Ulisses

UNIVERSITY OF LISBON
INTERDISCIPLINARY STUDIES
ON SUSTAINABLE ENVIRONMENT AND SEAS

Ocean Exploration using Marine Robotics Systems: Science and Technology

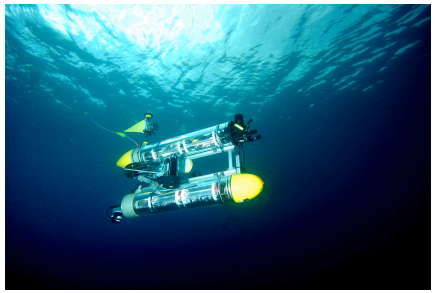
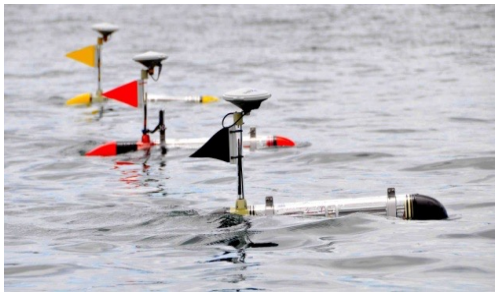
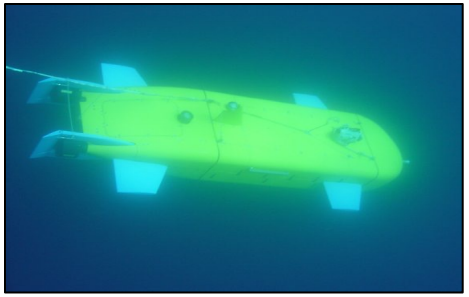
Part I

ulisses.ulisboa.pt

unite! University Network for Innovation, Technology and Engineering

U LISBOA | UNIVERSIDADE DE LISBOA

Co-funded by the Erasmus+ Programme of the European Union

Ocean Exploration using Marine Robotic Systems: Science and Technology
Part I

António Pascoal

Ulisses

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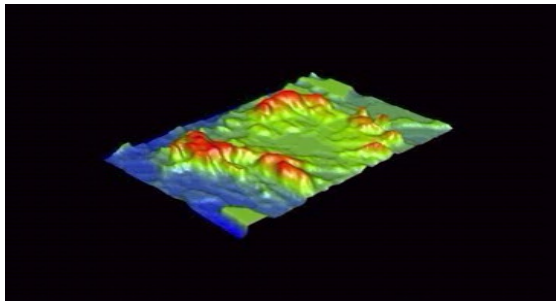
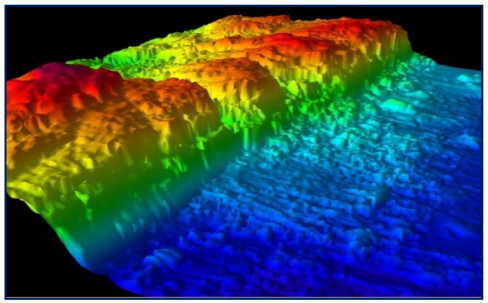
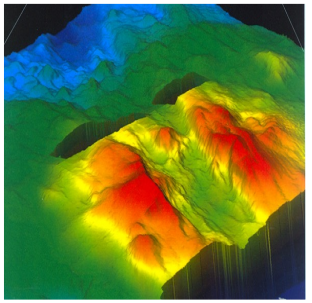
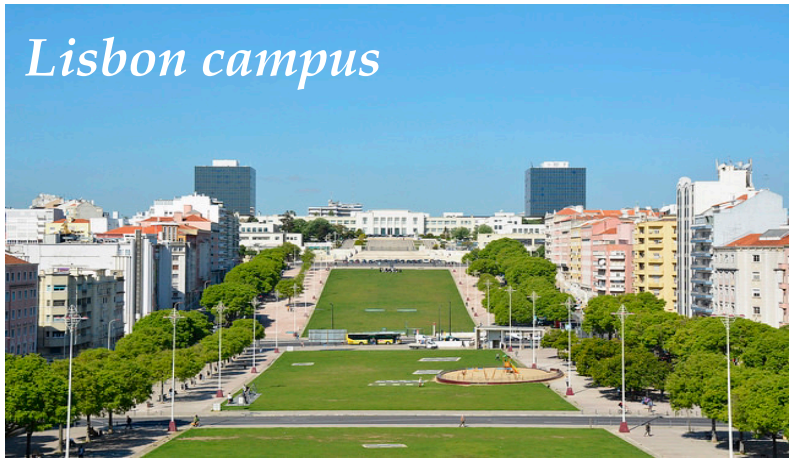
DSOR LAB
TÉCNICO LISBOA
ISR

IST – Univ. Lisbon, PT

The School of Engineering of the Univ. Lisbon, Portugal



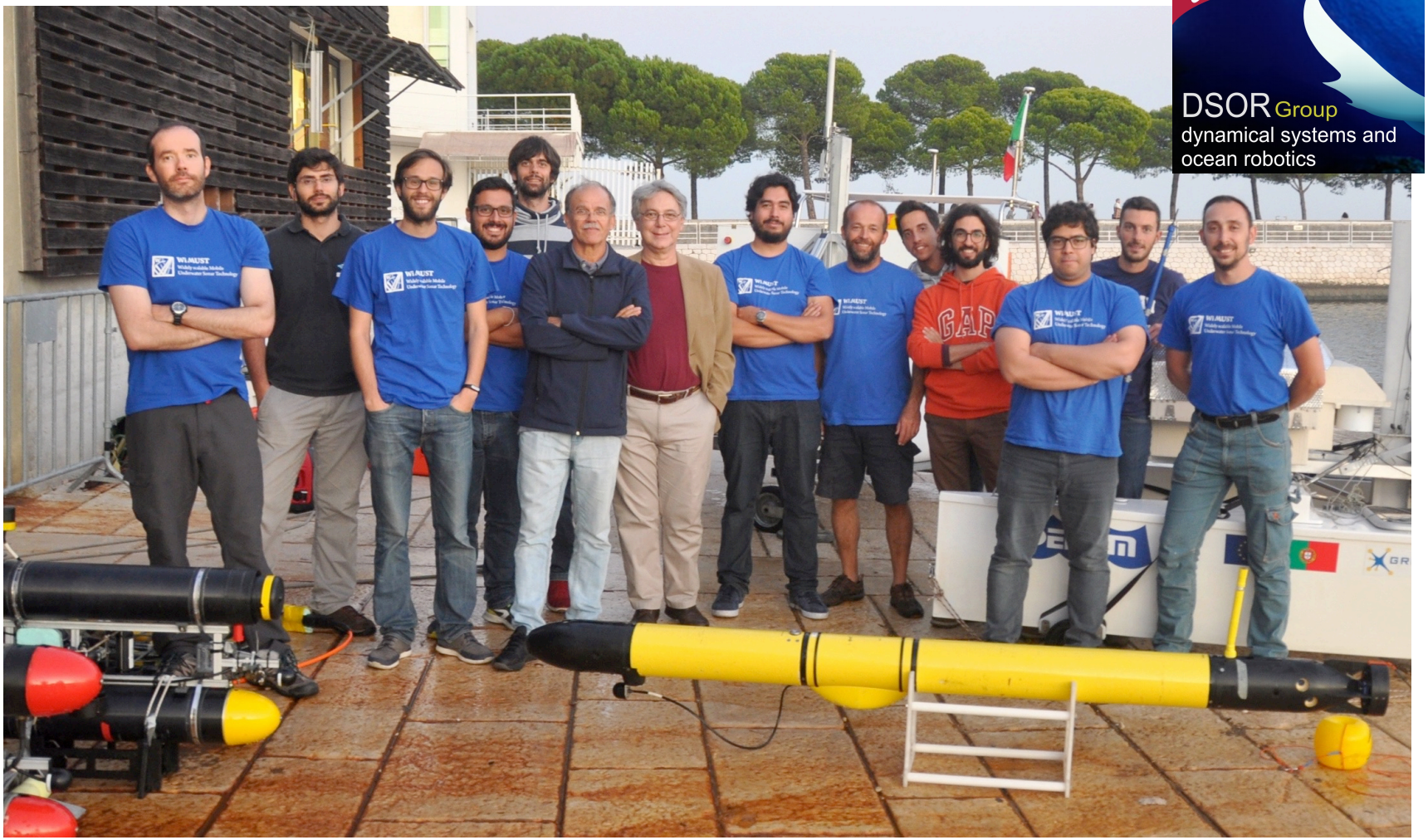
Teaching and Research

54 BSc /MSc programs – 9500 students
22 PhD programs – 600 students
937 Faculty members

Dual doctoral programs with the MIT, CMU, EPFL

DSOR Group
dynamical systems and ocean robotics

The work of many



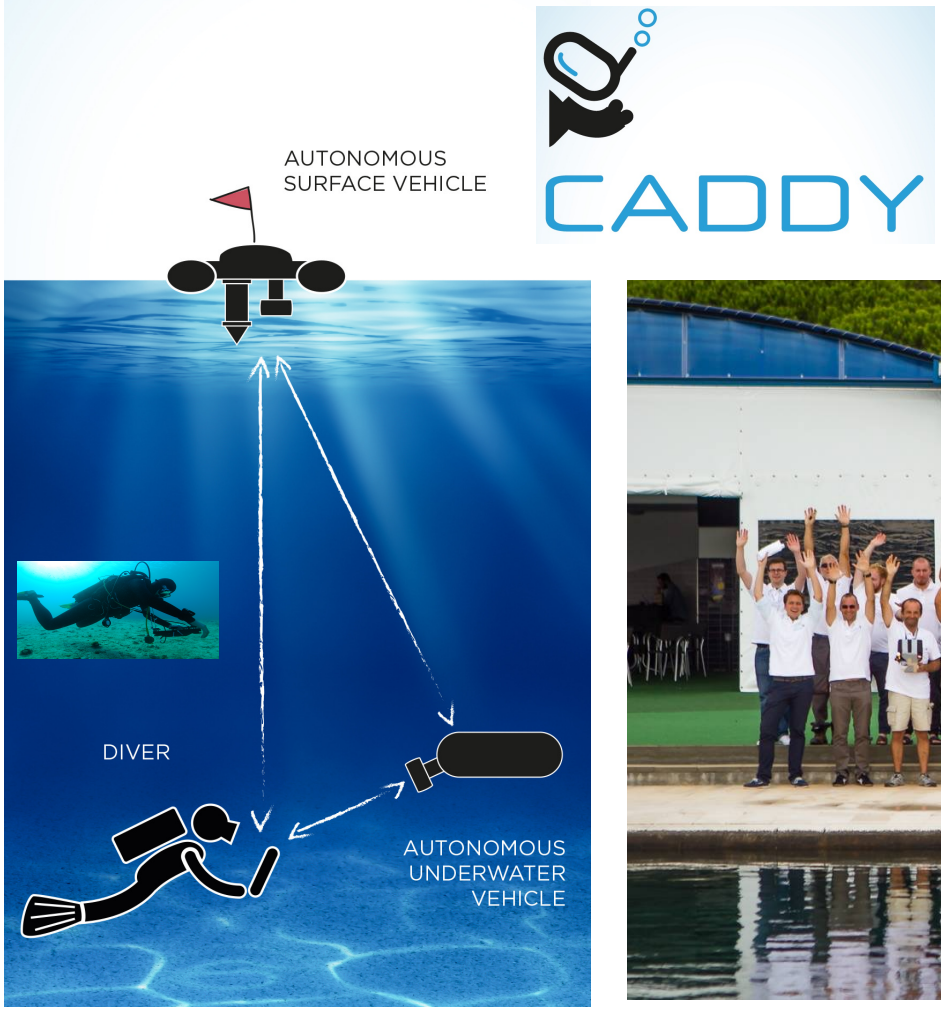
EC-CO_3AUVs 2009-2012

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



CADDY

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?

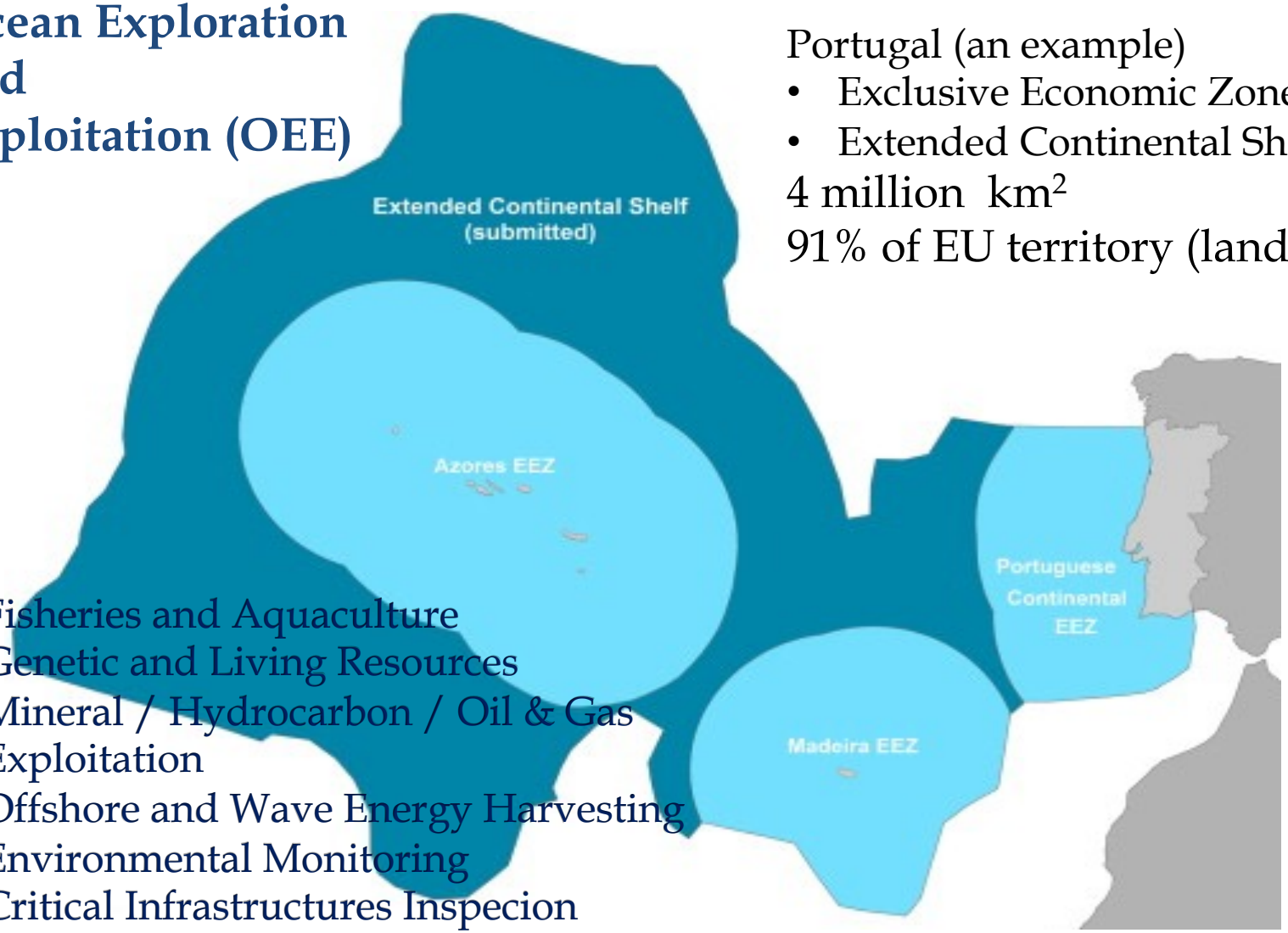
Ocean Exploration and Exploitation (OEE)

Portugal (an example)

- Exclusive Economic Zone
- Extended Continental Shelf

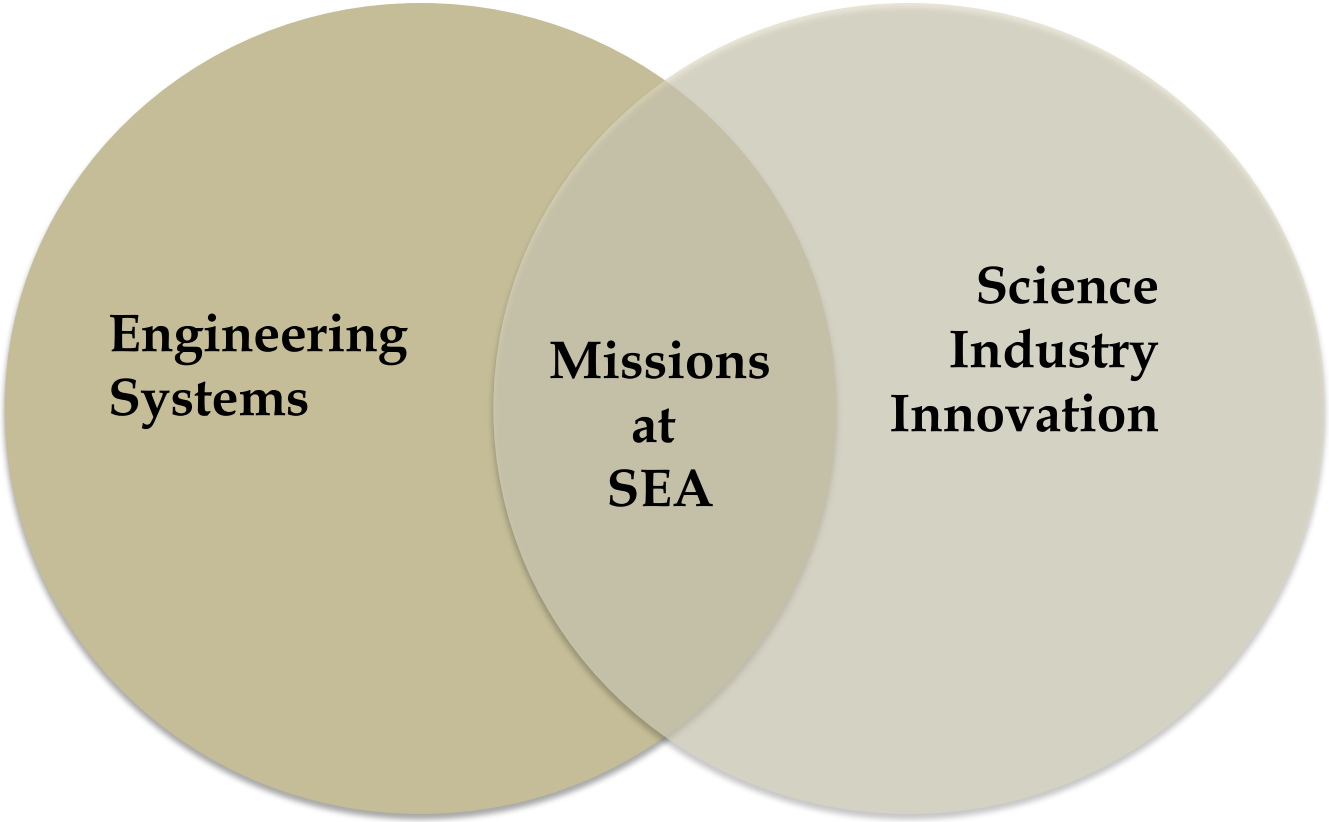
4 million km^2

91% of EU territory (land)



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

The Pillars of Ocean Exploration and Exploitation



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

Knowledge Transfer, Outreach Activities

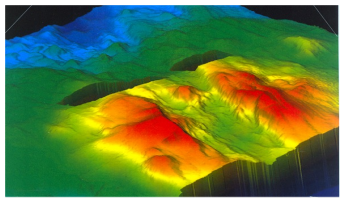
Technology for Science, Industry, and Management

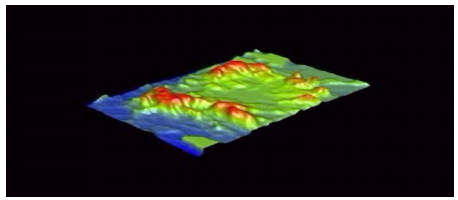
Automatic data acquisition in 3D

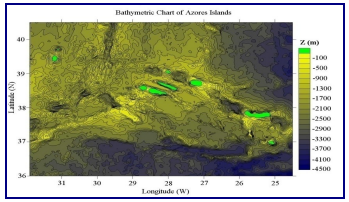
Data fusion

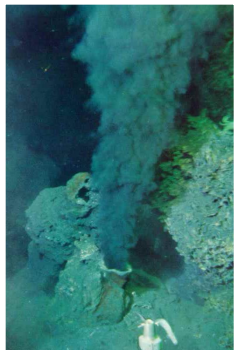
Info generation and dissemination

Scientific and commercial communities; civilian authorities

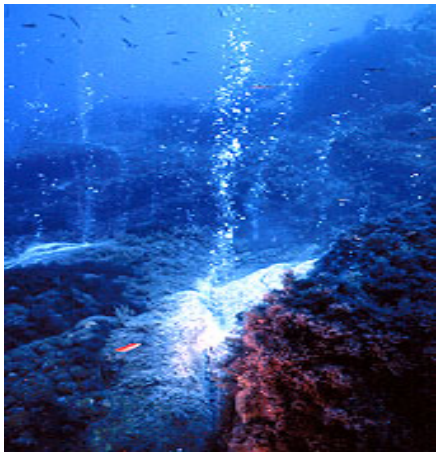


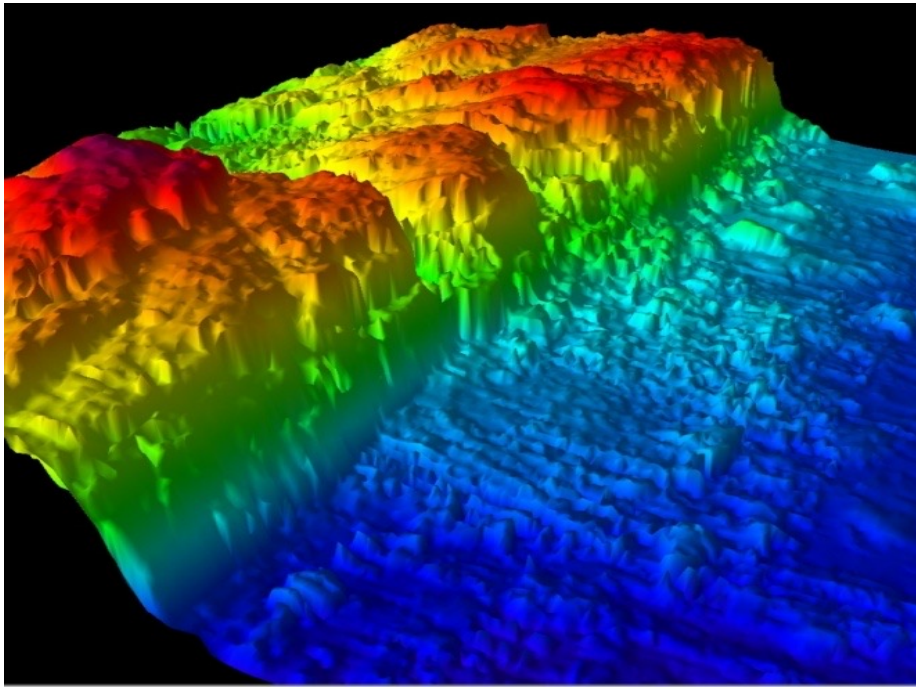






Scientific Challenges





To study the

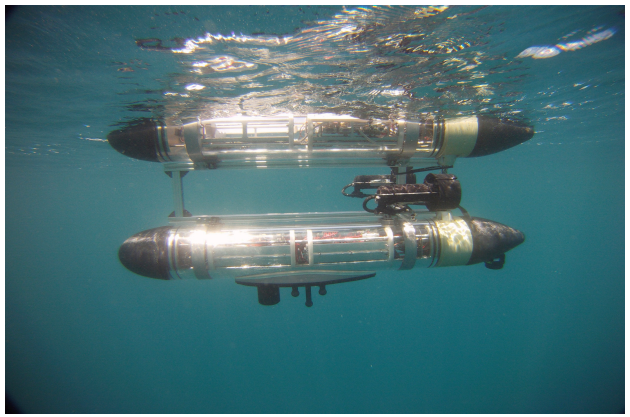
Physical,
Chemical,
Biologic,
and Geologic

