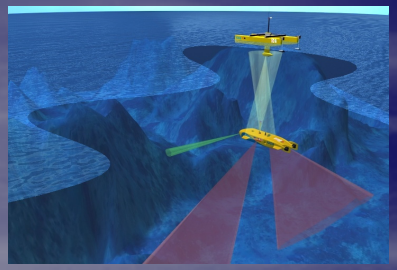
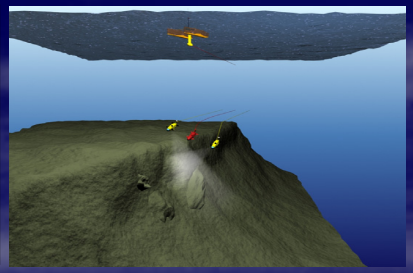





Cooperative Motion Planning, Navigation, and Control of Multiple Autonomous Marine Vehicles: Robots and Humans in the Loop

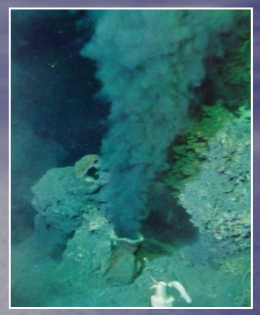
António Pascoal

Lab. Robotics and Systems in Eng. and Science (LARSyS)
Institute for Systems and Robotics (ISR)
IST - Univ. Lisbon Portugal

VEHITS 2015, 22-25 May, Lisbon, Portugal



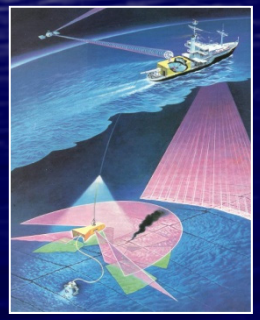
Robots for Ocean Exploration



Summary:

Ocean exploration: scientific and commercial challenges

The need for marine robots: technical challenges

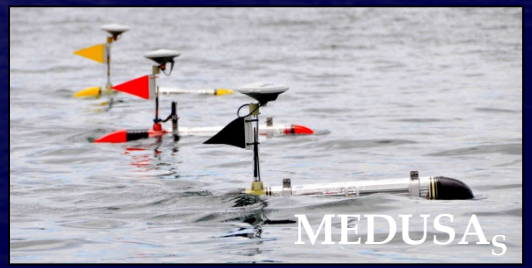


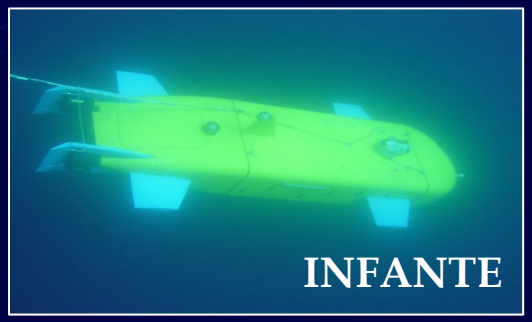
Theory and Practice: single and multiple robotic vehicle control; a vision of the future


The work of many!
MORPH, CADDY, CO3AUVs, GREX. WiMUST
A. Aguiar, B. Bayat, J. Botelho,
M. Bressel, P. Gois, V. Hassani, A. Maia,
P. Maurya, F. Morais, A. Pascoal, J. Ribeiro,
M.Ribeiro, F. Rego, Rufino,
A. L. Sebastião, J. Soares
INSTITUTO SUPERIOR TÉCNICO
PÓLO DO IST

Technologies for Ocean Exploration

Robotic Vehicles





Fleet of autonomous surface and underwater robots

Designed and built at IST

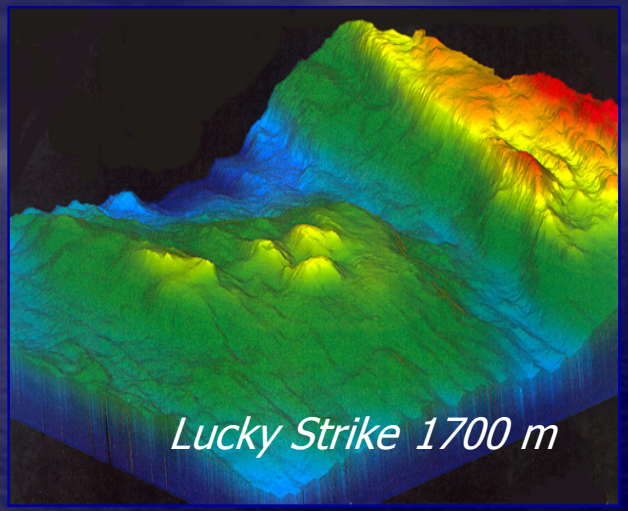
EC GREX PROJECT TEAM (2006-2009)

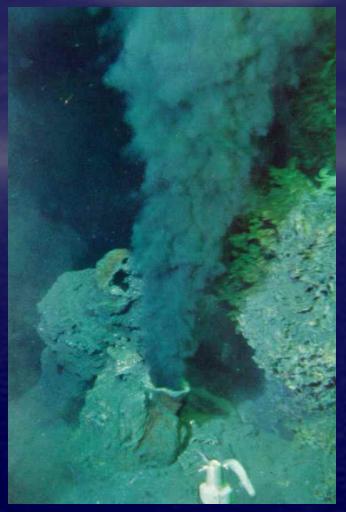
EC CO³AUVS PROJECT TEAM (2009-2012)

EC MORPH PROJECT TEAM (2012-2016)

Toulon, France
July 2013

Sea: the Ultimate Frontier



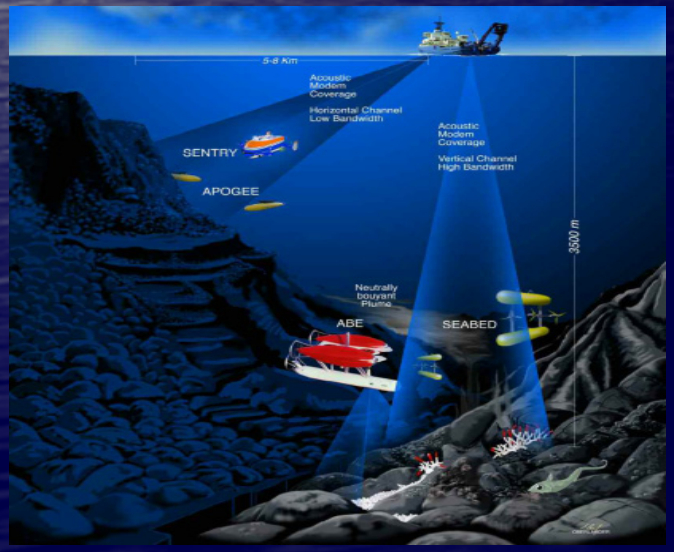


DEPARTAMENTO DE OCEANOGRAFIA E PESCAS UNIVERSIDADE DOS AÇORI

DOP

imar

CREMINER
Centro de Recursos Minerais, Mineralogia e Cristalografia



Explore the Ocean

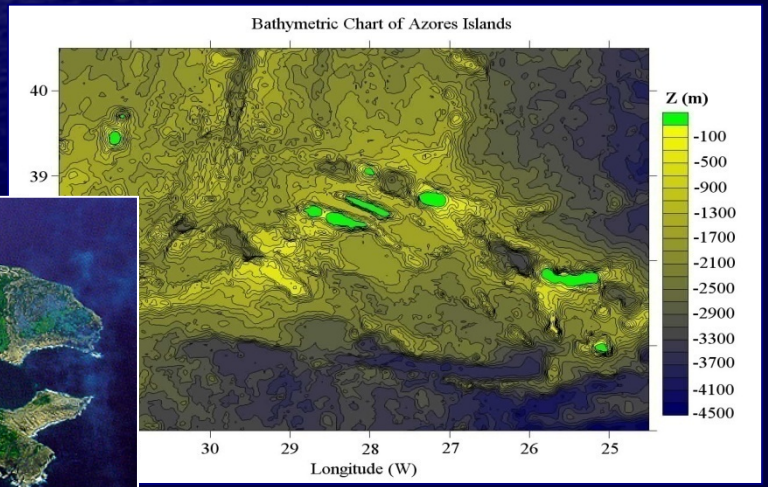
Advanced technology is mandatory

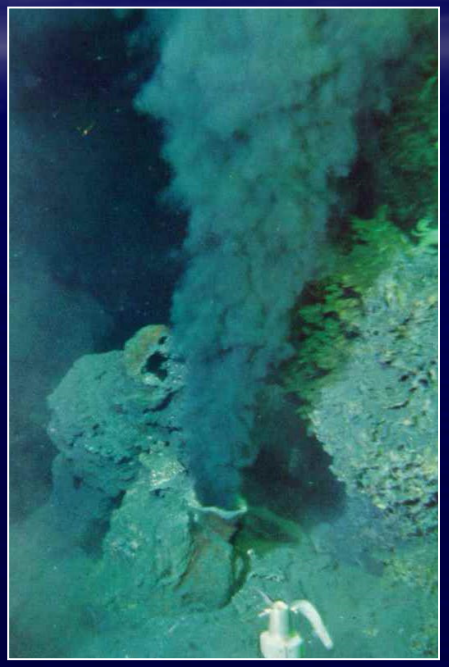
Future: Networked Mobile/Fixed Sensors (Moored systems, AUVs, ASCs, Gliders, Submersibles, Vessels, etc)

Marine data acquisition

Adequate 3-D
temporal and spatial sampling

Open sea



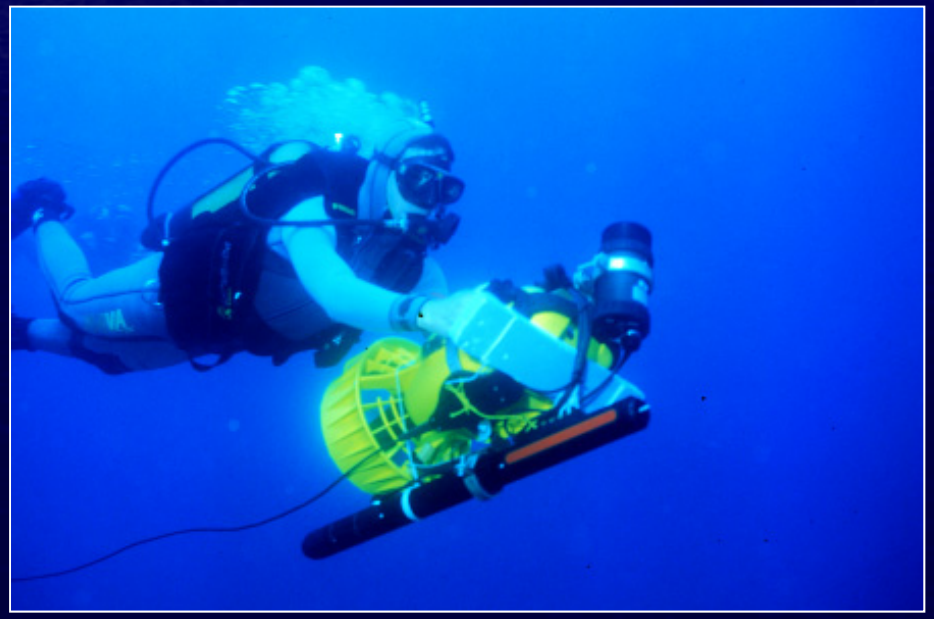


Deep ocean

Coastal areas

"Classical" Methods

Divers



Divers - restricted coverage; dangerous.
Hard to georeference data.

"Classical" Methods

Research Vessels

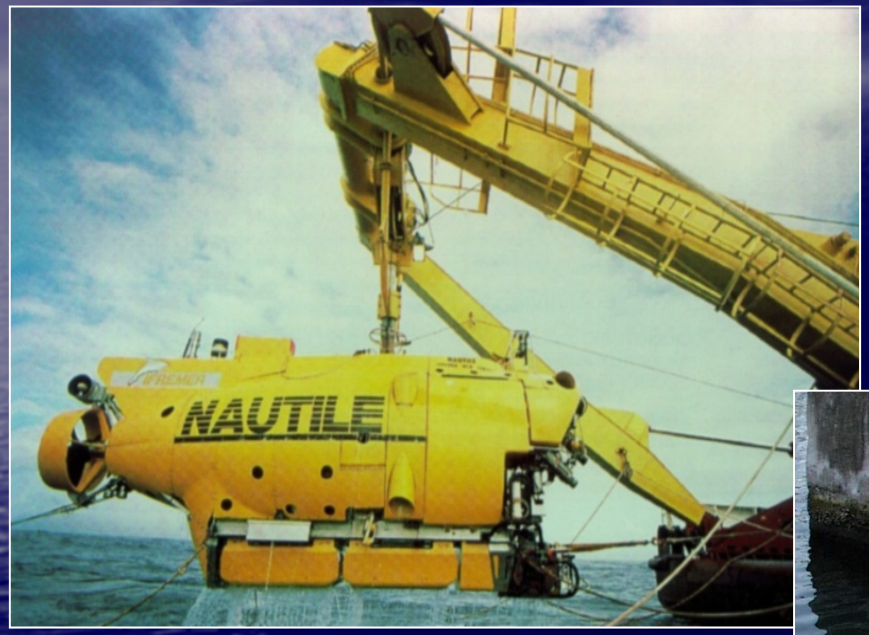
Vessels (tool par excellence) -

Poor maneuverability; poor 3-D + time coverage.

High operation costs.

"Semi-Classical" Methods

Manned Submersibles (direct observation of the deep sea)

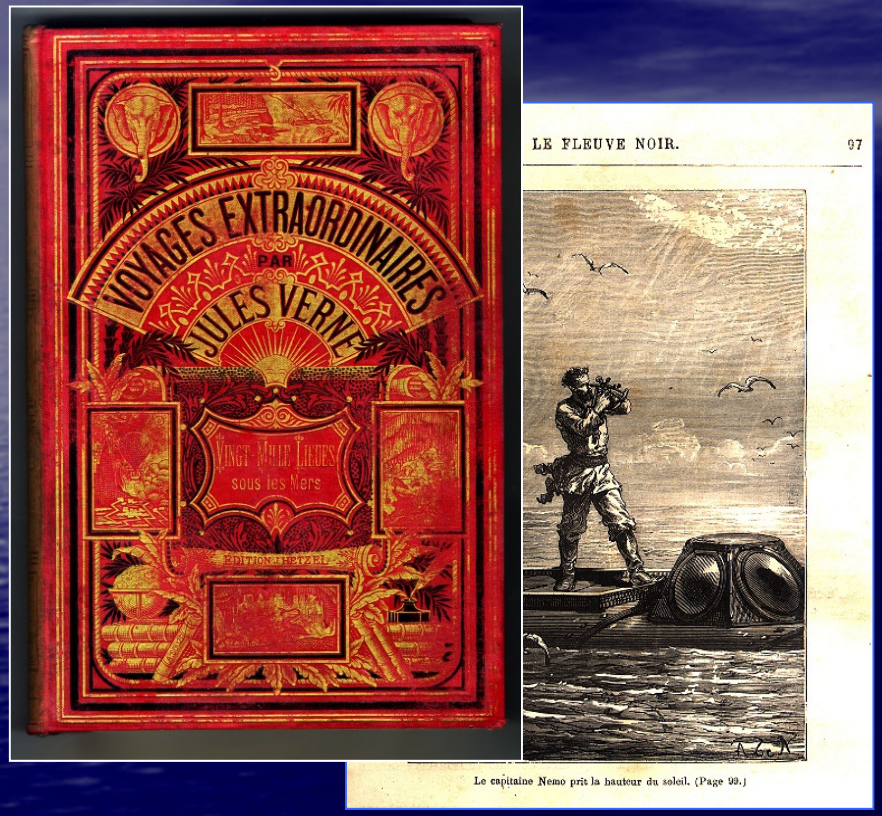


Nautile, IFREMER, FR

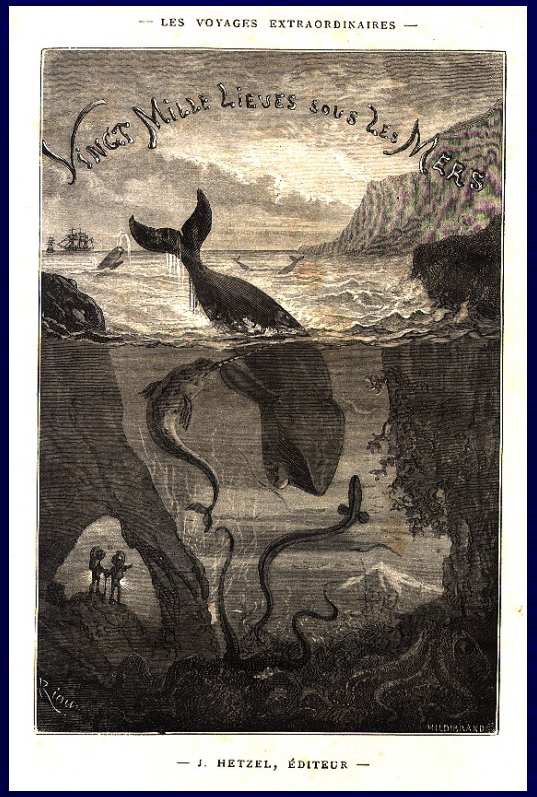
LULA, Rebikoff Foundation,

Azores, PT

"Semi-Classical " Methods



Glimpses of amazing undersea adventures



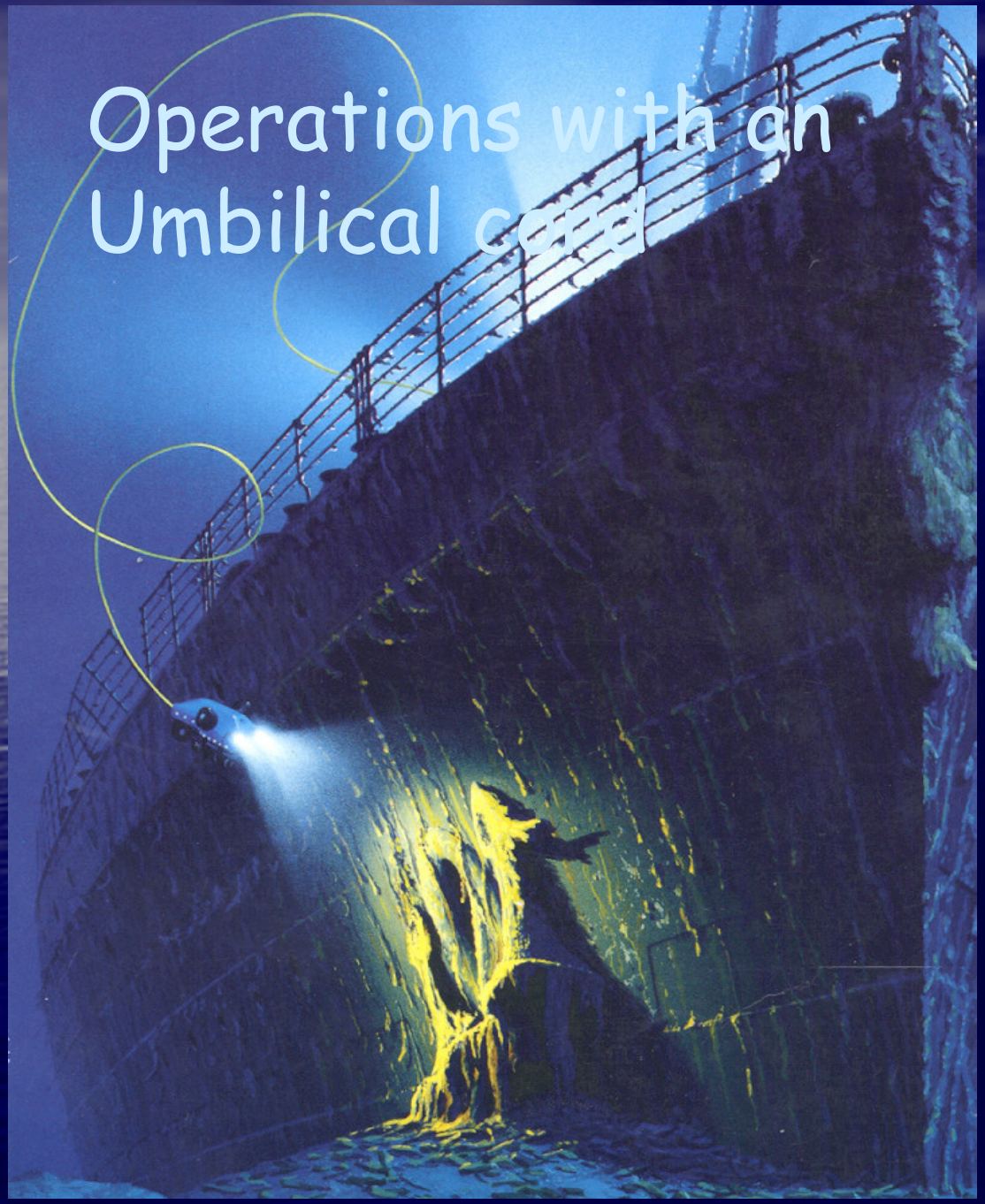
Limited ocean coverage

Jeopardize human lives

High operation costs

The jump forward:

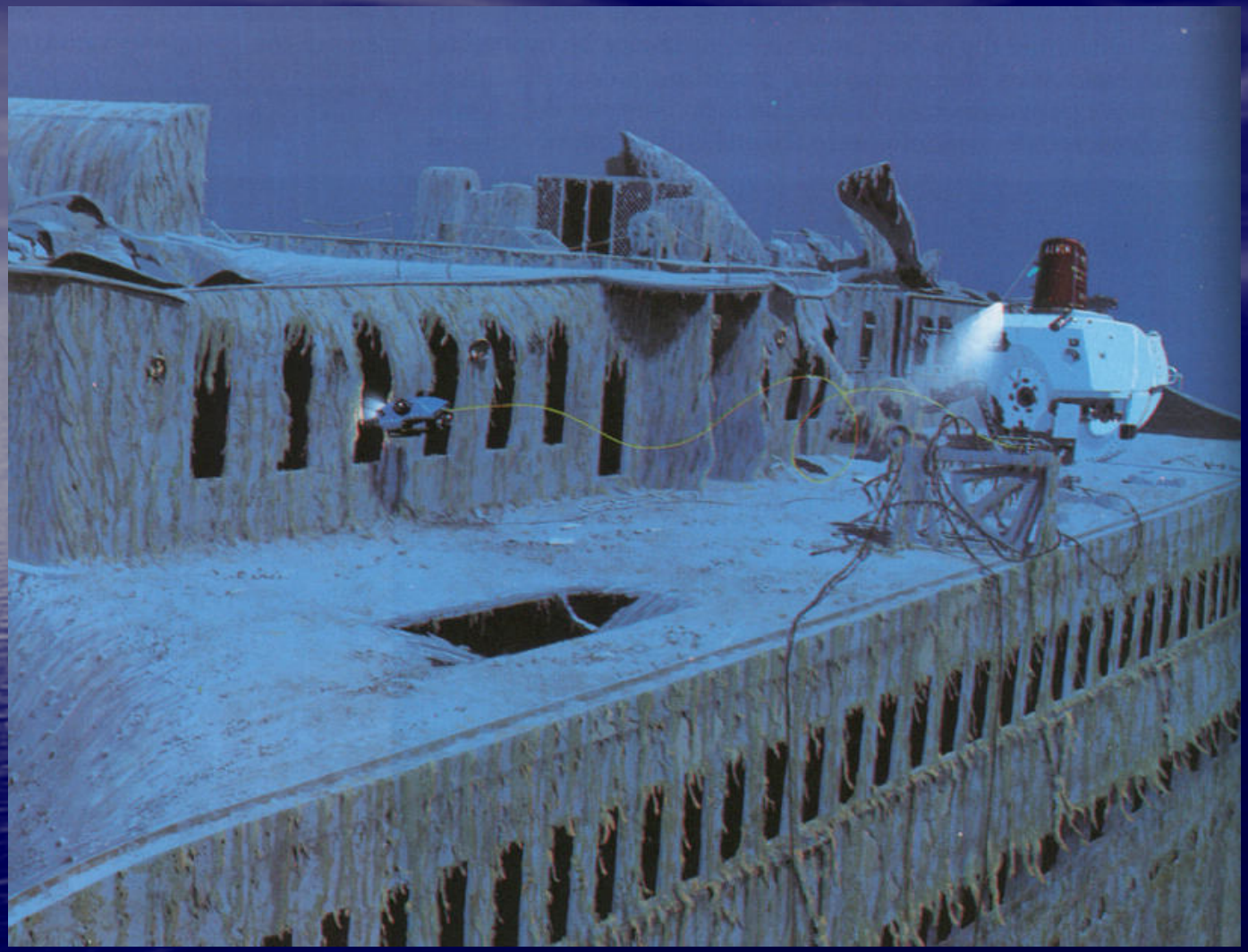
The discovery of the TITANIC!



Operations with an Umbilical cord

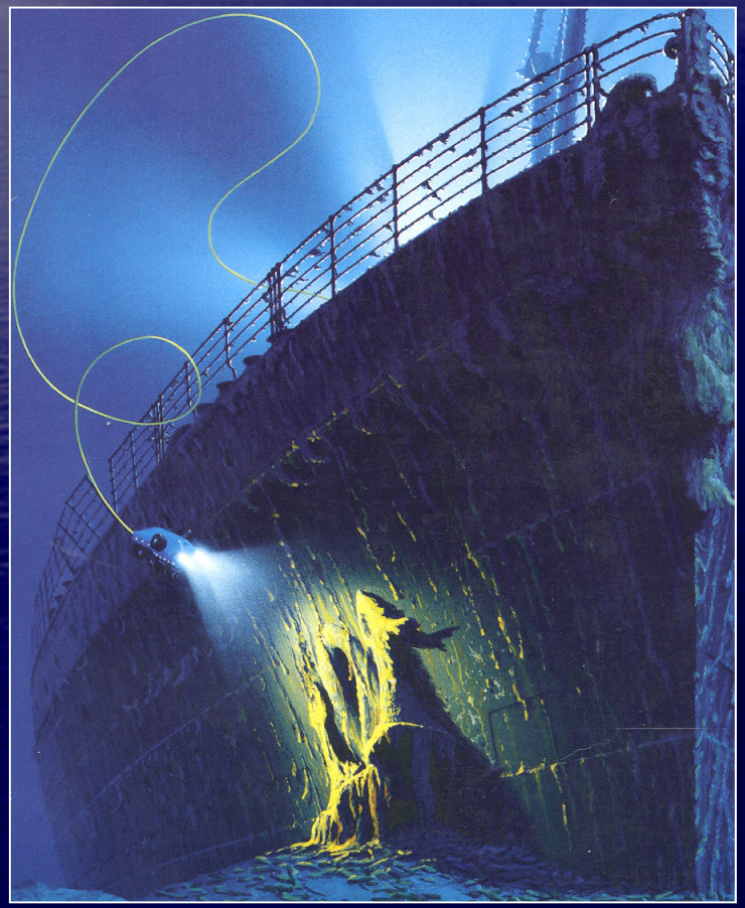
TITANIC:

ROBIN: the small robot



Joint operation of ALVIN and ROBIN

"Modern" Methods



ROVs – Remotely Operated Vehicles

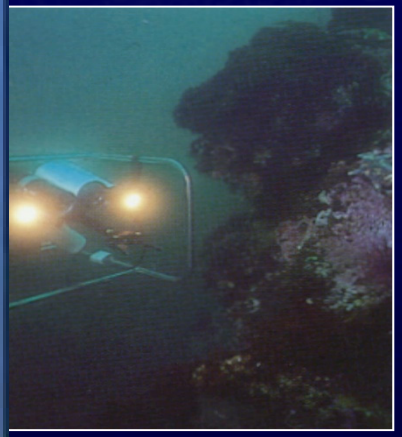
TITANIC

The small companion ROV

(carrying an umbilical)

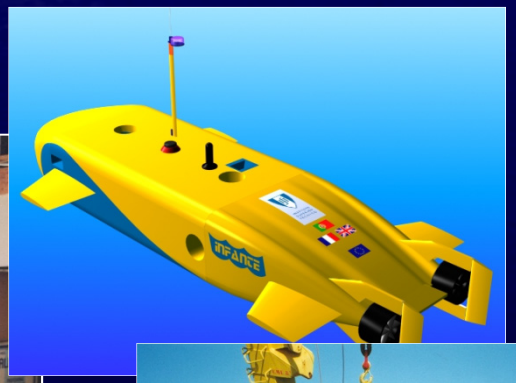
"Modern" Methods

ROVs – Remotely Operated Vehicles



"Modern" Methods

AUVs - Autonomous Underwater Vehicles (cut the umbilical!)



