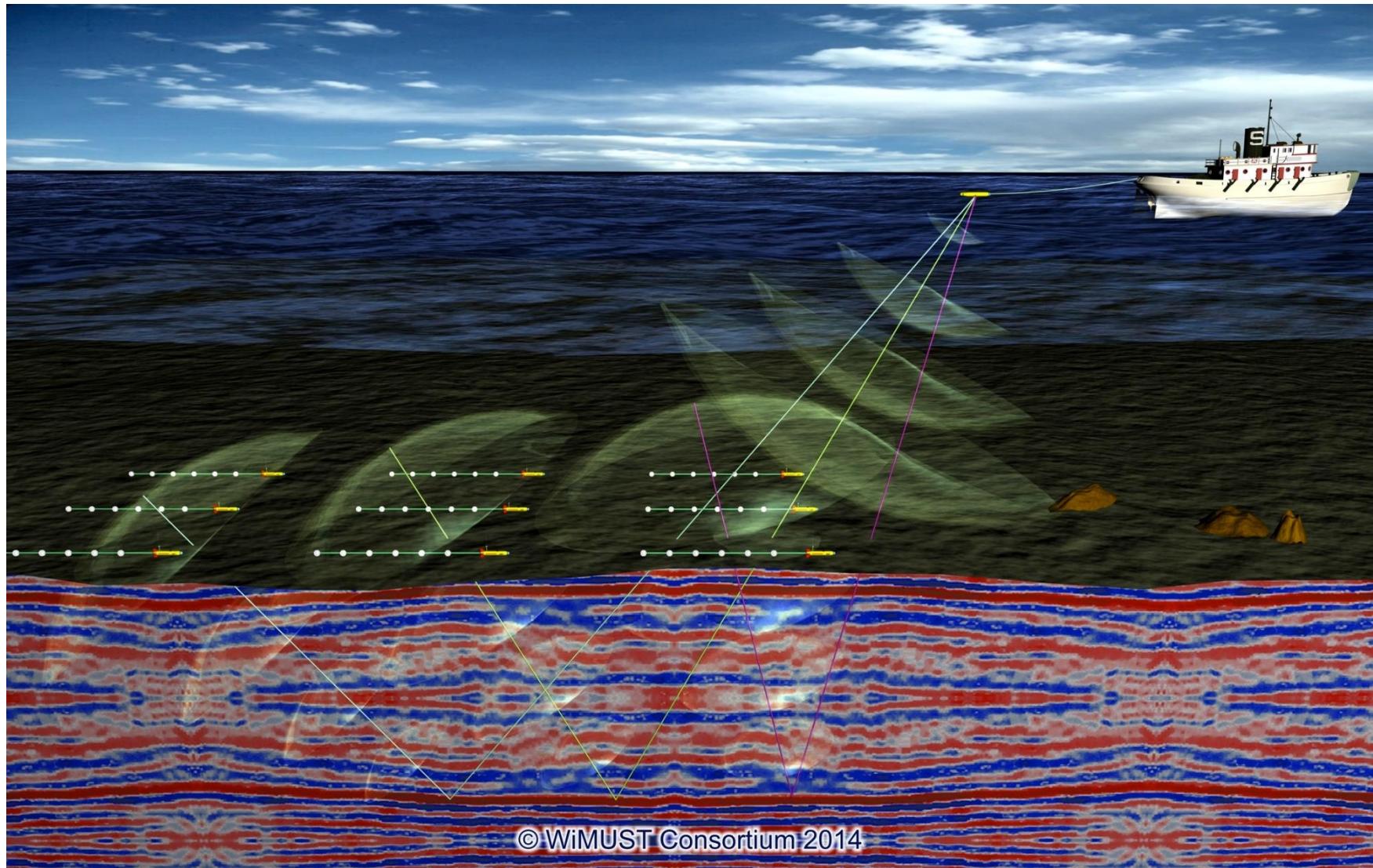


Courtesy of Henrique Duarte, GeoSurveys, Aveiro, PT

# The WiMUST concept



**WiMUST**  
Widely scalable Mobile  
Underwater Sonar Technology

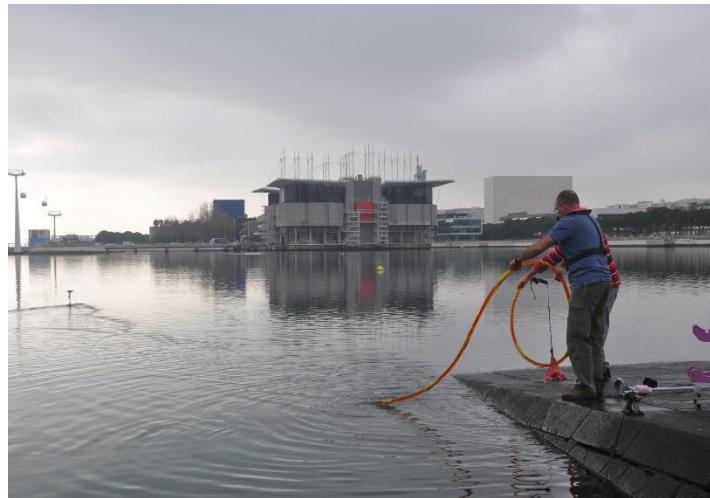


# The WiMUST concept

2:42



# A new concept: automated seismic surveys



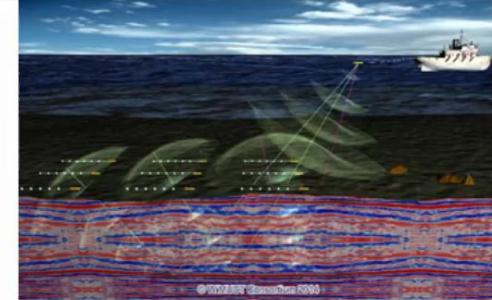
# A new concept: automated seismic surveys