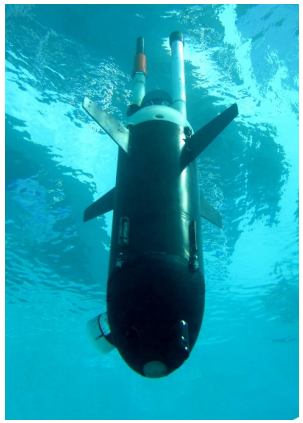
phenomena
that occur in the ocean
and its interfaces
(with the atmosphere
and the Earths´s
interior)

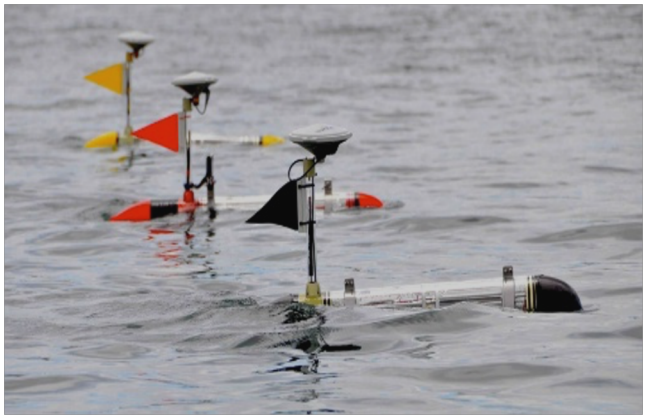
Observe, Monitor, and Map

The tools of the trade

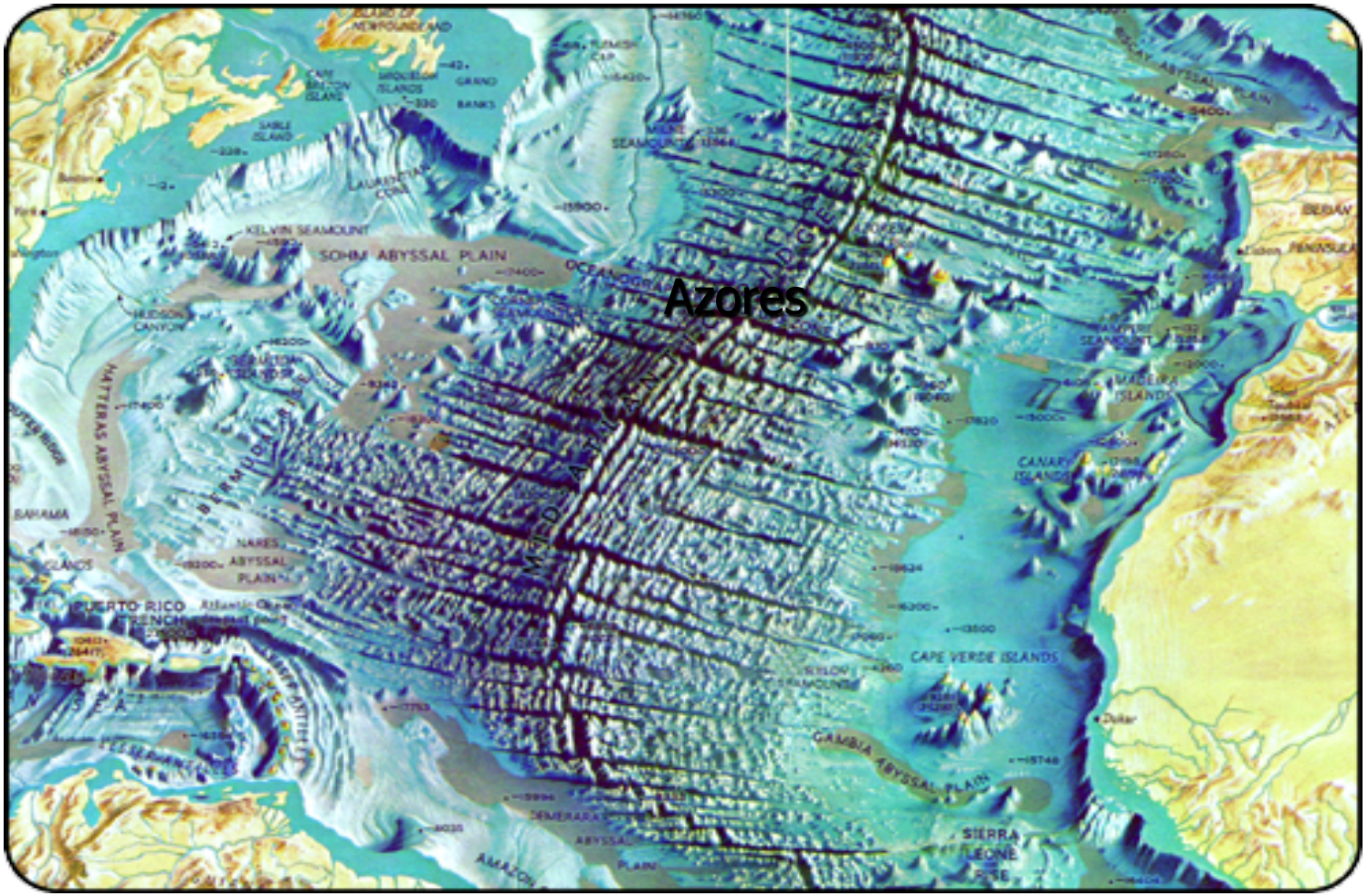
- **Technologies for ocean exploration including networked air and marine robots**
- **Robotic systems for the inspection of critical marine infrastructures and seabed/subbottom mapping**







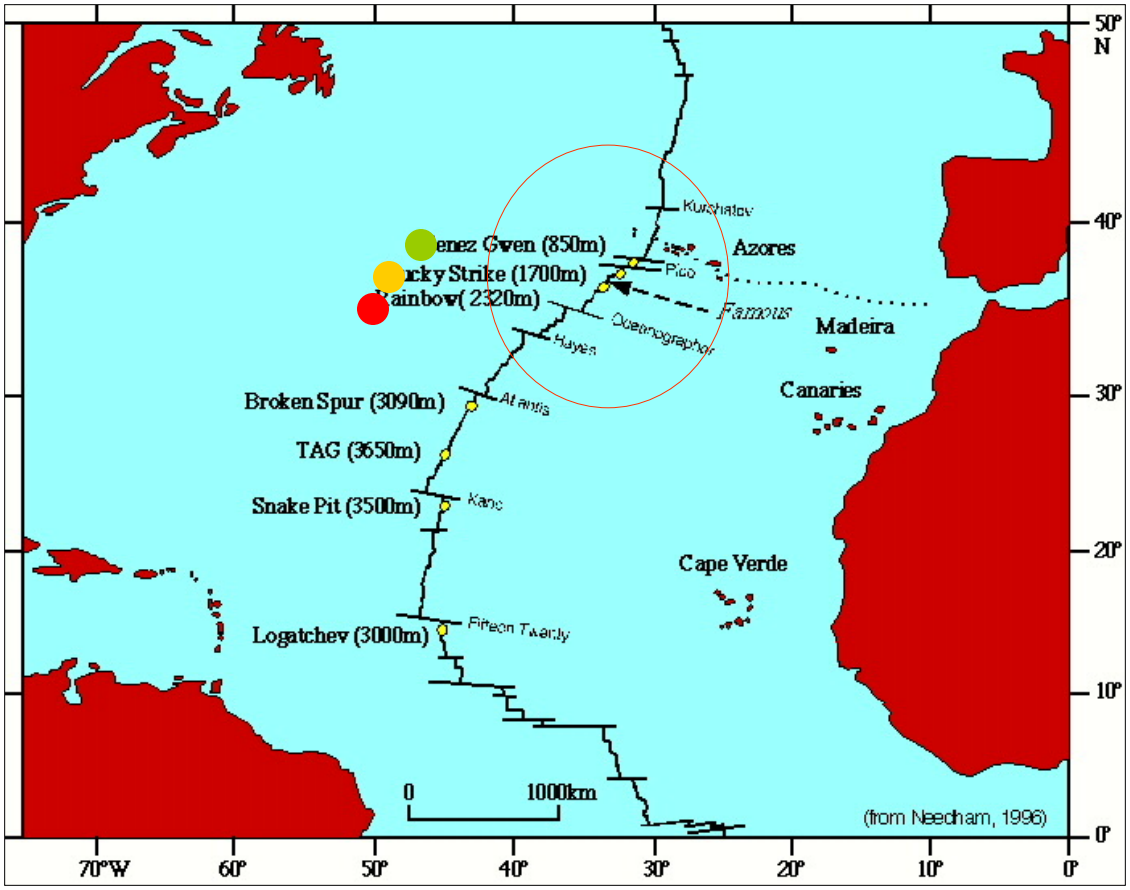
The Middle Atlantic Ridge and the Azores

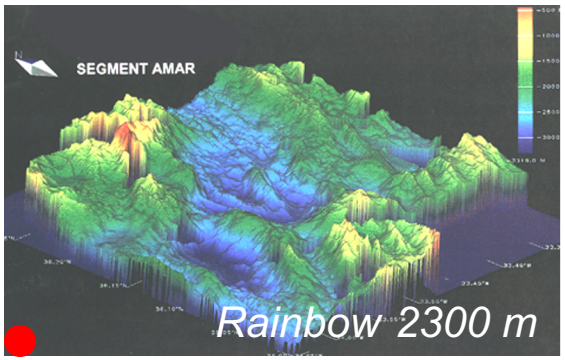


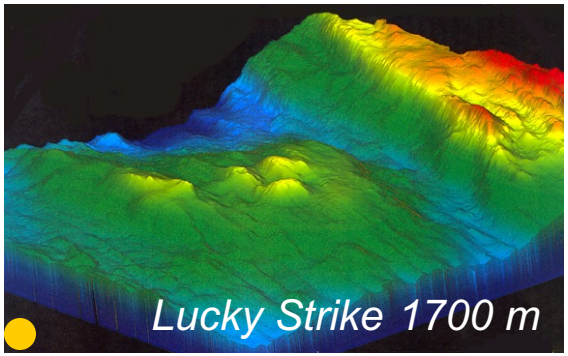
A chain of mountains at the bottom of the Atlantic ocean

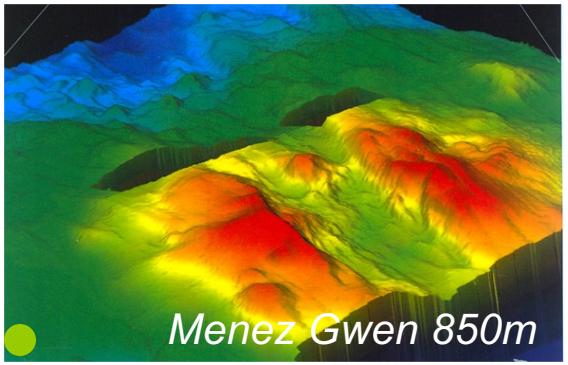
Mission Scenario

Underwater Hydrothermal Vents (Azores, Portugal)

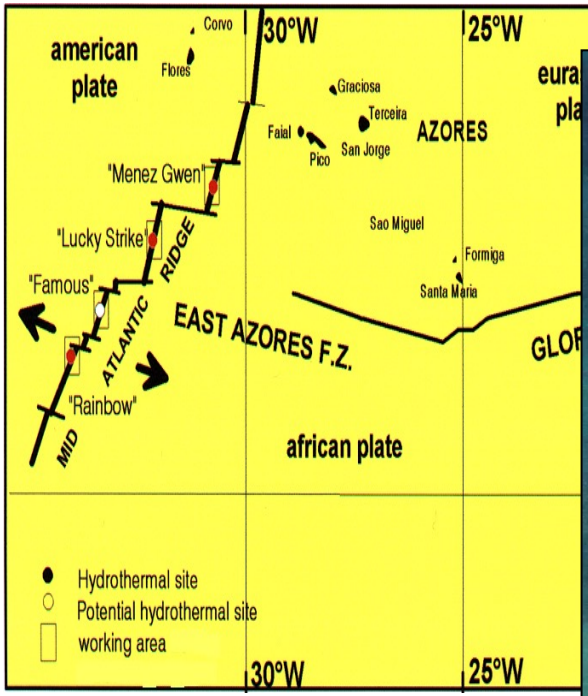


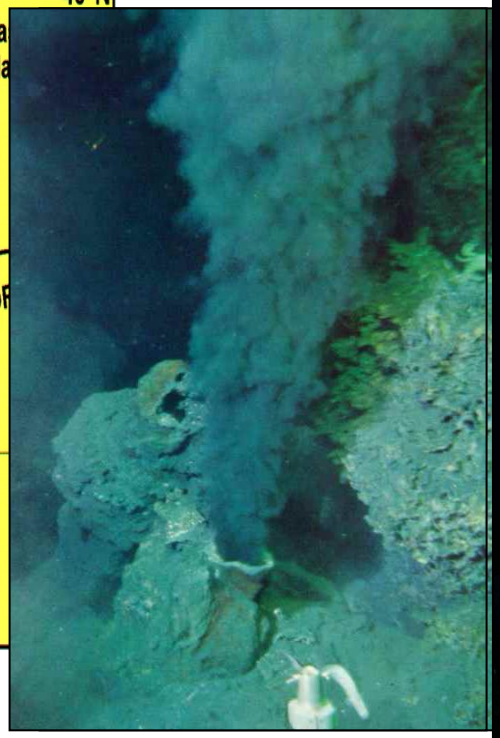


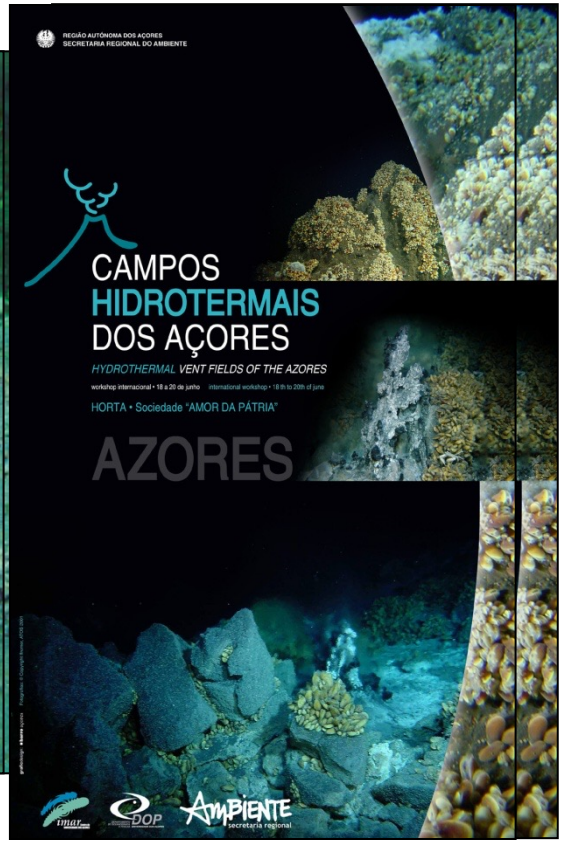




The Azores Triple Junction (ATP)

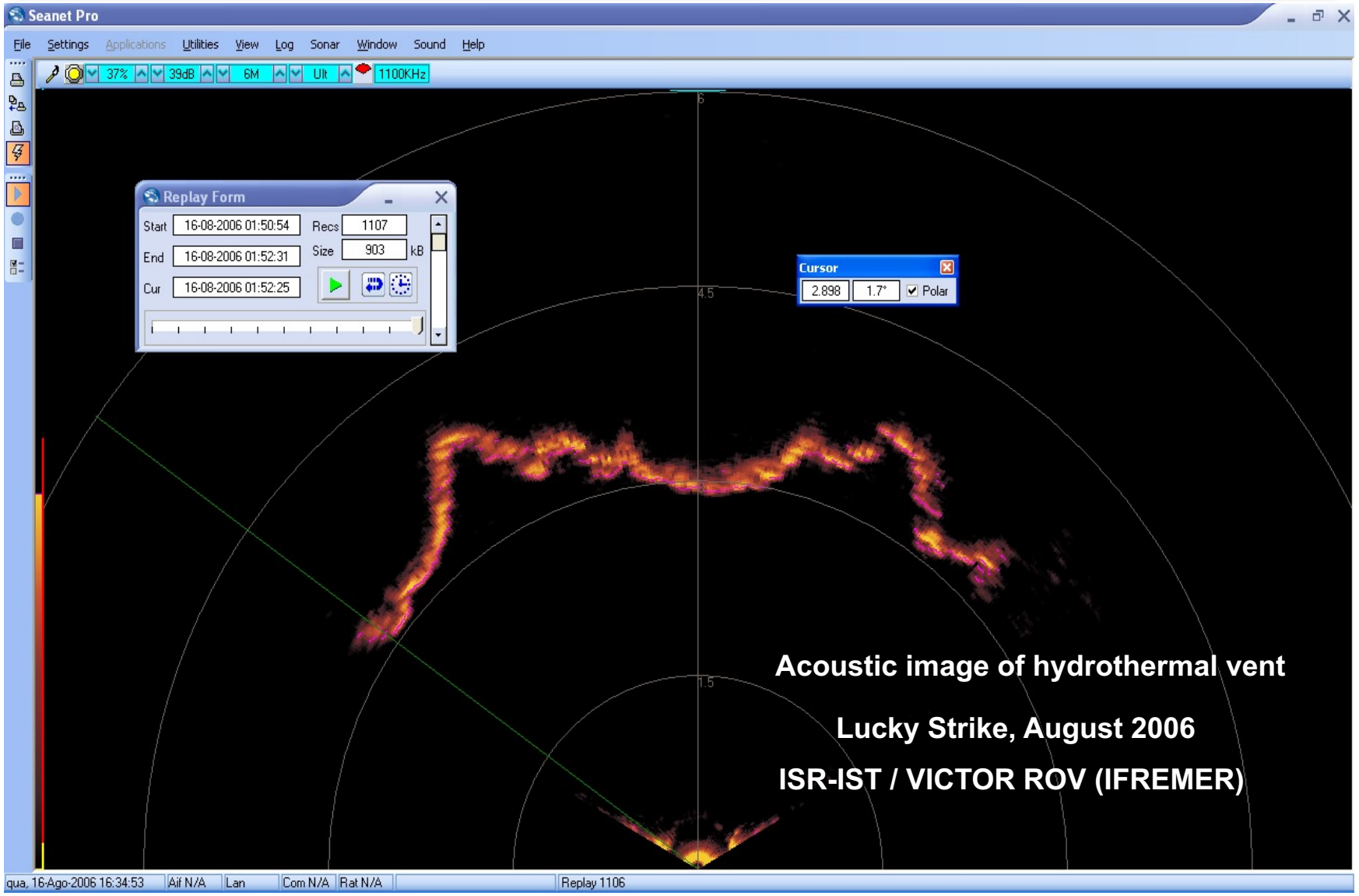






The region harbours a great variety of *seamounts, active underwater volcanoes, chemosynthetic ecosystems, and "extreme" life forms (extremophyles)*