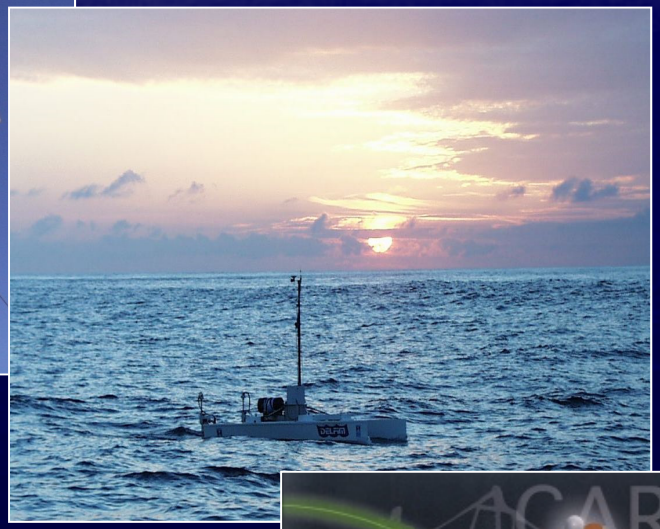
High maneuverability

Autonomy

Automatic execution of tedious tasks

"Modern" Methods

ASC - Autonomous Surface Craft



High maneuverability

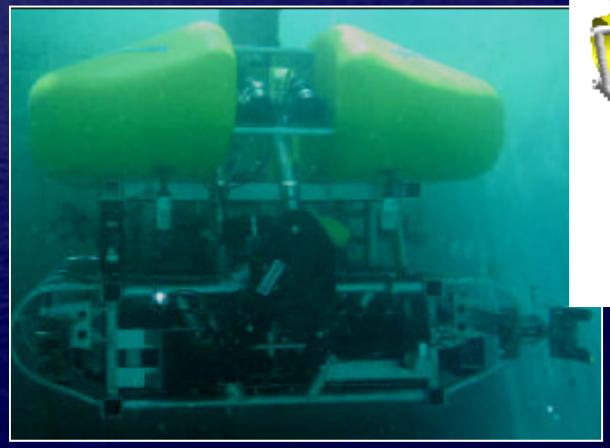
Autonomy

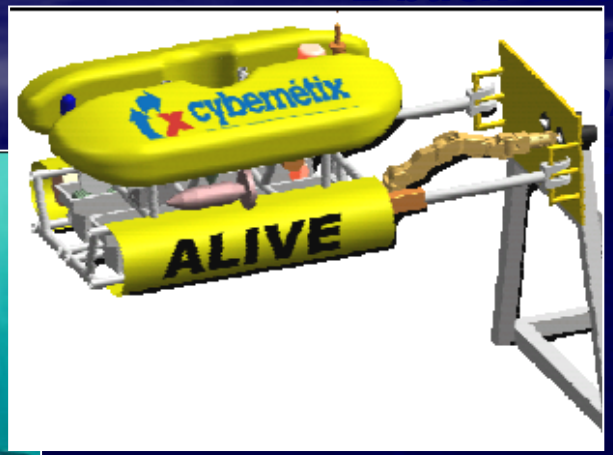
“Modern” Methods

Freesub

Network, EC

ALIVE (FR)





Intervention AUVs

AUV-like (no umbilical)
Bluff body
Hovering / Intervention capabilities

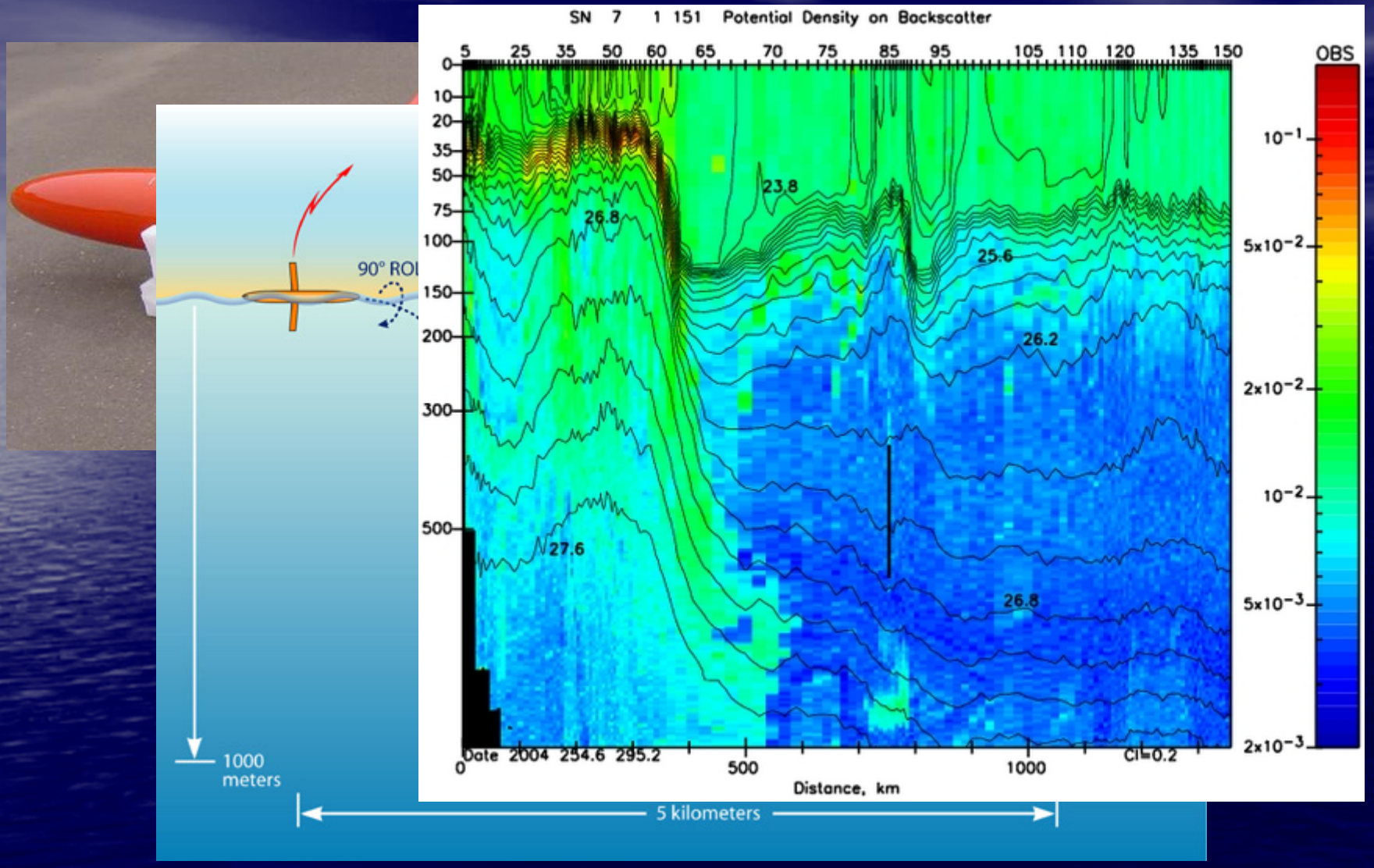
www.cybernetix.fr/freesub/

cea cybernétix Ifremer

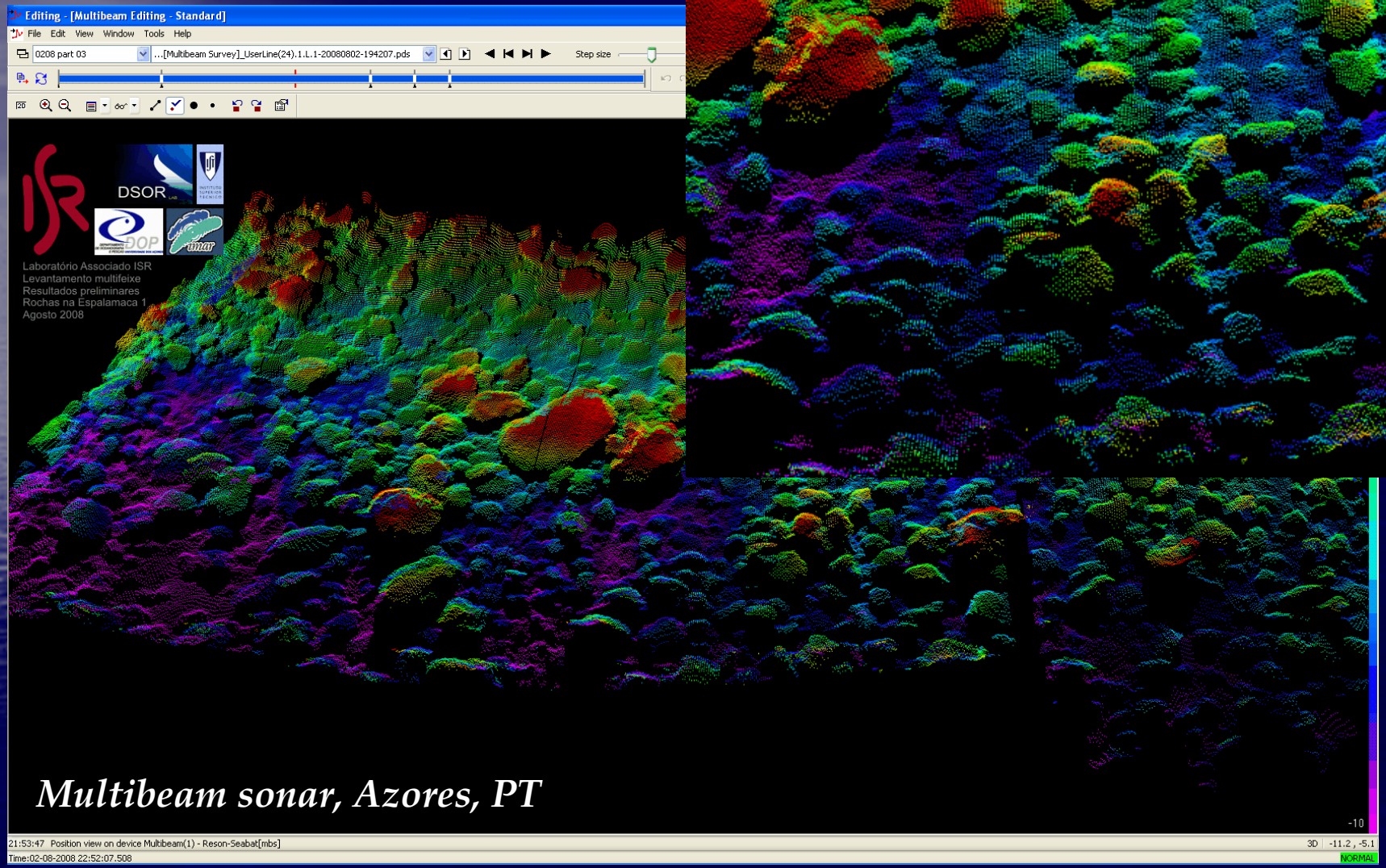
EUROPEAN COMMISSION JOINT RESEARCH CENTRE

University of Southampton

For further information please contact:
CYBERNETIX - Offshore Dept. - Peter WEISS - 36, Boulevard des Océans - 13009 Marseilles - France -
peter.weiss@cybernetix.fr OR www.cybernetix.fr/freesub/

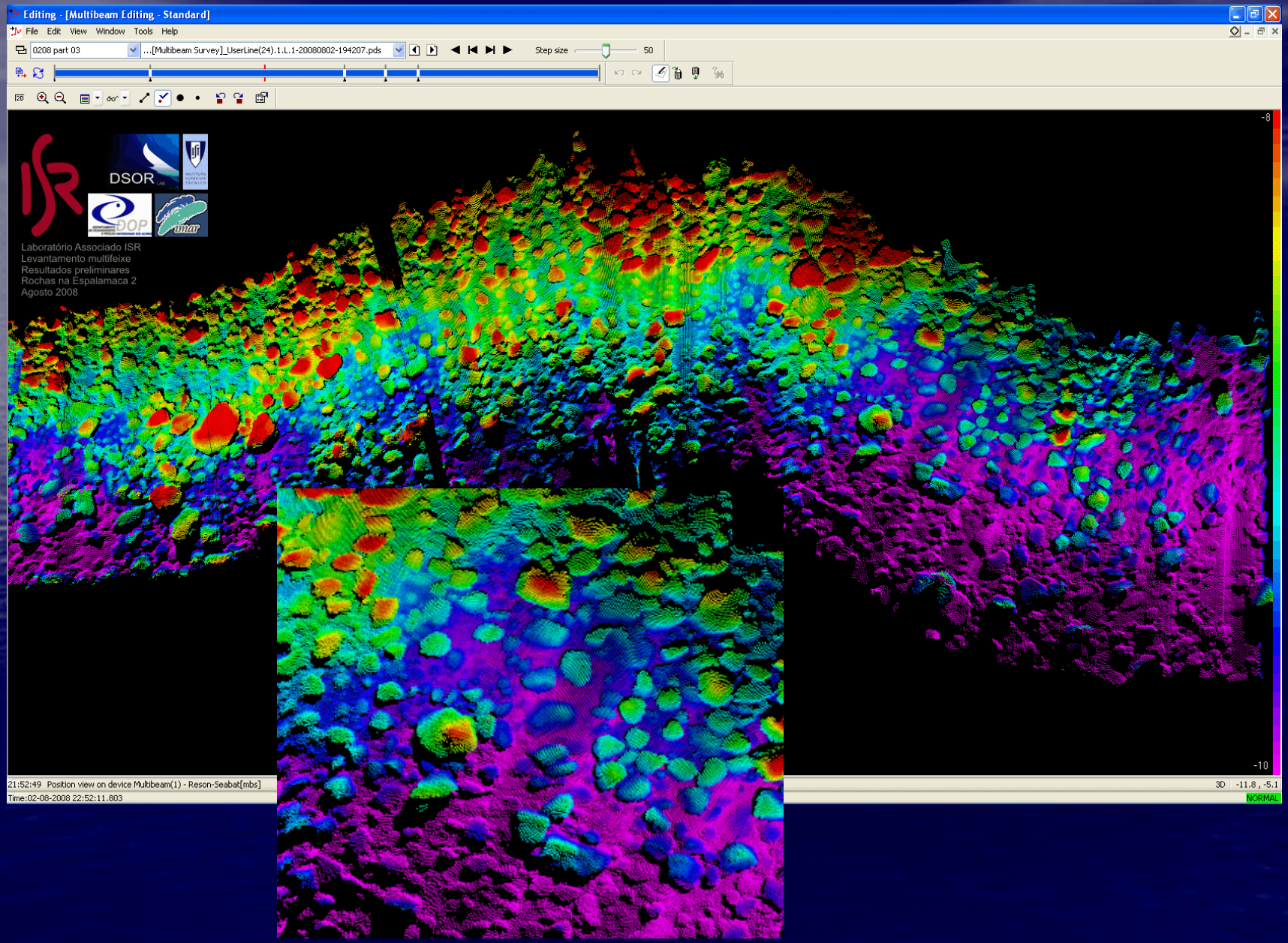


GLIDER TECHNOLOGY



Seeing with "acoustic" eyes

Seeing with "acoustic" eyes



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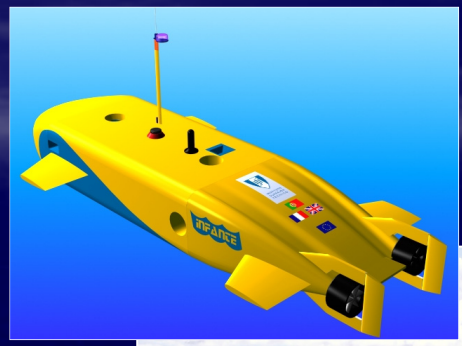
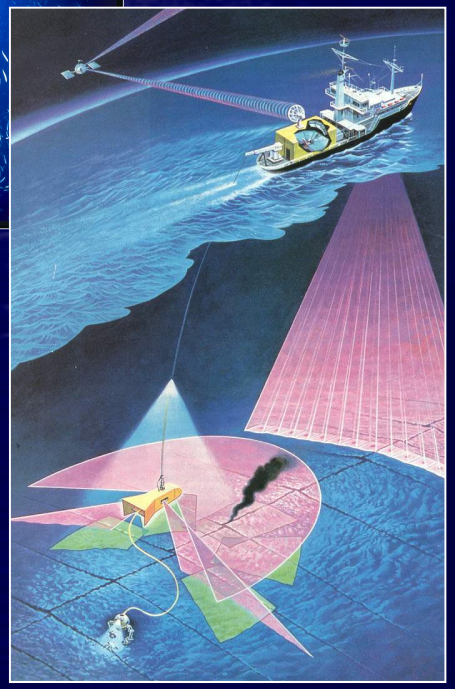
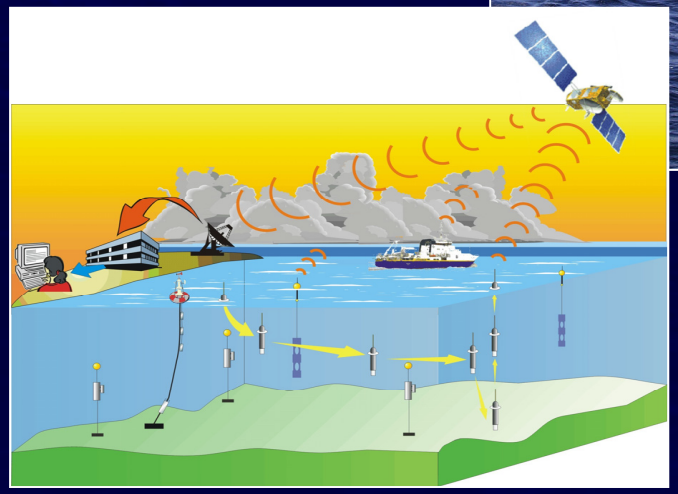
"Future" Trends

Sampling networks – fixed and moving units

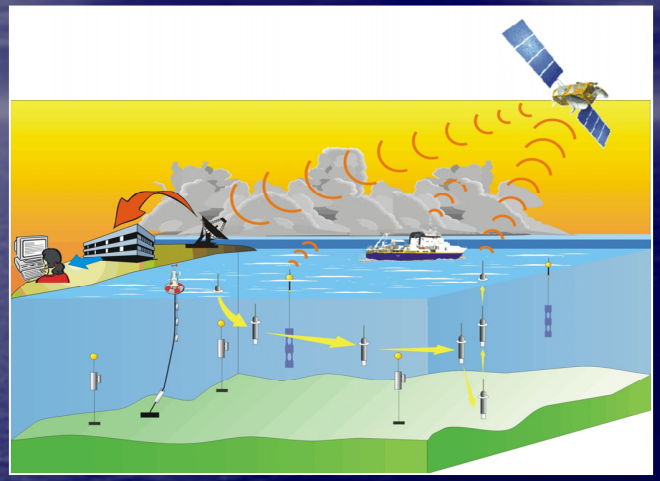
(Divers, Floating devices, Moored equipment, Inhabited submersibles, Ocean vessels, ROVs, AUVs, ASCs, Benthic stations).







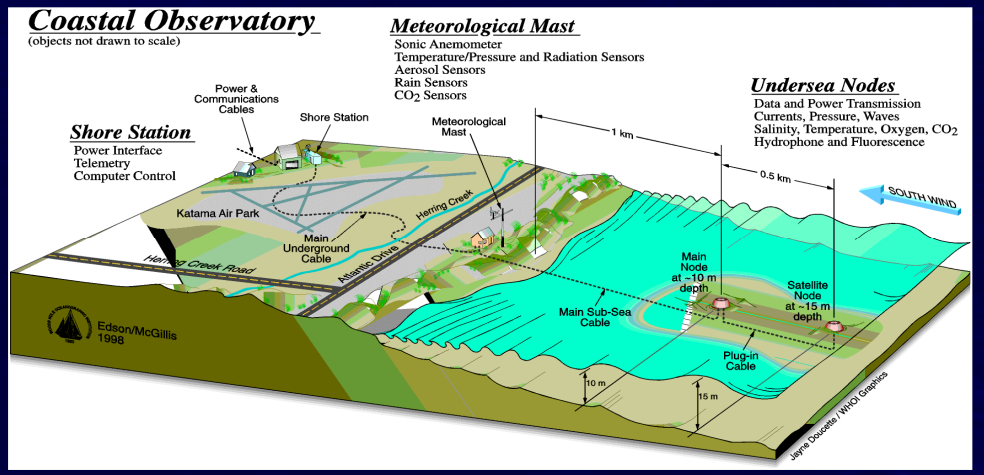
Sampling Networks



AUVs deployed to monitor episodic events.

Coriolis Initiative, FR

Martha's Vineyard coastal observatory, USA



Marine Board, ESC
Marine Technoloy Frontiers for Europe

Key Issues: Communications, Information, Decision, Control.

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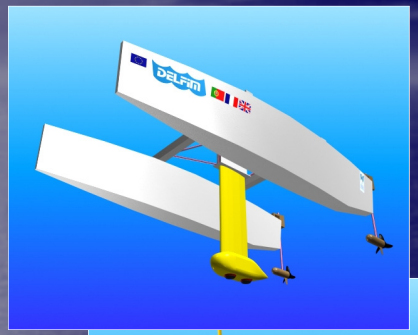
Meeting the Challenges: the wonderful swimming machines



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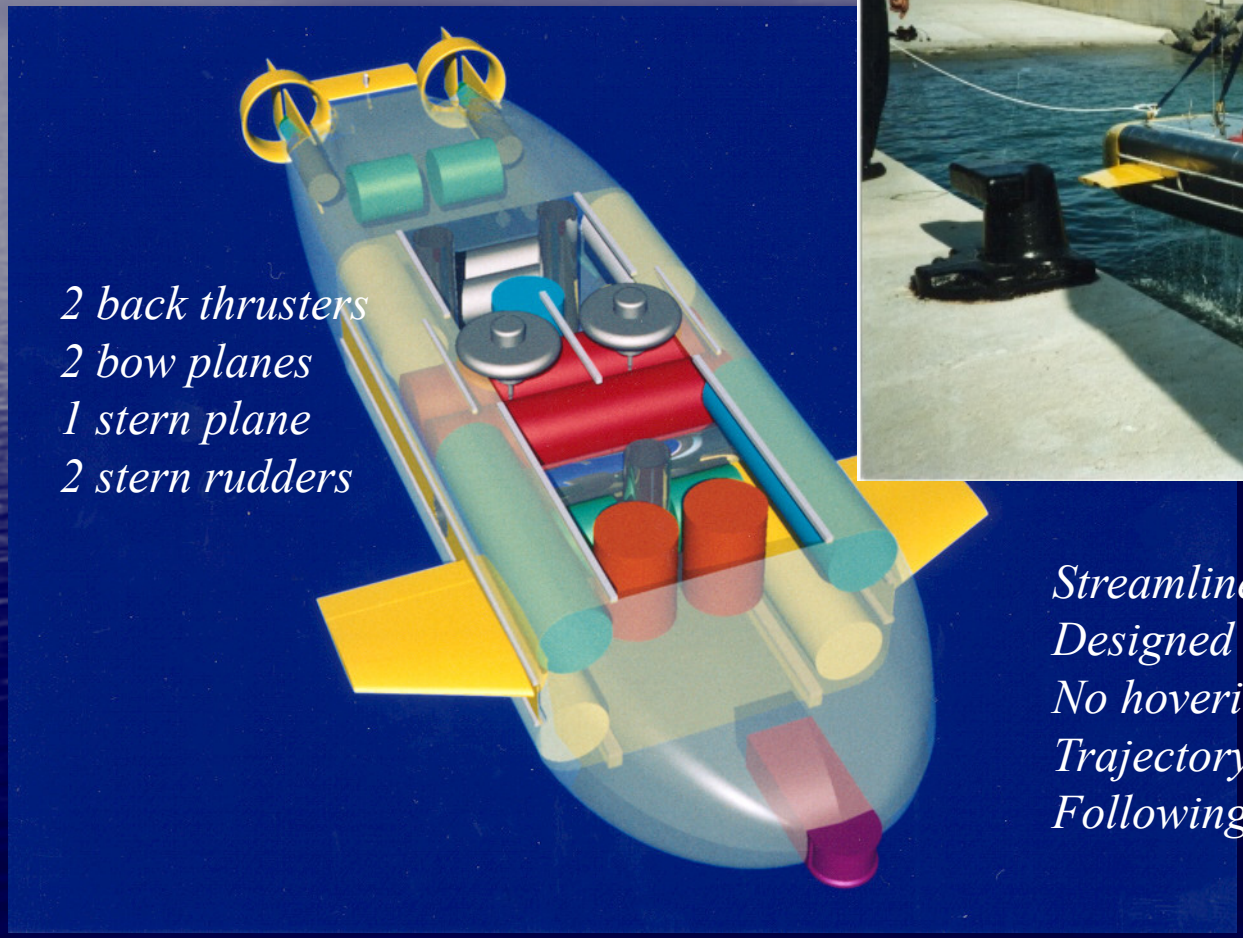
The MARIUS AUV

The *MARIUS* AUV

MAST II
EC Project

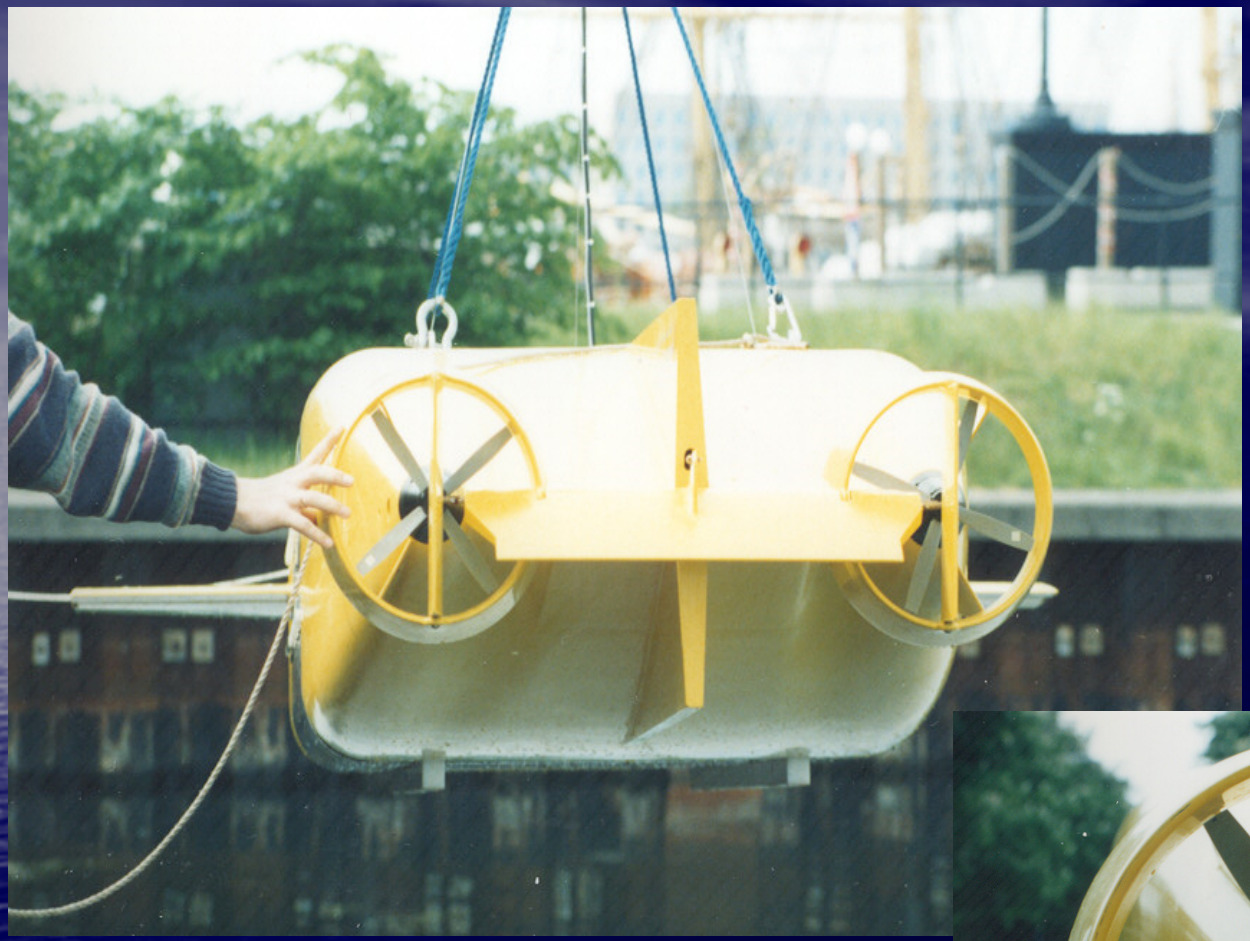
IST (PT)
MARIDAN (DK)
ORCA (FR)
THOMSON (FR)

The MARIUS AUV



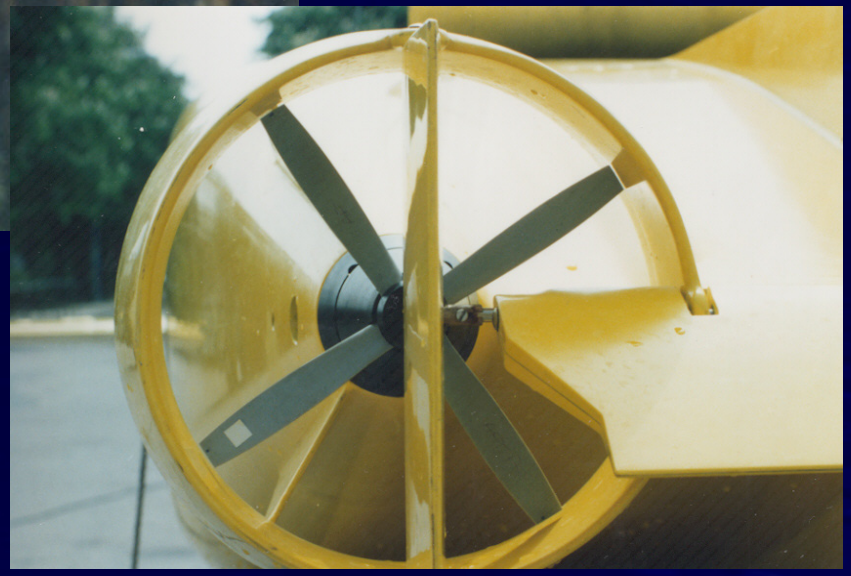
2 back thrusters
2 bow planes
1 stern plane
2 stern rudders

Streamlined
Designed to "fly" above the seabed
No hovering capabilities
Trajectory Tracking and Path Following required.