**WiMUST**  
Widely scalable Mobile  
Underwater Sonar Technology

**WiMUST**

**Widely scalable Mobile Underwater Sonar  
Technology**



**lisbon trials December 2015  
- 2 ASVs towing 2 streamers -**

<http://www.wimust.eu/>



University of  
Hertfordshire



# Integration of Sparkers and Power Supplies on Autonomous Vehicles (world premiere)



# Integration of Sparkers and Power Supplies on Autonomous Vehicles



# Integration of Sparkers and Power Supplies on Autonomous Vehicles



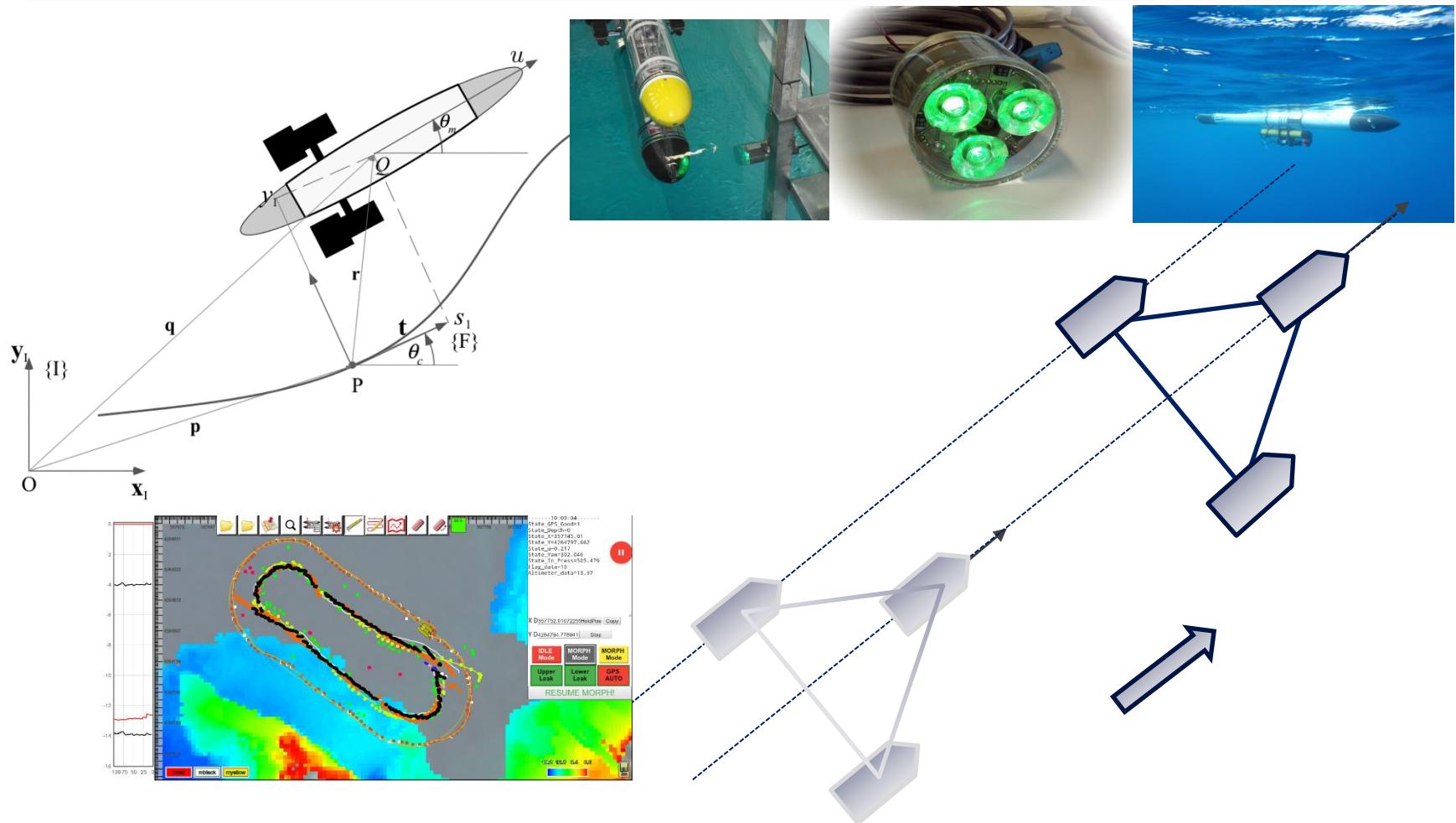
**ULISSE, ISME, Italy**

# Automated Sparkers/Receivers: Field Tests



SINES. July 2017

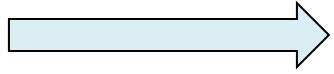
# The theory behind: a glimpse



**Cooperative, Networked Motion Planning, Navigation, and Control**  
*Nonlinear Control and Estimation, Range-based Localization, Optimization,  
Event-Driven Systems, Optical and Acoustic Communications*



Mission  
specification



## Cooperative motion planning

Nominal trajectories &  
desired vehicle formation

## Cooperative motion control

Global and local, relative vehicle positions

## Cooperative navigation

Cooperative systems: key blocks required

# Strong parallel with Cooperative UAVs

**Time-Critical Cooperative Control of Autonomous Air Vehicles**

I. Kaminer • A. Pascoal • E. Xargay • N. Hovakimyan  
V. Cichella • V. Dobrokhodov

The advent of powerful embedded systems and communications networks has spawned widespread interest in the problem of cooperative motion control of multiple autonomous vehicles that will be engaged in increasingly demanding scientific and commercial missions.

*Time-Critical Cooperative Control of Autonomous Air Vehicles* presents a theoretical framework that addresses new and challenging multiple vehicle mission requirements, yielding control strategies for temporal coordination of networked autonomous agents that are subjected to tight spatial constraints.

The book gives the reader a thorough, integrated presentation of the different concepts, mathematical tools, and networked control solutions needed to tackle and solve a number of problems in the general area of time-critical cooperative control. In particular, it integrates algorithms for path following and time-critical coordination that together give a team of unmanned air vehicles (UAVs) the ability to meet simultaneously desired spatial and temporal specifications.