Deep Water Hydrothermal Vents

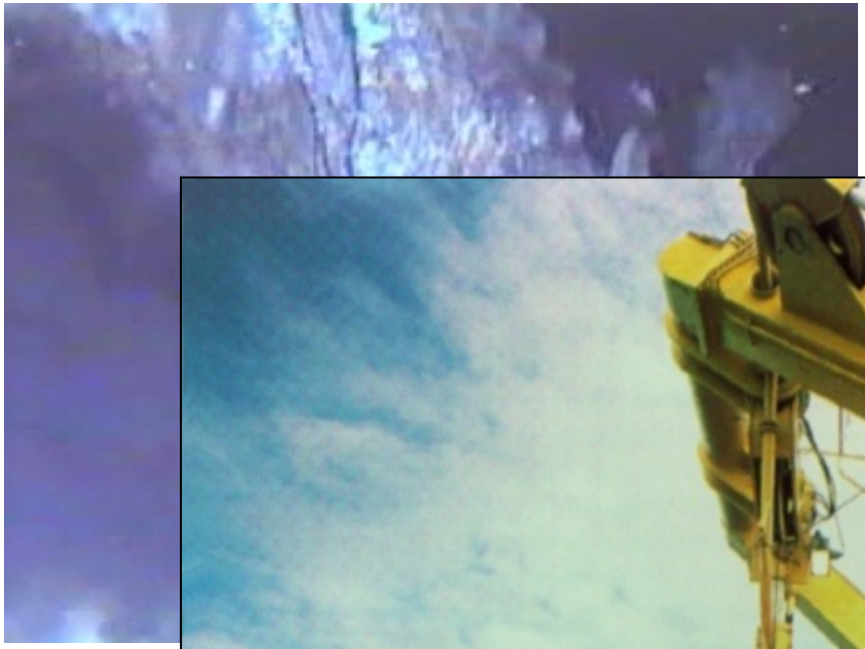


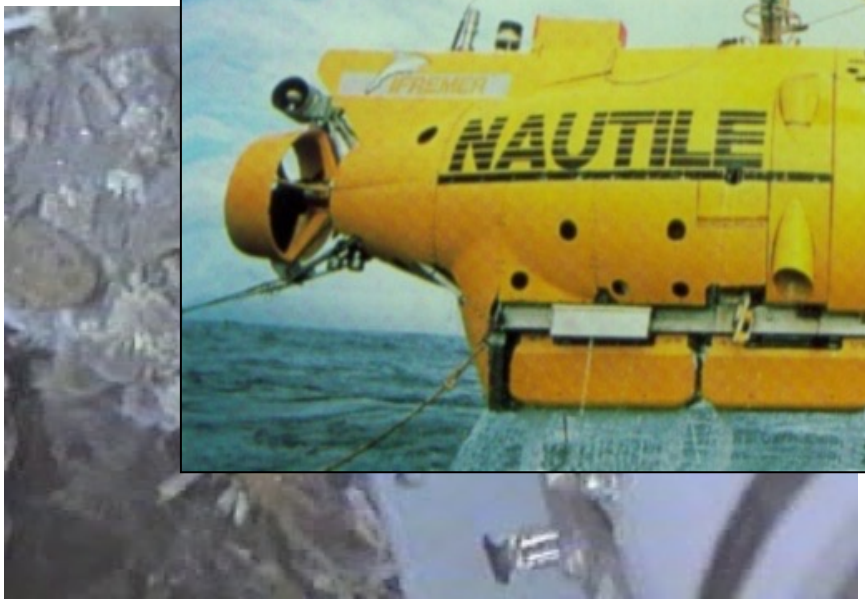
Acoustic image of hydrothermal vent

Lucky Strike, August 2006

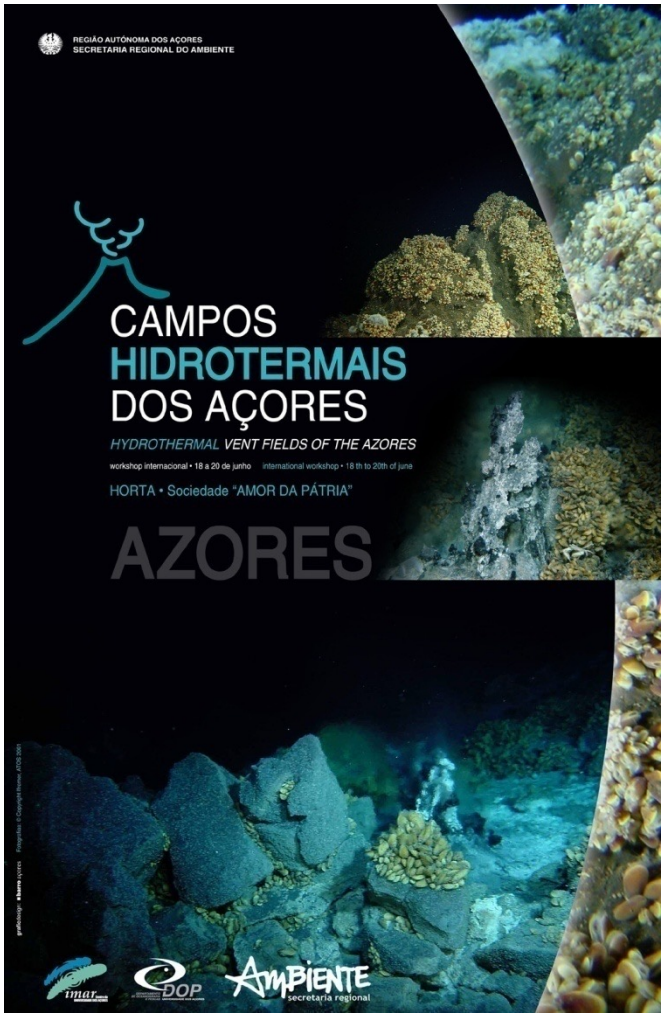
ISR-IST / VICTOR ROV (IFREMER)

Underwater Hydrothermal Vents





The Need for Technology



Vents are very hard to study:

Large depth (pressure is high)

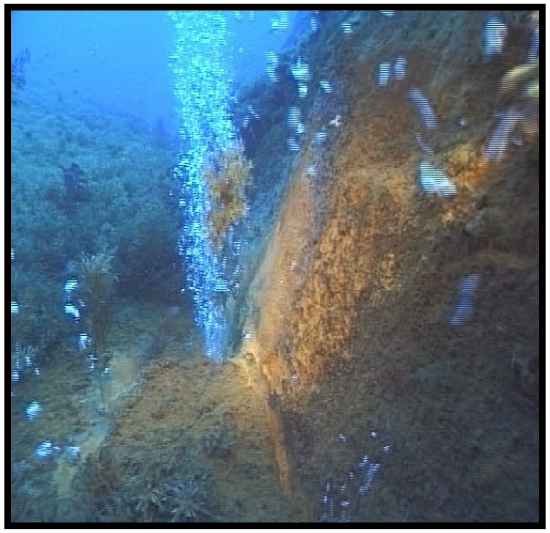
Highly corrosive environment

Lack of optical visibility

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

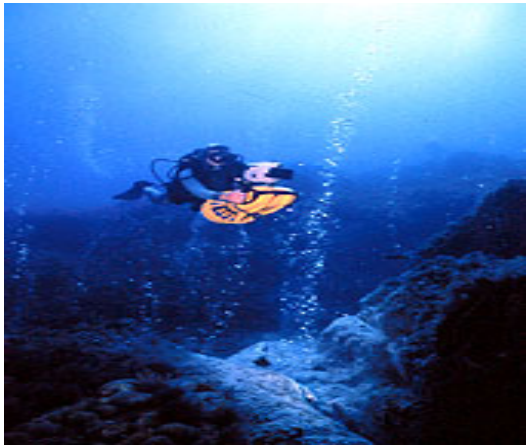
Submersibles: place human lifes at risk

Shallow Water Hydrothermal Vents

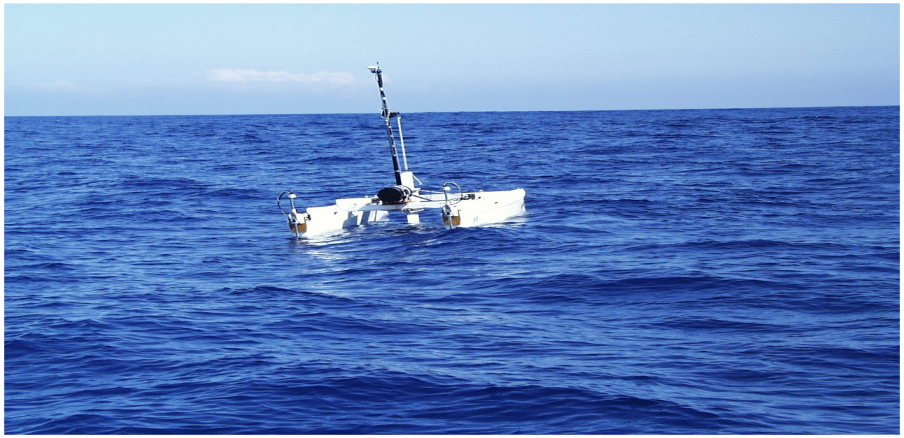


Hydrothermal activity at the D. João de Castro seamount
Azores, PT

Single Agent Operations: shallow water



No humans on board, please



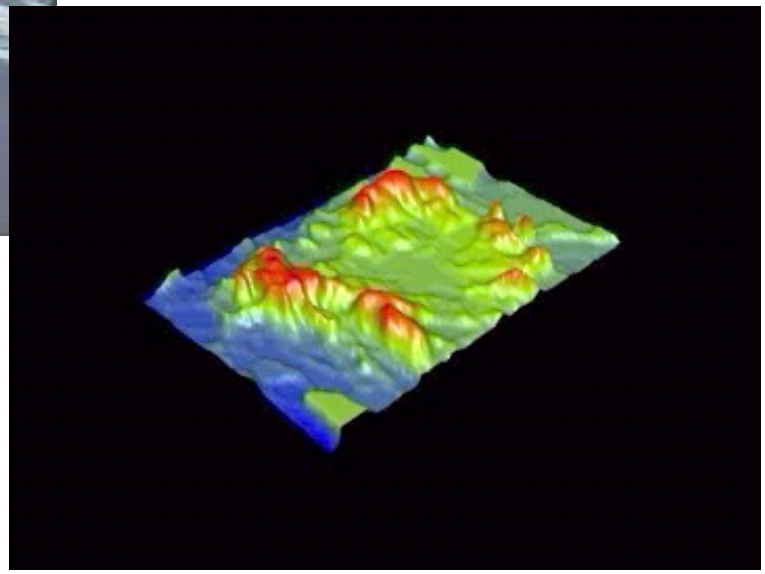
Use an Autonomous Surface Vehicle to MAP the seafloor

Mapping the seabed with an ASV

Navigation: GPS

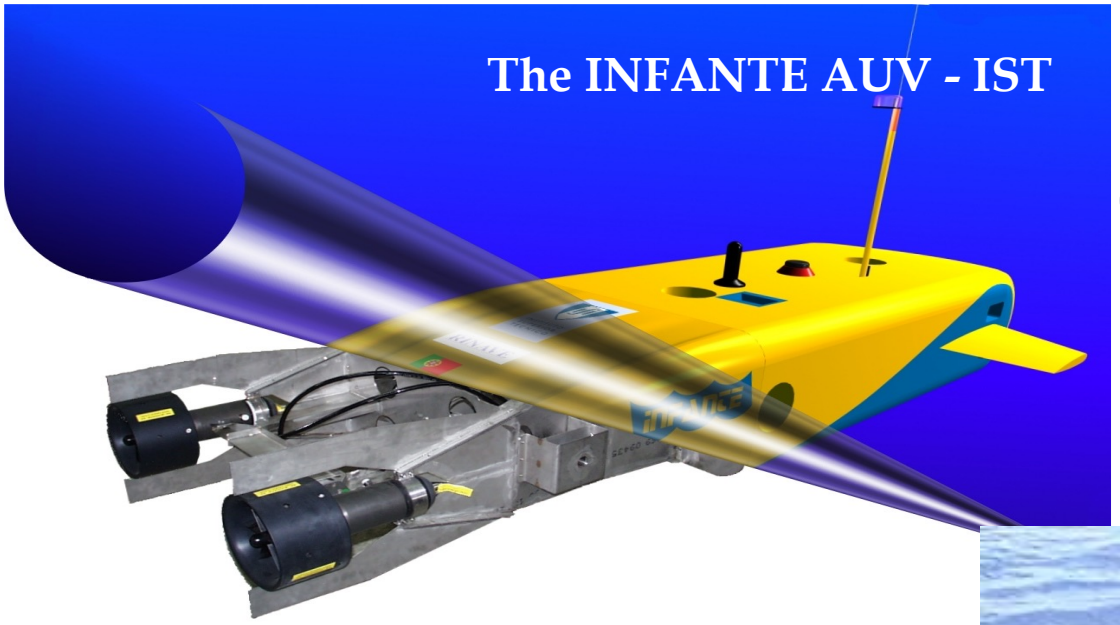
Comms: radio

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



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

Go deeper with an AUV



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

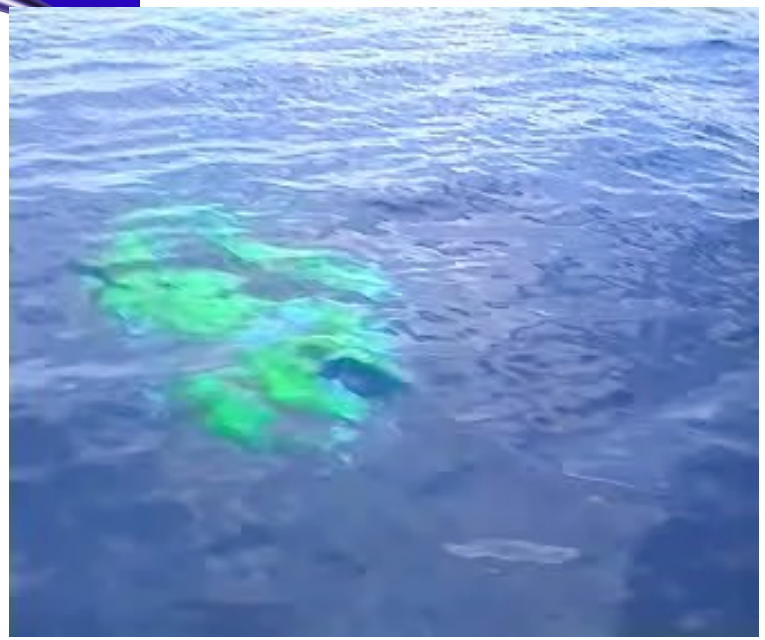
Comms: **acoustic**

Systems in place:

NGC for

- *Path Following in 3D*
- *Altitude Control*

Mapping sensor suites



Cooperation with Goa (NIO)

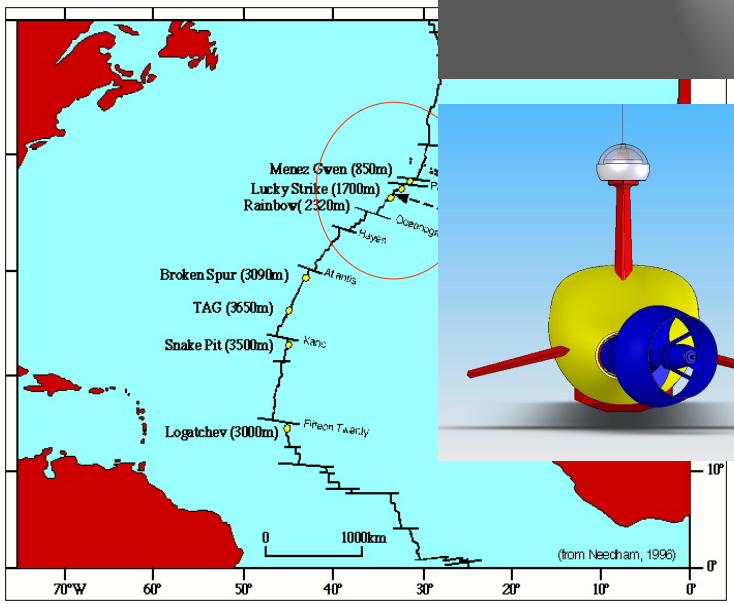
Meeting IN-PT (since 1999)

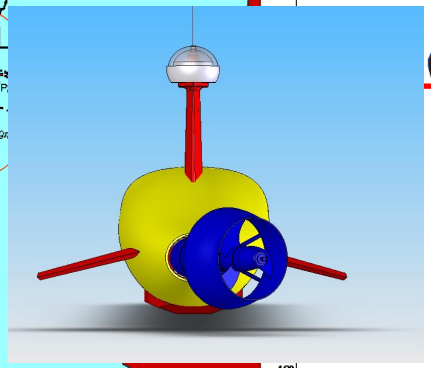
INSTITUTO SUPERIOR TÉCNICO

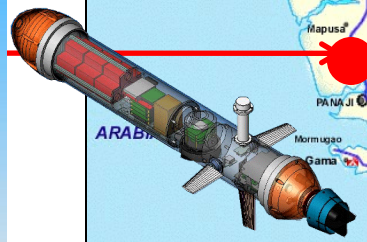
PÓLO DO IST

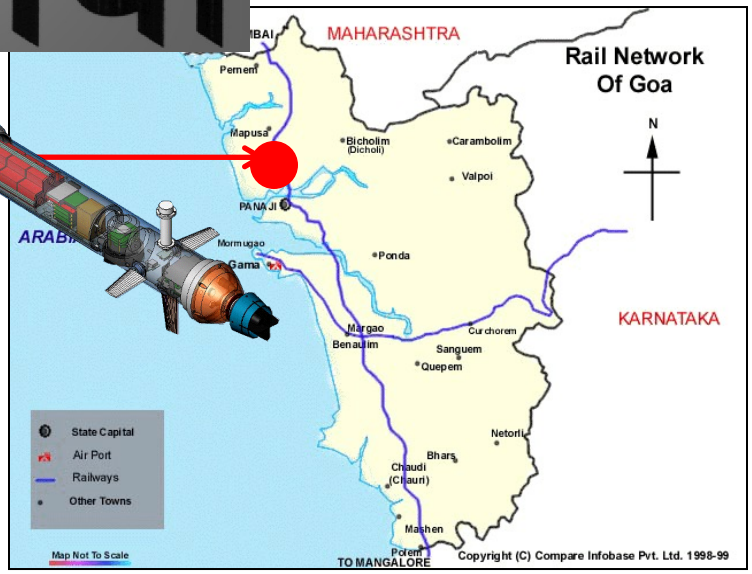
Maya

माया

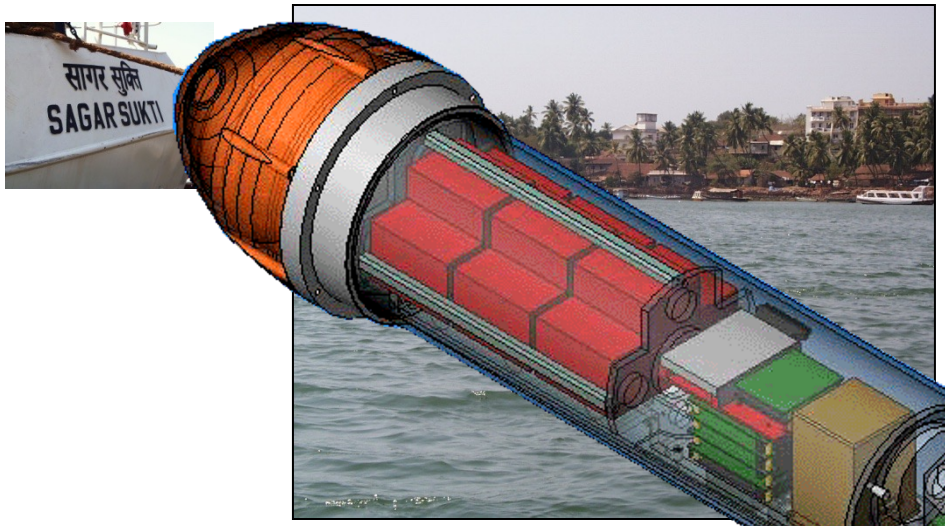




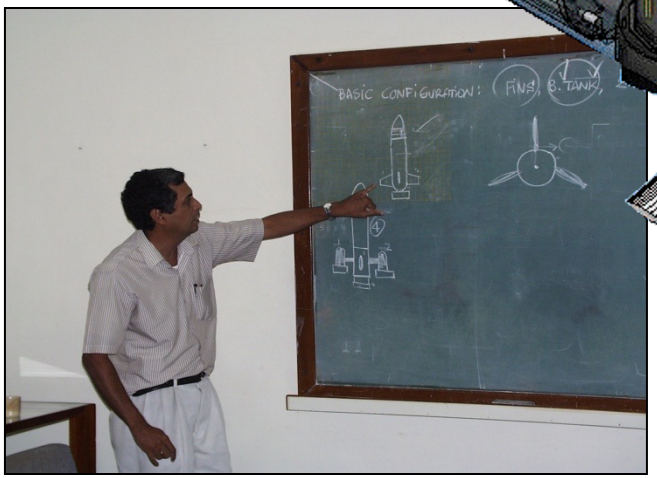


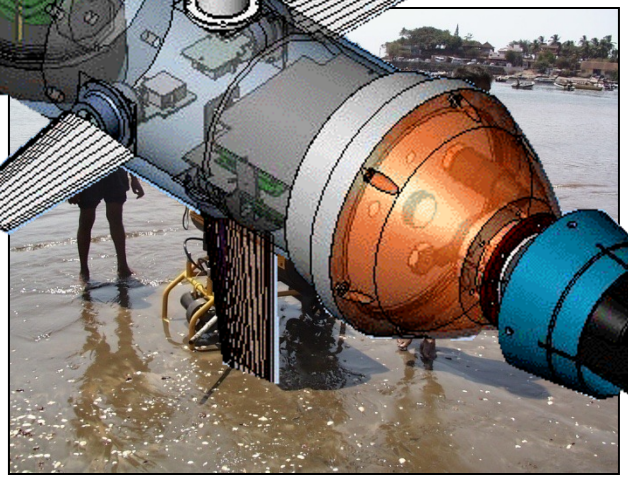


The MAYA AUV – IST/NIO



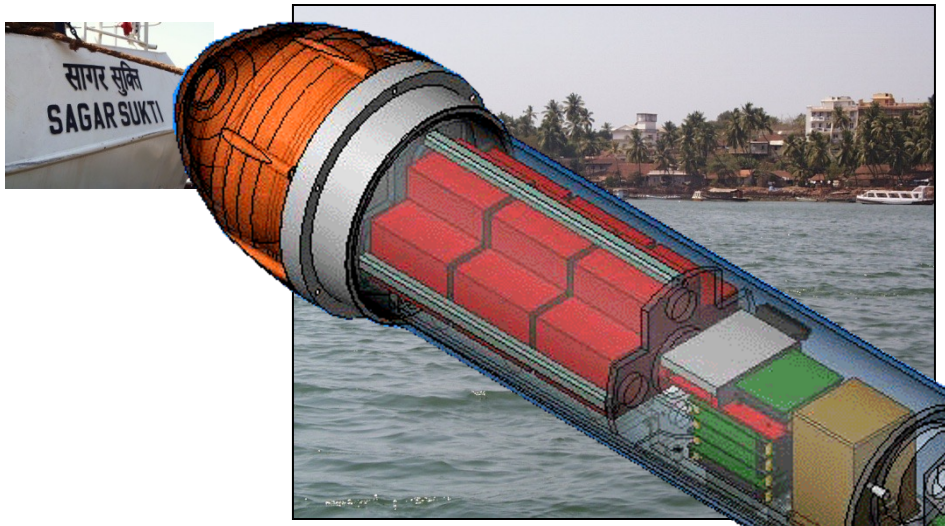
MAYA-Sub work and tests in India





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

The MAYA AUV – IST/NIO



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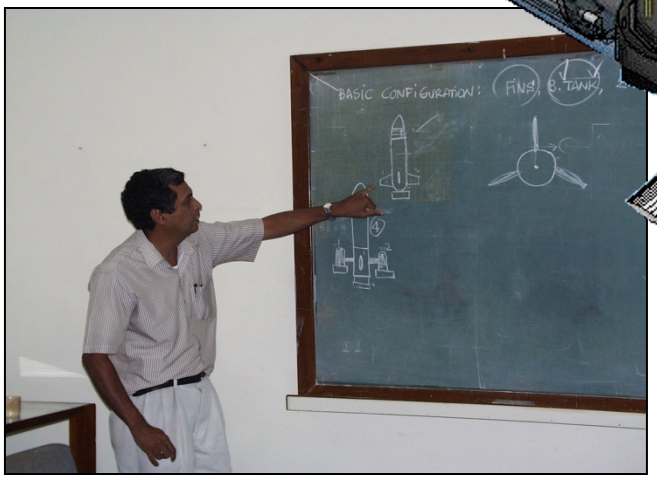
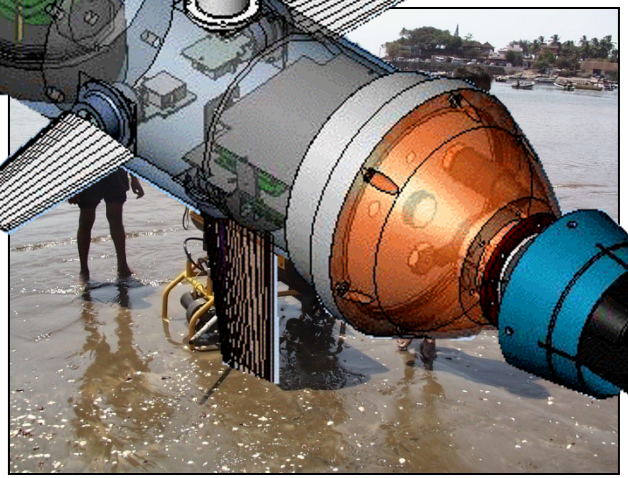
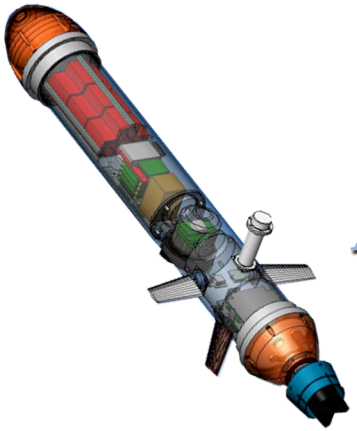