Speed of Rotation of propellers

Thrust force

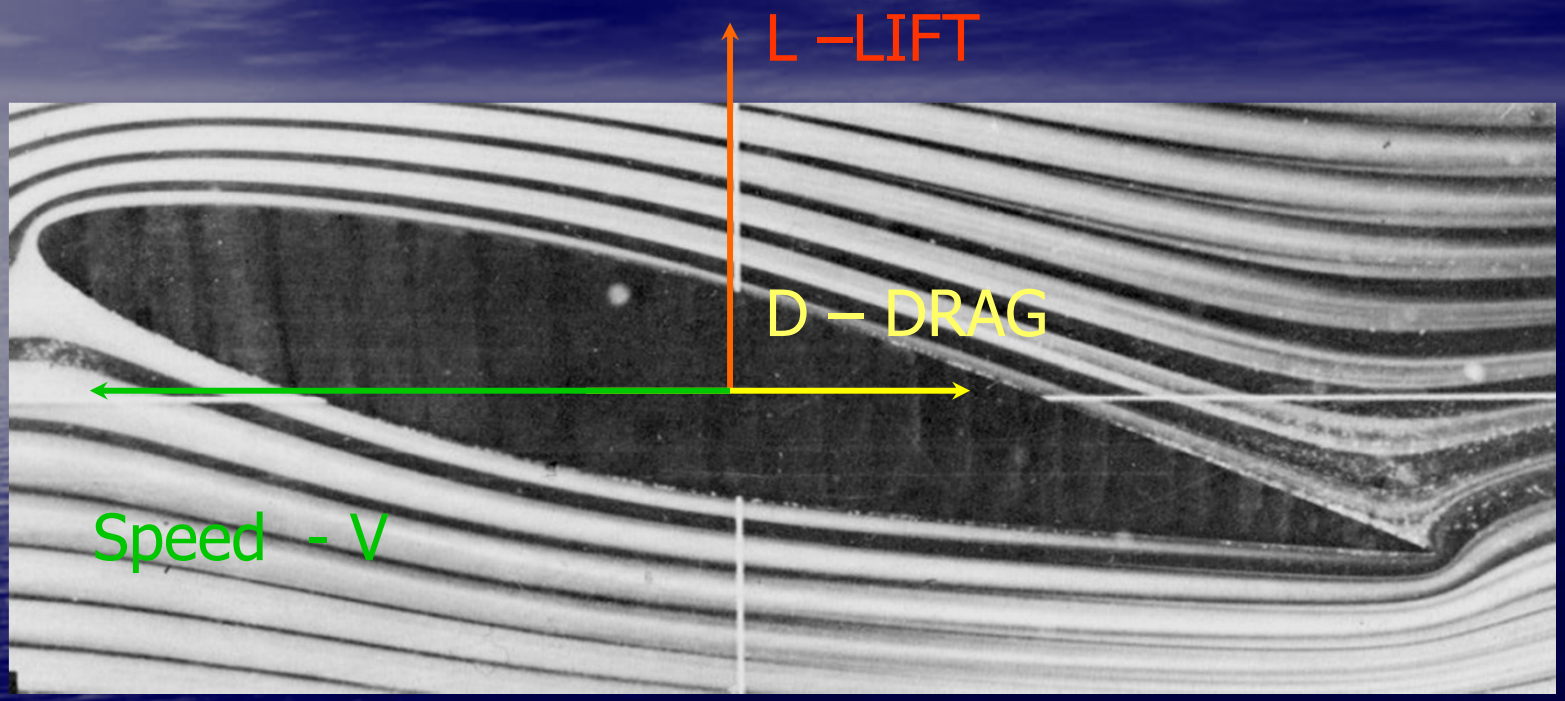


Acuators – Propulsion

Actuators
(Surfaces)

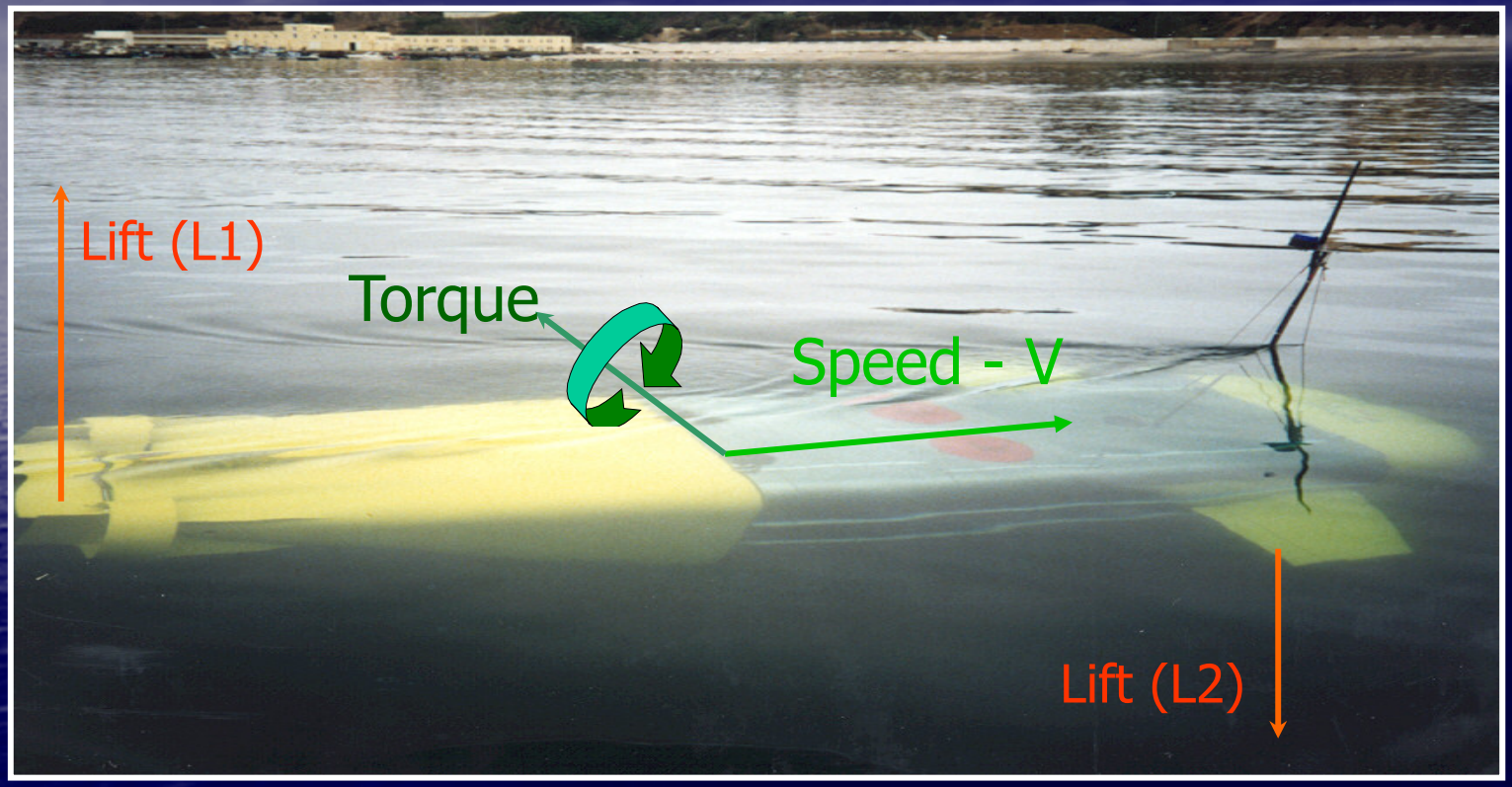
Surface Deflection → Forces and Torques

Hydrodynamic Forces



Flow around a wing

Hydrodynamic forces



Vertical plane motion

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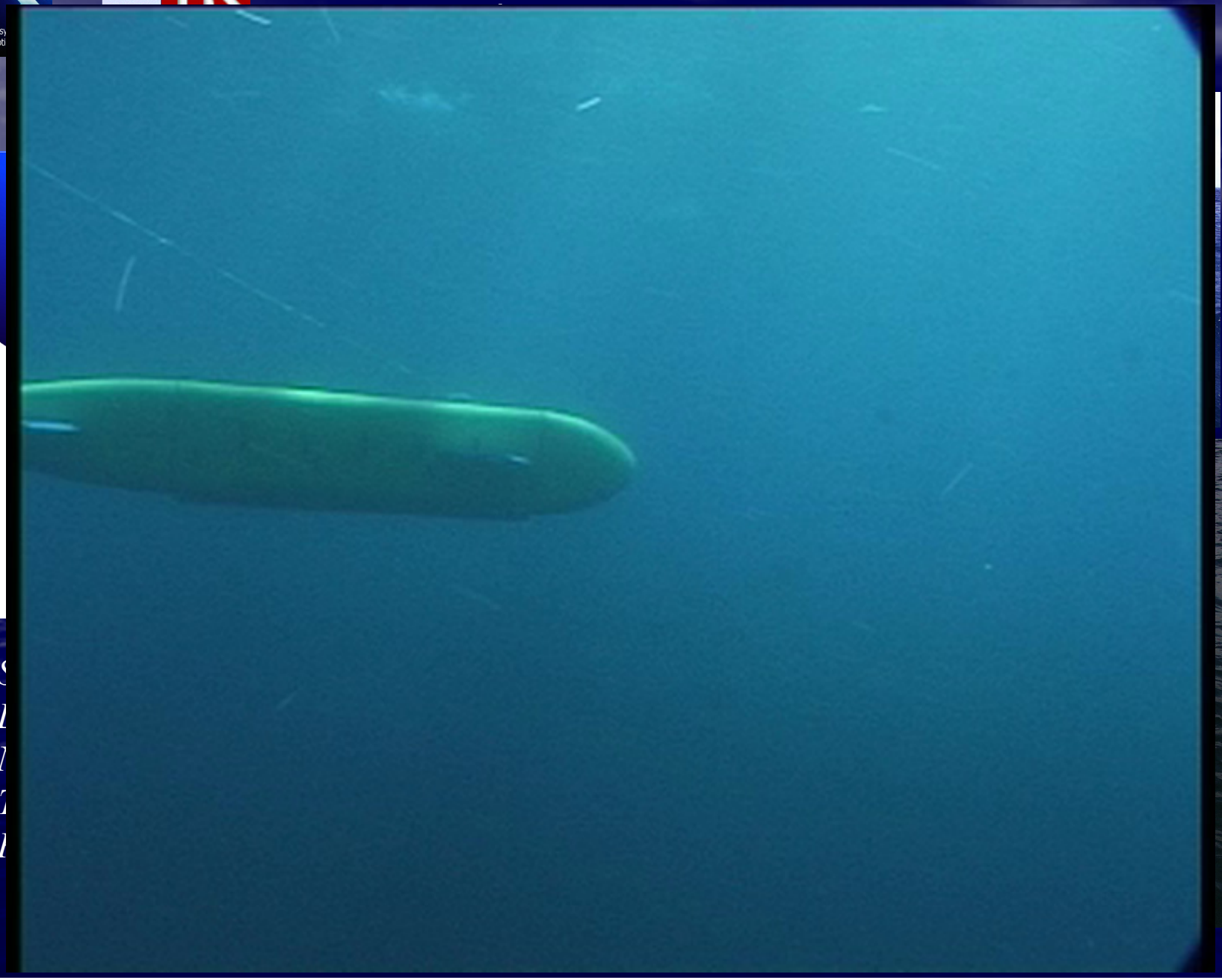
The MARIUS AUV

Tests with the
MARIUS AUV

SINES, Portugal



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The SIRENE "ROV-LIKE" AUV

THE *SIRENE*
UNDERWATER
SHUTTLE

MAST II EC Project

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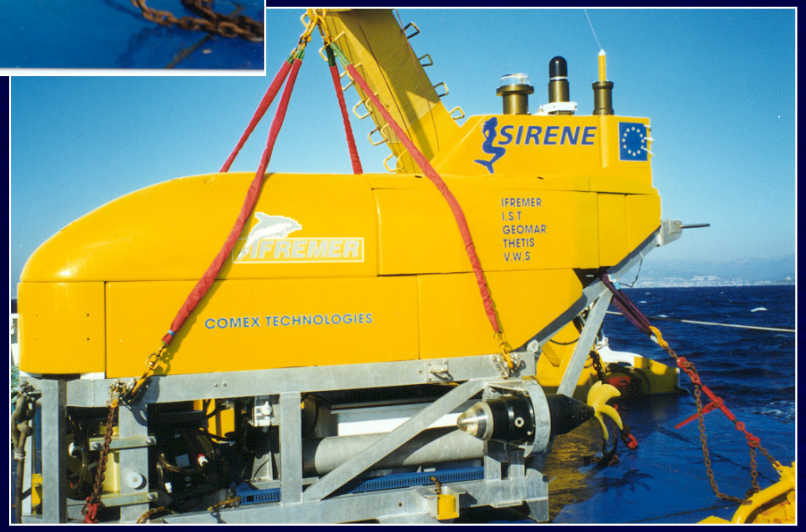
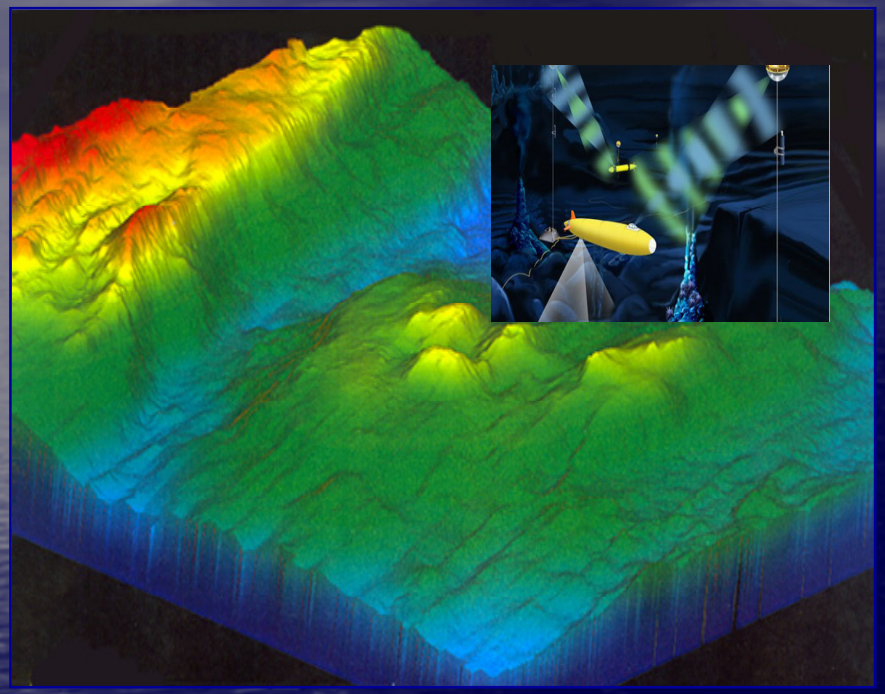
The SIRENE "ROV-LIKE" AUV

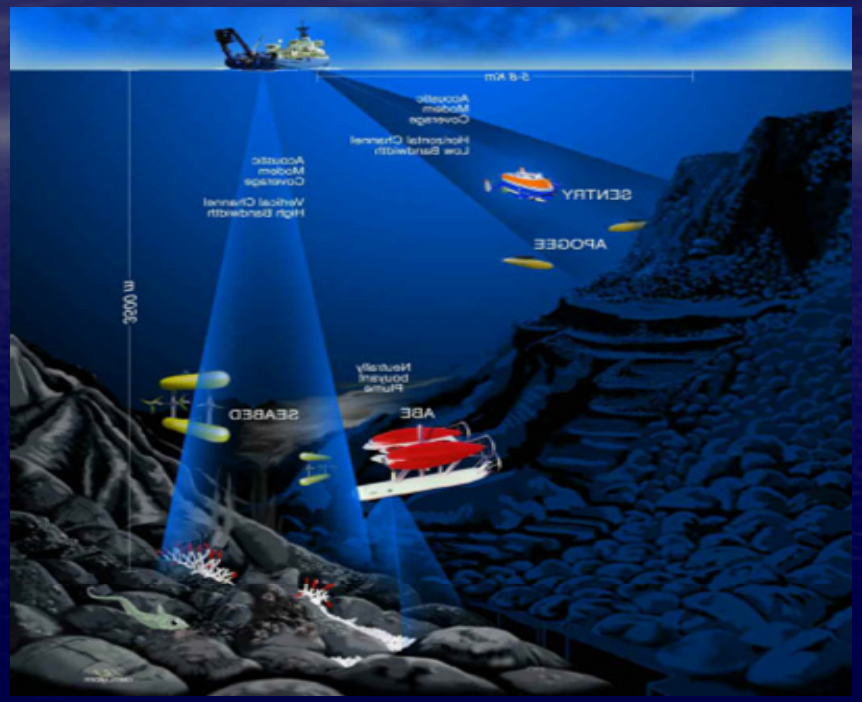
2 back thrusters
1 vertical thruster
NO side thruster



"Bluff body "
Depth Control
Point stabilization required

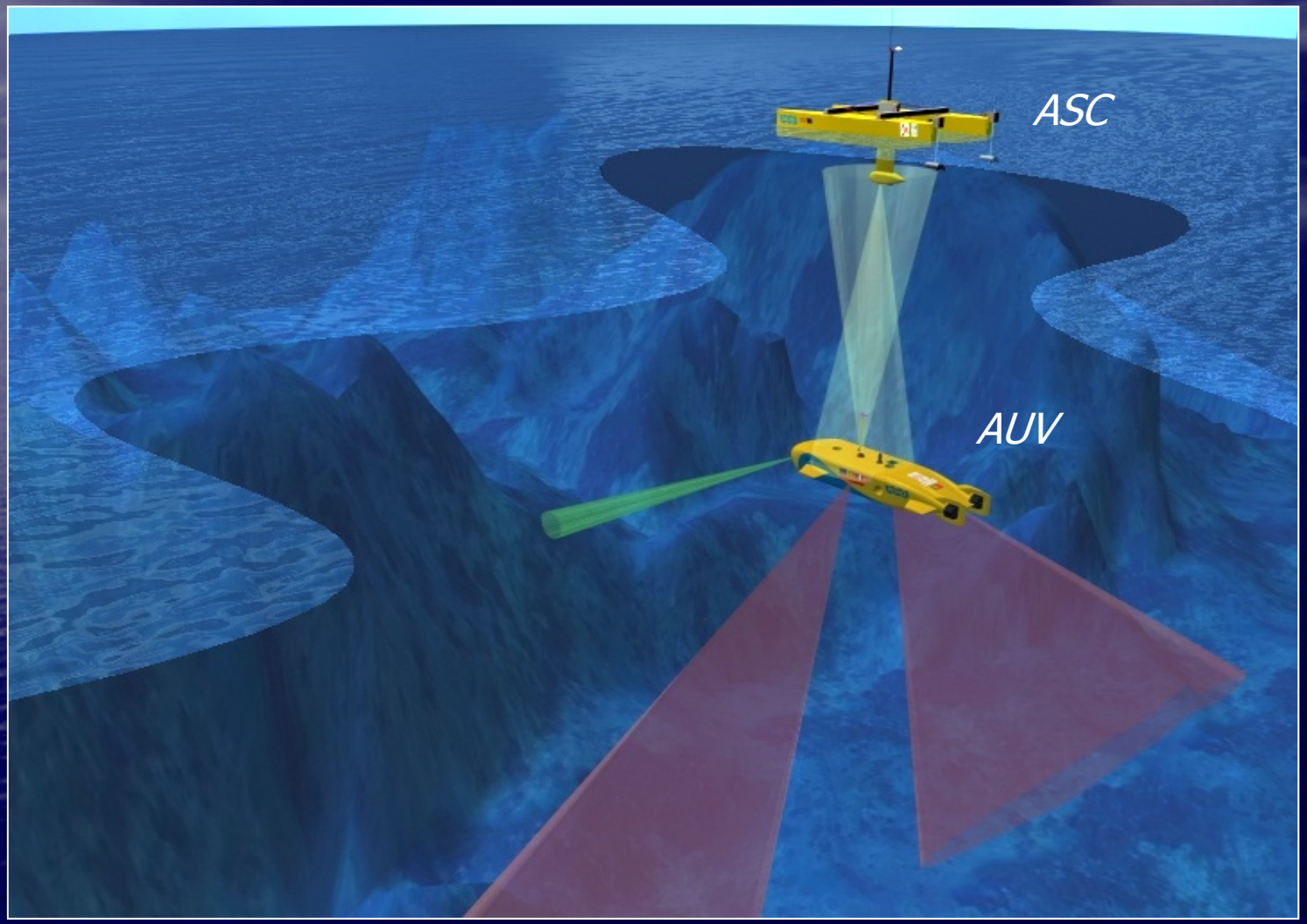
Sea: the Ultimate Frontier





Make room for multiple vehicles!

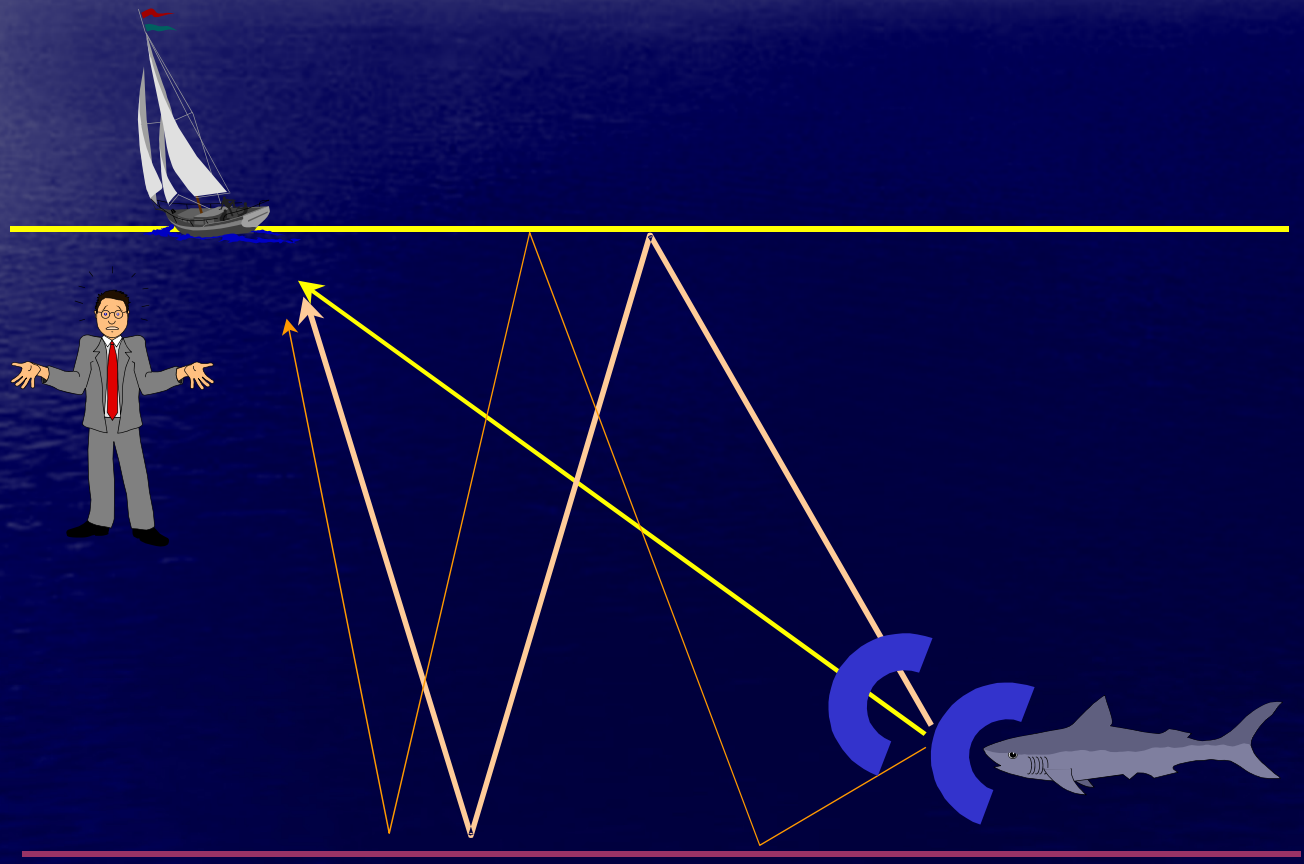
Cooperative Missions at Sea: the ASIMOV project



Surface and underwater vehicle operating in master / slave configuration (ASIMOV, 2000)

Problem to be solved: Communications

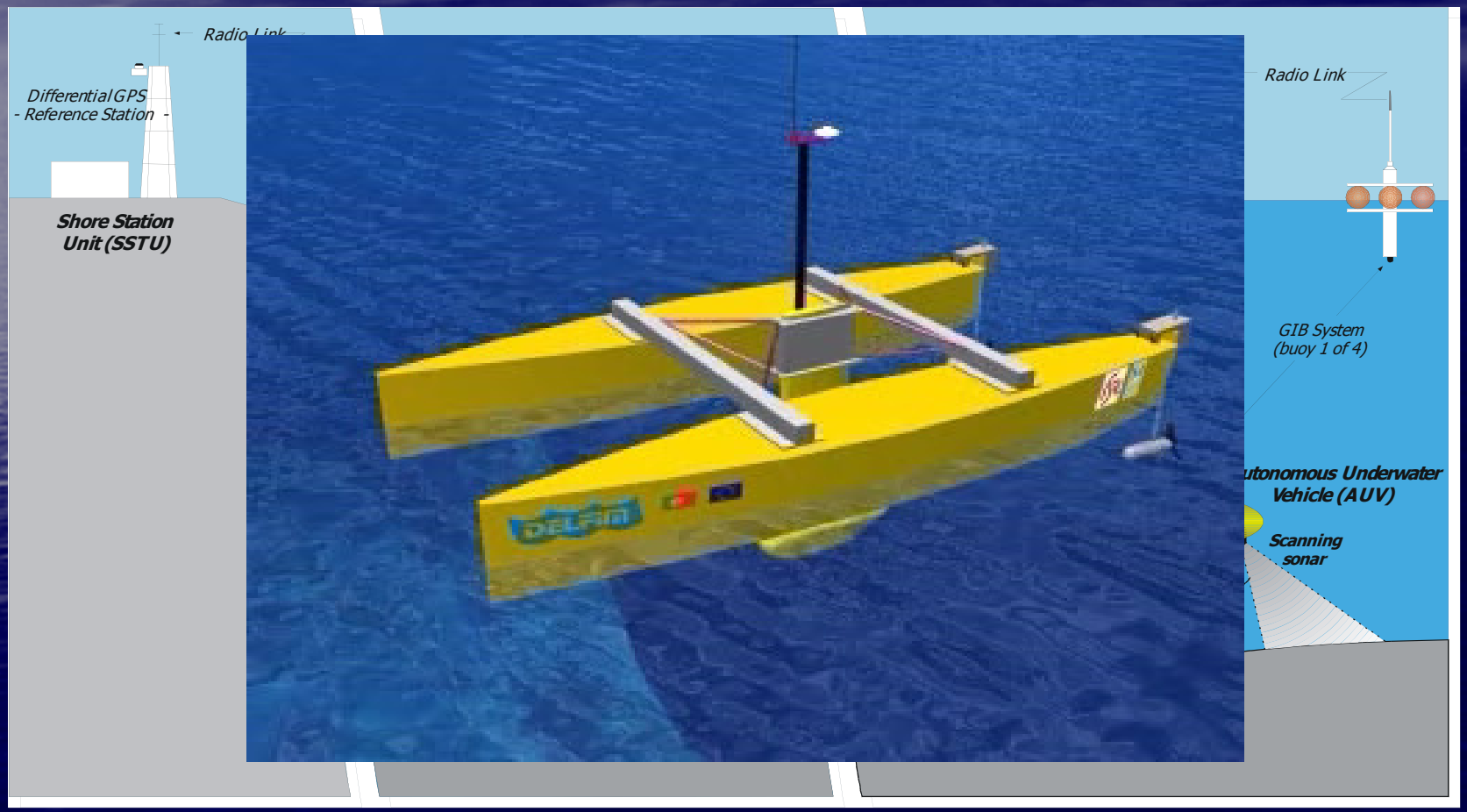
Underwater Communications – *very hard!*



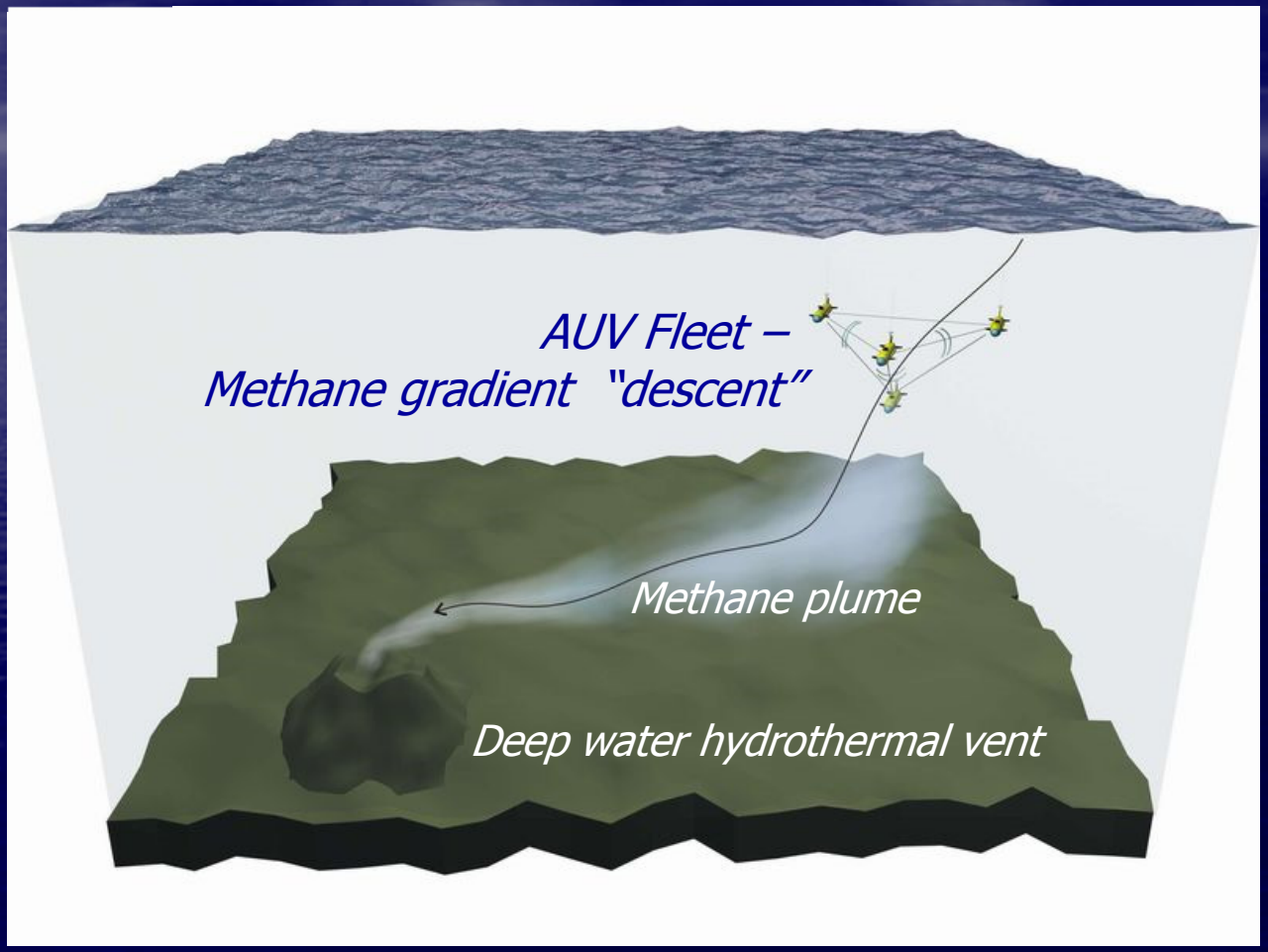
Underwater Communications

Transmit in the vertical !