By including case studies in the control of fixed-wing and multirotor UAVs, the book effectively broadens the scope of application of the methodologies developed. The theoretical presentation and simulations are complemented with the results of actual flight tests with real UAVs.

This book is intended for researchers and practitioners from academia, research labs, commercial companies, government agencies, and the international aerospace industry.

**About the authors**

**Isaac Kaminer** received his PhD in Electrical Engineering Systems in 1992 from the University of Michigan, MI, USA. He is a Professor at the Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA, USA.

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**Enric Xargay** earned his PhD in Aerospace Engineering in 2013 from the University of Illinois, Urbana, IL, USA. He is Cofounder and Director of CSTAR Pte Ltd, a company that focuses on the development of guidance, navigation, and control technologies for autonomous systems.

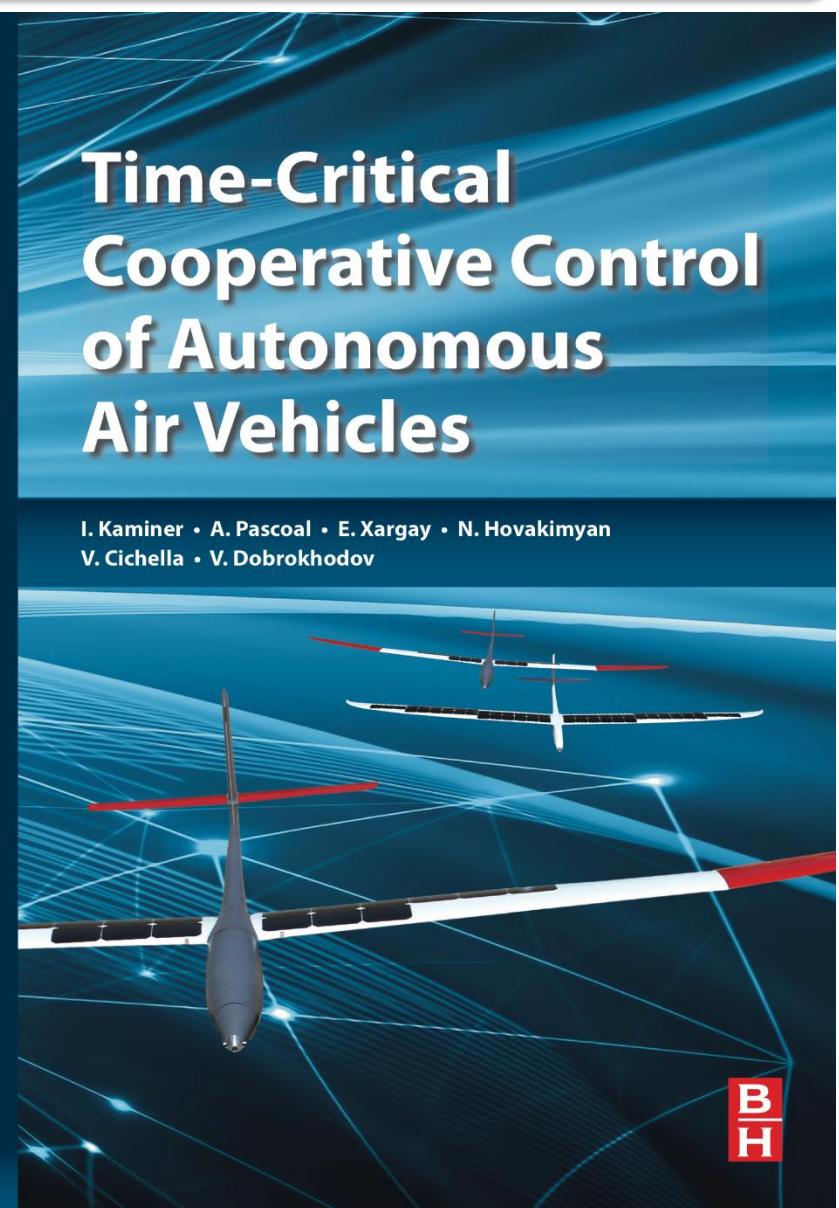
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# Questions ?

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