Interchange of Researchers PT-INDIA; co-project via Web

Cooperation with India (NIO and NIOT)

Work and tests in India

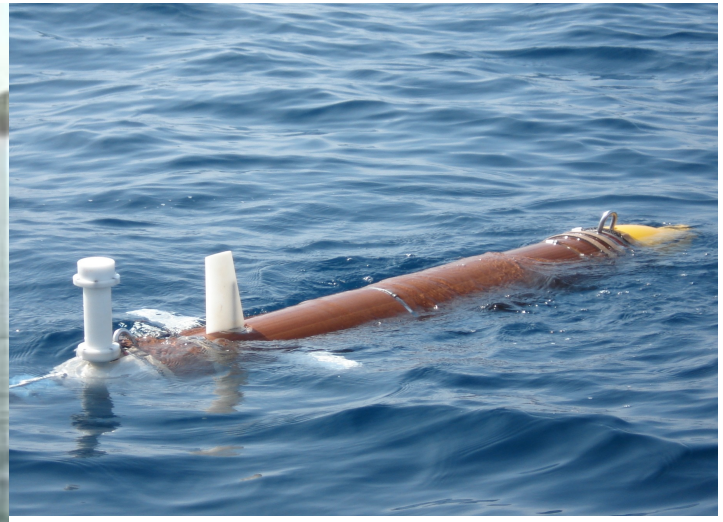


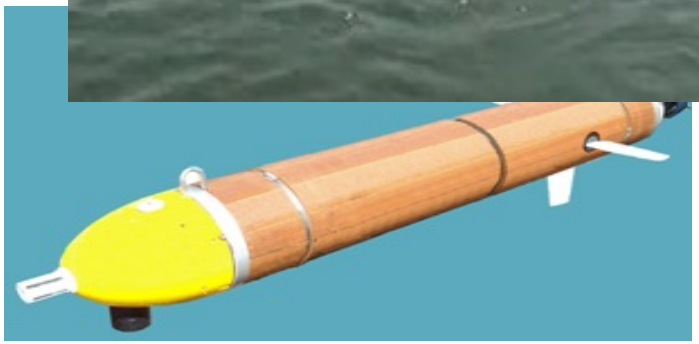
Maya
माया

Amthnem, Goa

Cooperation with India (NIO and NIOT)

Cooperation with India (NIO and NIOT)

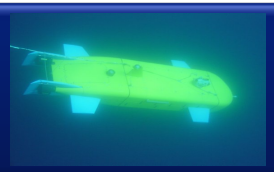




India - Portugal

Maya
माया

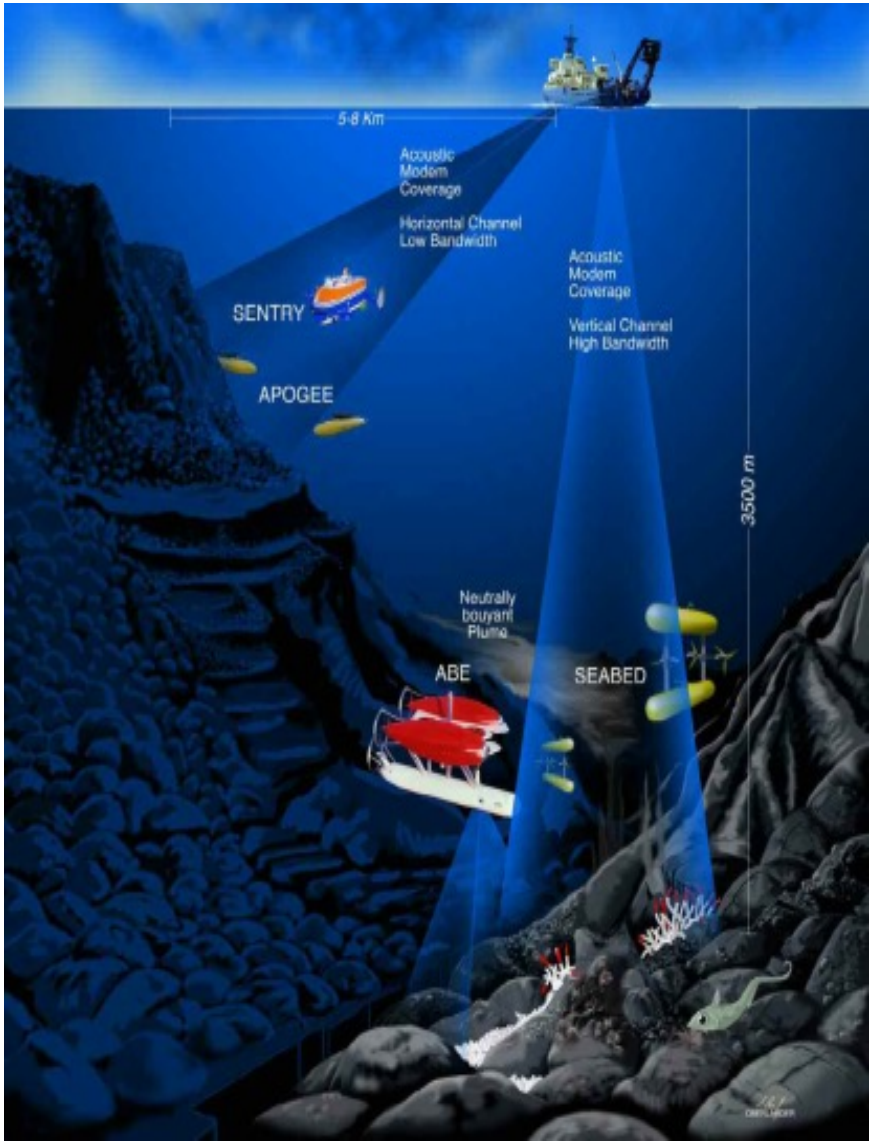
MAYA - AUV



Penetrating the Deep Sea

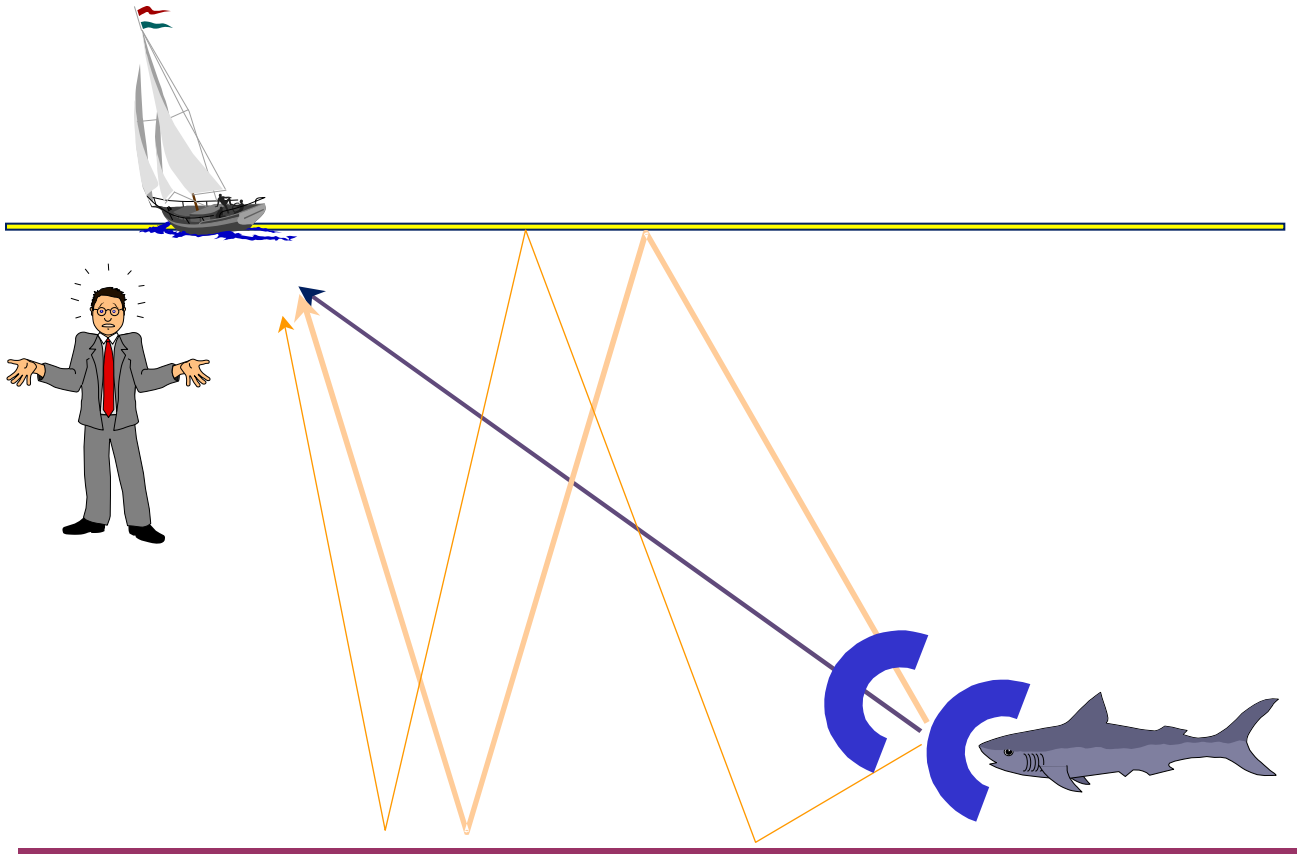
Challenges

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



Opening the multiple vehicle frontier

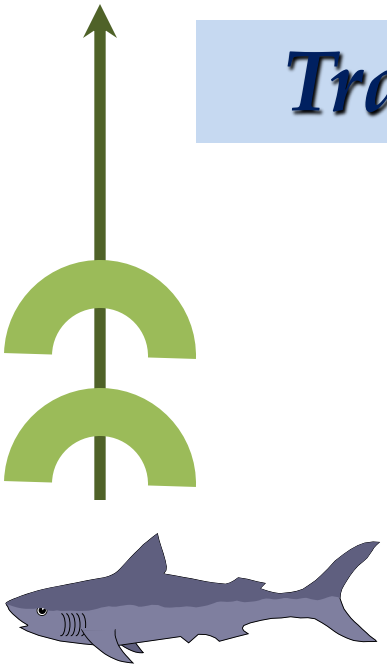
Underwater Communications – *very hard!*



Opening the multiple vehicle frontier

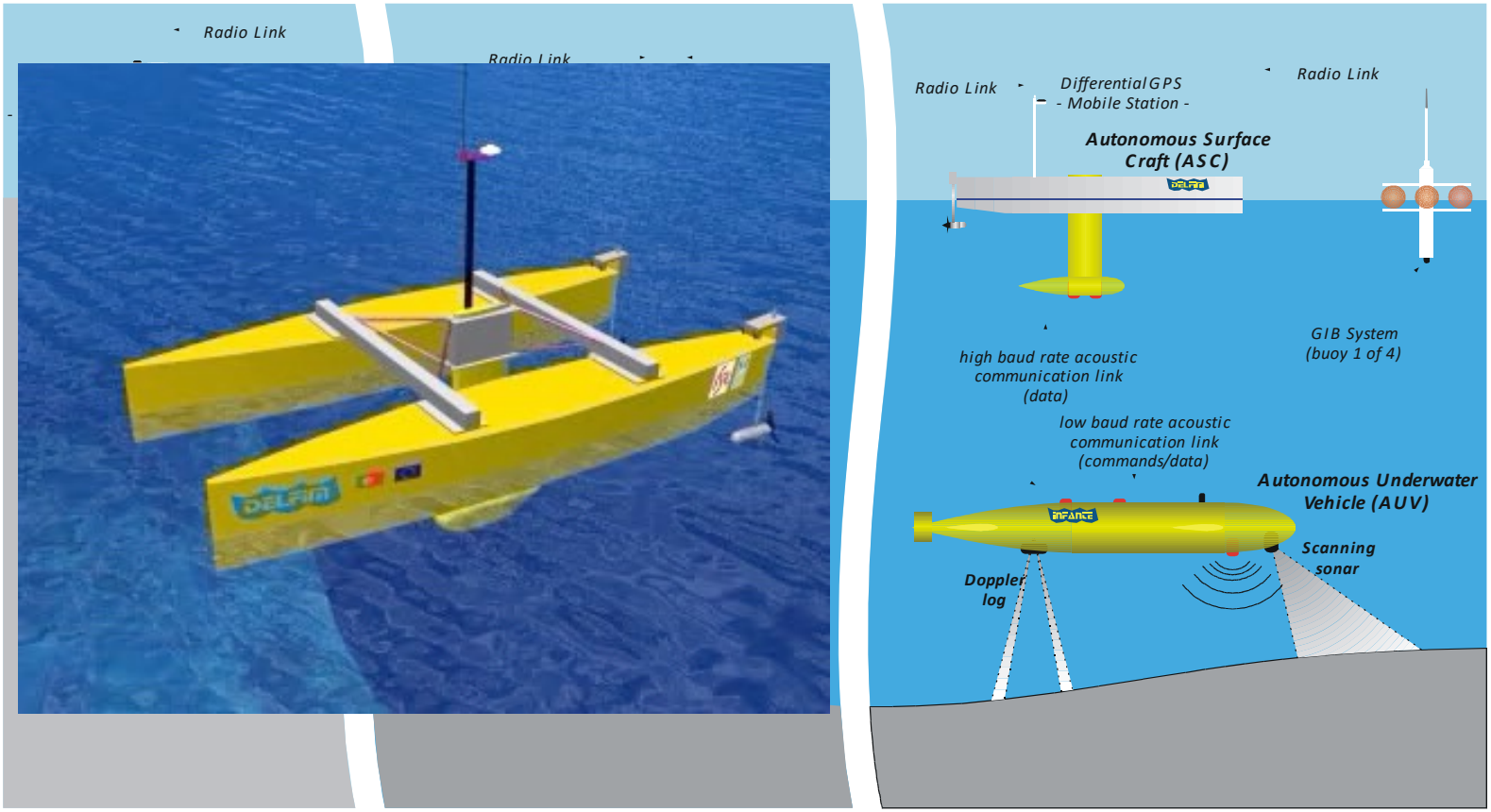
Underwater Communications

Transmit in the vertical !



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 -)

-
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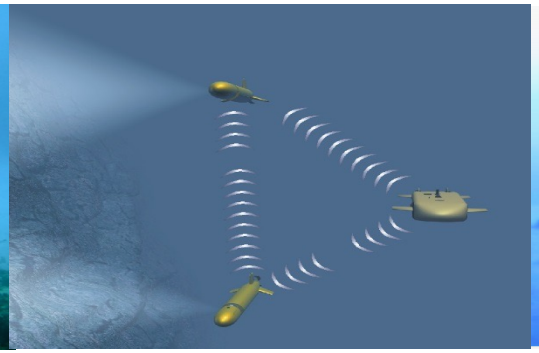
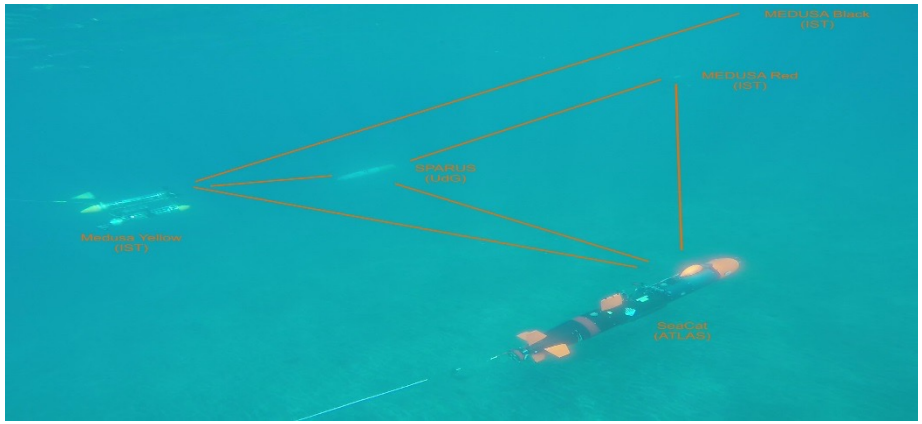
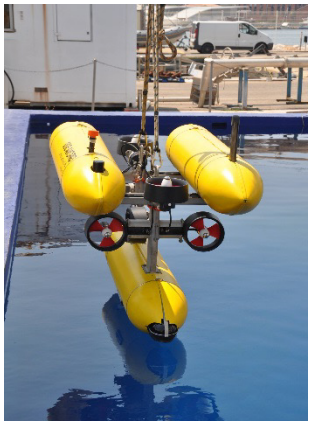
and Control

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

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S&T organization CMRE

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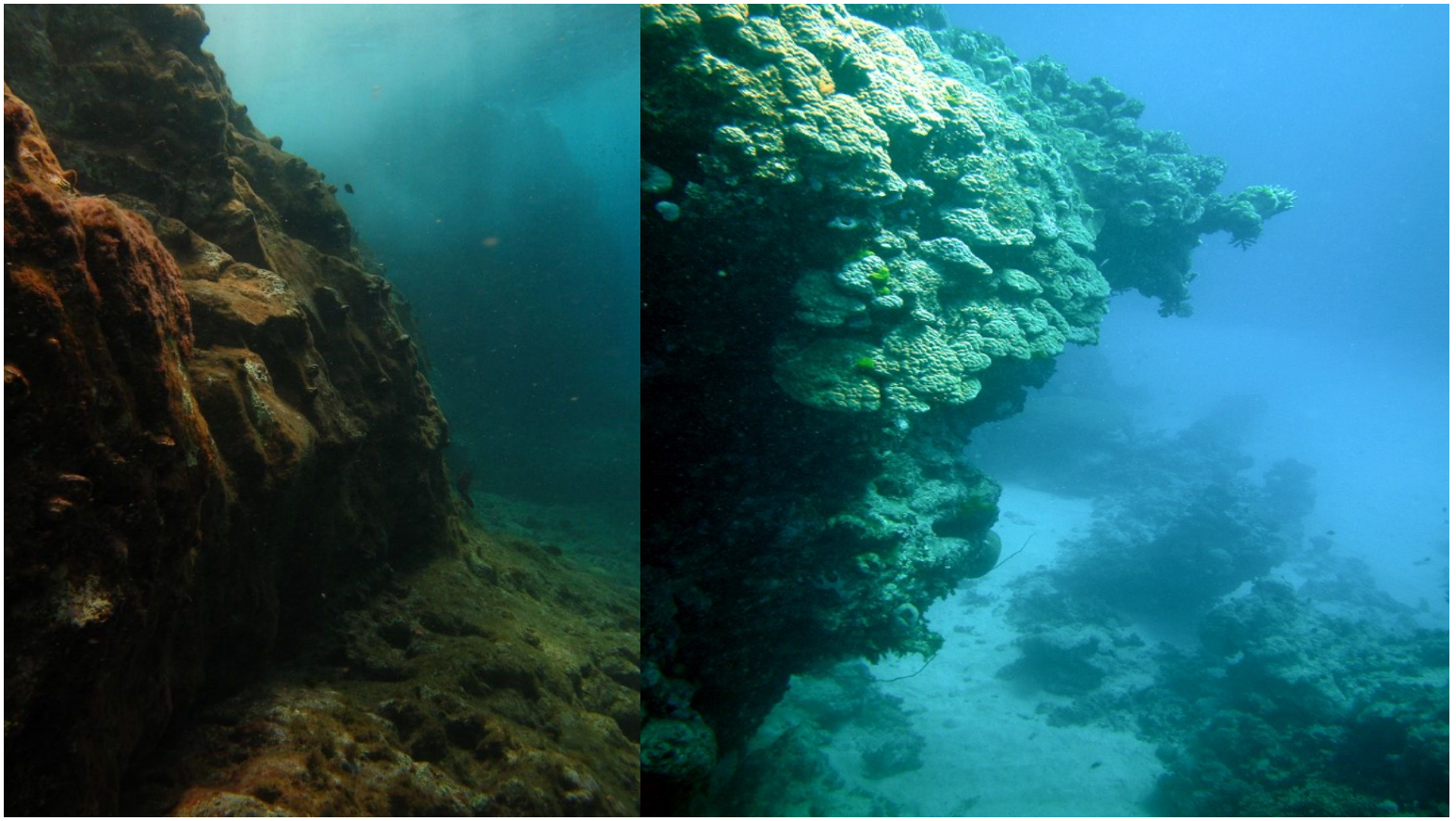
DOP