Coordinated Motion Control



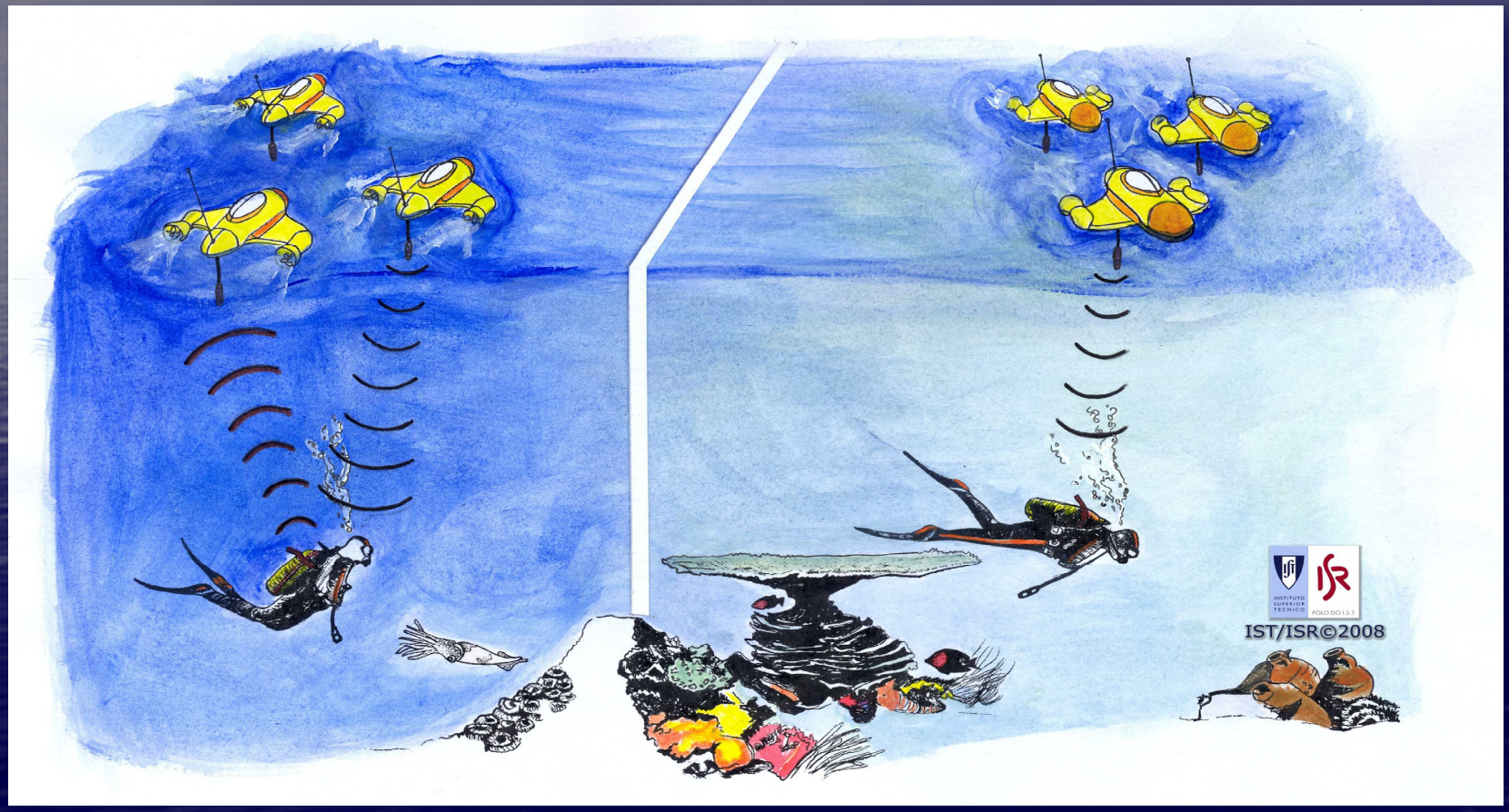
The ASIMOV concept
(ASIMOV project, EC - 2000)



The quest for mid-water column hydrothermal vents, Azores, PT

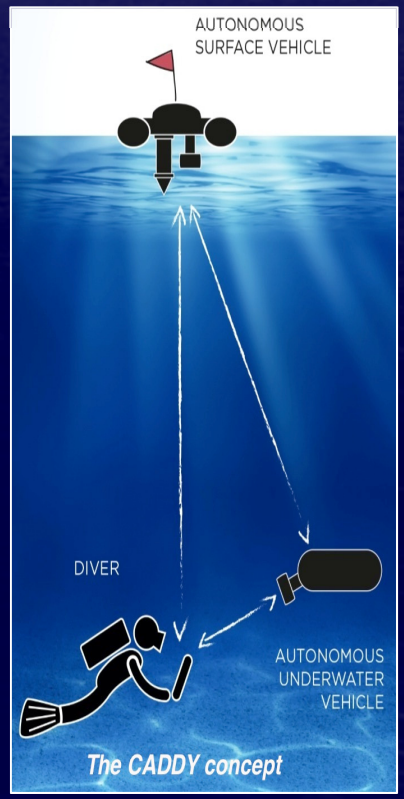
Robots and Humans in the Loop

CO3 AUVs
Cooperative Cognitive Control for Autonomous Underwater Vehicles

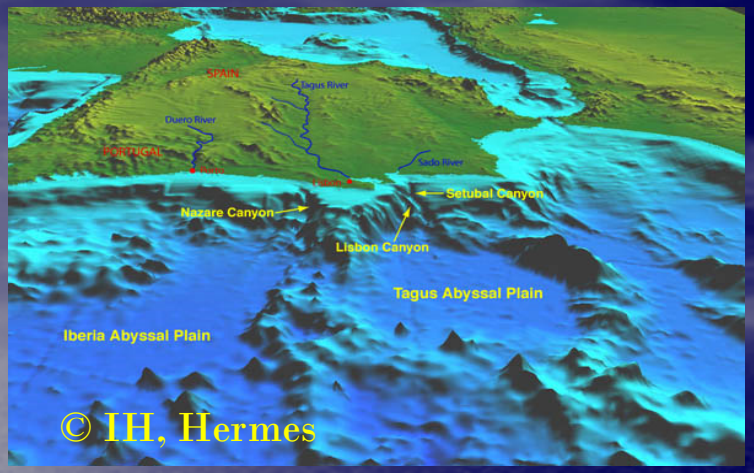


CADDY

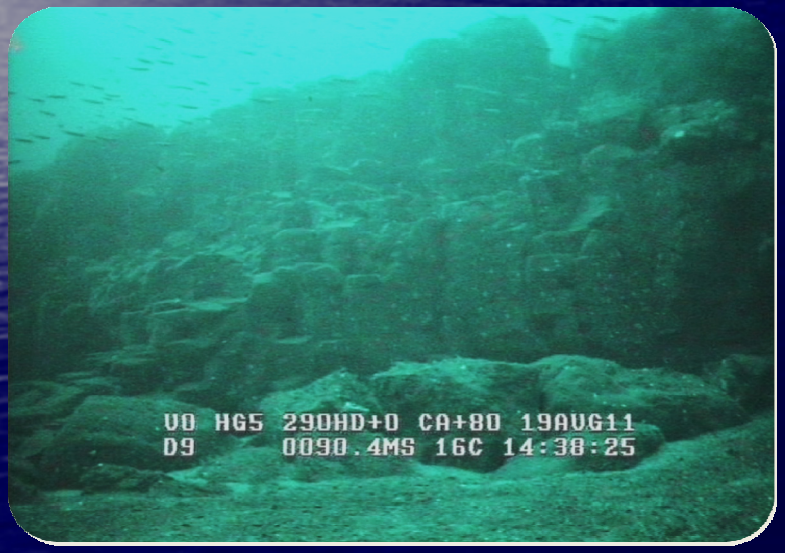
Cognitive Autonomous Diving Buddy

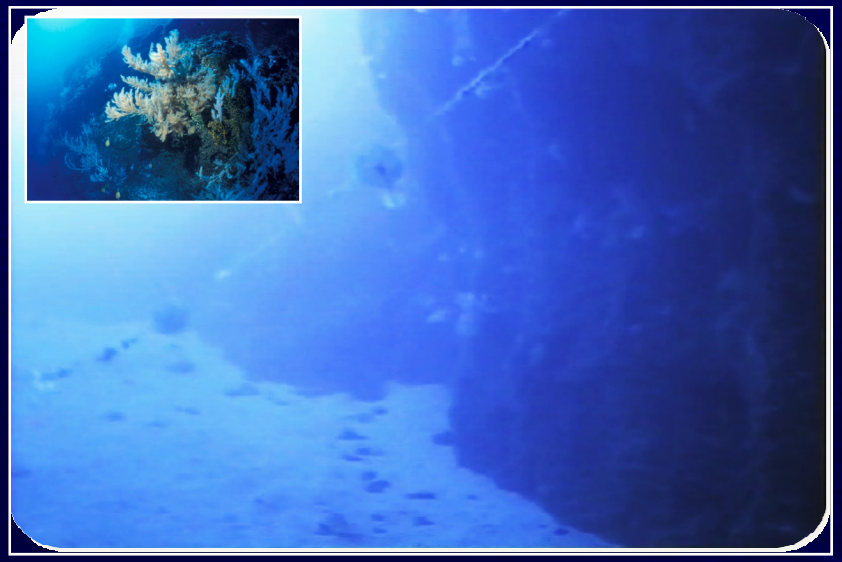


New Challenges



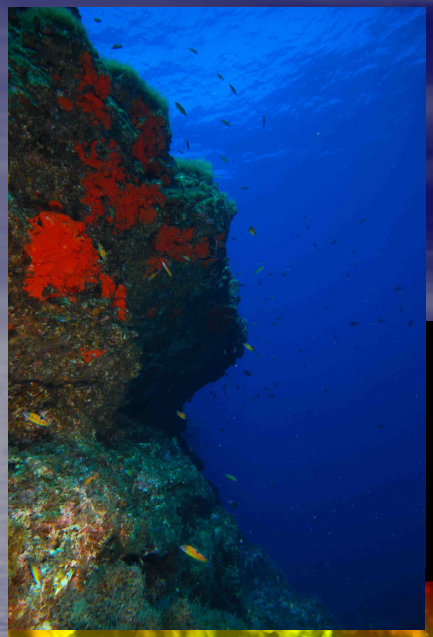
Deep Sea Habitat Mapping near hydrothermal vents and in complex 3D environments





Underwater cliffs, canyon walls, mass wasting walls, mid-ocean ridges, fracture zones, seamount flanks, continental margins, hydrothermal vent edifices

End Products
Habitat maps (acoustics and vision)



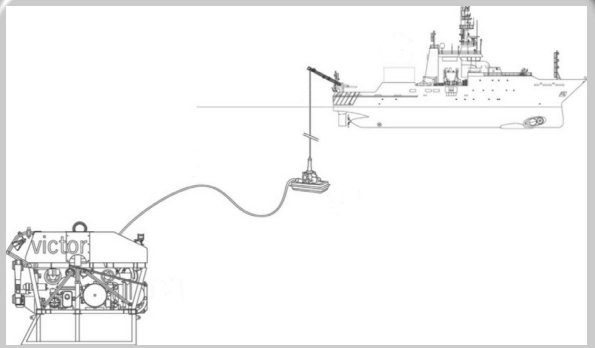
The cliff scenario

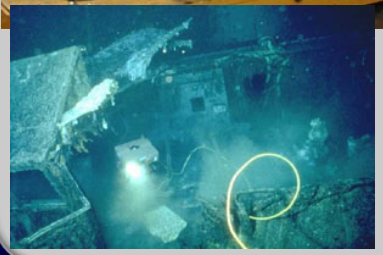
Key challenge: i) obtain *marine habitat maps* of complex underwater structures including steep cliffs and "overhangs" with a negative slope

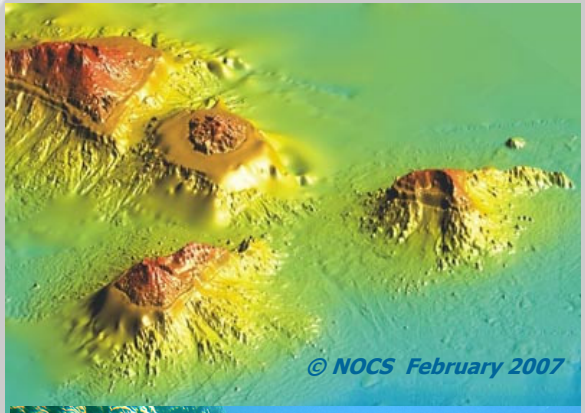
The cliff scenario

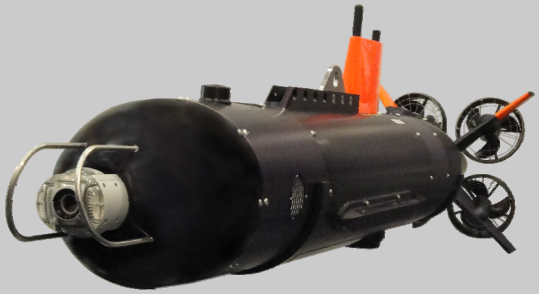
Can we learn from humans? (“hugging the cliff)

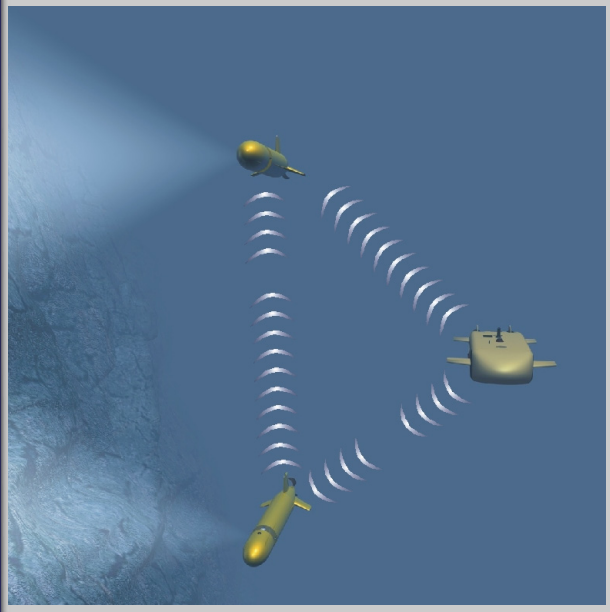
The Cliff scenario











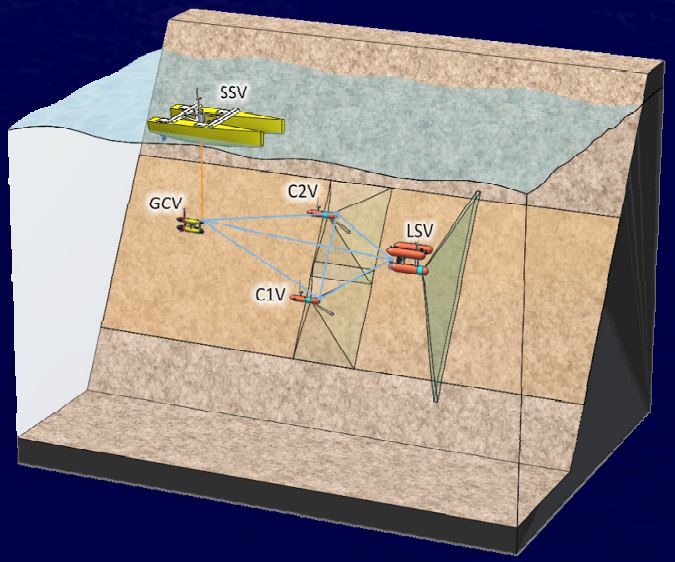
The MORPH supra-vehicle

Proposed technological solution: from single to *supra-vehicles with spatially self-organizing capability*

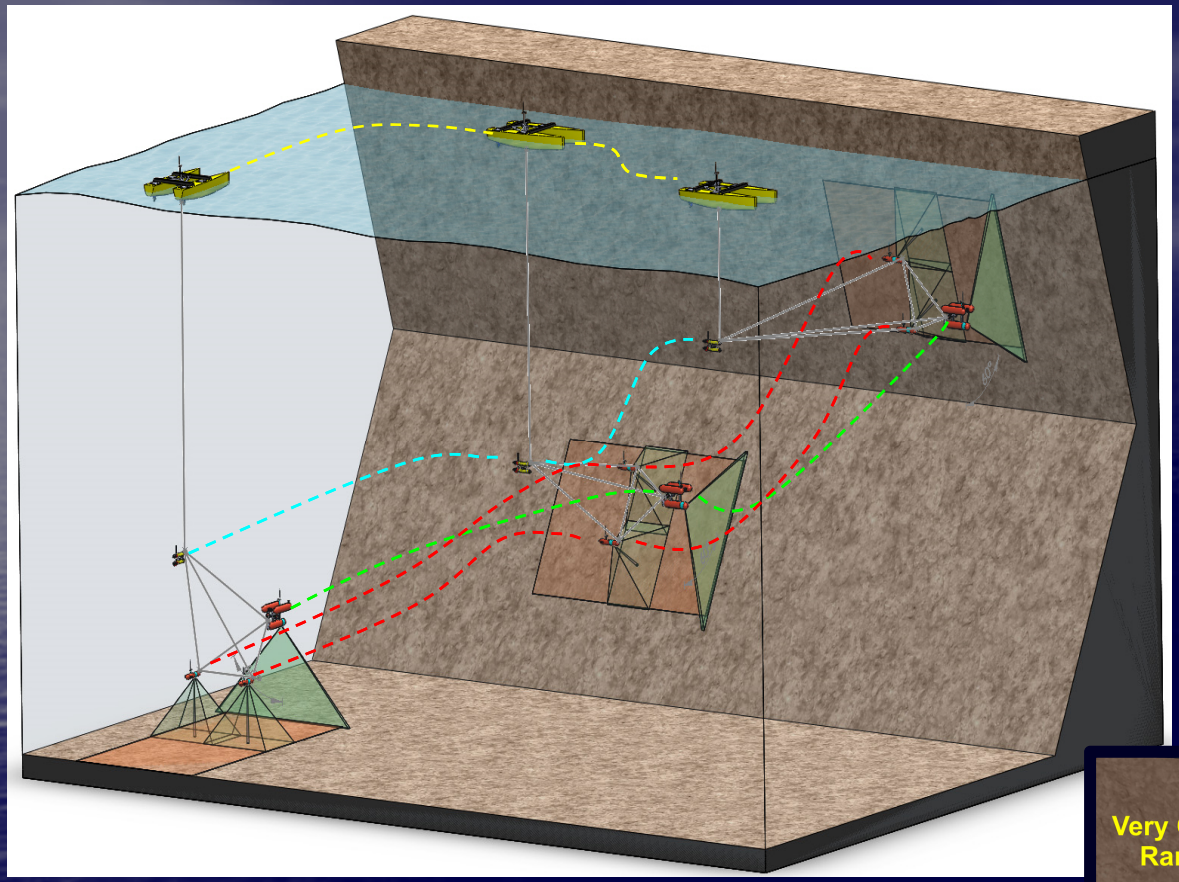
FP7-ICT-2887704
MORPH PROJECT

Marine robotic system of self-organizing, logically linked physical nodes

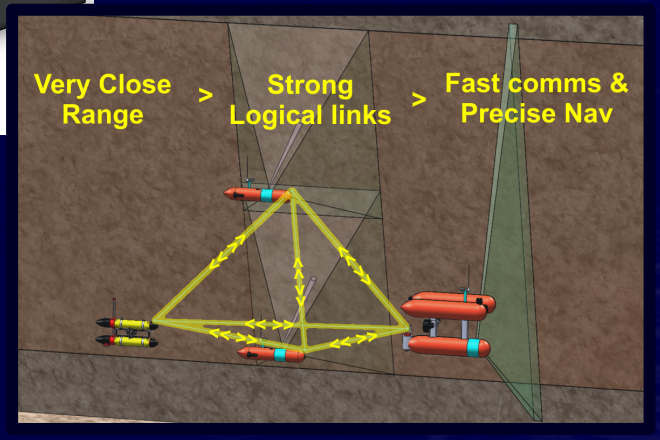
MORPH
Consortium



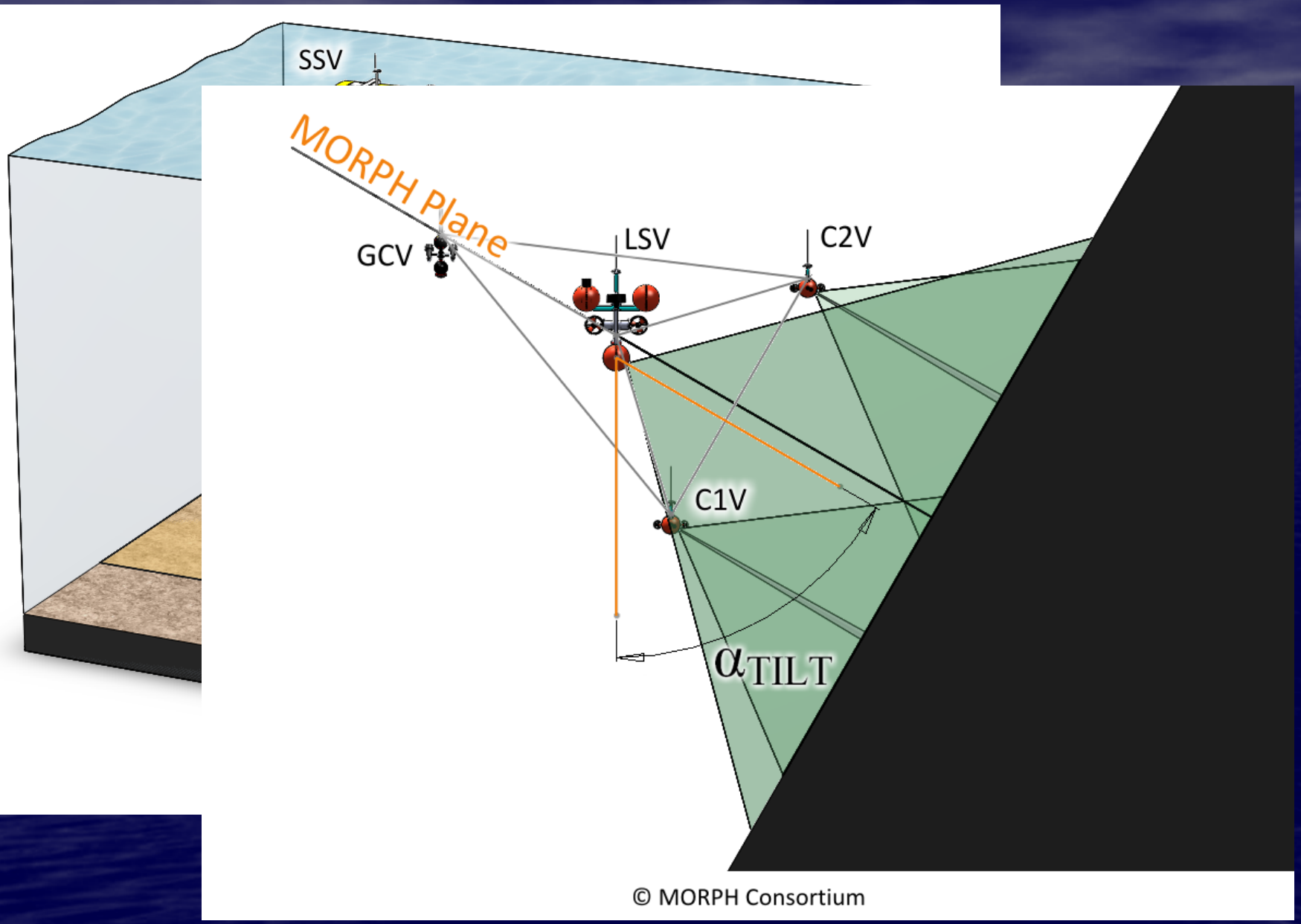
A new Paradigm is needed for Adaptive Mapping



A cluster
of modules
operating as a
virtual
marine vehicle



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



The Morph Consortium

1. ATLAS ELEKTRONIK (Germany)
2. Consiglio Nazionale delle Ricerche - Istituto di studi sui sistemi intelligenti per l'automazione, CNR (Italy)
3. Institut français de recherche pour l'exploitation de la mer, IFREMER (France)
4. Jacobs University (Germany)
5. Instituto Superior Tecnico / Institute for Systems and Robotics, IST/ISR (Portugal)
6. Ilmenau University of Technology, IUT (Germany)
7. NATO Undersea Research Centre, NURC (Italy)
8. Universitat de Girona, UDG (Spain)
9. Institute of Marine Research, IMAR (Portugal)
10. *Woods Hole Oceanographic Institution, WHOI (USA)*

Experimental Facilities



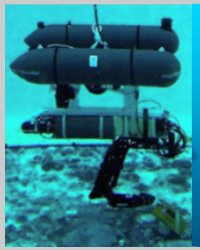
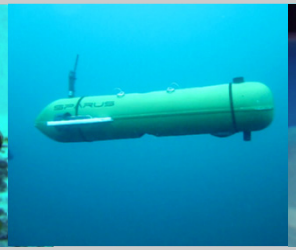
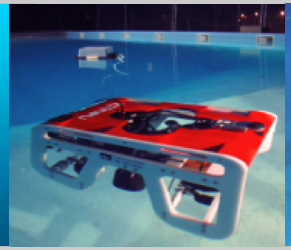


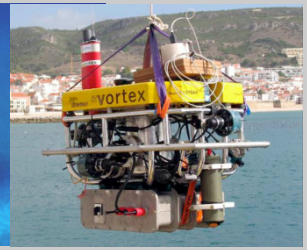


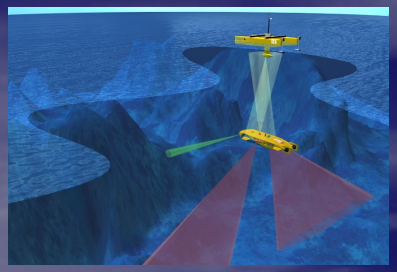
Robotic Vehicles

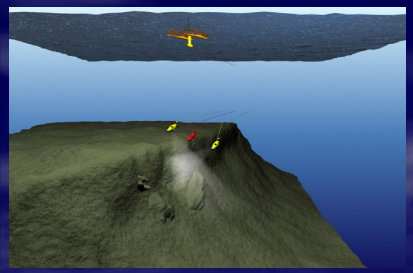











Mission specification

Cooperative motion planning

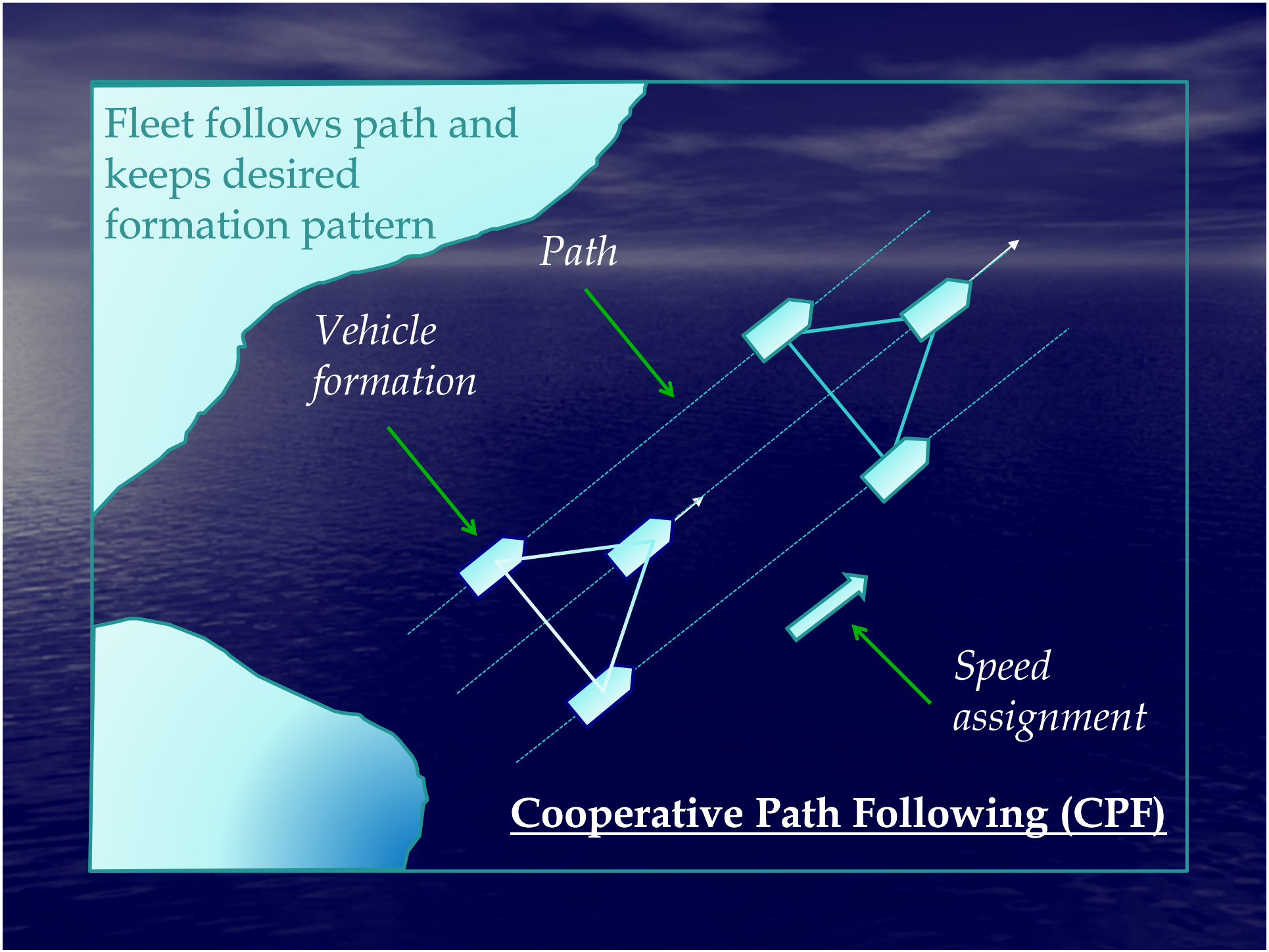
Nominal trajectories & desired vehicle formation

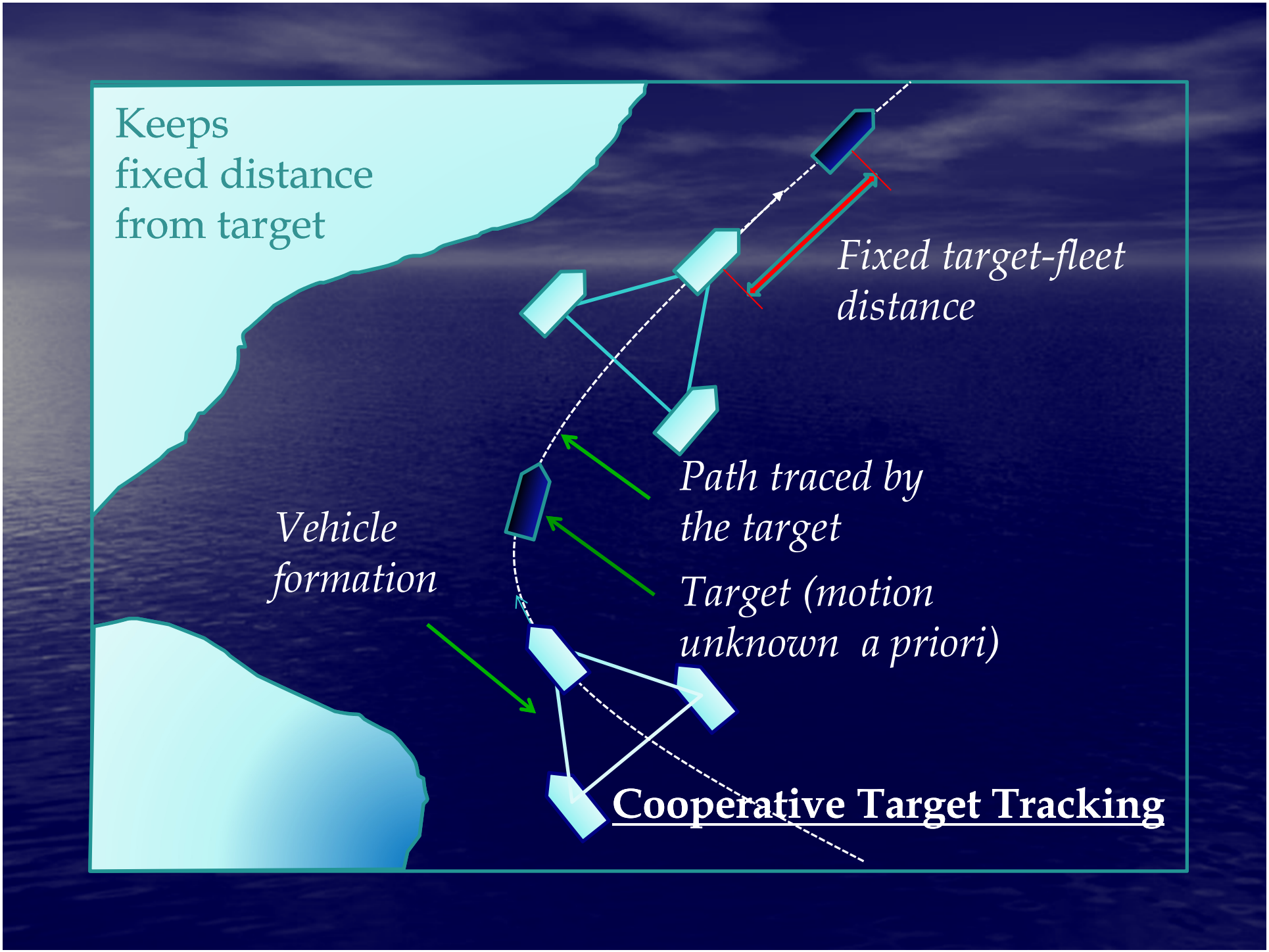
Cooperative motion control

Global and local, relative vehicle positions

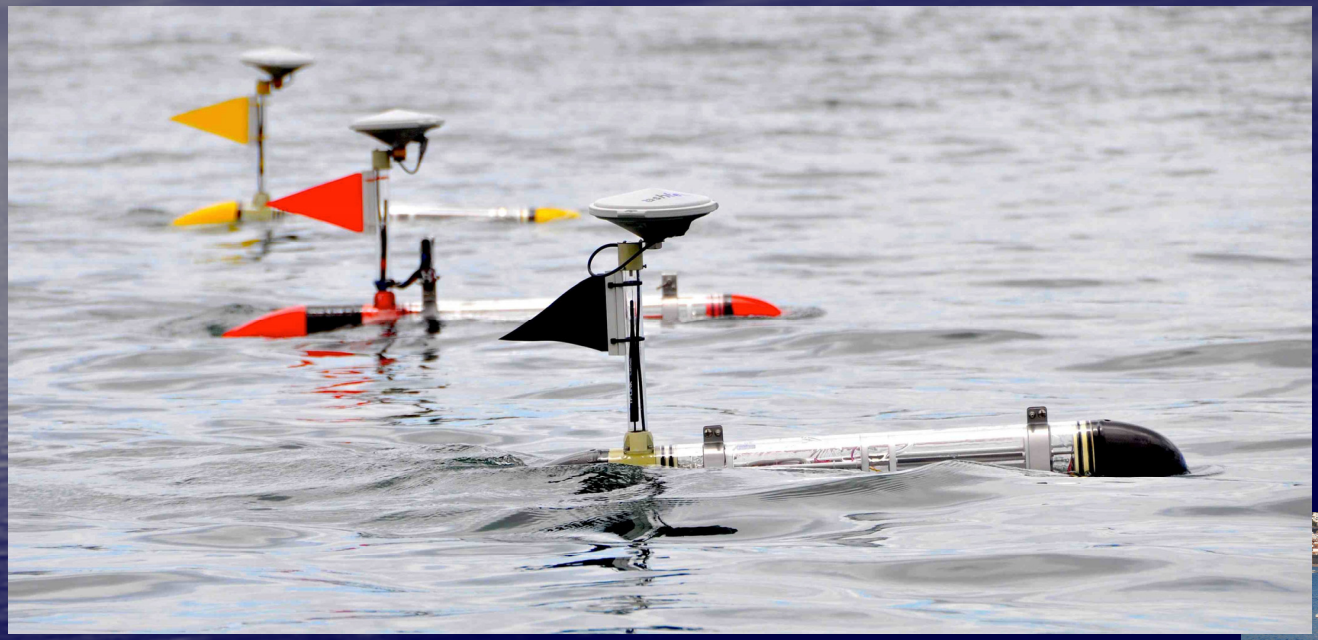
Cooperative navigation

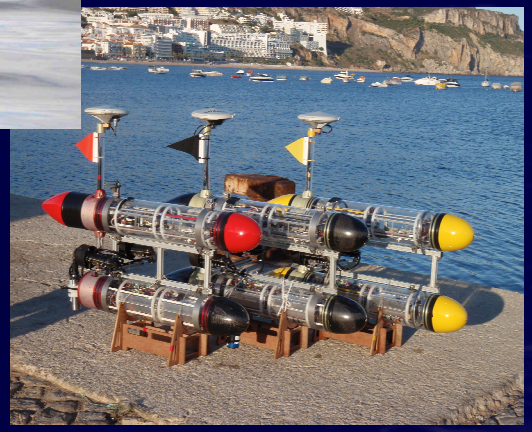
Cooperative systems: key blocks required


Fleet follows path and keeps desired formation pattern
Path
Vehicle formation
Speed assignment
Cooperative Path Following (CPF)


Keeps
fixed distance
from target
Fixed target-fleet
distance
Path traced by
the target
Target (motion
unknown a priori)
Vehicle
formation
Cooperative Target Tracking

From theory to practice: the MEDUSA ASVs



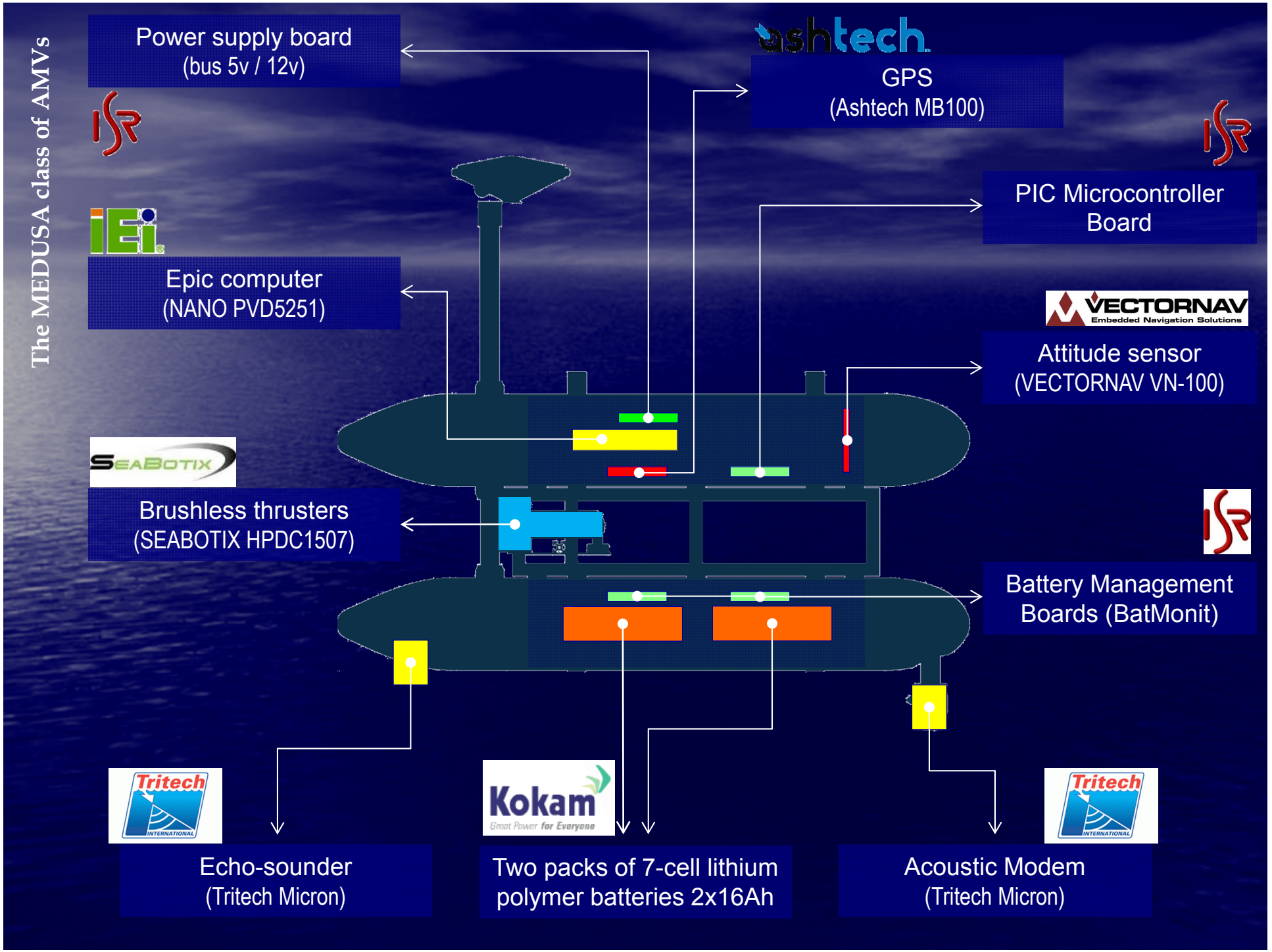


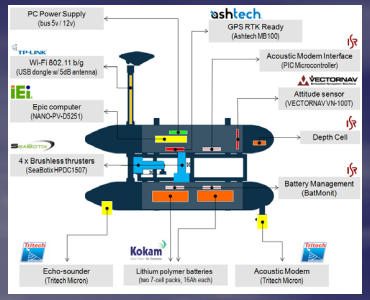
. *3 autonomous vehicles (cooperative motion control capability)*

. *Acoustic network (Tritech micromodems)*

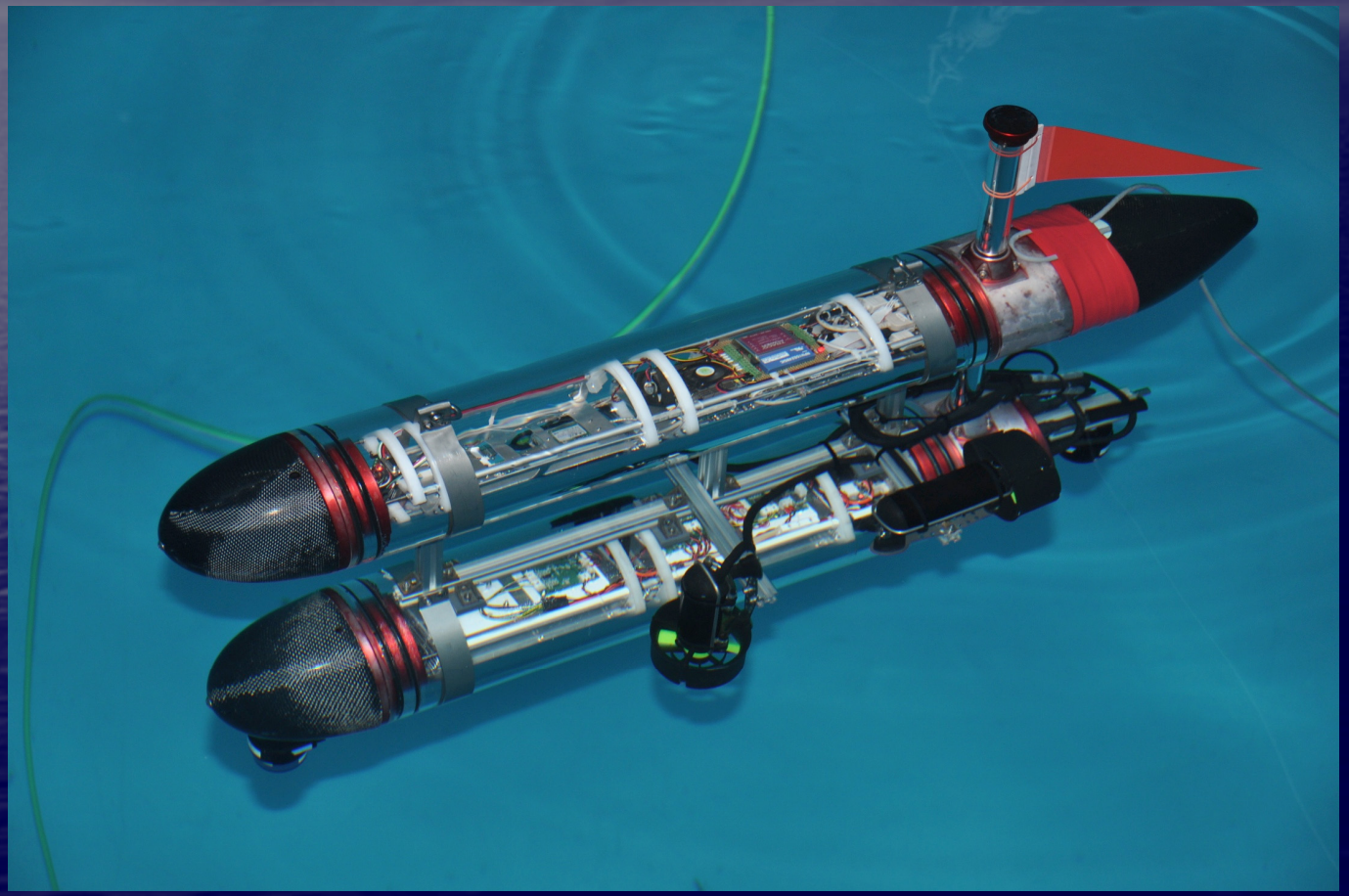
The MEDUSA class of AMVs

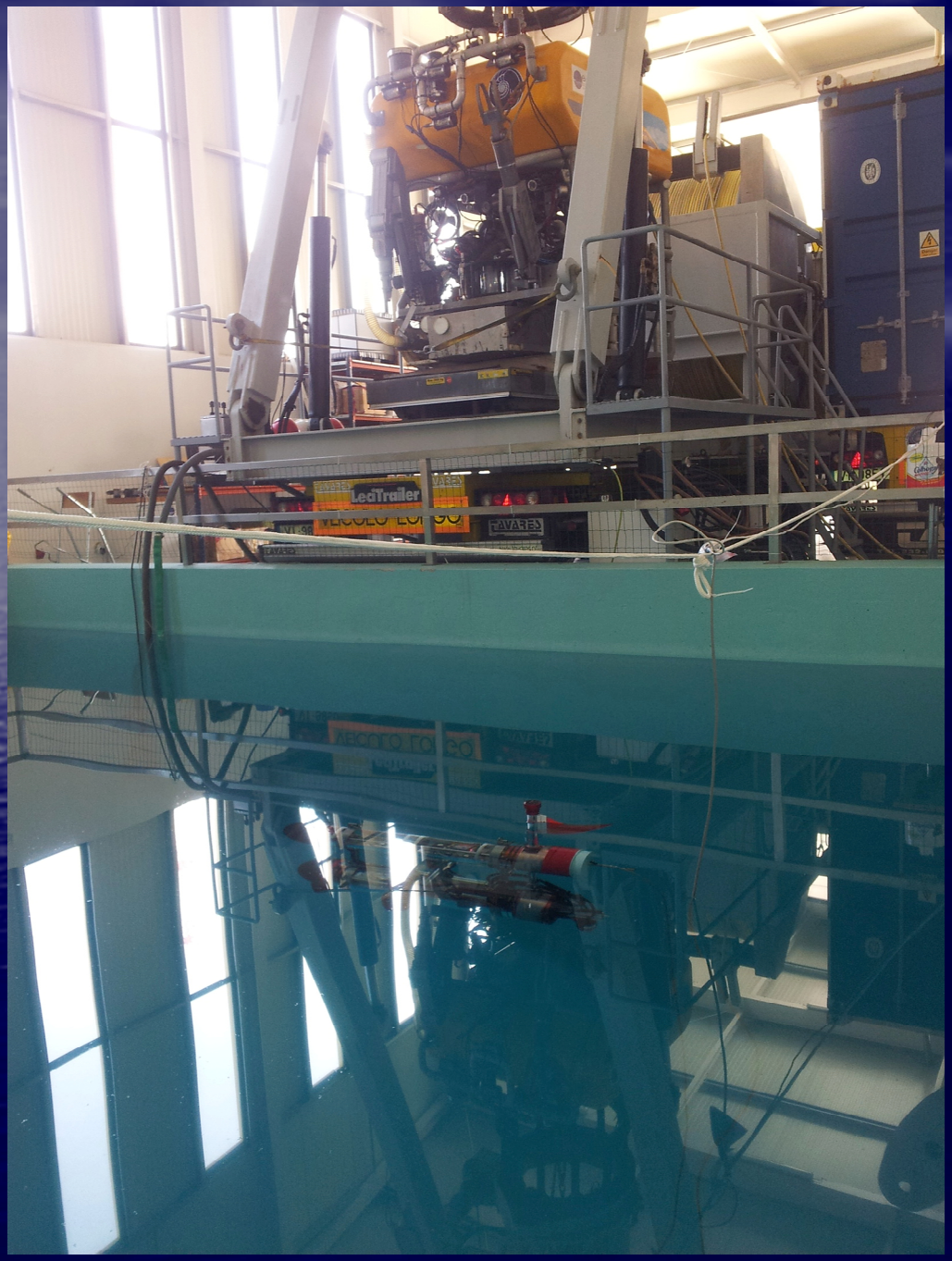
The MEDUSA class of AMVs

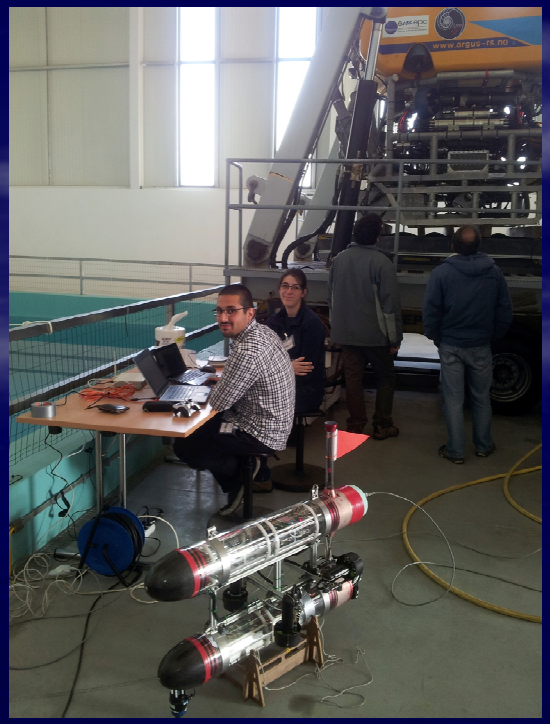

The MEDUSA class of AMVs
Power supply board
(bus 5v / 12v)
GPS
(Ashtech MB100)
PIC Microcontroller
Board
Epic computer
(NANO PVD5251)
Attitude sensor
(VECTORNAV VN-100)
Brushless thrusters
(SEABOTIX HPDC1507)
Battery Management
Boards (BatMonit)
Echo-sounder
(Tritech Micron)
Two packs of 7-cell lithium
polymer batteries 2x16Ah
Acoustic Modem
(Tritech Micron)


PC Power Supply
(out 5v / 12v)
ashtech
GPS RTK Ready
(Ashtech MB100)
TP-LINK
Wi-Fi 802.11 b/g
(USB dongle w/ 5dB antenna)
Acoustic Modem Interface
(PIC Microcontroller)
VECTORNAV
Attitude sensor
(VECTORNAV VN-100T)
Epic computer
(NANO-PV-D5251)
Depth Cell
4 x Brushless thrusters
(SeaBotix HPDC1507)
Battery Management
(BatMonit)
Tritech
Kokam
Tritech
Echo-sounder
(Tritech Micron)
Lithium polymer batteries
(two 7-cell packs, 16Ah each)
Acoustic Modem
(Tritech Micron)