MORPH / EC (2012-2016)

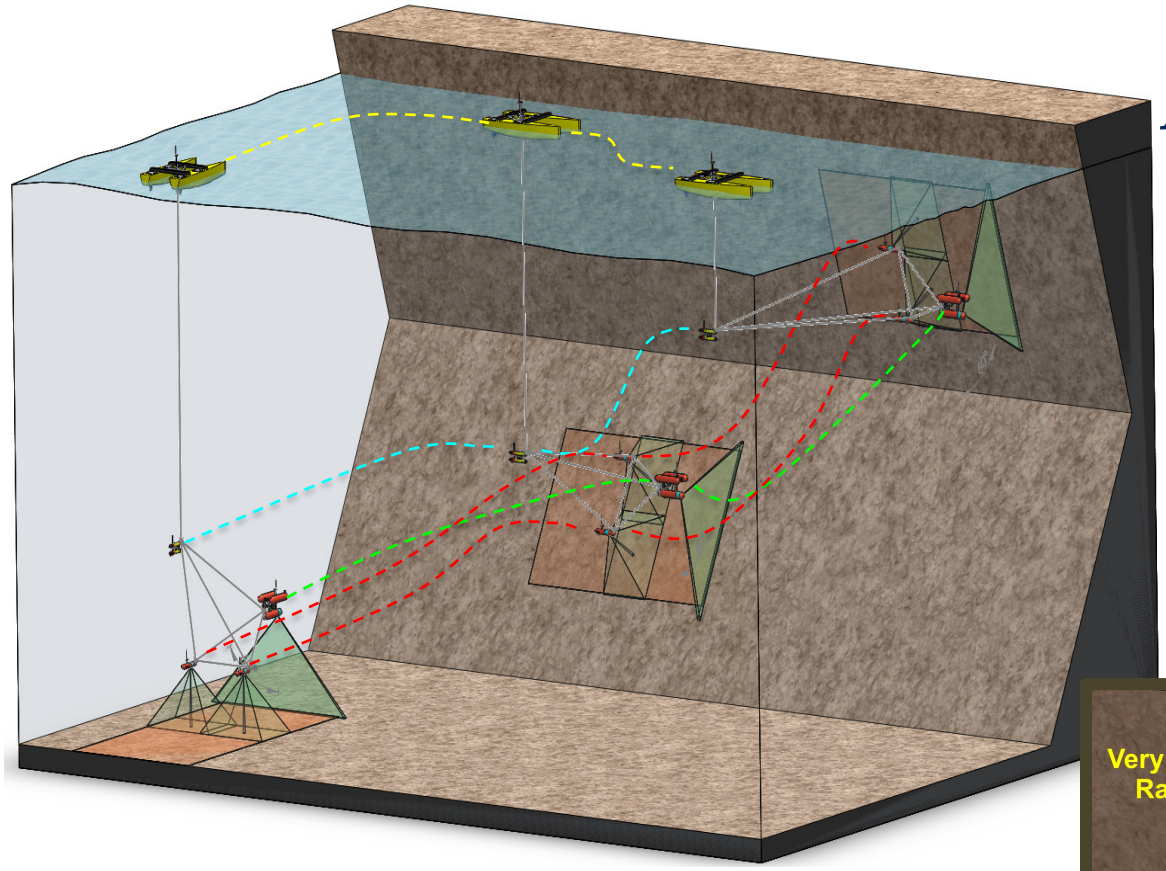
Habitat Mapping in complex 3D environments



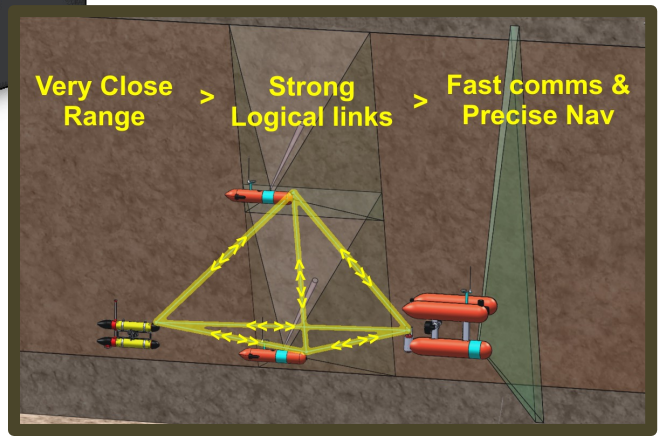
Underwater cliffs, canyon walls, fracture zones, seamount flanks, hydrothermal chimneys

The EC MORPH project

MORPH / EC (2012-2016)

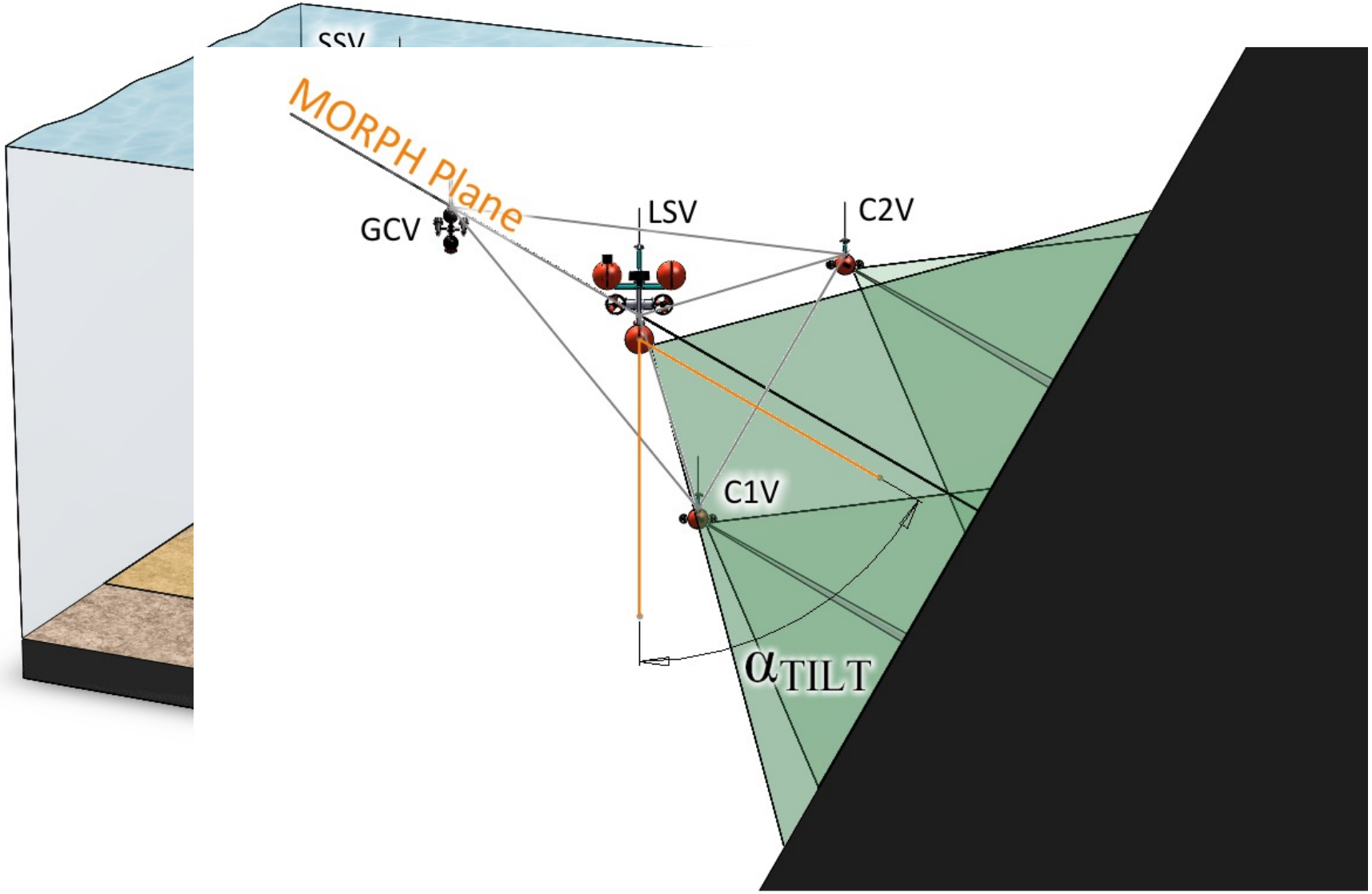


A team of agents operating as a virtual super marine vehicle



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

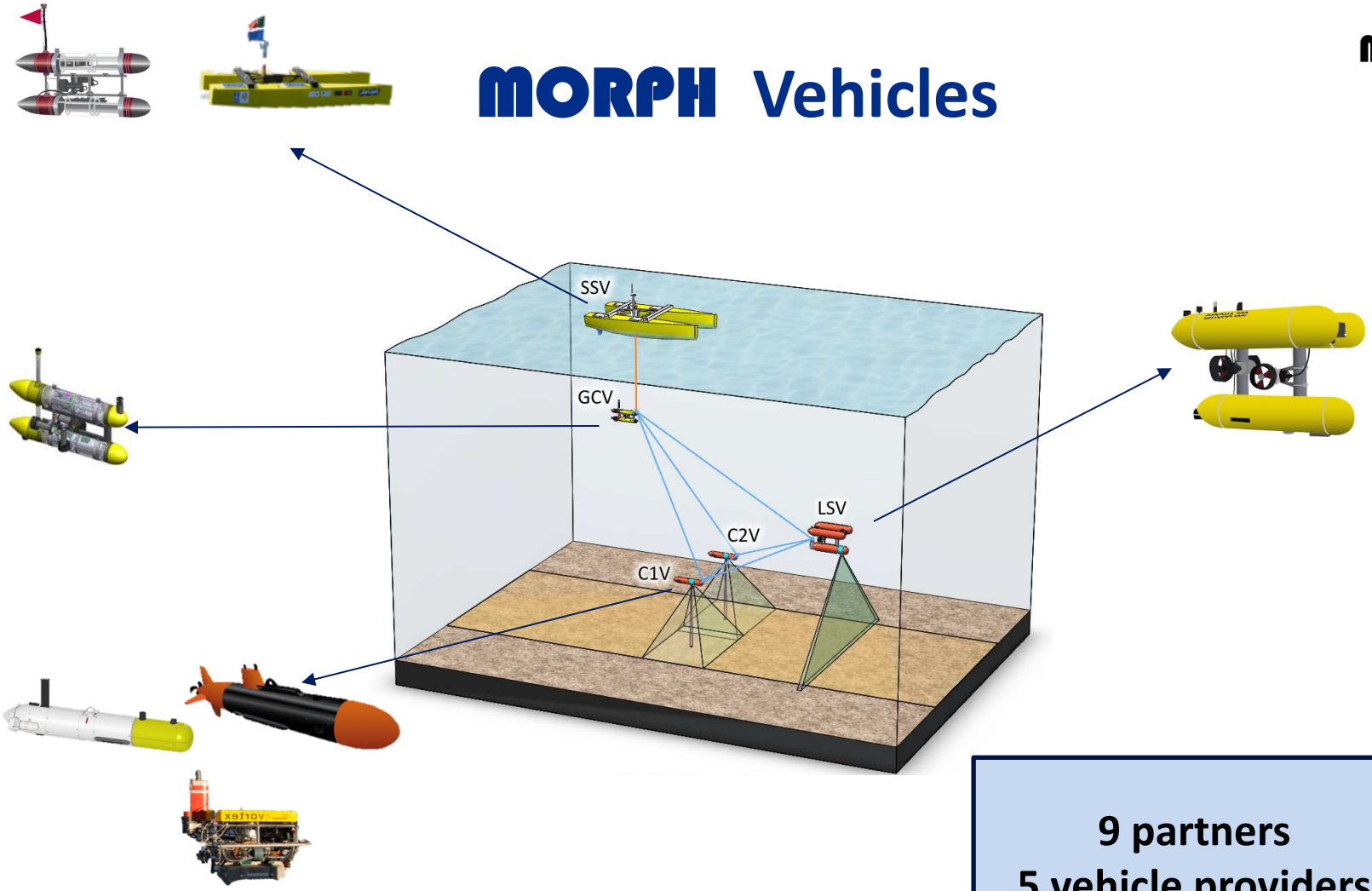
The adaptive MORPH configuration



© MORPH Consortium

MORPH

MORPH Vehicles



9 partners
5 vehicle providers

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S&T organization
CMRE
DOP
ATLAS ELEKTRONIK
A joint company of ThyssenKrupp and EADS
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Consiglio Nazionale delle Ricerche

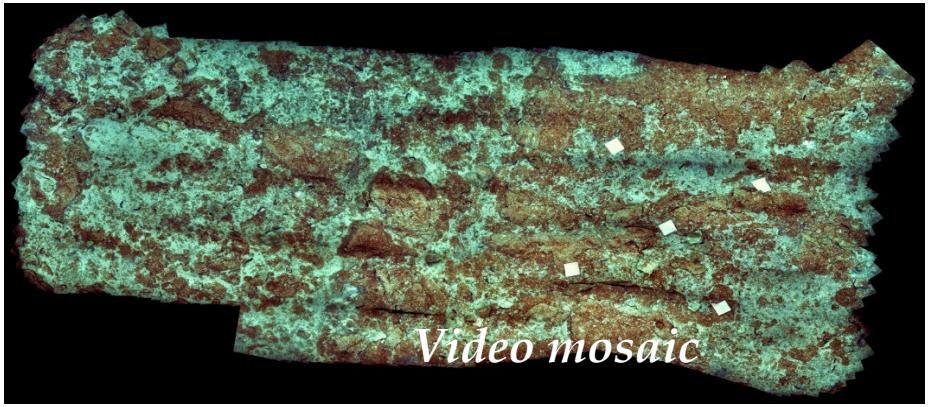
The EC MORPH project

MORPH / EC (2012-2016)

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

9 European partners

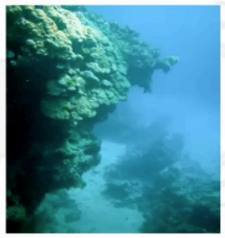
Mapping of vertical walls

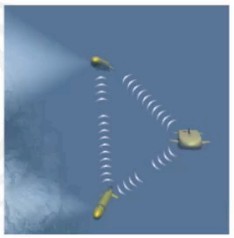


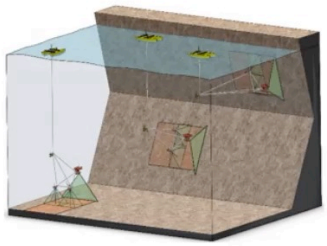
Video mosaic

The EC MORPH project

MORPH Azores, PT, 2014







Marine robotics system of self-organizing logically linked physical nodes

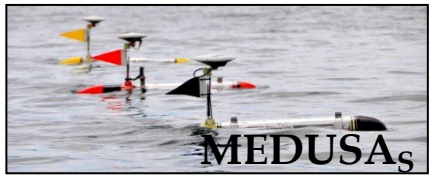
Azores trials 2014

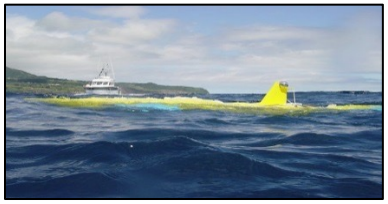
Universitat de Girona · ISR · IST · TÉCNICO LISBOA · JACOBS UNIVERSITY · TECHNISCHE UNIVERSITÄT ILMENAU · DOP · S&T organization CMRE · ATLAS ELEKTRONIK A joint company of ThyssenKrupp and EADS · Ifremer · Consiglio Nazionale delle Ricerche

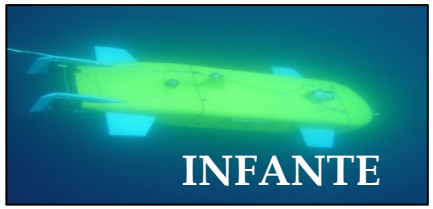
MORPH Girona , SP, 2015

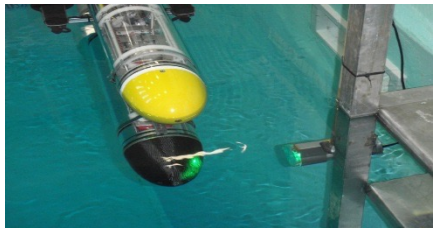
Making it all happen: UAVs, AUVs, ASVS

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).



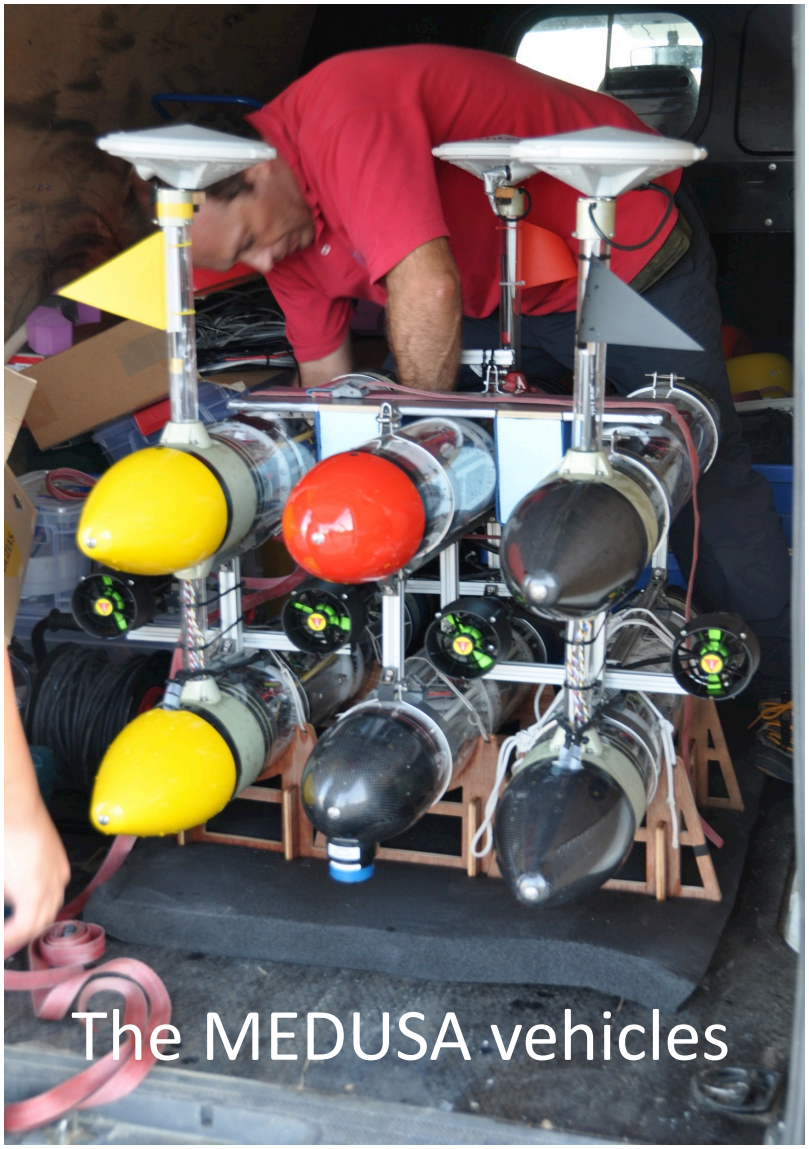






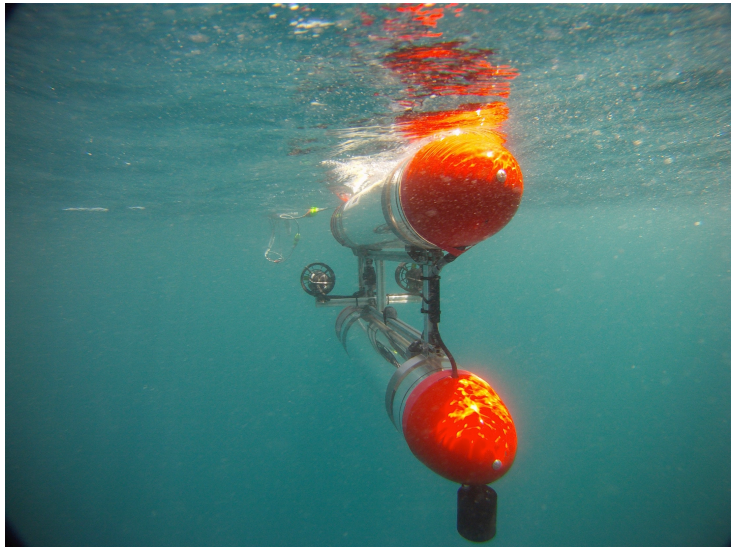
Fleet of 3 autonomous surface and 4 underwater robots Several air vehicles

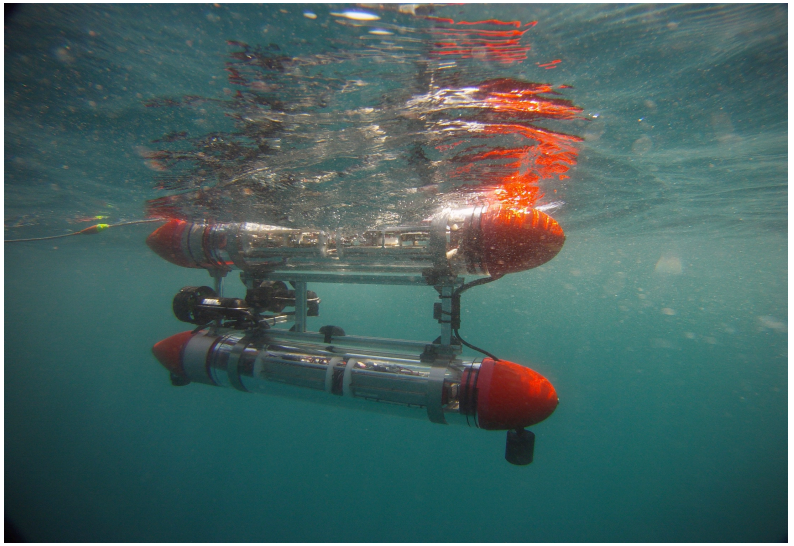
The sea-going machines

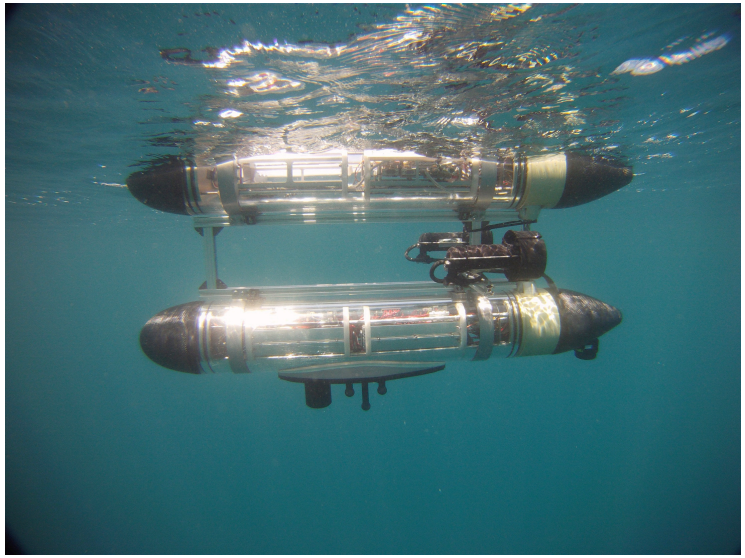


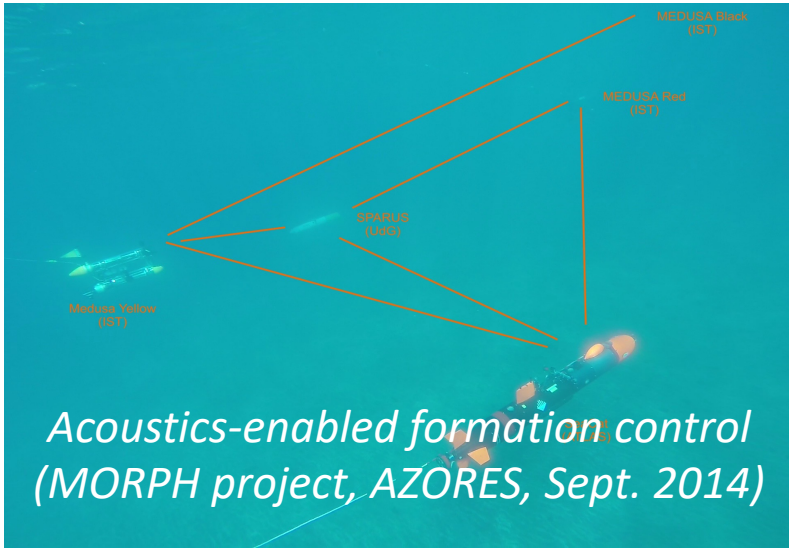
The MEDUSA vehicles

Labs and equipment









Acoustics-enabled formation control (MORPH project, AZORES, Sept. 2014)

The MEDUSA-class vehicles (AUV/ASV)

Transportation and deployment

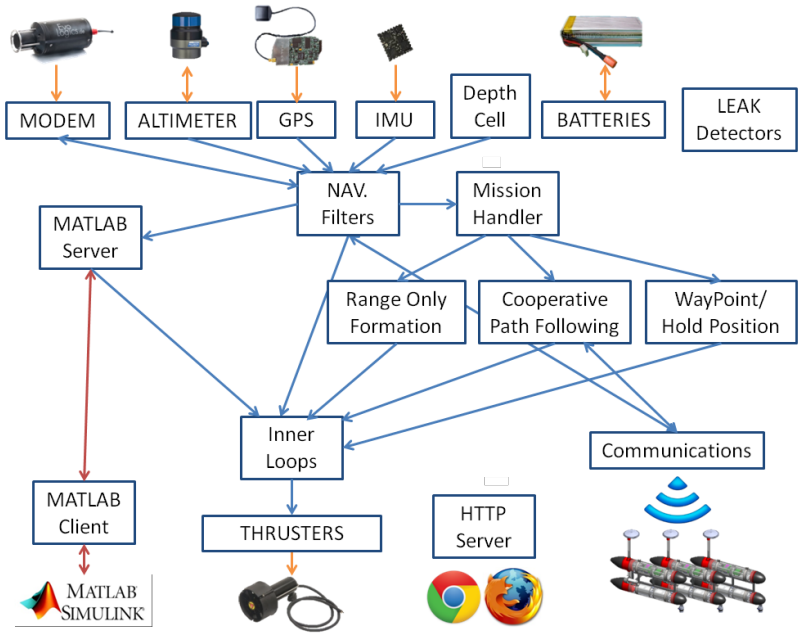
3 MEDUSAs can be transported in a van or small trailer

Transportation to water by a single person in a cart

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

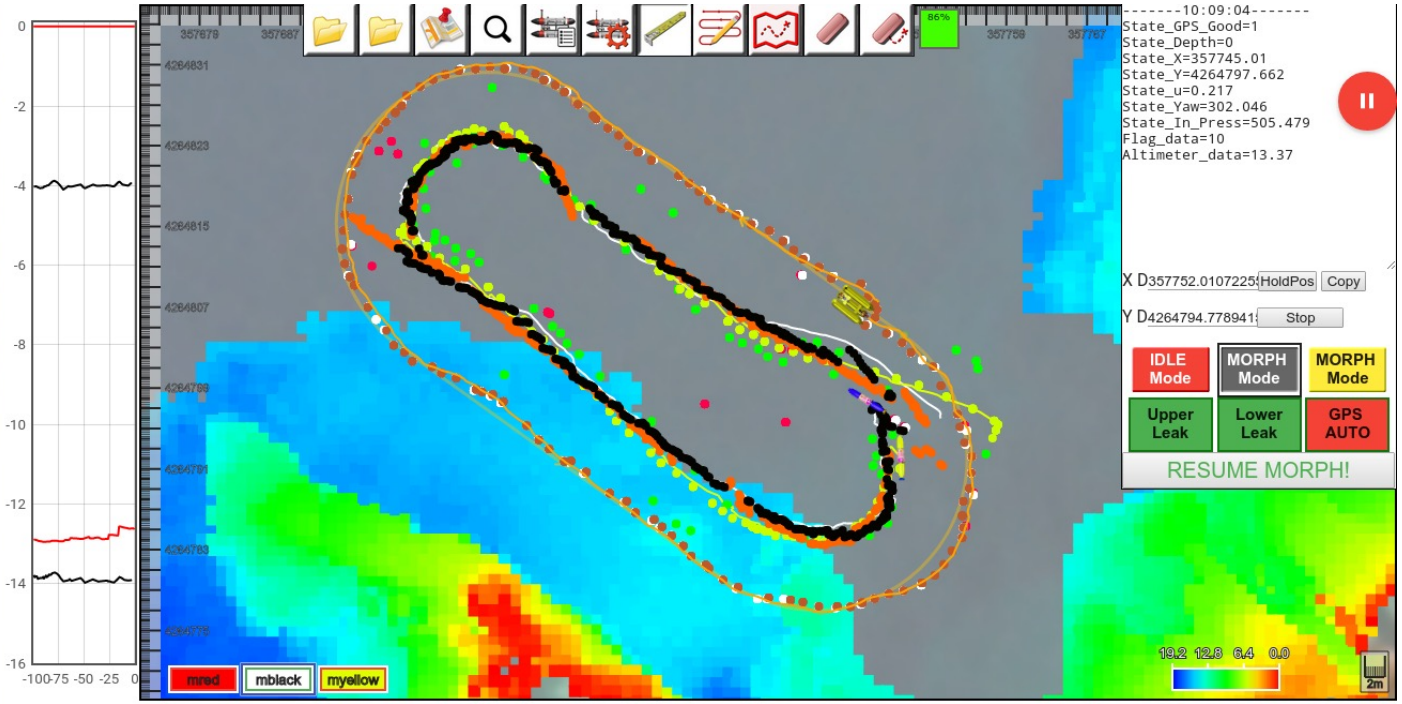
Software architecture overview

- 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



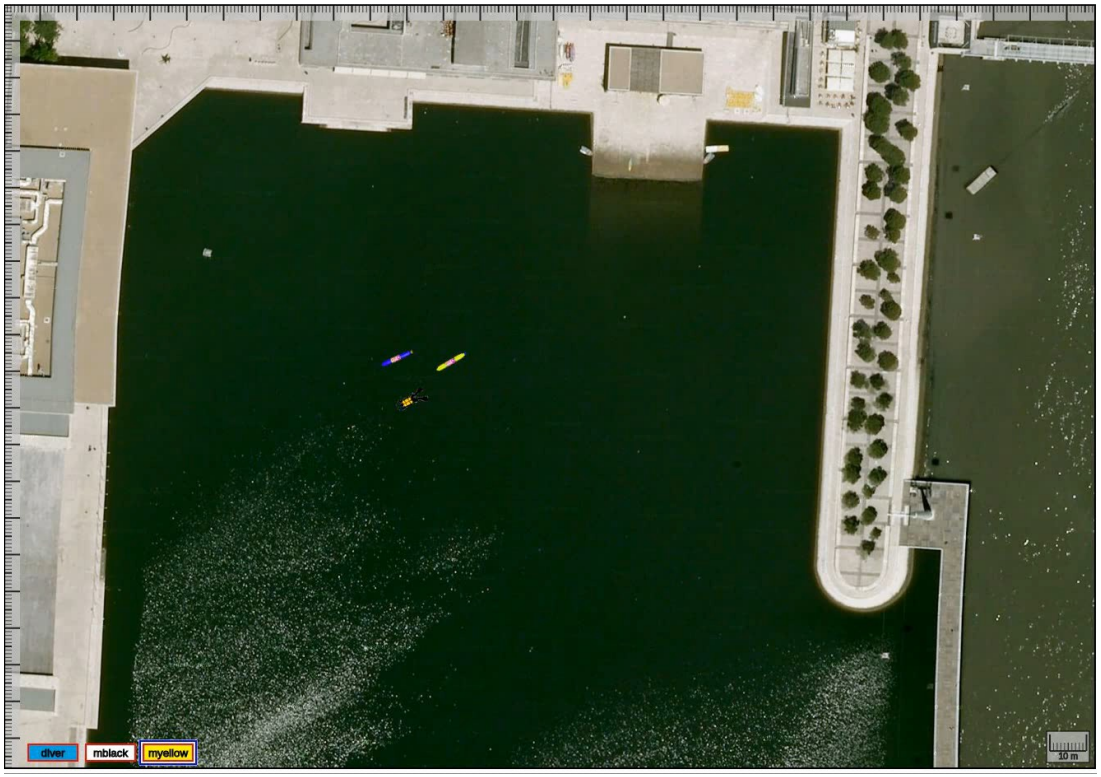
Mission control console

- 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

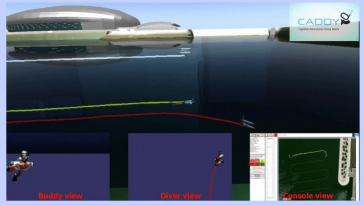


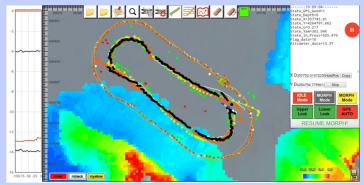
Mission programming

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



Simulation pipeline





Visualization systems
(console and/or UWSim)
+
access to raw
data for debug

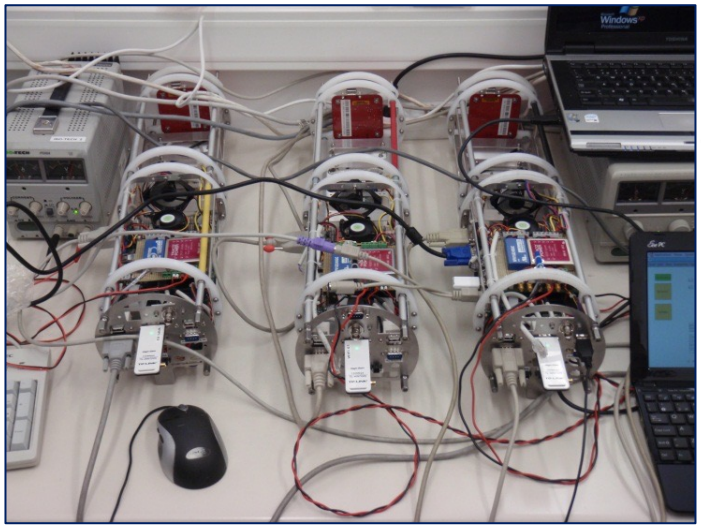
Acoustic modems/USBL
emulators

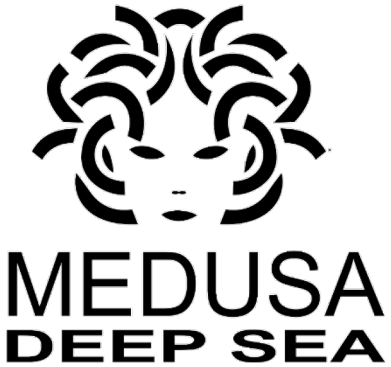
Simulated vehicle state

Simulated vehicle
positions and messages
to be broadcast

Commands and
simulated
environment data

Simulated modem/
USBL outputs





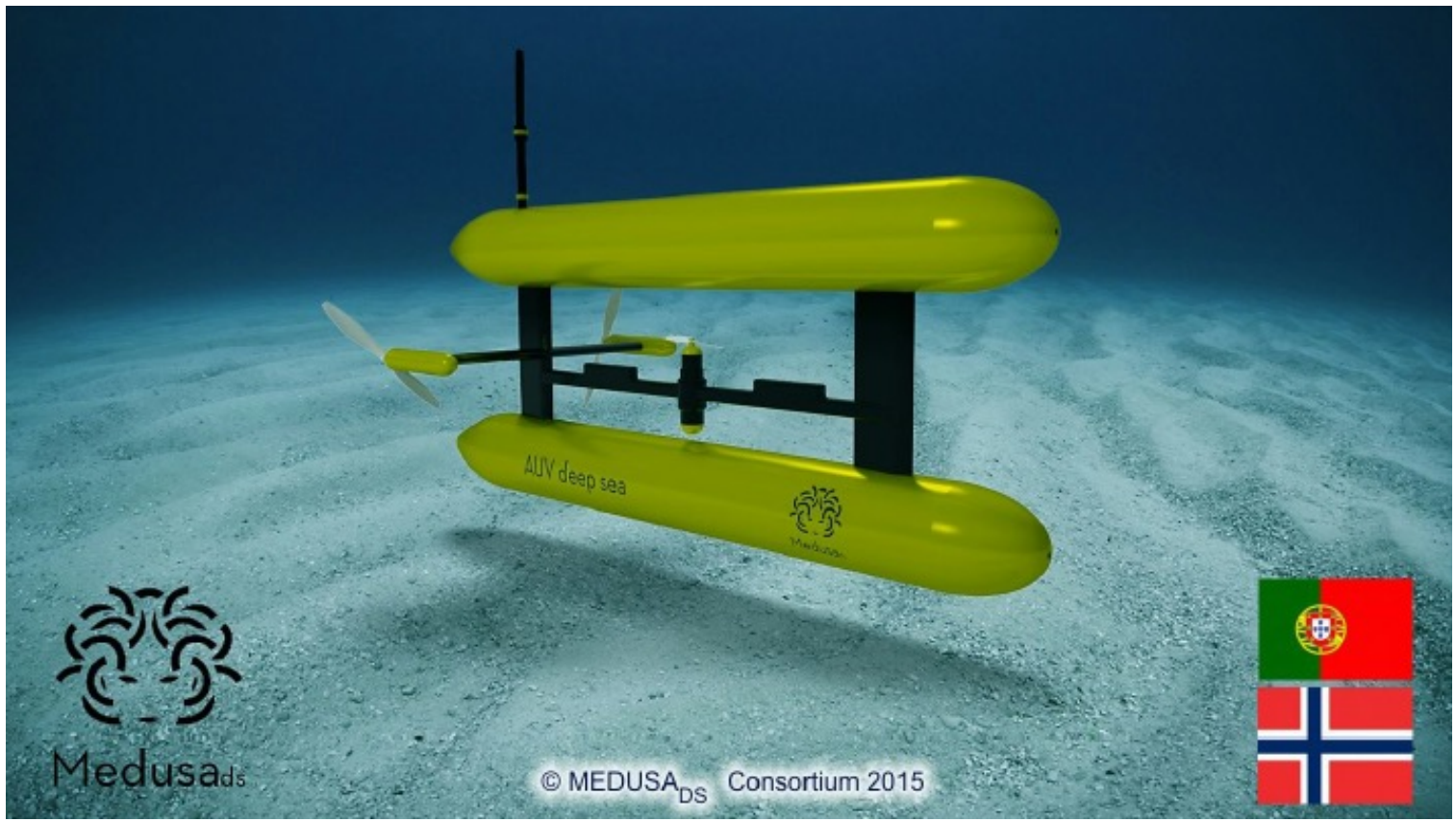
"$MEDUSA_{DS}$ – OPENING THE DEEP SEA FRONTIER"

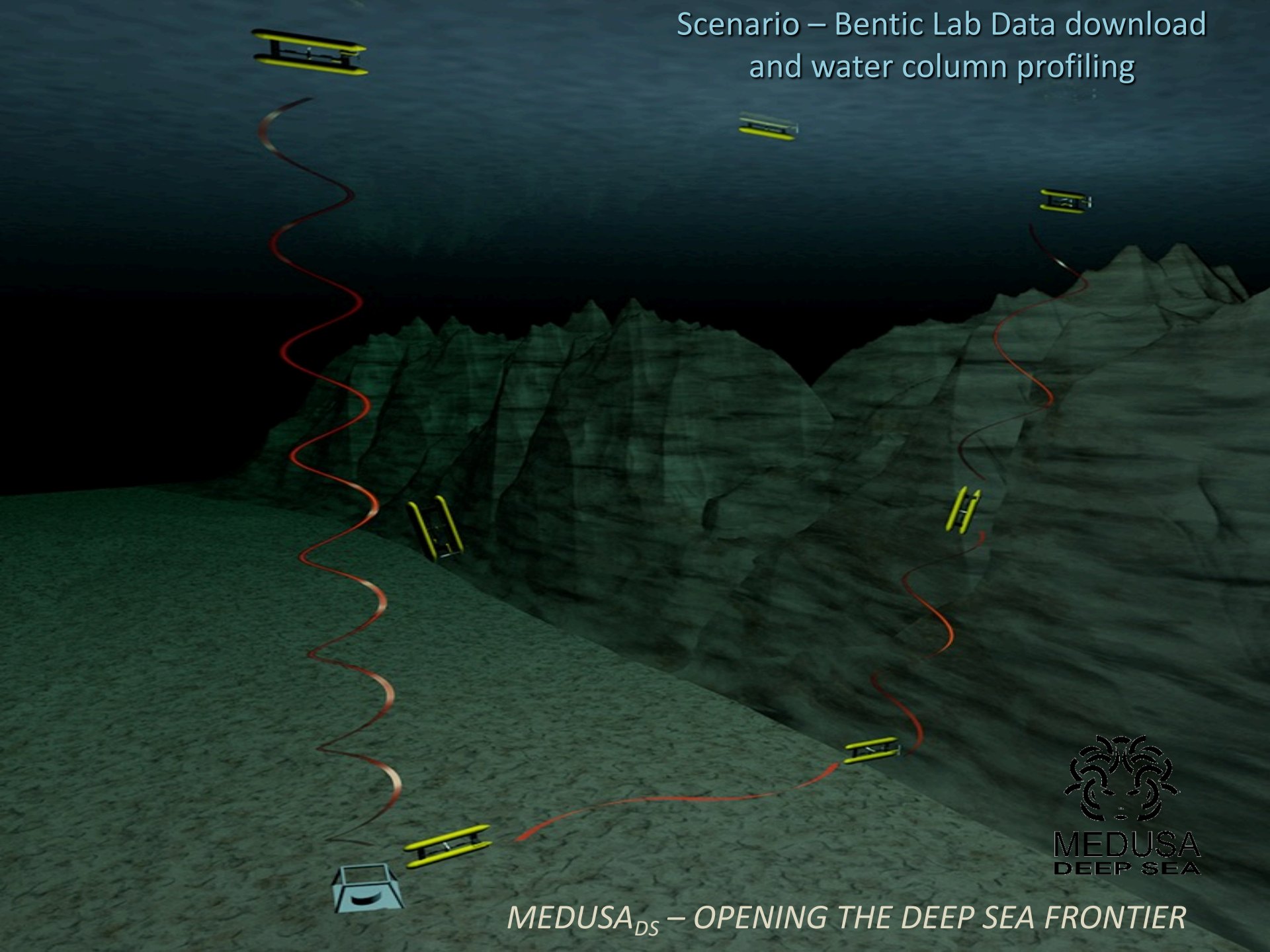
(2015-2017)

GOVERNO DE PORTUGAL | MINISTÉRIO DA AGRICULTURA E DO MAR

dgpm Direção-Geral de Política do Mar

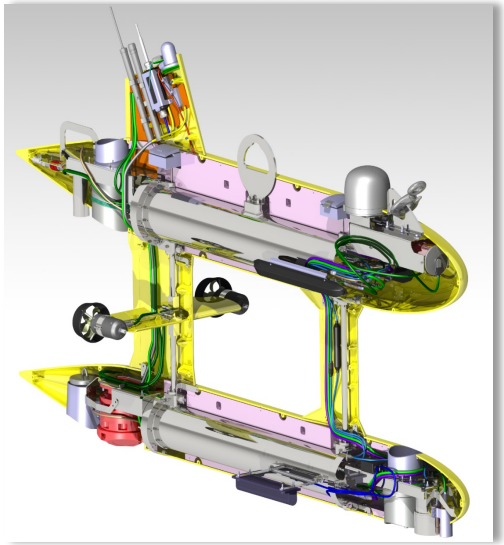
MEDUSA$_{DS}$ / EC (2015-2017)