MEDUSA$_D$



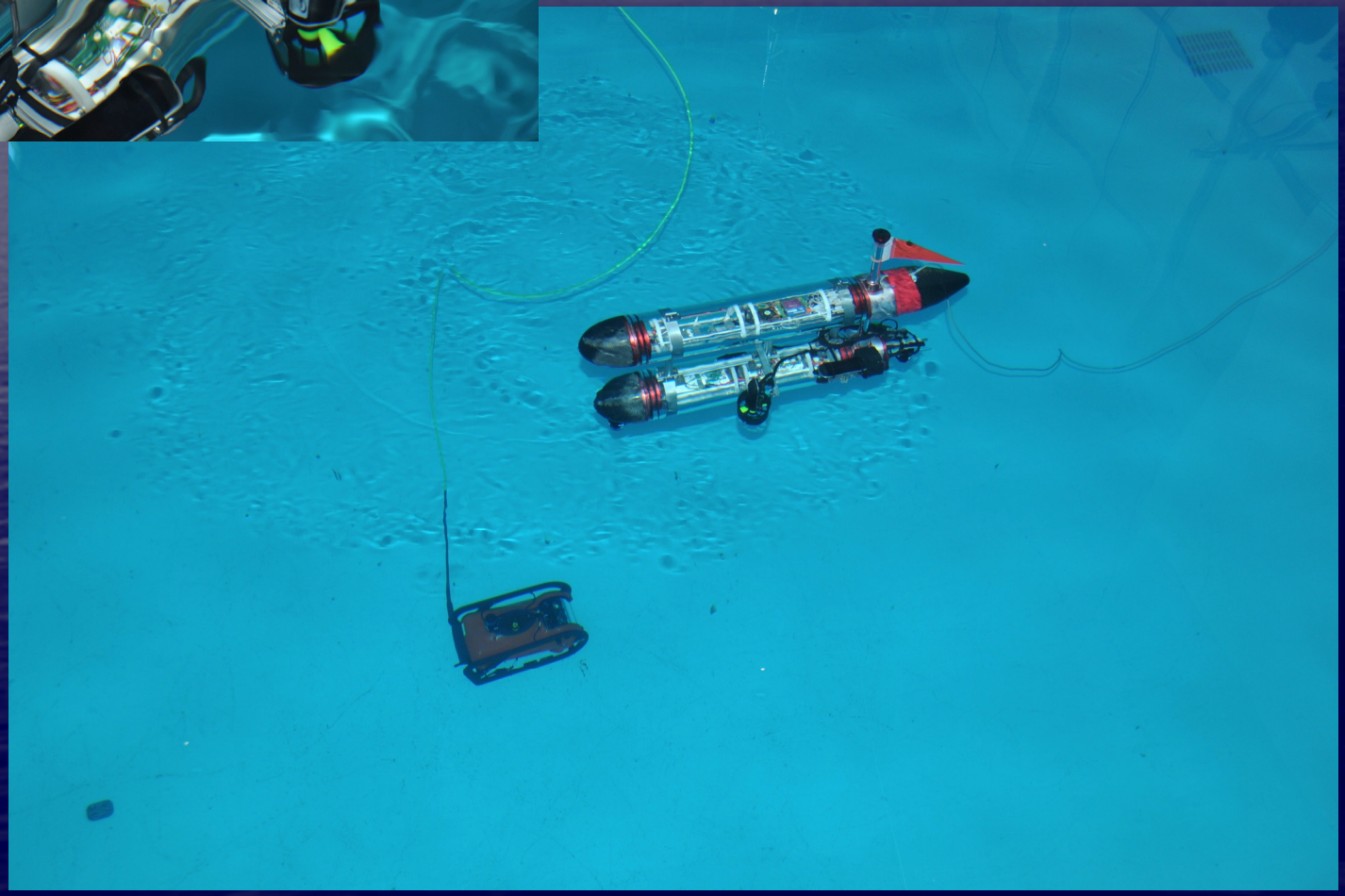




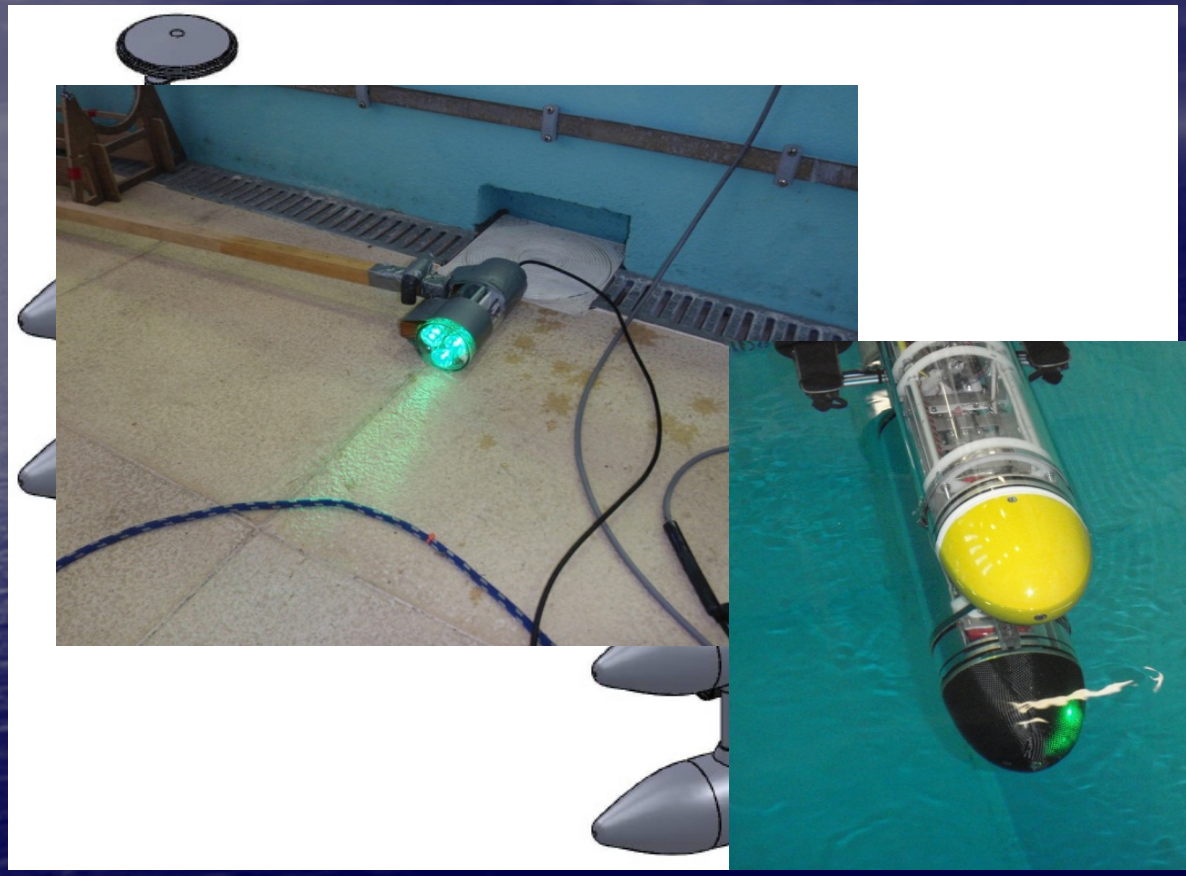
Diving Tests with MEDUSA$_D$

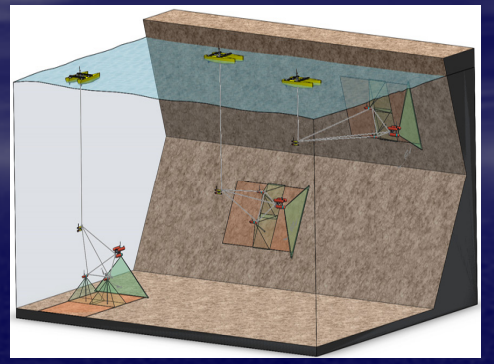
2013

MEDUSA$_D$



Communications at close range

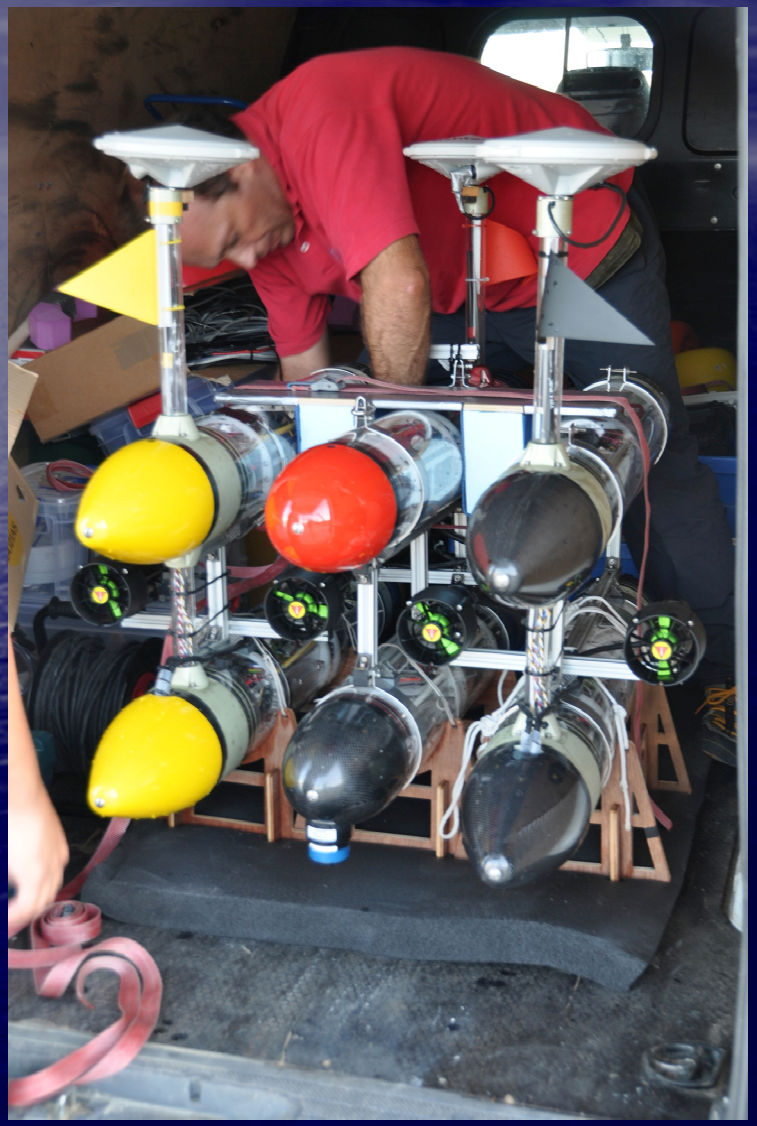




Compact, lightweight, low cost optical communication system to exchange data and commands among vehicles

Transportation

Transportation



Deployment

Operations in Lisbon, PT

Motion Control of the Medusa ASVs: Systems Design and Tests at Sea

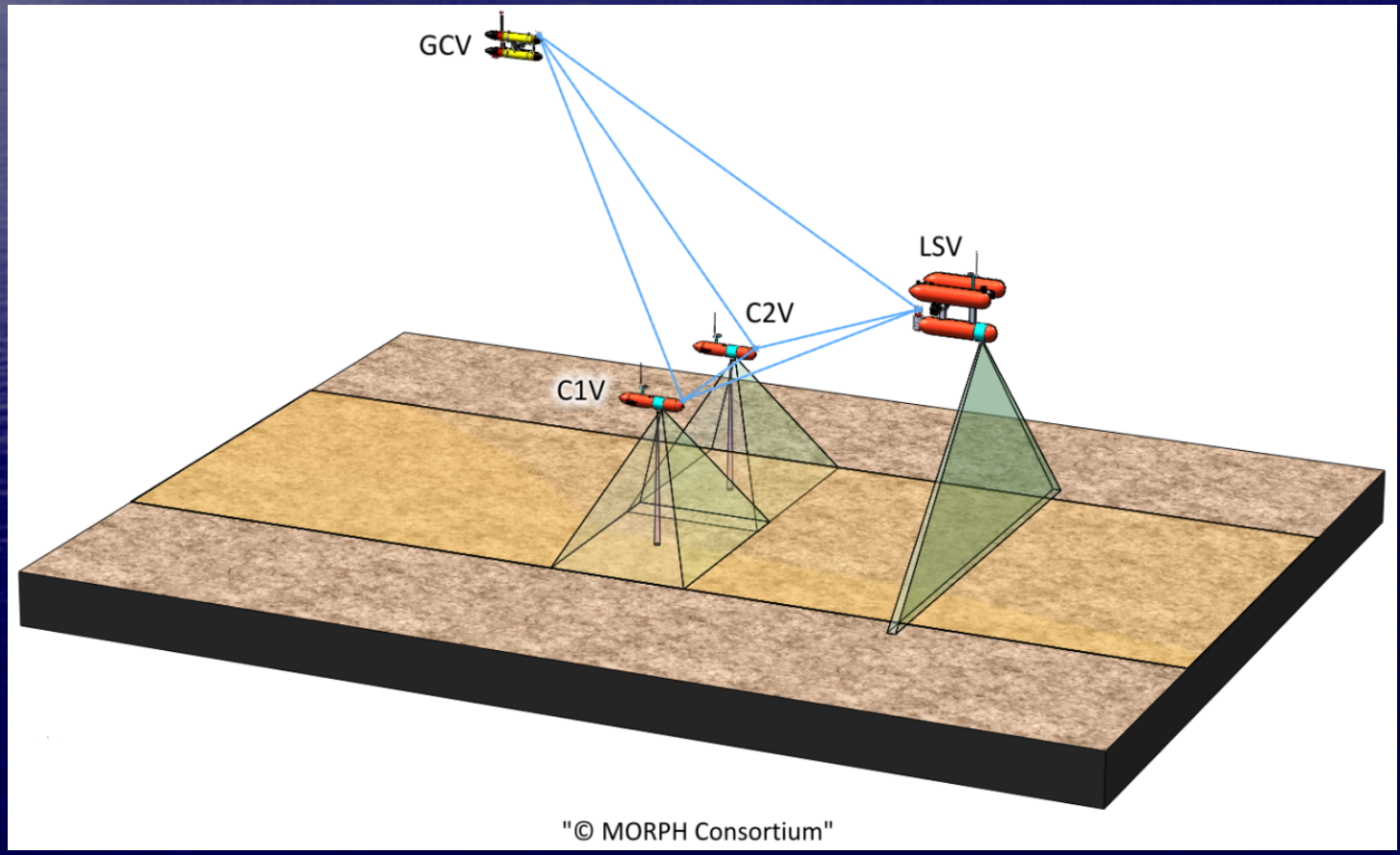
The Medusa Robotic Vehicles

Autonomy	+6 hours (depending on average speed)	
Weight	20 Kg	
Depth rate	---	
Surge Speed	1.7 m/s max	
CPU	SBC + PC104	
Software	Linux OS + MOOS + IST proprietary	
Power	Batteries (Lipo)	
Comms	Wi-fi	
Actuators	2 horizontal brushless DC thrusters	
DOF	Surge, Yaw.	
Sensors	**Navigation**	GPS; Attitude and Heading Reference System (AHRS);
Payload	**Sonar/ Cameras/ Video/ Lights**	Micron acoustic modem; Video camera

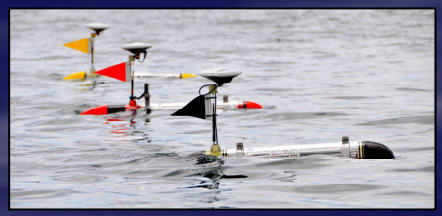

CO3 AUVs
Cooperative Cognitive Control for
Autonomous Underwater Vehicles
www.Co3-AUVs.eu
SEVENTH FRAMEWORK
PROGRAMME

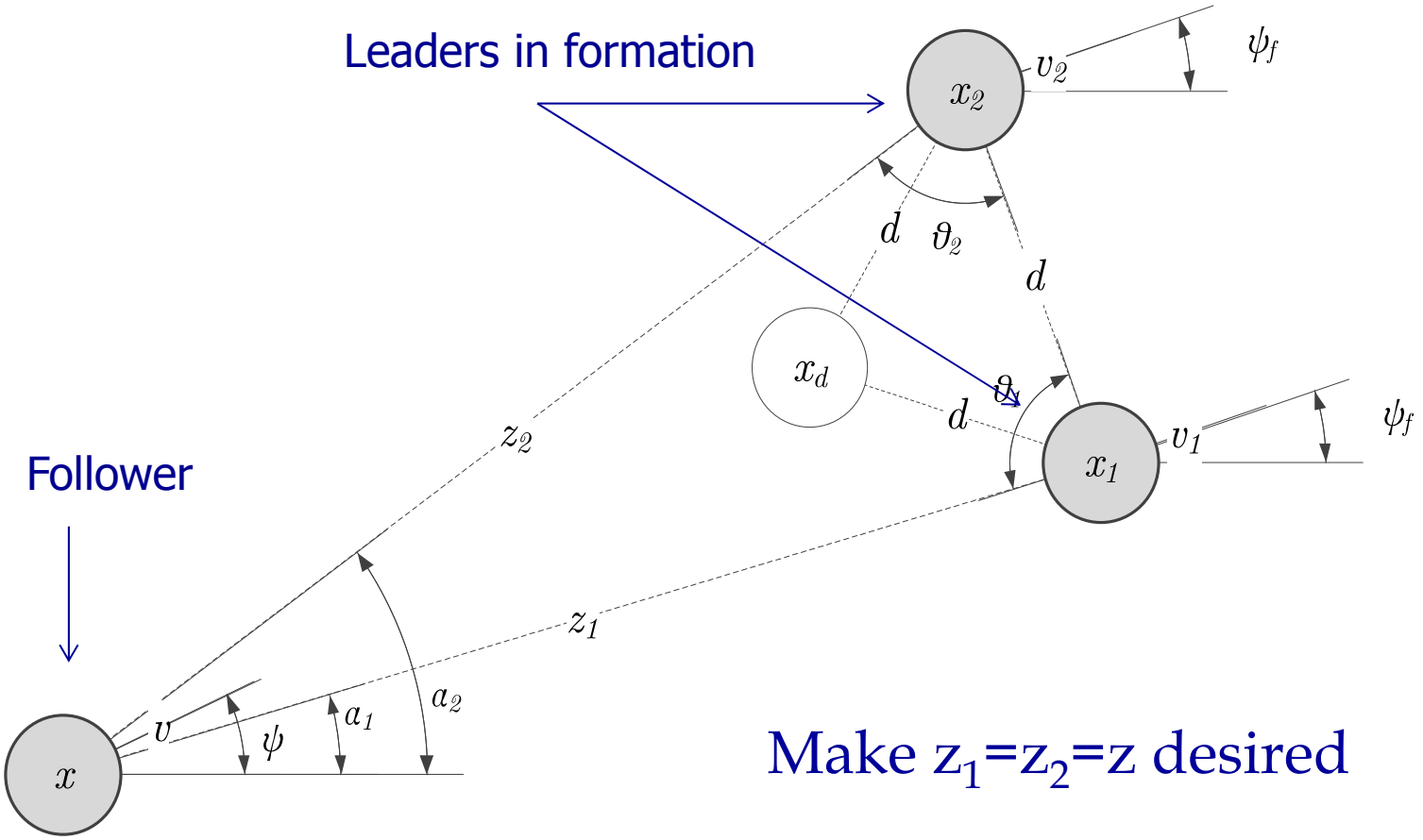
Range-Only Formation (ROF) Control

(first step towards meeting the functionalities of the MORPH underwater segment)

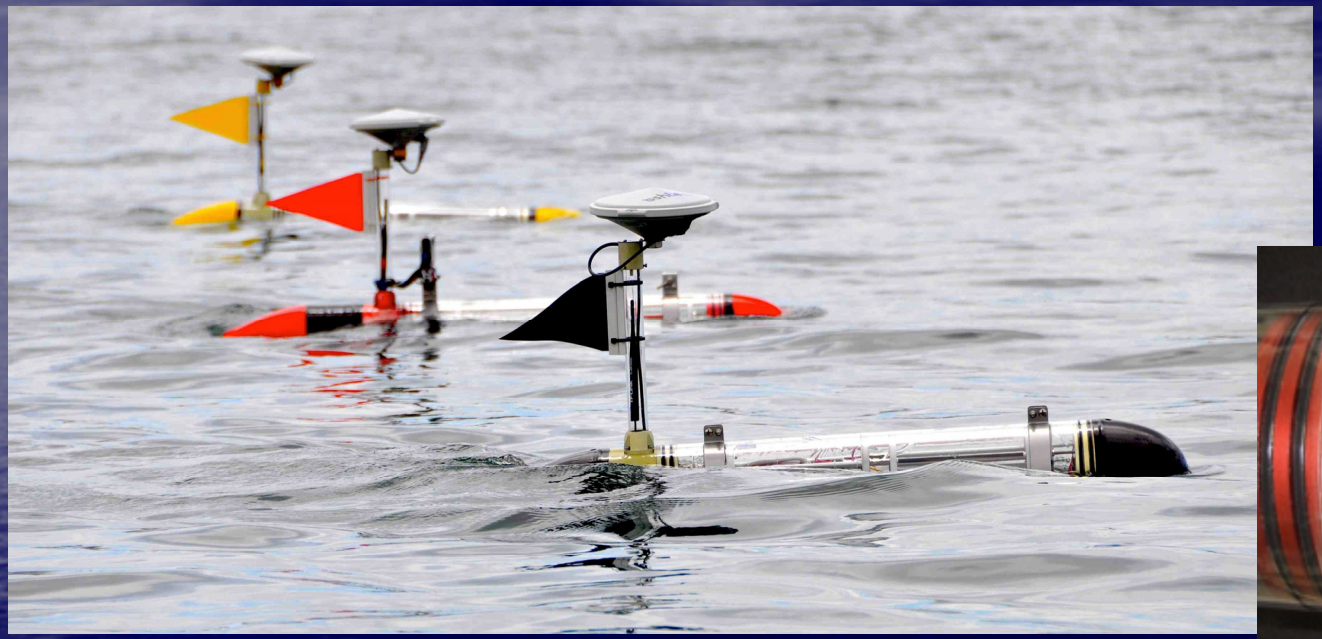


Range only formation control





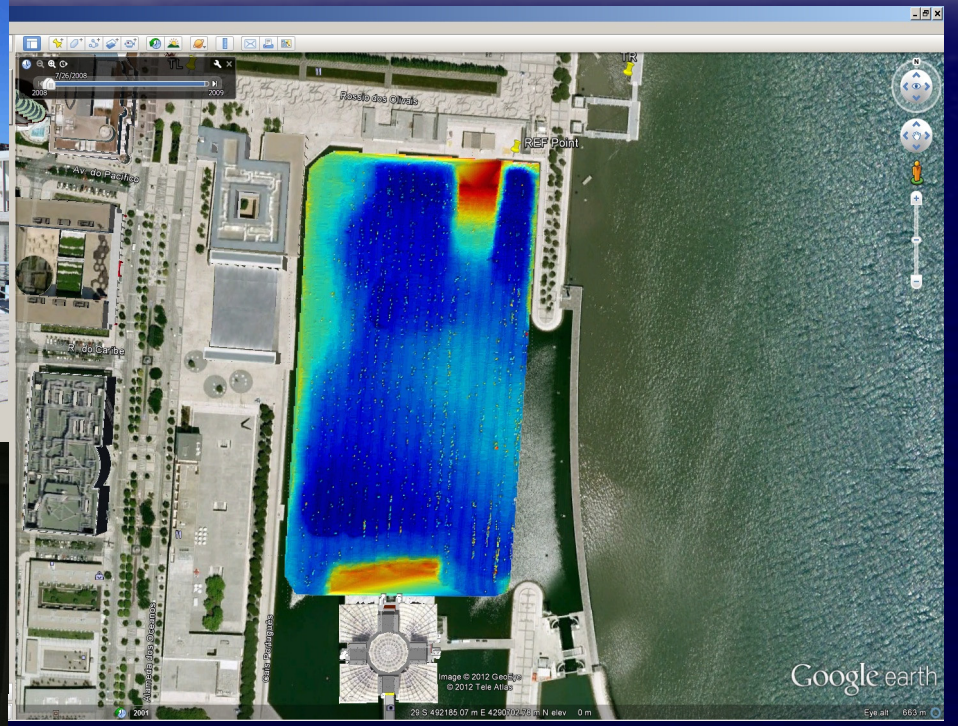
Field Tests



3 Medusa vehicles exchanging ranges and data over a Tritech modem-enabled acoustic network

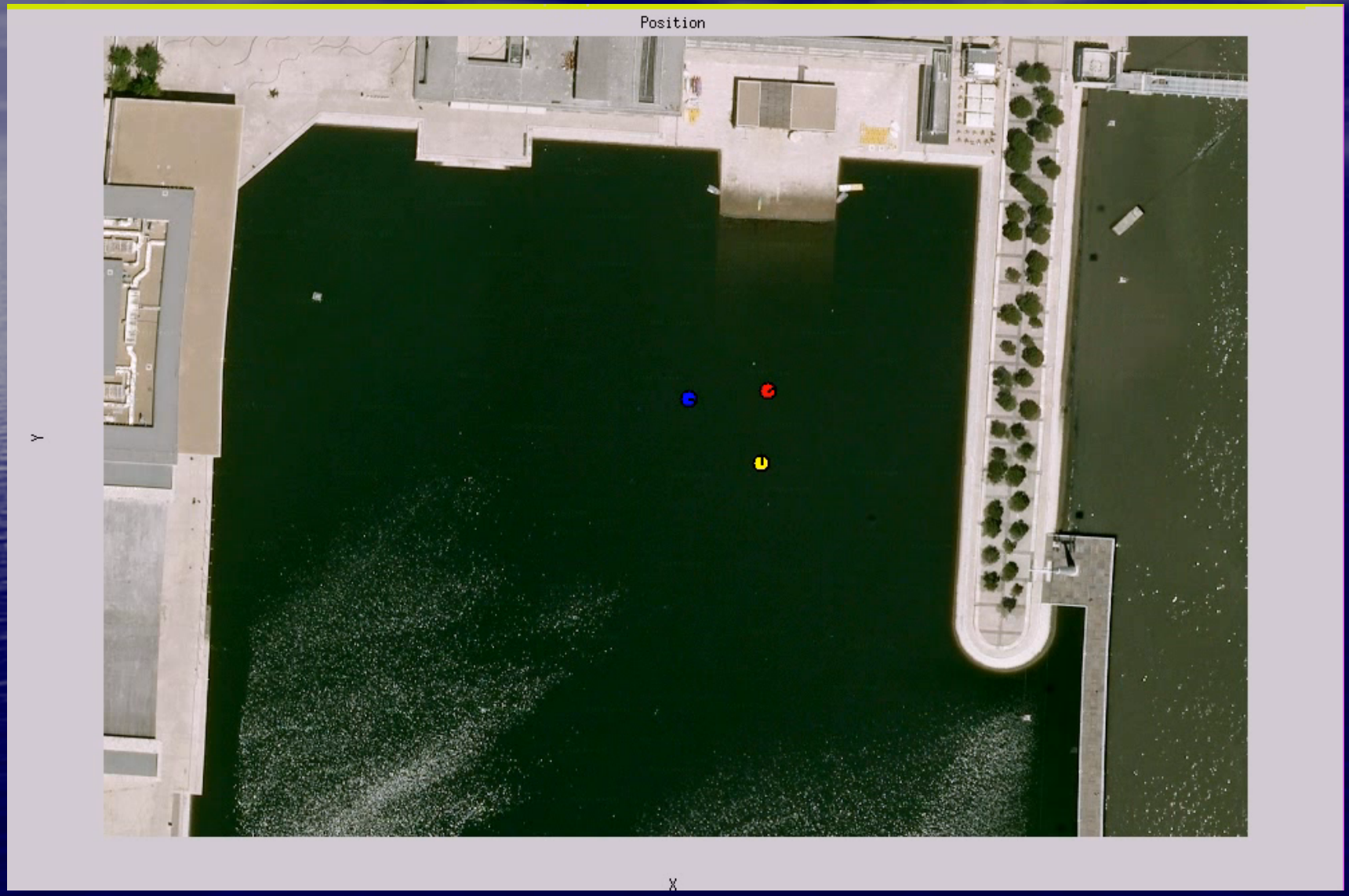
Test Site – Expo 98 site

2012



Test Results *- 2012*

Test Results – *22 Nov. 2012*



Test Results

Triangular formation control using acoustic range measurements

Sea trials @ Parque das Nações, Lisbon, Portugal

J. M. Soares, A. P. Aguiar, A. M. Pascoal
J. Botelho, J. Ribeiro, L. Sebastião, M. Rufino, M. Bayat, P. Góis, V. Hassani

INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

12 June 2012

Range Only Formation (ROF) Control using the EVOLOGICS modems

Two MEDUSA$_S$ (surface vehicles, ROF leaders) &
One MEDUSA$_D$ (underwater vehicle, ROF follower)

LISBON, EXPO – July 15, 2013

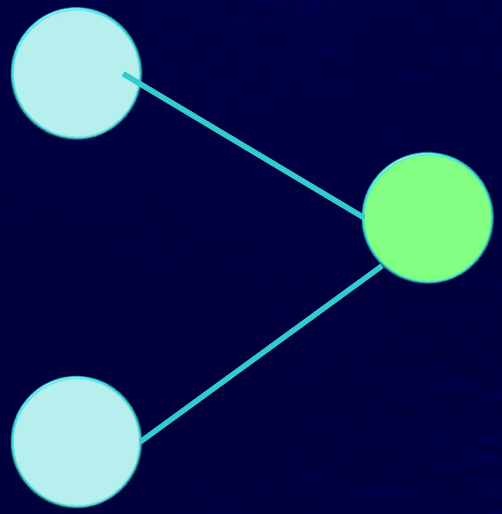
"Lateral" versus "Longitudinal" ROF

Longitudinal ROF

Leaders in formation

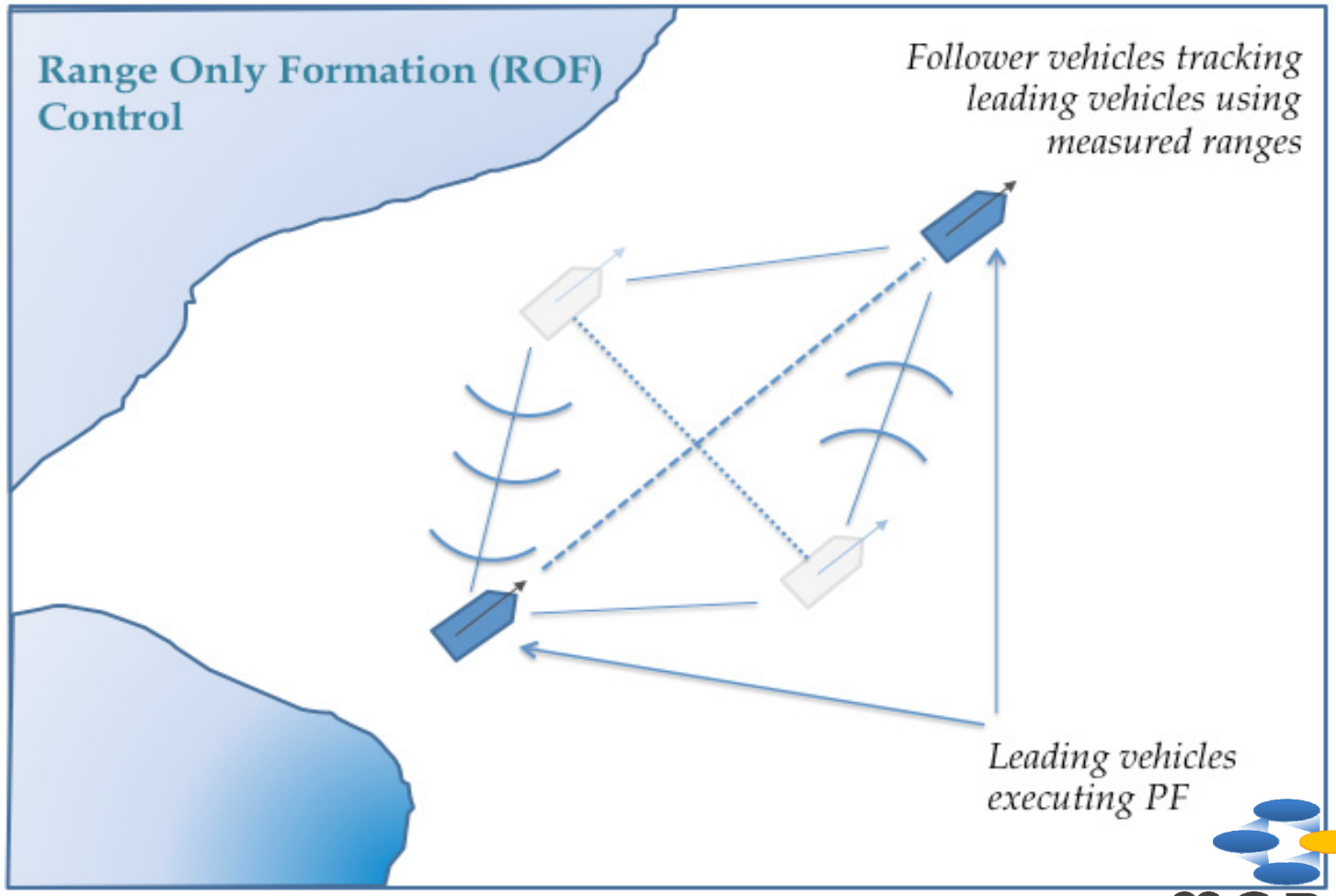
Follower

Lateral ROF



A new algorithm

The Toulon Trials, July 2013: Motion Control Objectives

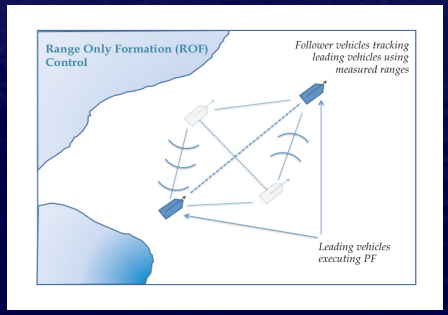


MORPH

Tasks executed

Leading vehicles:

- CPF, with the vehicles exchanging information over an aerial link.



Follower vehicles:

- Run depth control.
- Measure ranges to the leading vehicles; receive their heading angles via the acoustic communication network; adjust their speeds and headings to reach a desired formation pattern

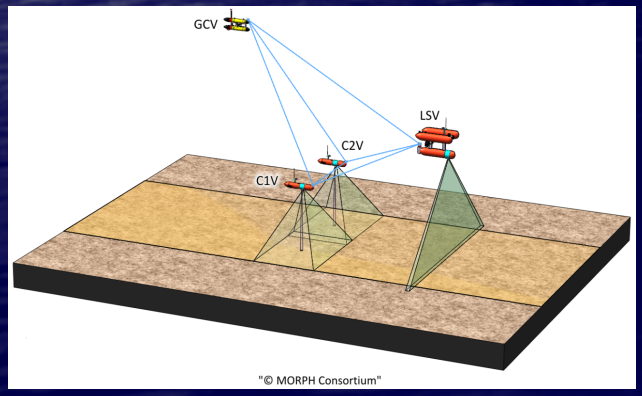
Vehicle Resources

Resources available at each vehicle

- Depth controller
- Heading controller
- Speed controller
- Acoustic ranging to surface vehicles (FVs)
- Acoustic comms to receive headings from leader vehicles (FVs)

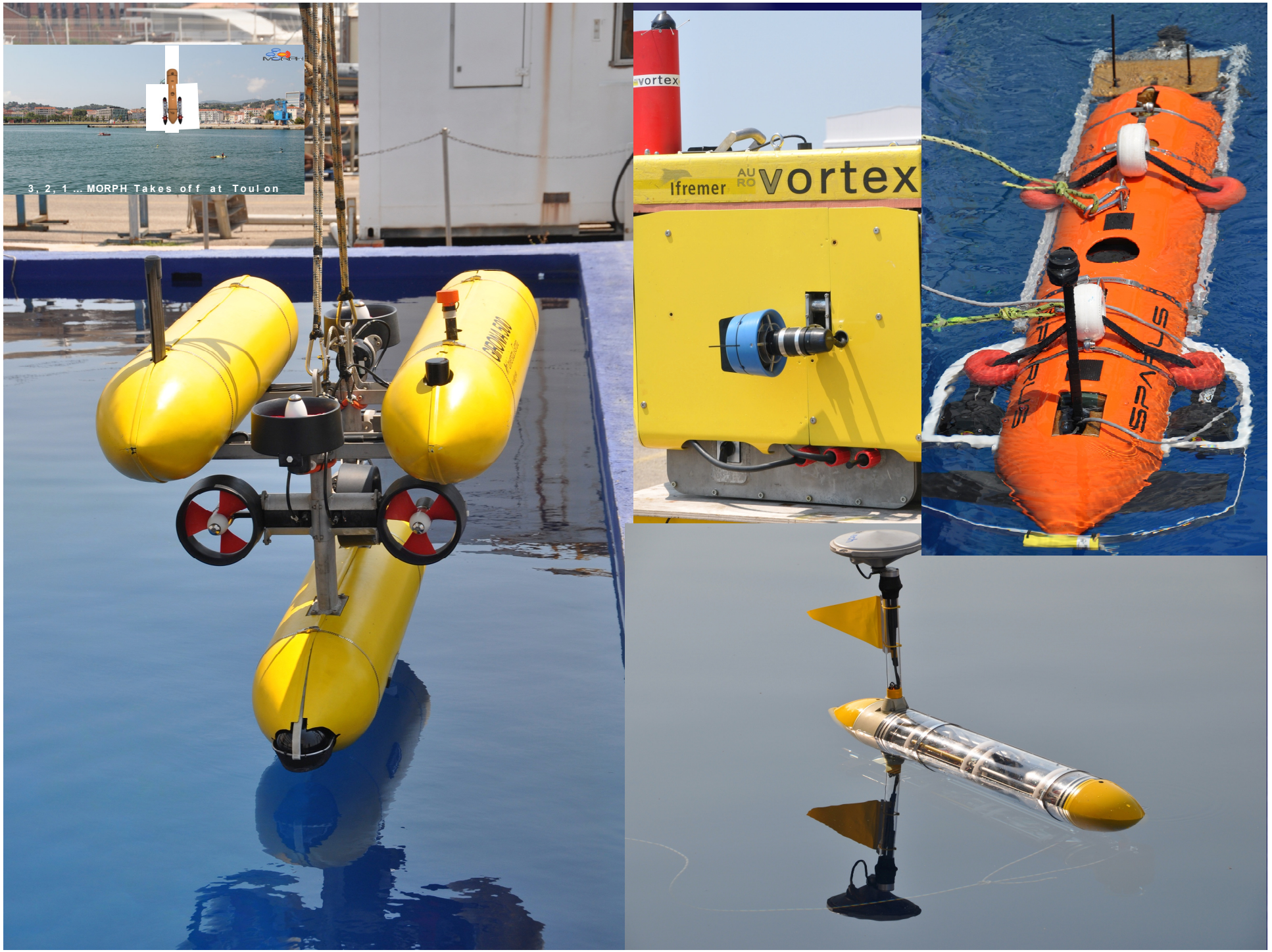



MORPH PROJECT – ROF with 2 ASVs and 2 AUVS

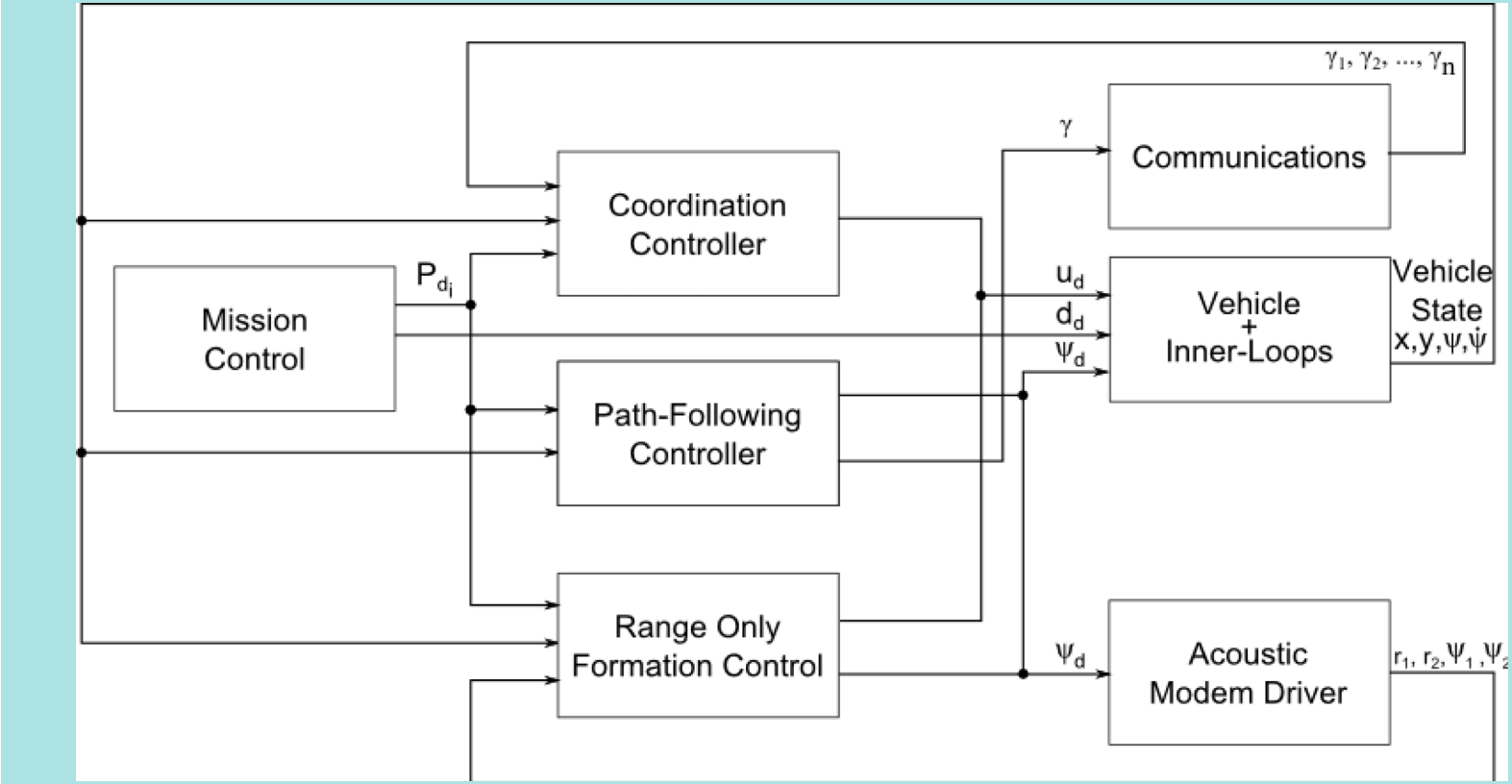


Toulon, France
July 2013


Toulon, France
July 2013
MORPH
3, 2, 1 … MORPH Takes off at Toulon


3, 2, 1 ... MORPH Takes off at Toulon
vortex
Ifremer
AUR
vortex

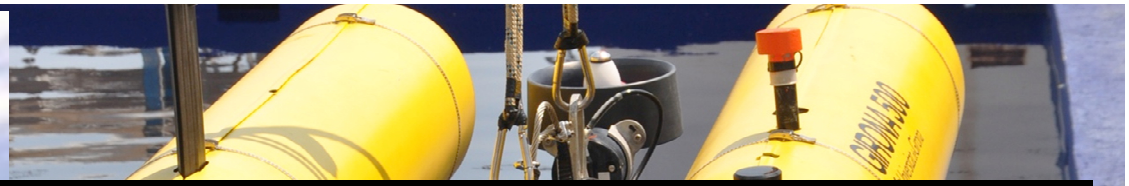
Toulon, France
July 2013

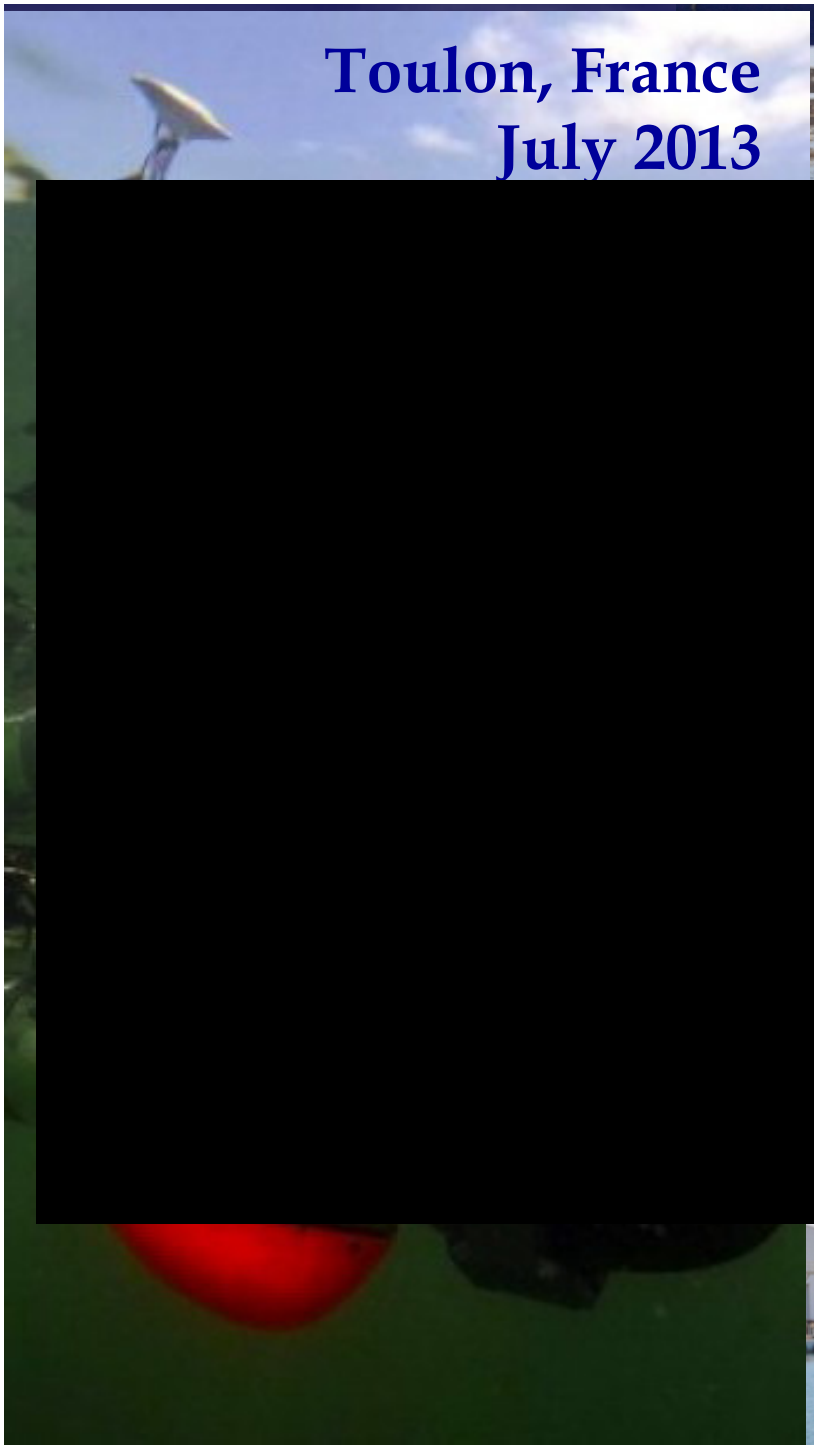


Toulon, France
July 2013

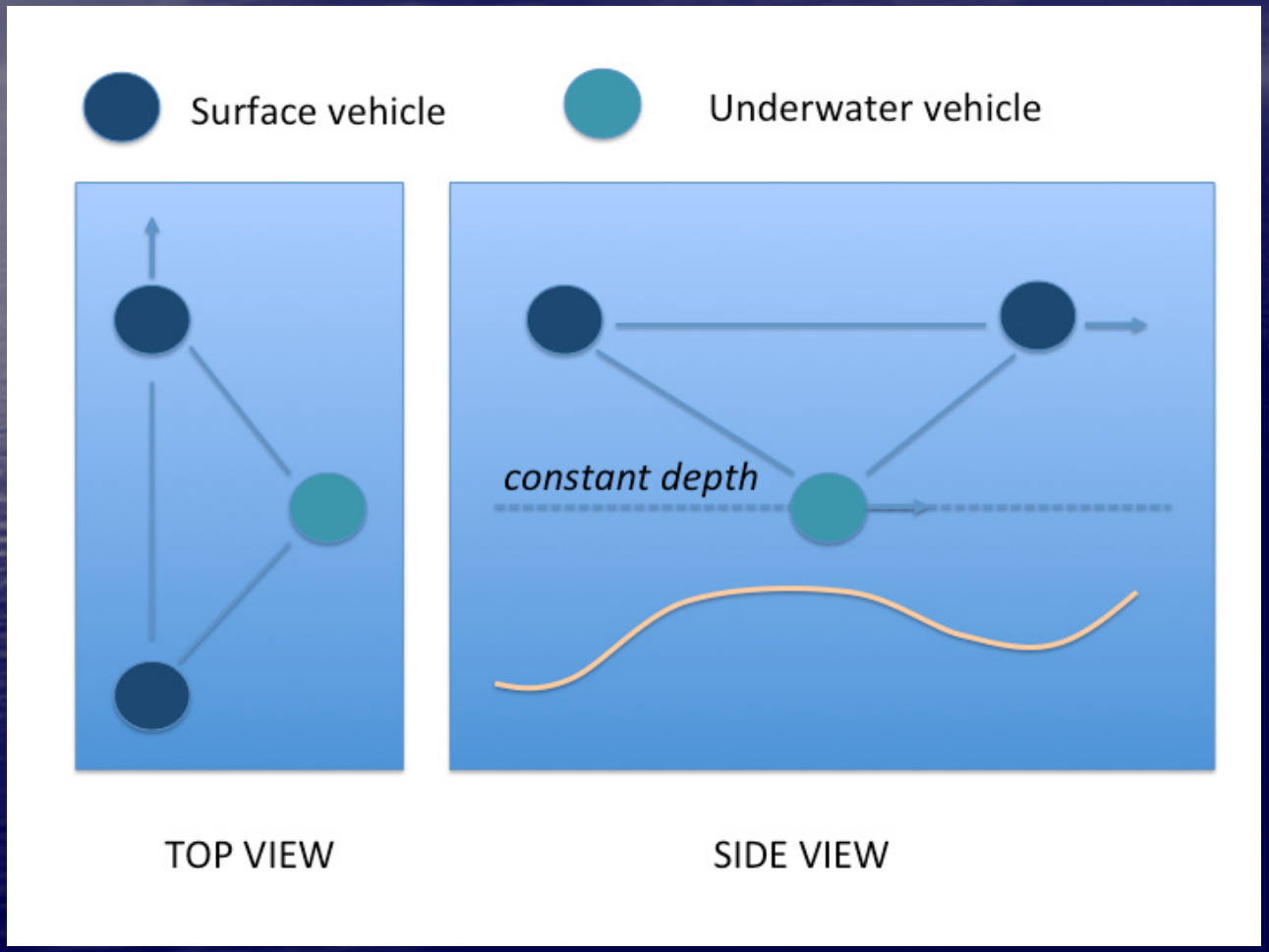
3, 2, 1 ... MORPH Takes off at Toulon

Toulon, France
July 2013





Towards Terrain Compliant Variable-Geometry ROF Control

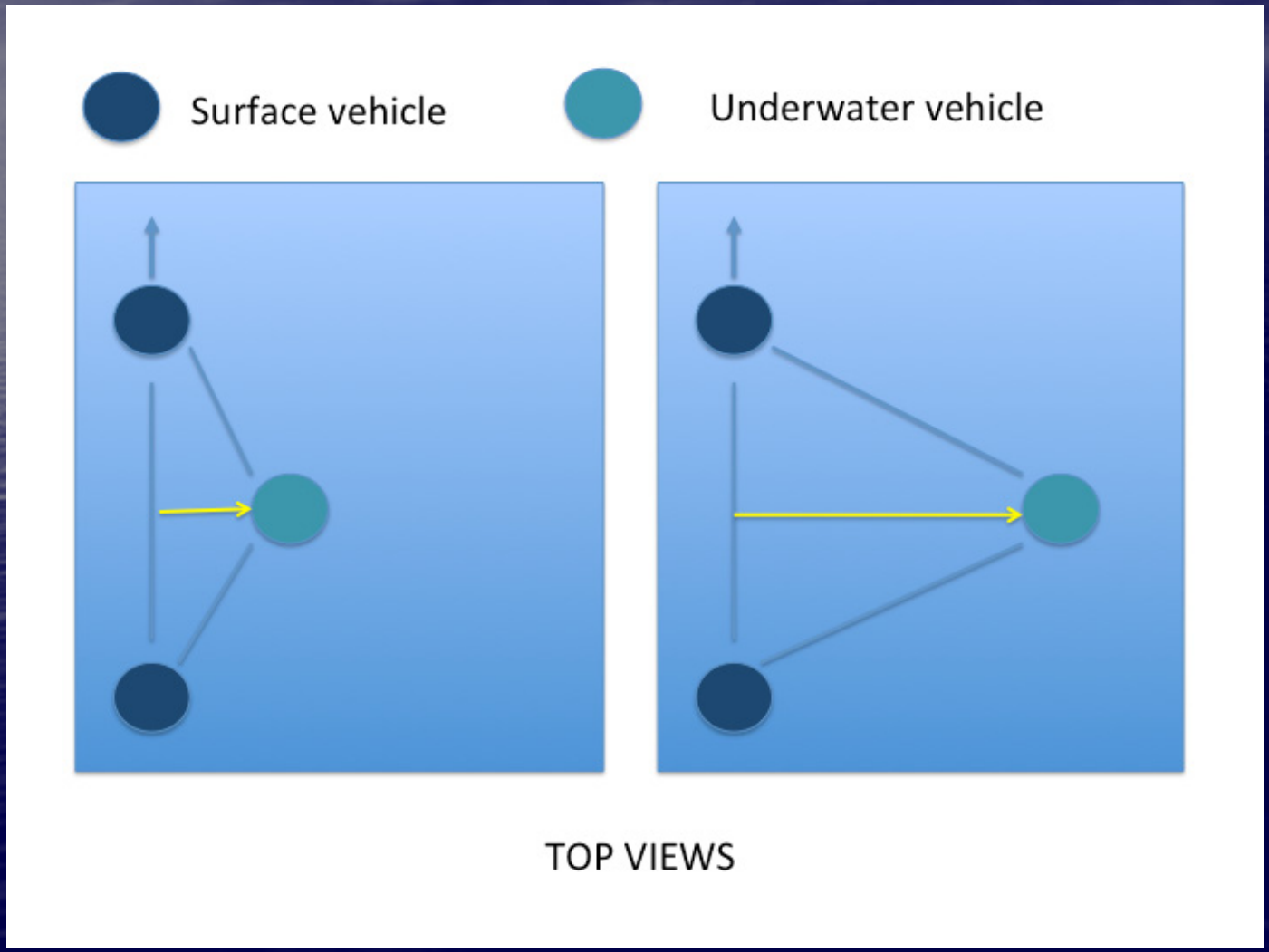


ROF only

Demo in March 2014, Lisbon

MORPH

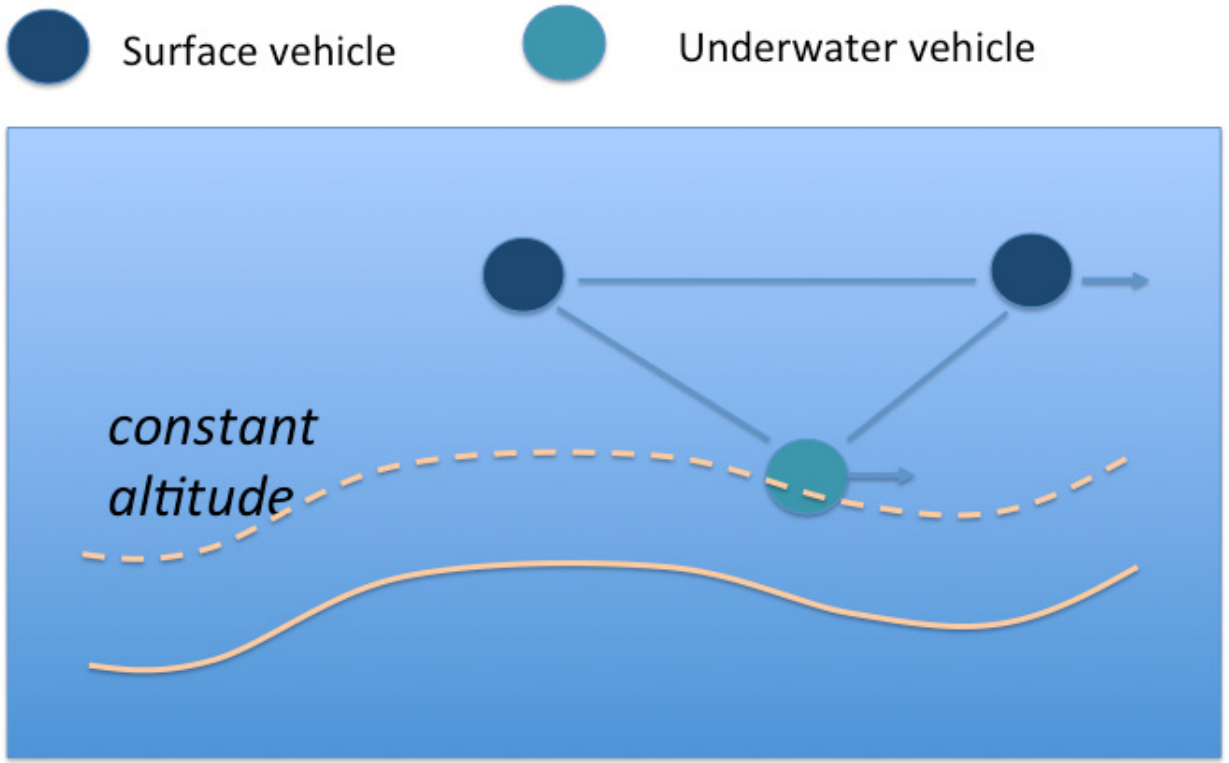
Towards Terrain Compliant Variable-Geometry ROF Control



Variable Geometry ROF

MORPH

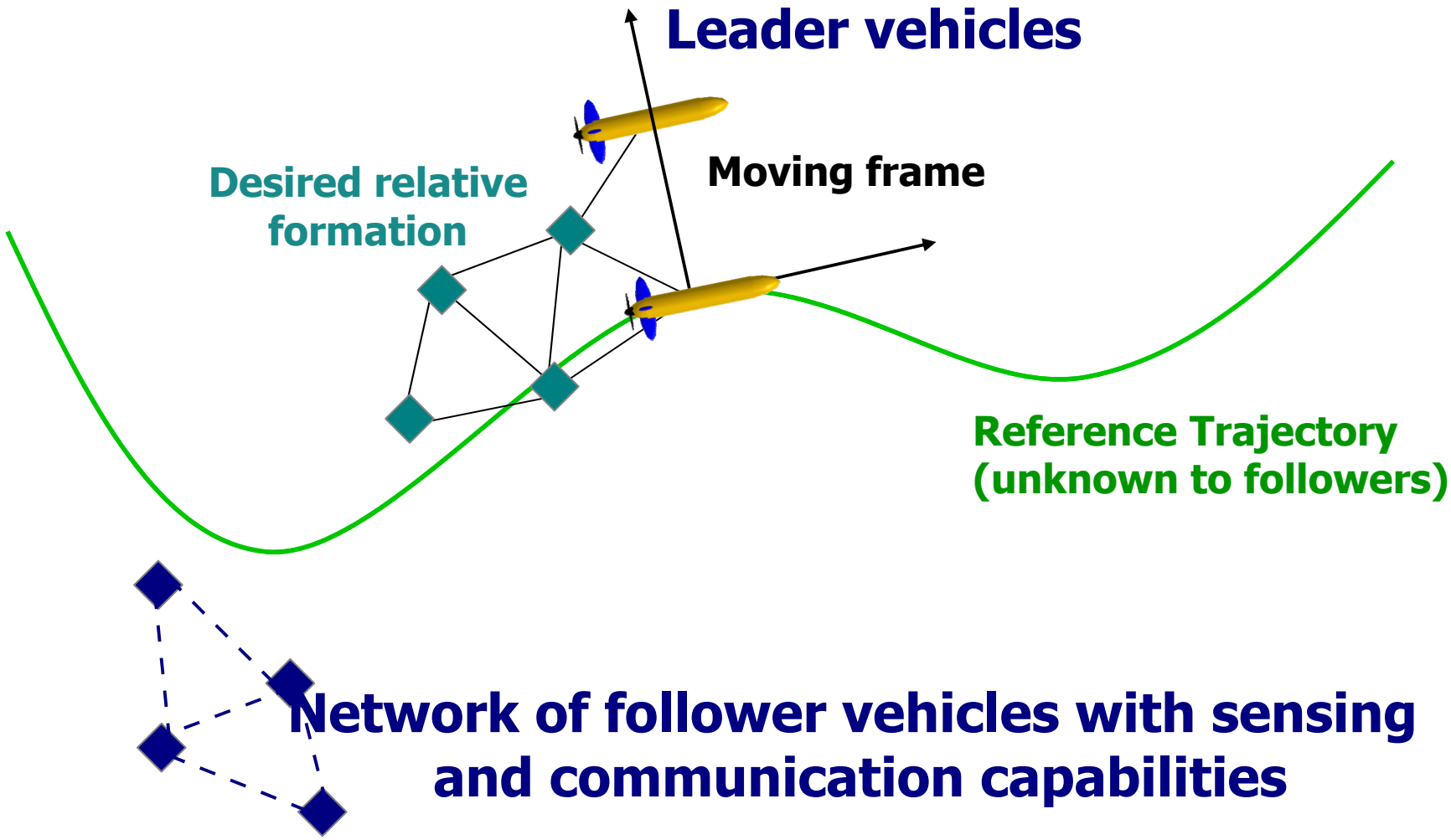
Towards Terrain Compliant Variable-Geometry ROF Control