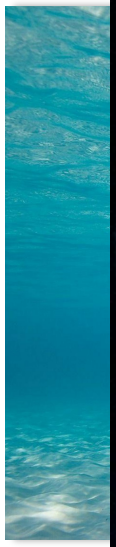



Scenario – Bentic Lab Data download
and water column profiling
MEDUSA
DEEP SEA
MEDUSA$_{DS}$ – OPENING THE DEEP SEA FRONTIER

MEDUSA
DEEP SEA

OPENING THE DEEP-SEA FRONTIER

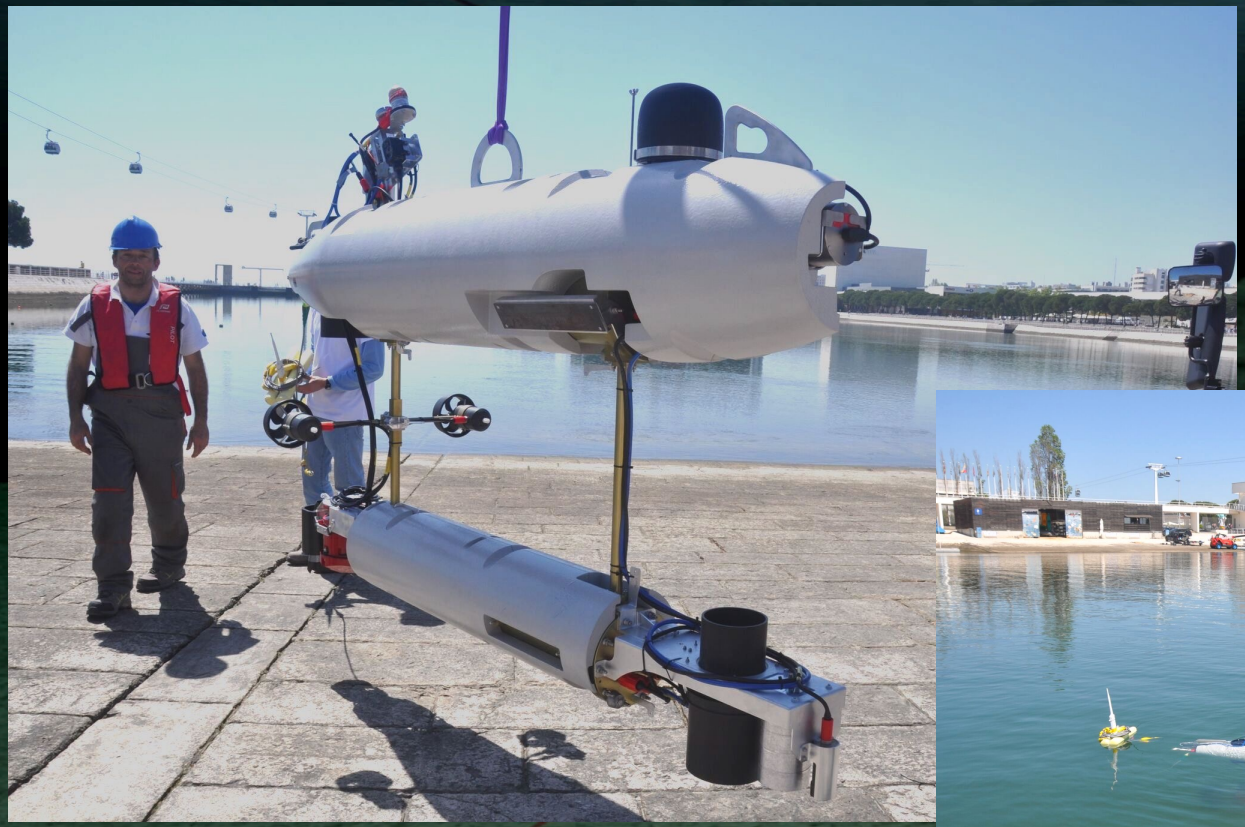




Tales of

Housing pre

Scenario – Bentic Lab Data download and water column profiling

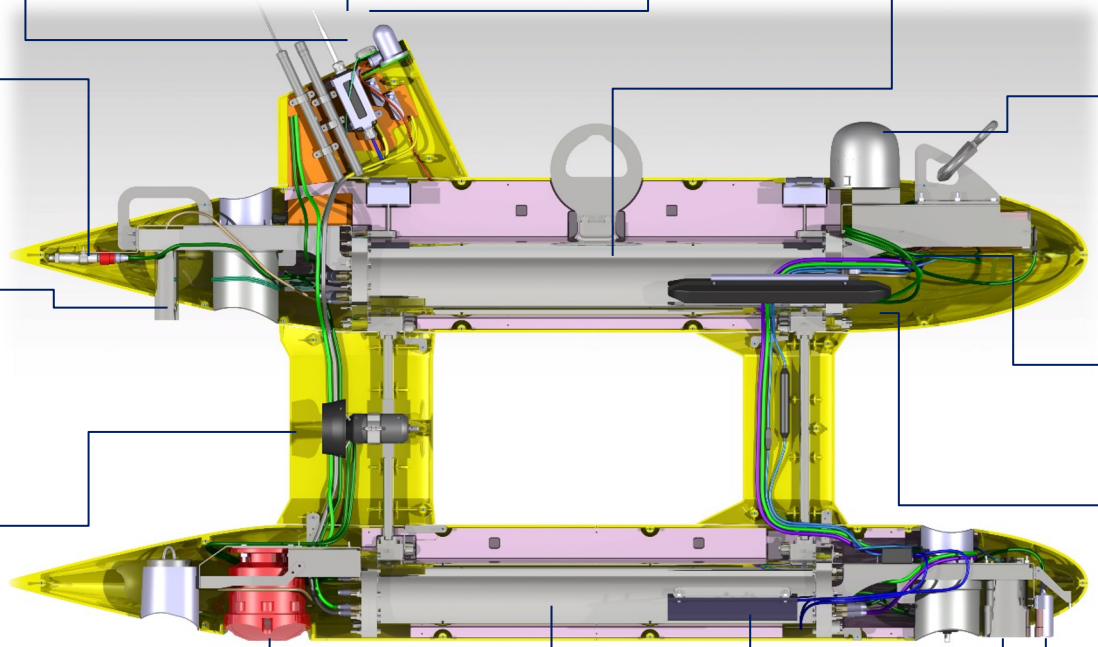


MEDUSA DEEP SEA

MEDUSA$_{DS}$ – OPENING THE DEEP SEA FRONTIER

System Breakdown

MEDUSA DEEP SEA



ADVANCED NAVIGATION

POSEIDON GPS Antenna

NOVATECH™

Iridium Beacon
Mini Flasher Beacon

UBIQUITI NETWORKS

Wi-Fi 802.11 b/g

GPS Board | AHRS Vectornav | Gyros | EPIC Computers | Wi-Fi elect | Hard Disks | SSS + SBP electronics |

KELLER

KELLER PAA-33XEi Depth Cell

EvoLogics®

EvoLogics USBL Modem

SEA-BIRD SCIENTIFIC

ECO FLNTU Fluorometer and Scattering Meter

KONGSBERG

O2 Subsea Oxygen Sensor

ARGUS

4x Thrusters
Argus ARS-800
Mini-Thruster

EdgeTech
The Leader in Underwater Technology

EdgeTech 2200
Side Scan Sonar

ImpactSubsea

ISA 500 Altimeter

TELEDYNE RD INSTRUMENTS
Everywhereyoulook™

Workhorse Navigator
Doppler Velocity Log

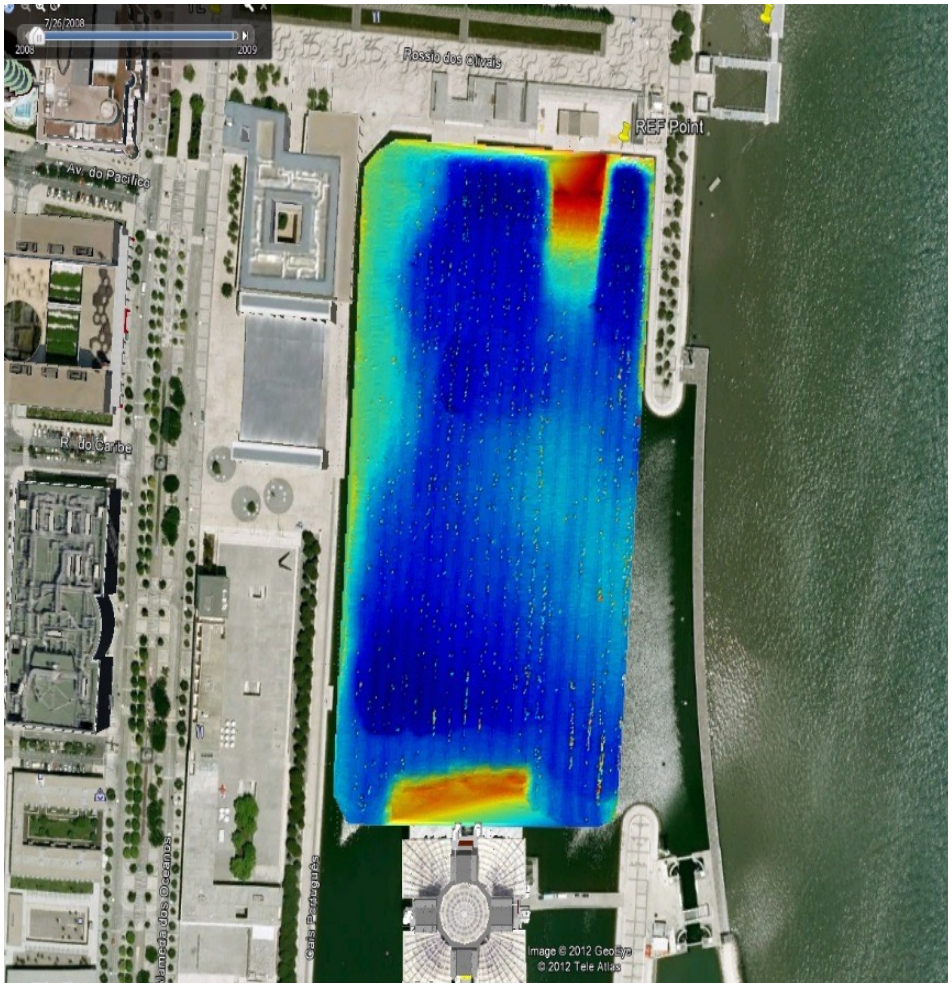
Kokam
Great Power for Everyone

Lithium polymer batteries

EdgeTech
The Leader in Underwater Technology

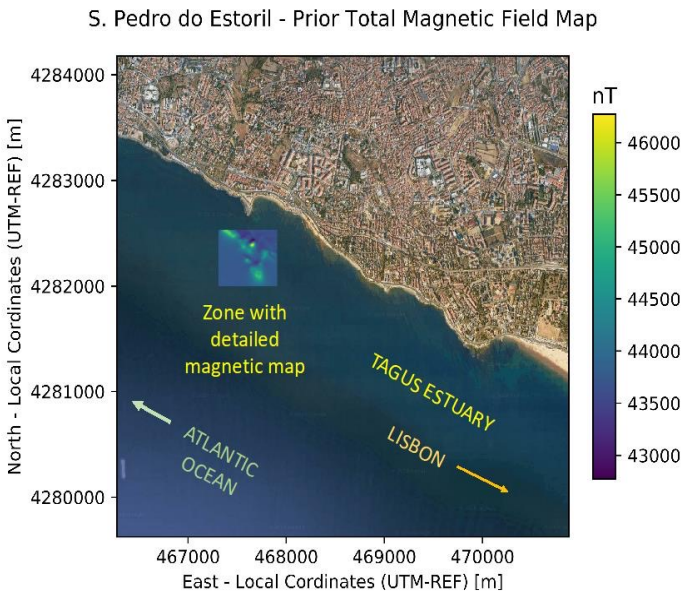
EdgeTech 2200
Sub-Bottom Profiler

Test Facilities



EXPO'98 Site, Lisbon, PT

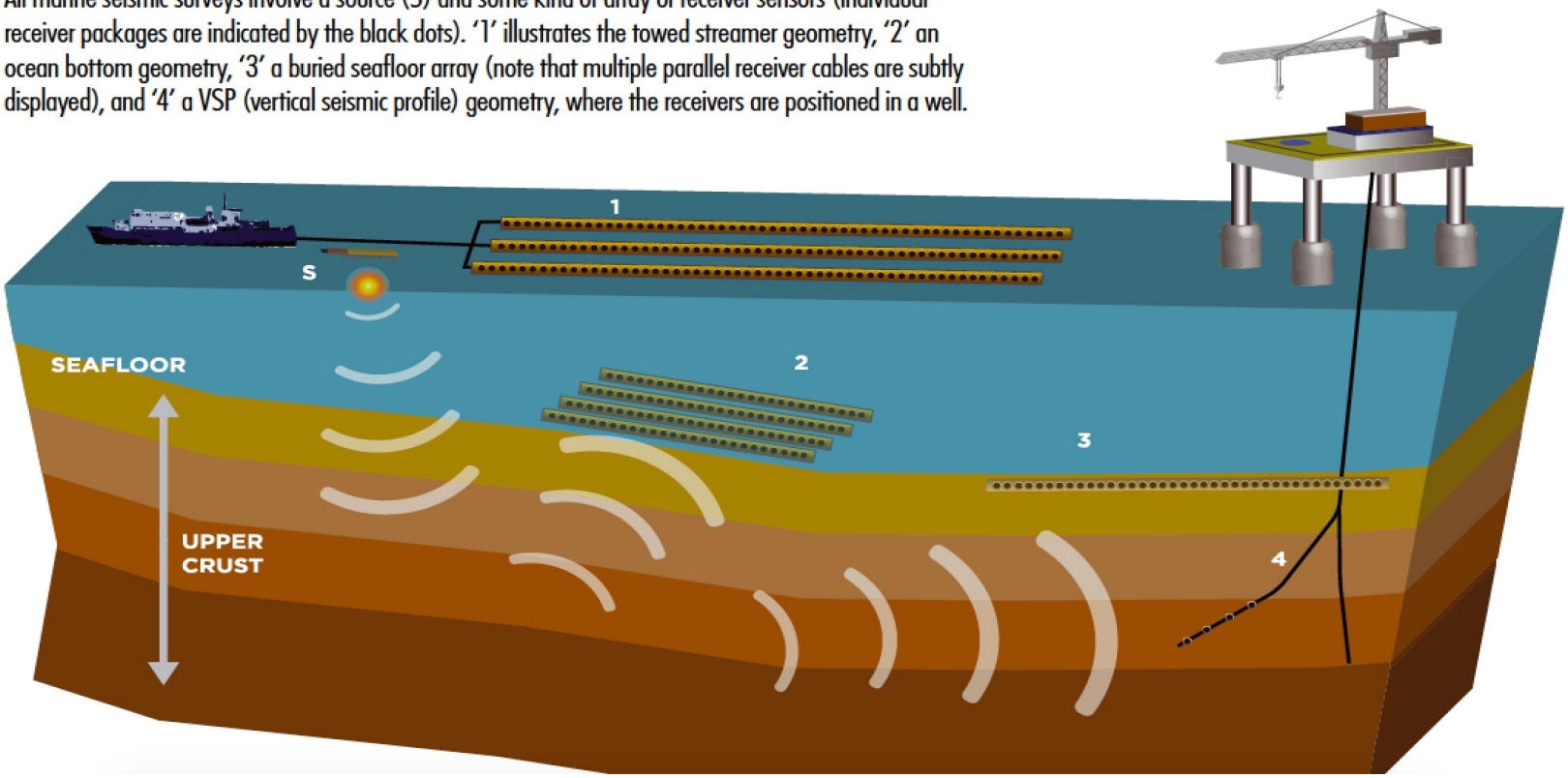
Test Facilities



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.

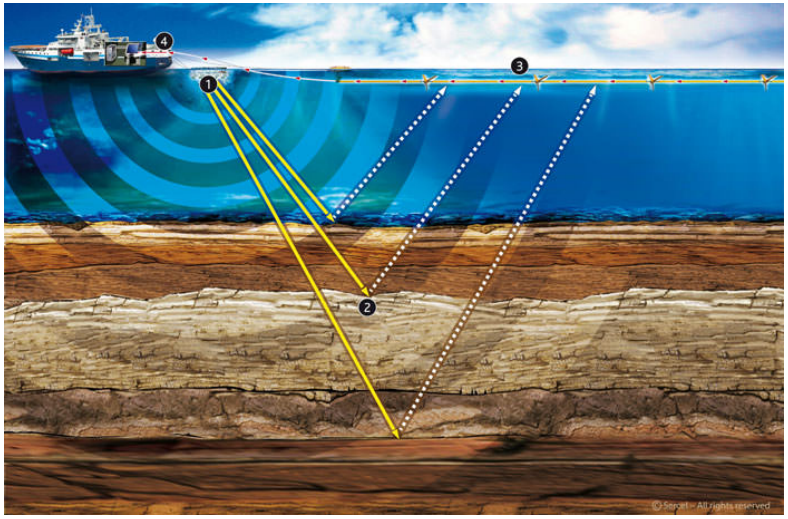


S-acoustic source
1-Towed receiver geometry (hydrophones)
2- Ocean bottom geometry
3- Buried seafloor array
4- Vertical seismic profiler

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

3D seismic surveys: $40.000 - $500.000 per km²!

Very long streamers

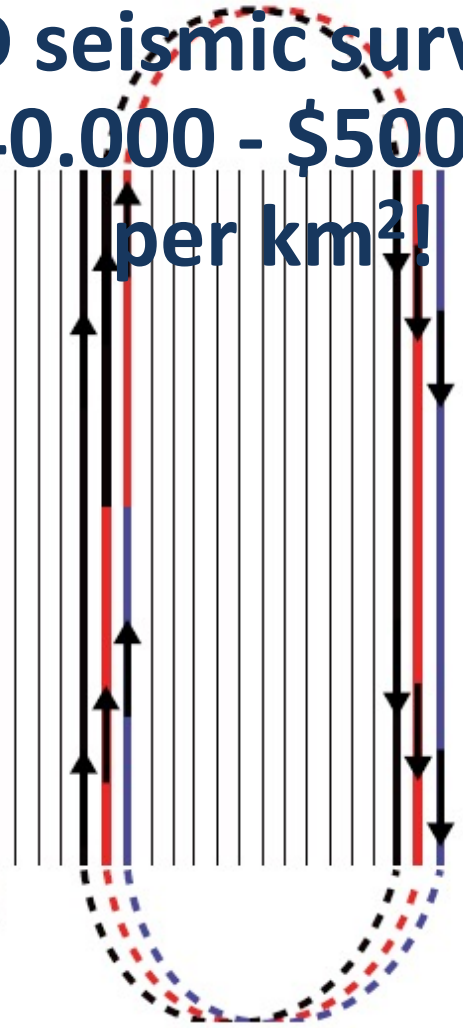
Hours to deploy and re

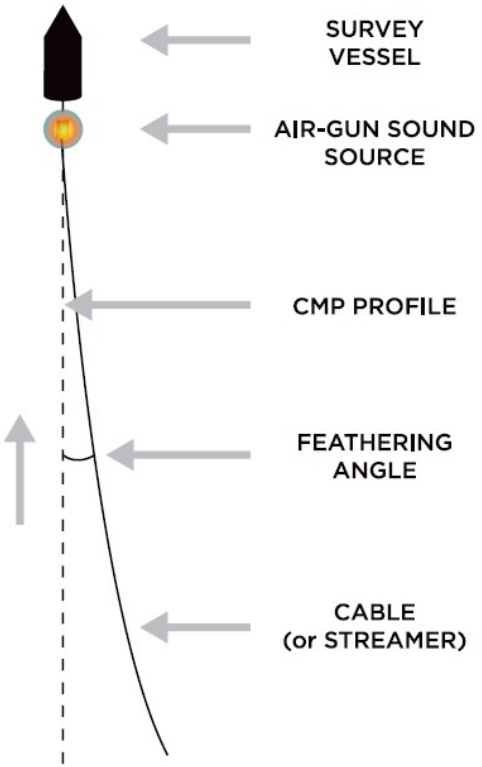
Curve with lateral currents (feathering)

Get entan

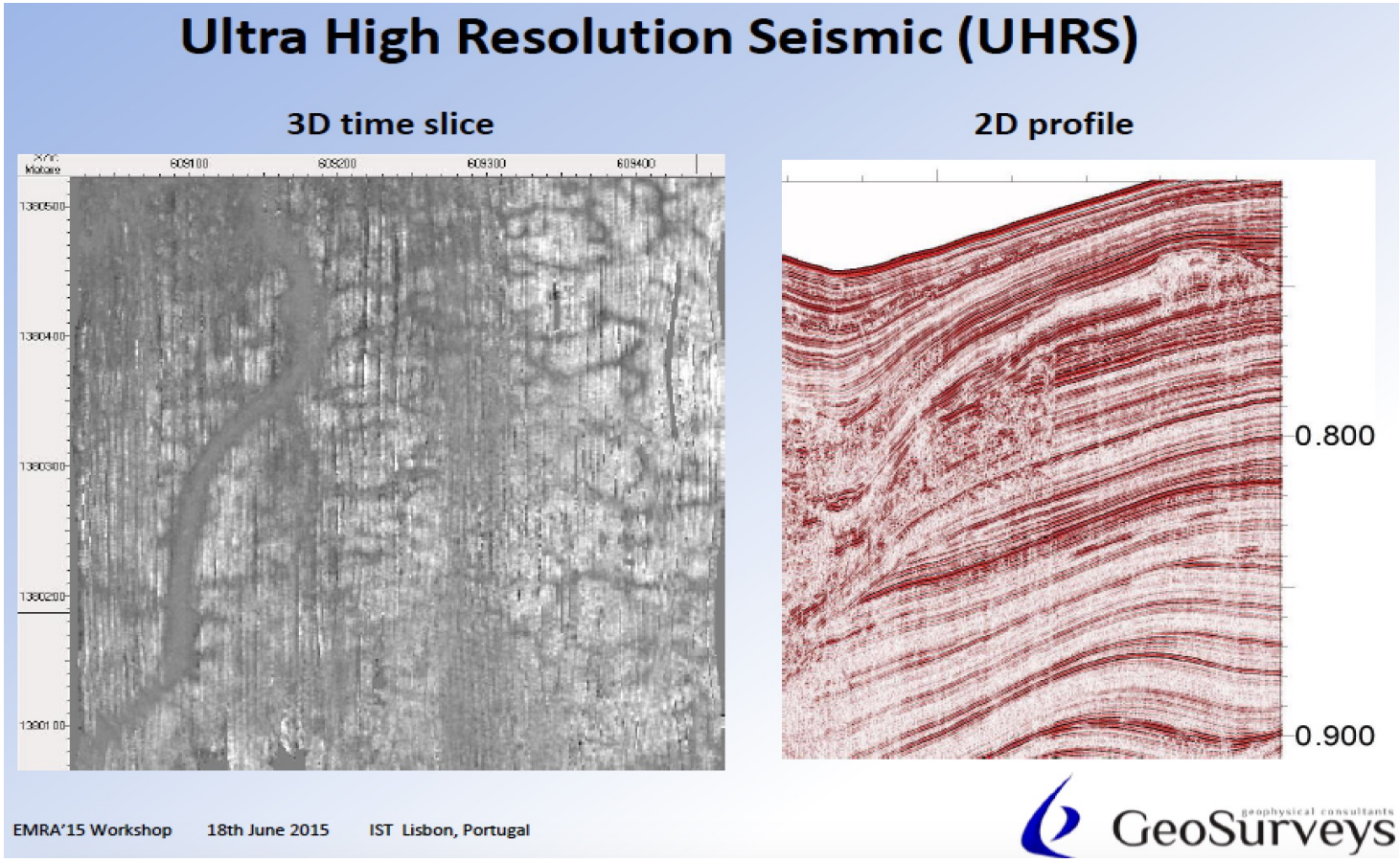
Very hard to steer; low maneuverability

Low produc expensive c



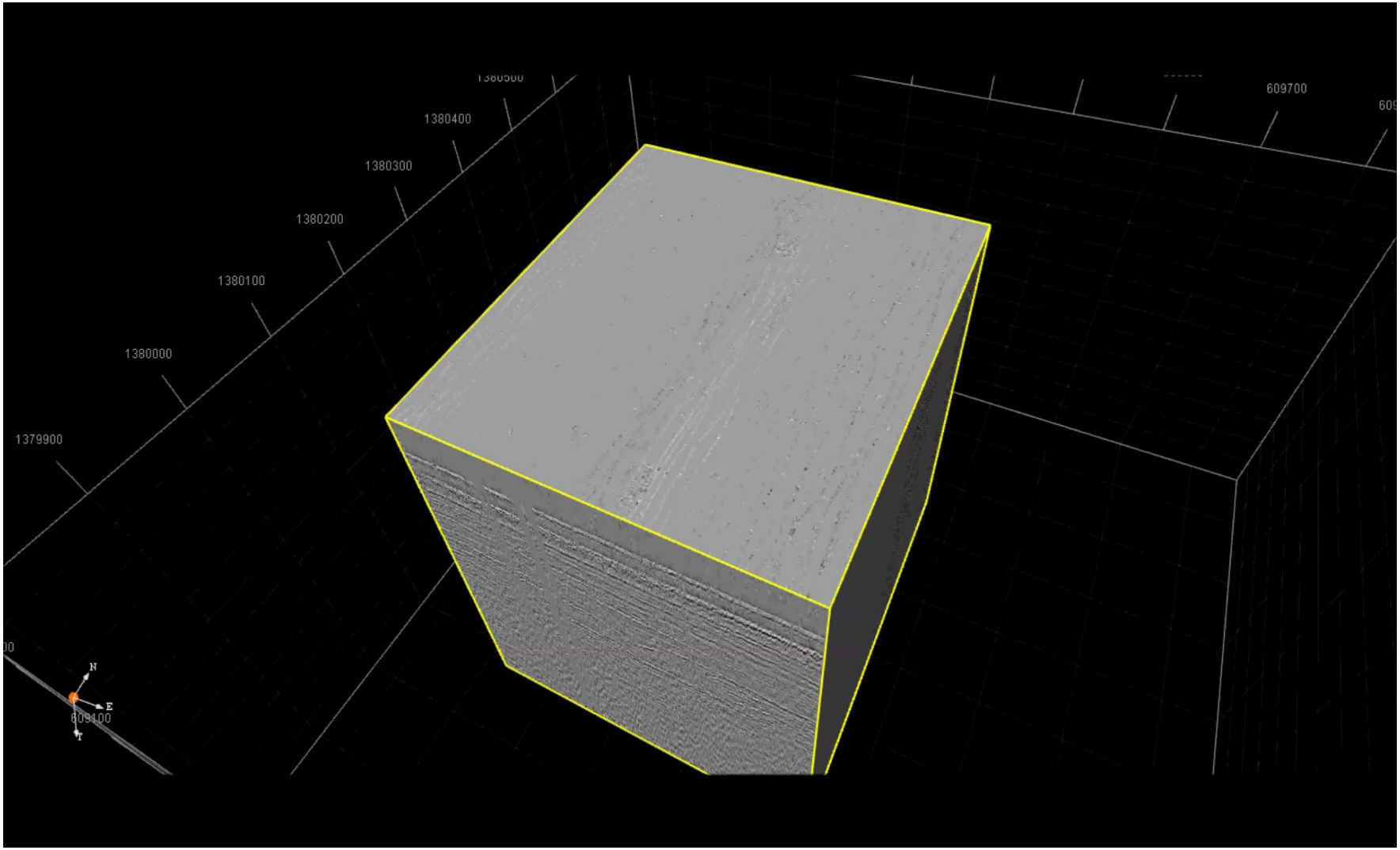


Ultra high resolution Seismic Surveys in 2D and 3D



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

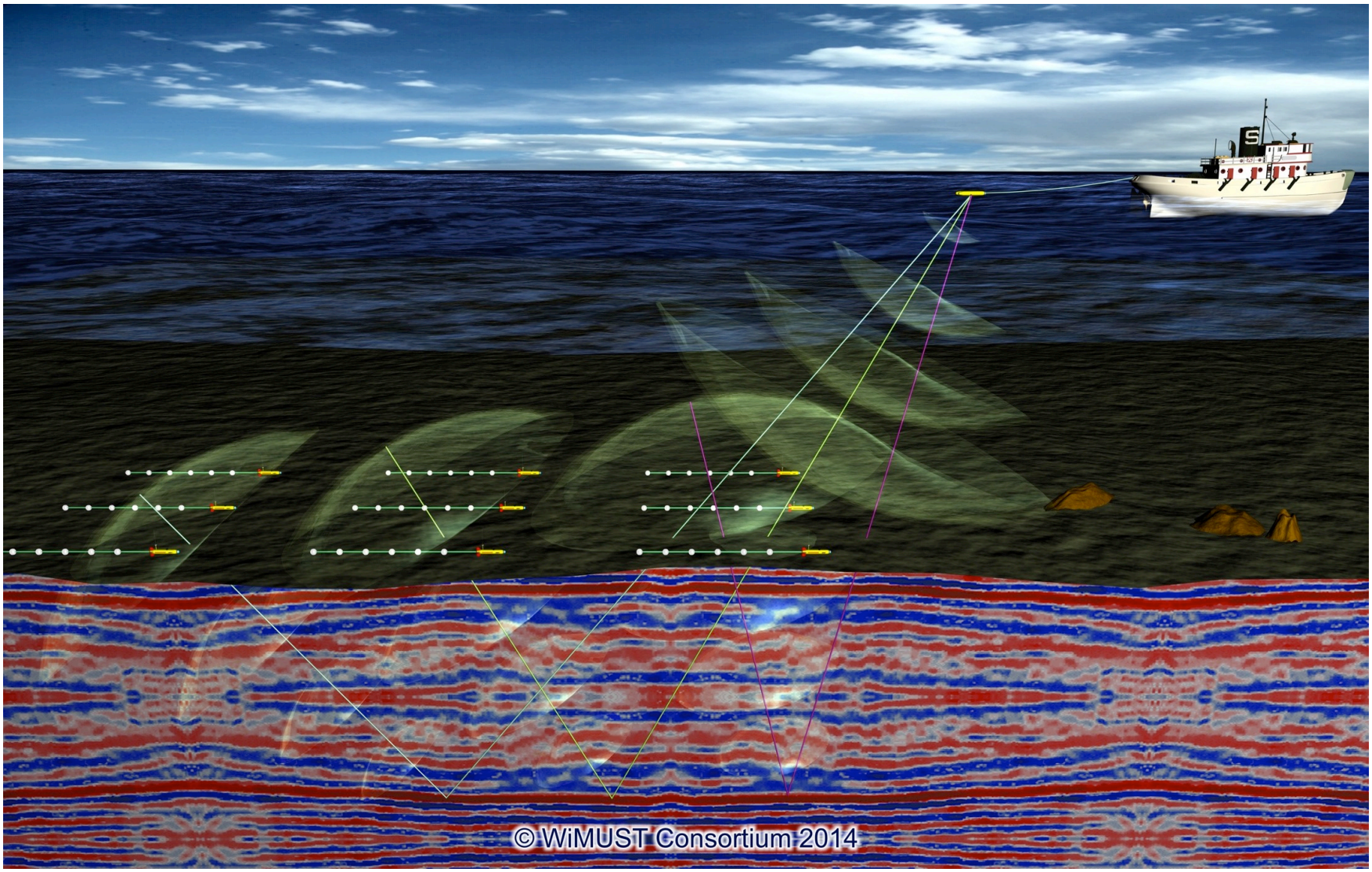
Ultra High Resolution Seismic (UHRS) surveys



Courtesy of Henrique Duarte, GeoSurveys, Aveiro, PT

The WiMUST concept

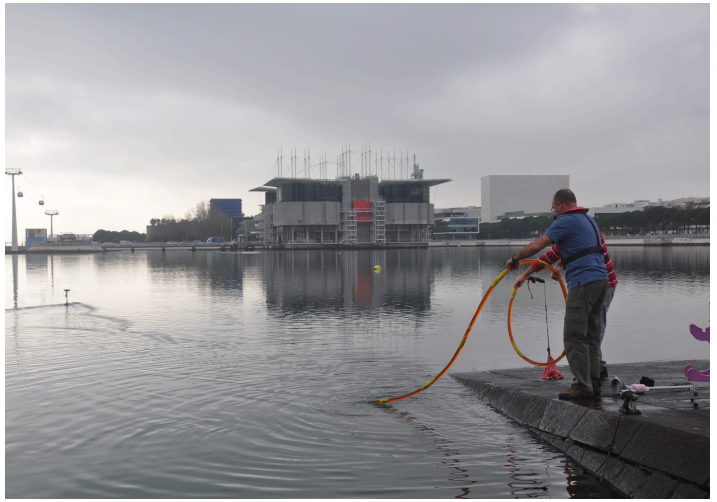
WiMUST
Widely scalable Mobile
Underwater Sonar Technology



The WiMUST concept

2:42

A new concept: automated seismic surveys



A new concept: automated seismic surveys

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

Integration of Sparkers and Power Supplies on Autonomous Vehicles

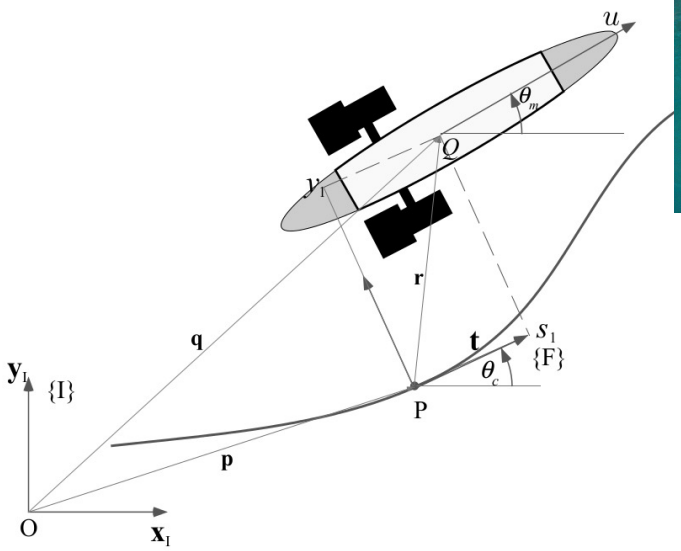
Integration of Sparkers and Power Supplies on Autonomous Vehicles

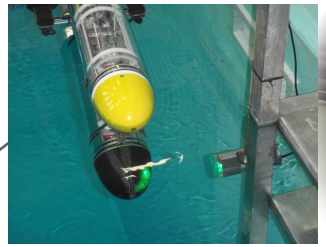
ULISSE, ISME, Italy

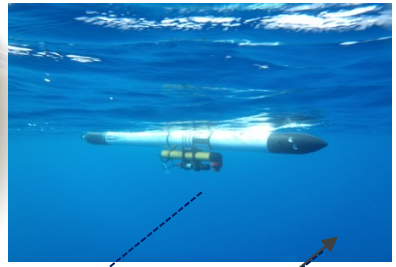
Automated Sparkers/Receivers: Field Tests

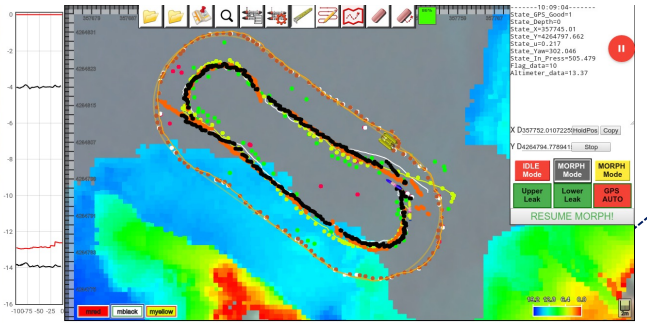
SINES. July 2017

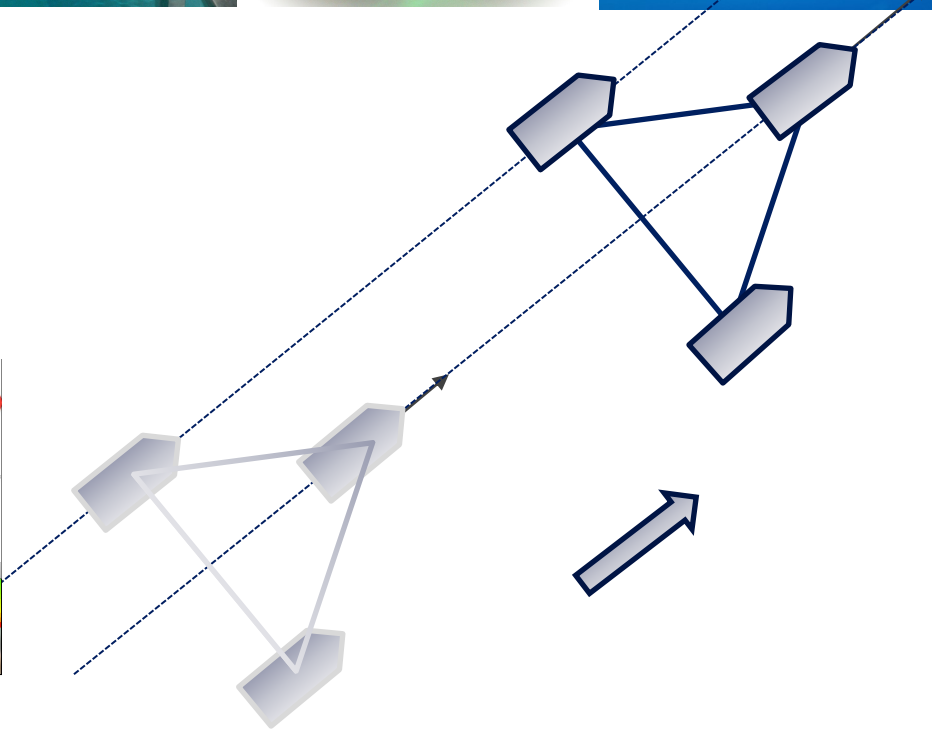
The theory behind: a glimpse





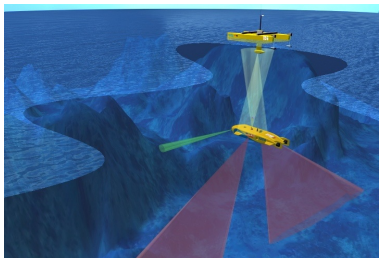
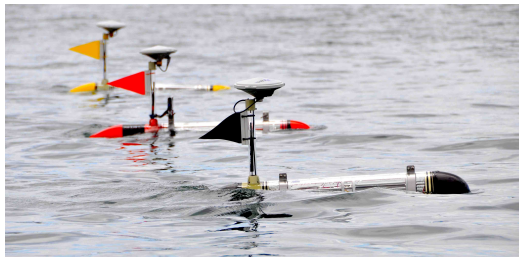
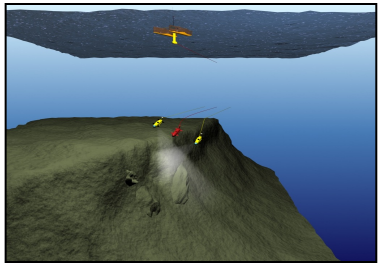
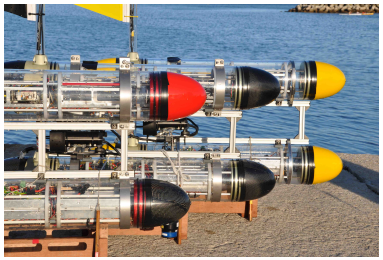






Cooperative, Networked Motion Planning, Navigation, and Control

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 authours

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

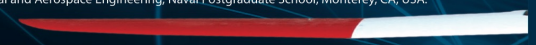
António Pascoal received his PhD in Control Science in 1987 from the University of Minnesota, Minneapolis, MN, USA. He is an Associate Professor of Control and Robotics at IST, University of Lisbon, Portugal and a Senior Researcher at the Institute for Systems and Robotics-Lisbon. He is also an Adjunct Scientist with the National Institute of Oceanography (NIO), Goa, India.

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.

Naira Hovakimyan received her PhD in Physics and Mathematics in 1992, in Moscow, from the Institute of Applied Mathematics of the Russian Academy of Sciences, in the area of optimal control and differential games. She is currently a W. Grafton and Lillian B. Wilkins Professor of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign.

Venanzio Cichella received his BS and MS degrees in Automation Engineering in 2007 and 2011, respectively, from the University of Bologna, Italy. He is currently a PhD student in Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign.

Vladimir Dobrokhodov received his PhD in Aerospace Engineering in 1999, from the Zhukovsky Air Force Engineering Academy of the Russian Academy of Sciences in Moscow, in the area of aircraft flight dynamics and control. He is currently an Associate Professor at the Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA, USA.



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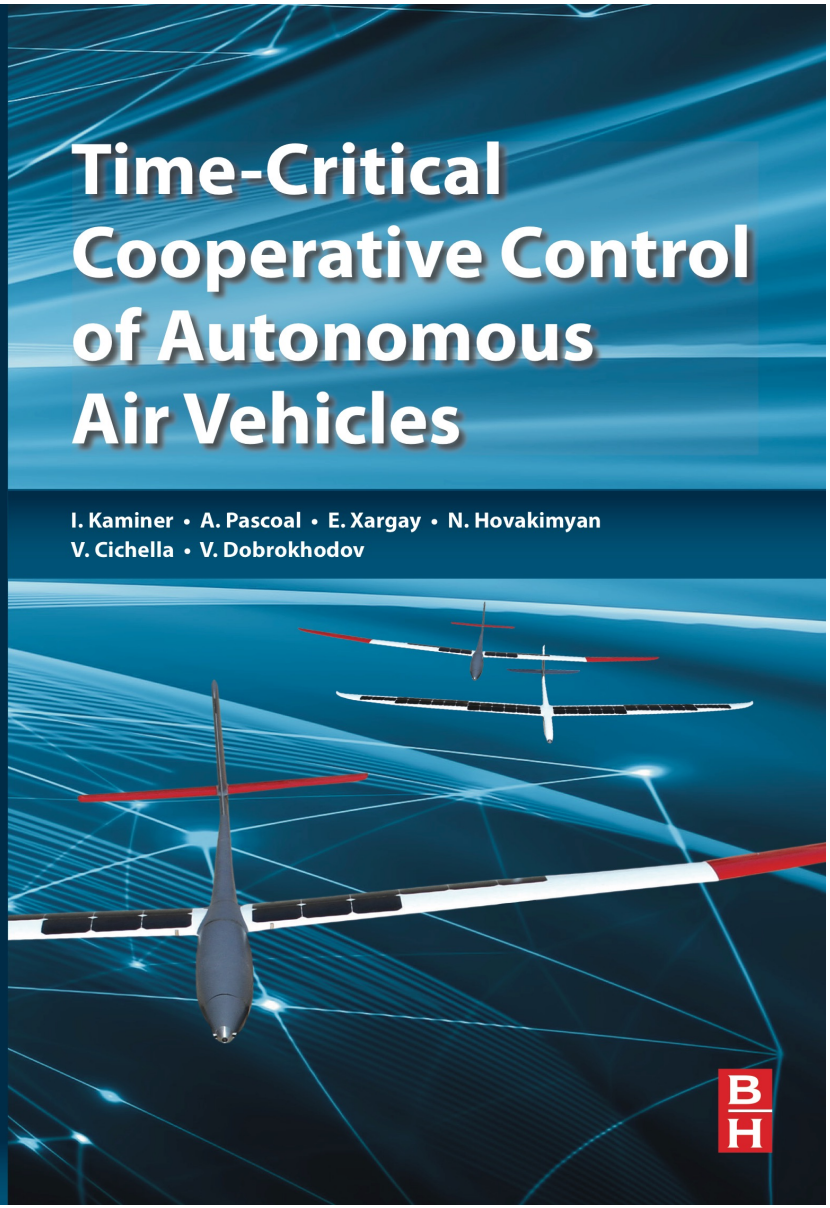

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