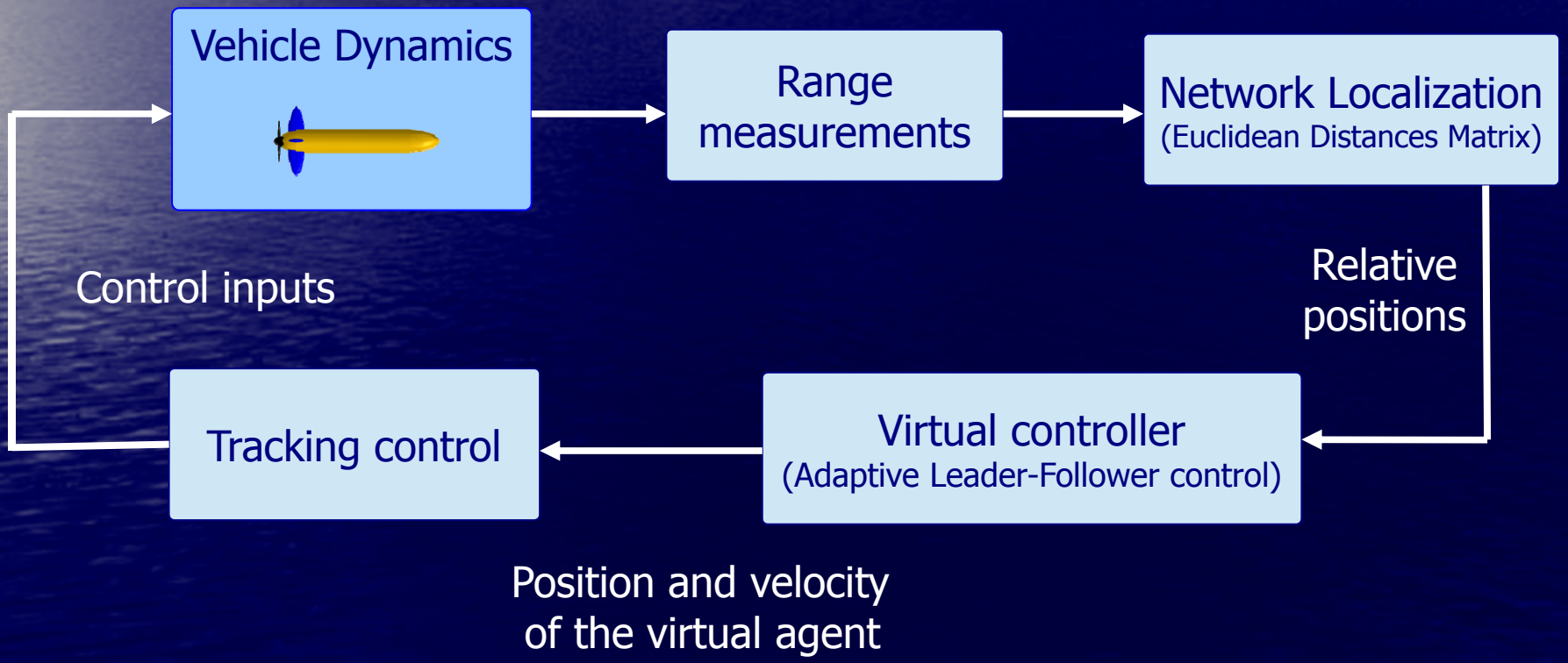
Compliant Control

MORPH

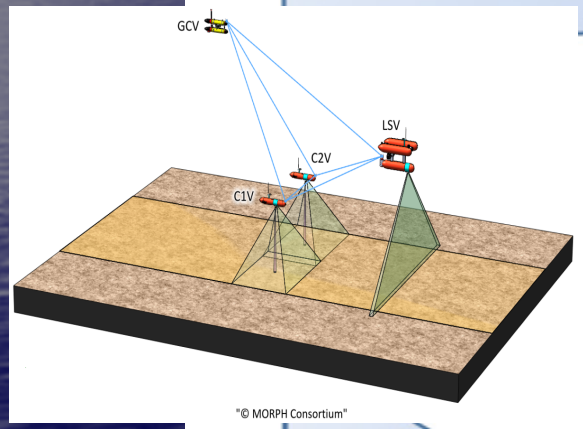
Range-Only Formation : the BIG picture



Control Strategy

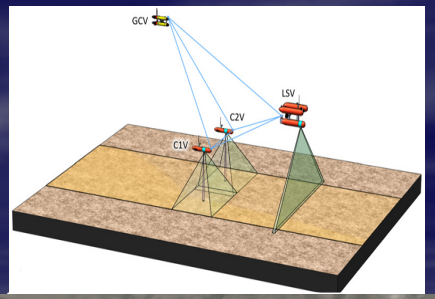


The Lisbon Trials (June 2014) Upper Morph Segment

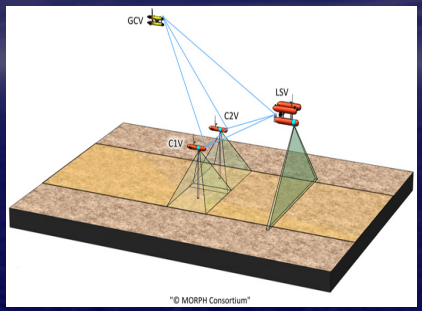


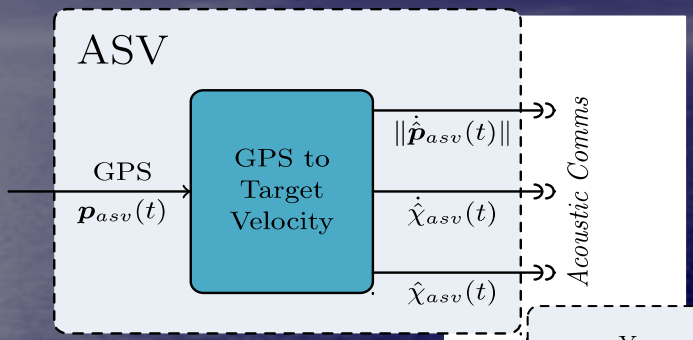
The Lisbon Trials (June 2014)

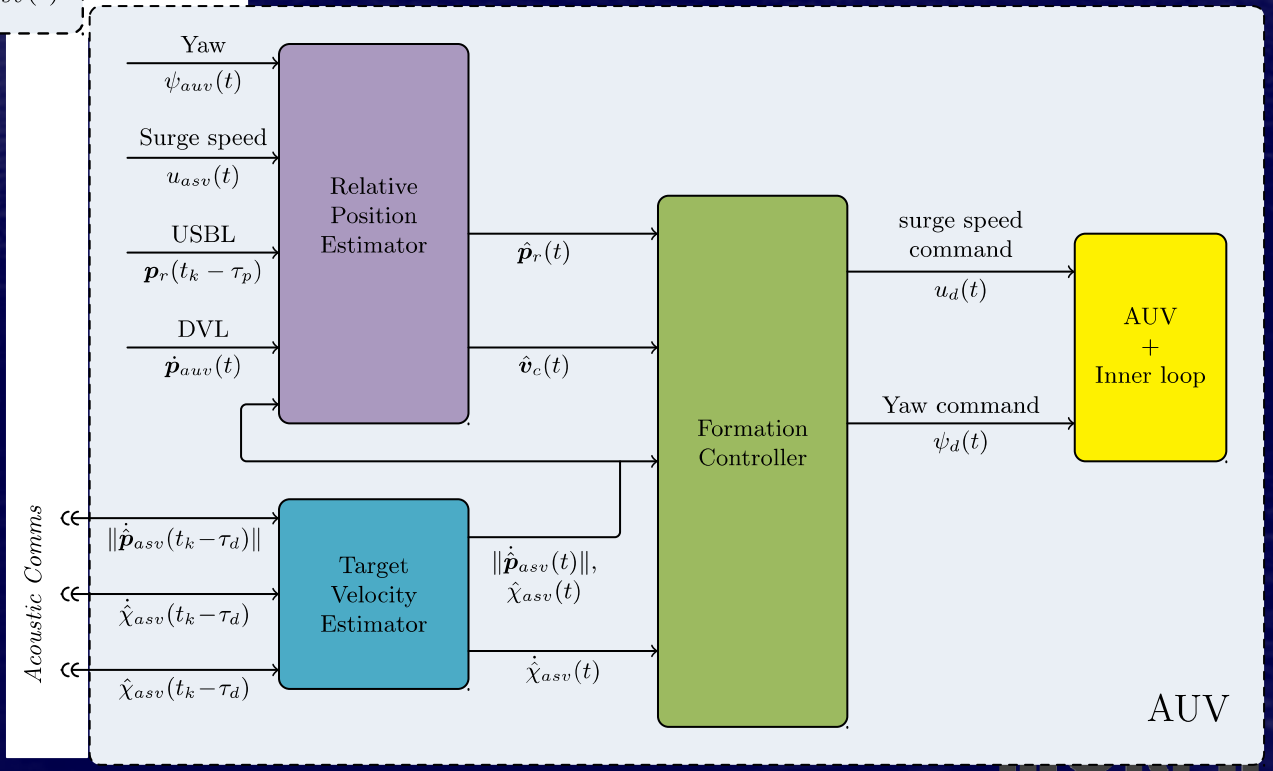
USBL / Modems - EVOLOGICS



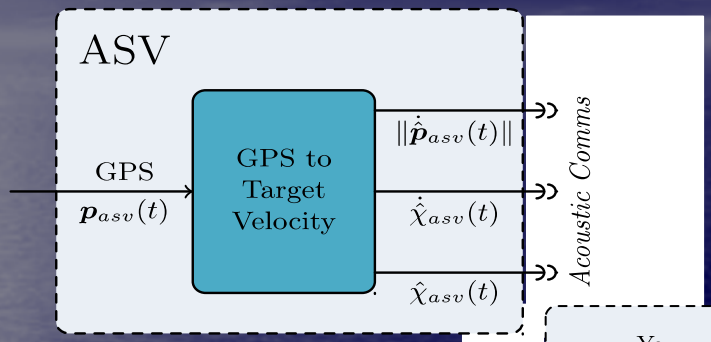
The Lisbon Trials (June 2014)
Upper Morph Segment

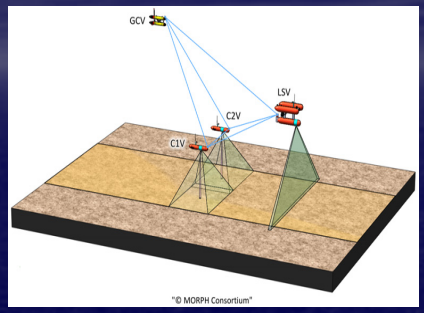


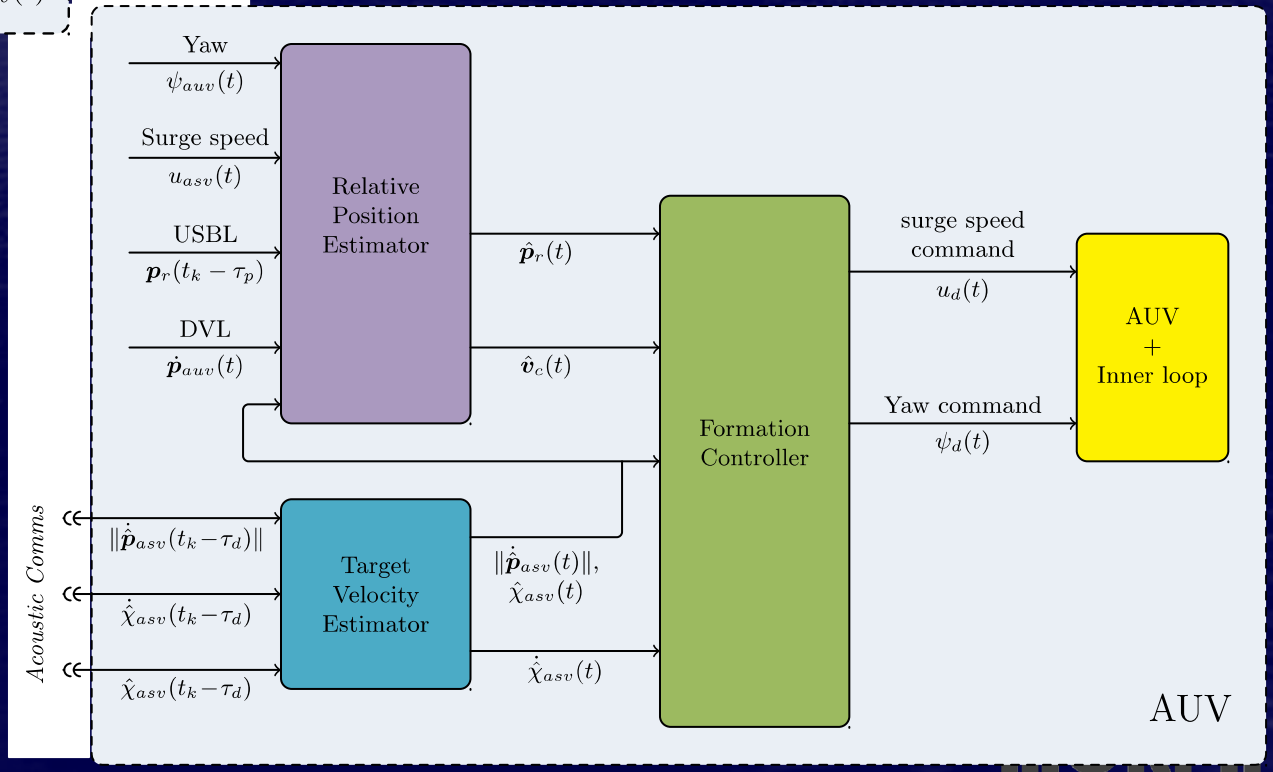


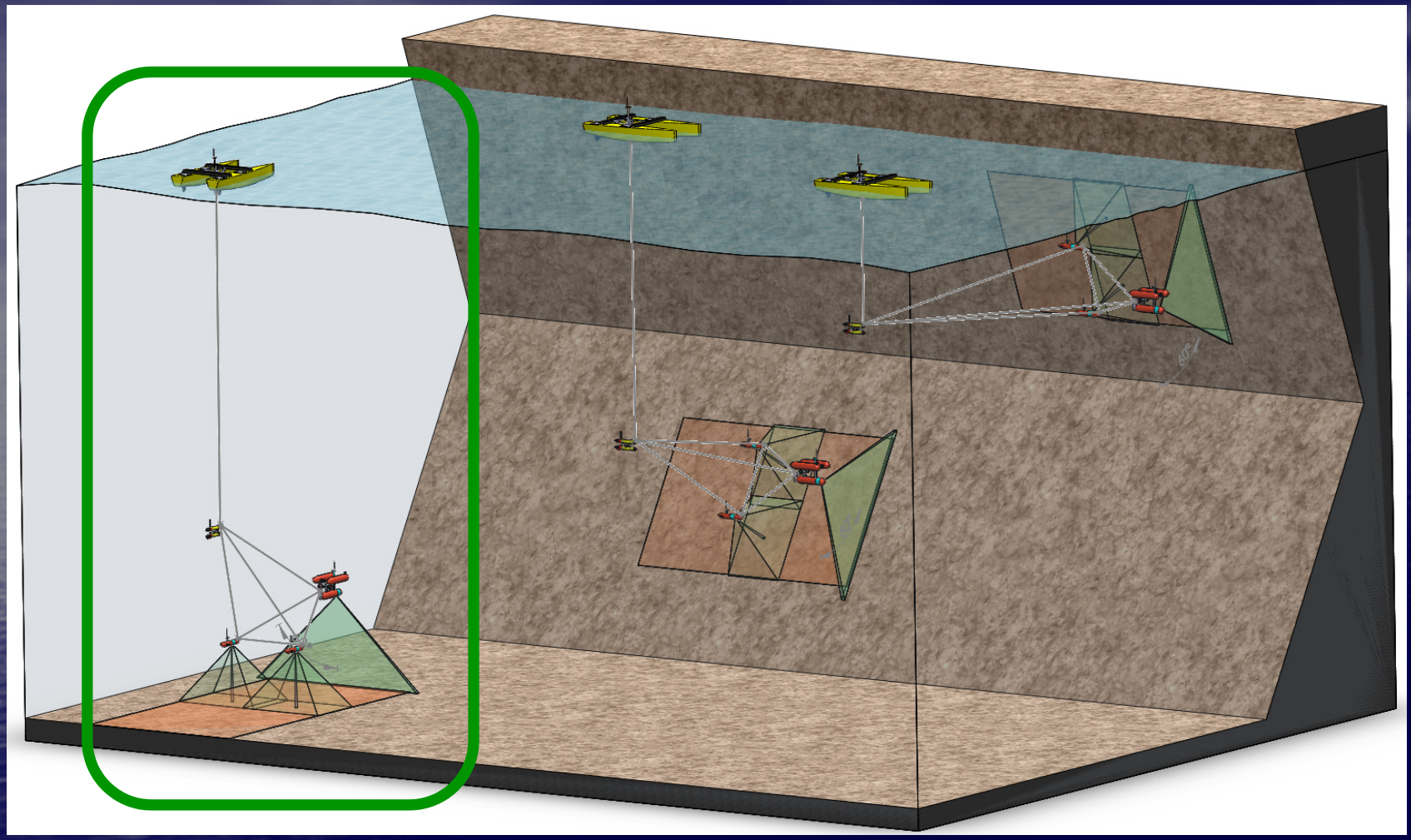


The Lisbon Trials (June 2014)
Upper Morph Segment





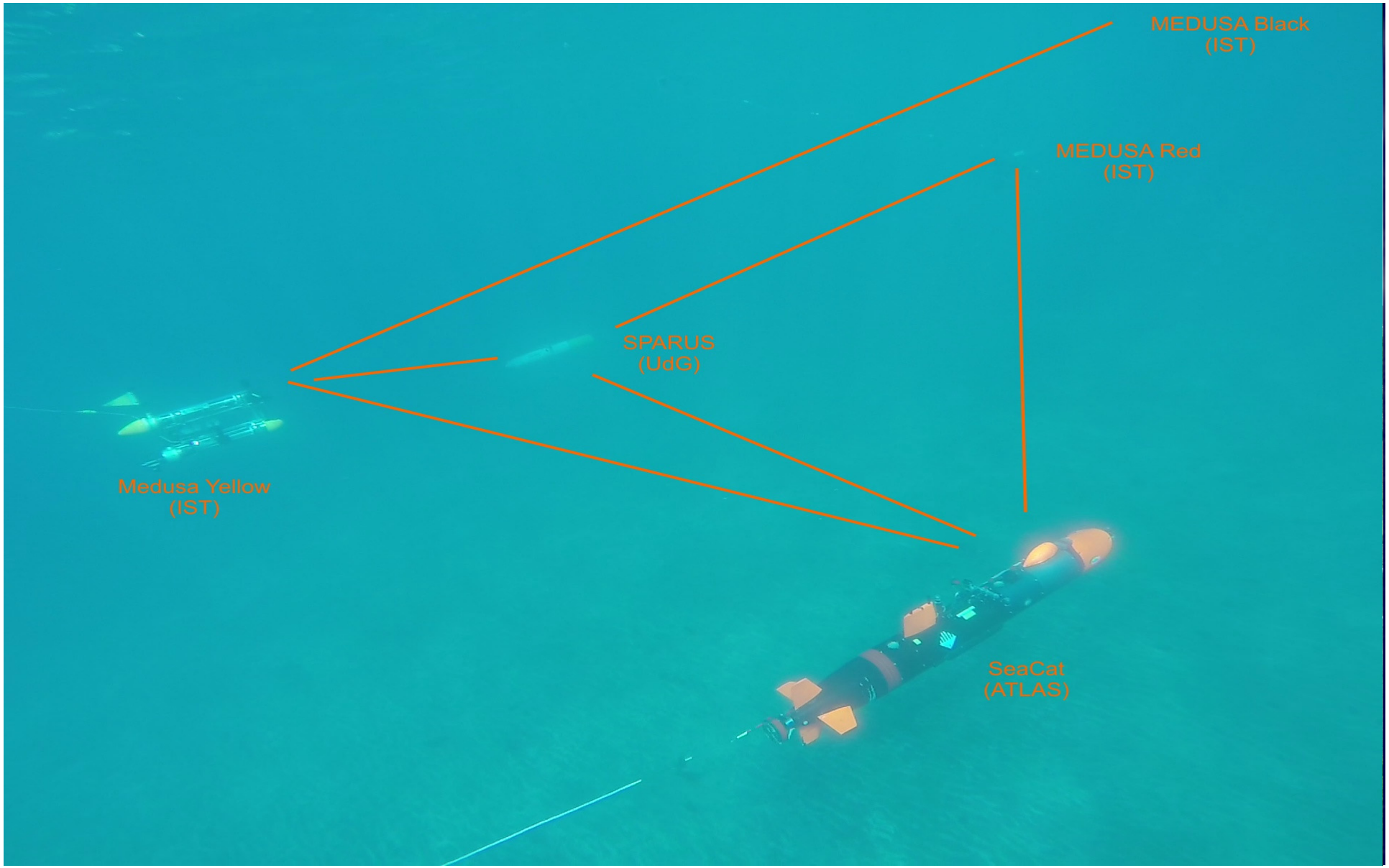




The FULL MORPH SEGMENT

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



Universitat de Girona

TÉCNICO LISBOA

JACOBS UNIVERSITY

TECHNISCHE UNIVERSITÄT ILMENAU

DOP

S&T organization CMRE

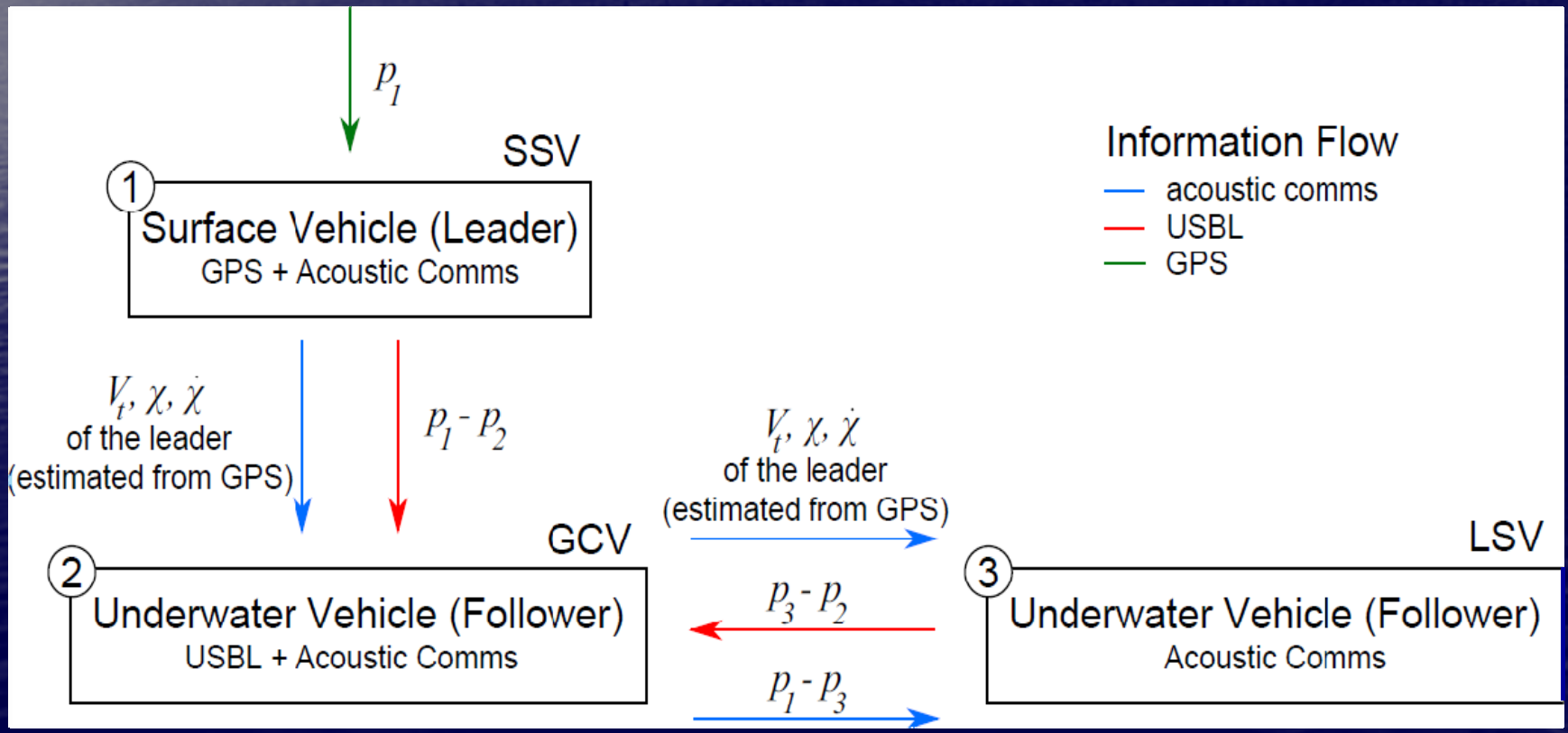
ATLAS ELEKTRONIK
A joint company of ThyssenKrupp and EADS

ifremer

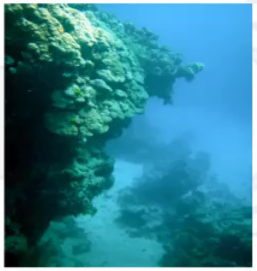
Consiglio Nazionale delle Ricerche

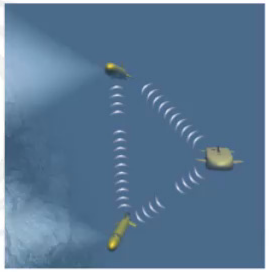
Information Flow

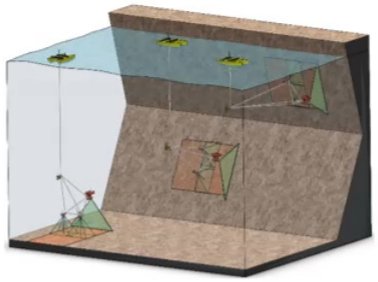
- Two followers, only one USBL, no communication link between SSV and LSV
- Use GCV to relay information to LSV



MORPH







Marine robotics system of self-organizing logically linked physical nodes

Azores trials 2014

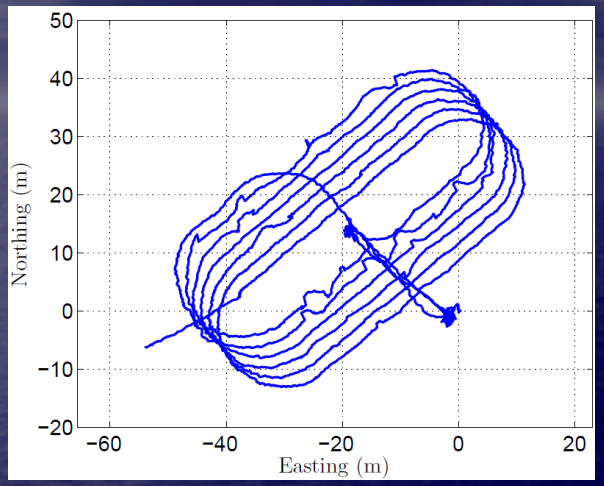
Universitat de Girona

Work Package 5

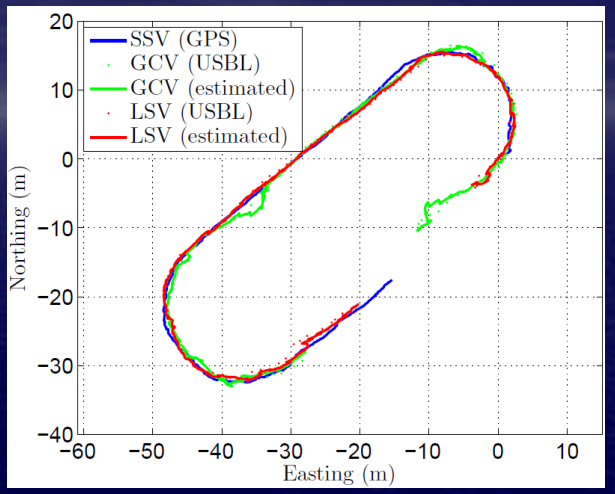
September 2014

LEADER TRACKING SYSTEM

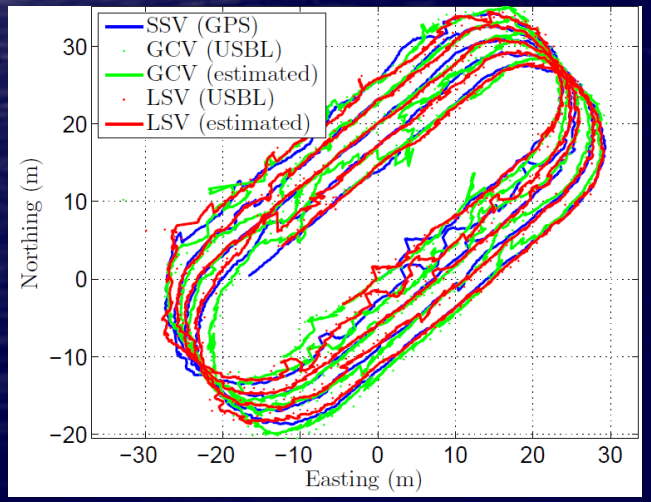
Results: Azores (1)



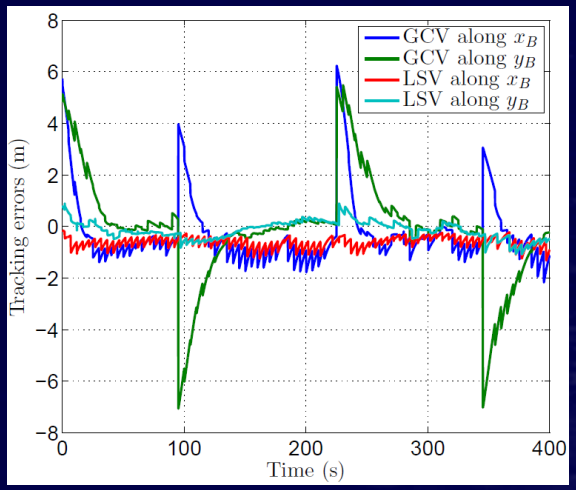
SSV Trajectory: Full mission



Upper segment trajectories: one loop

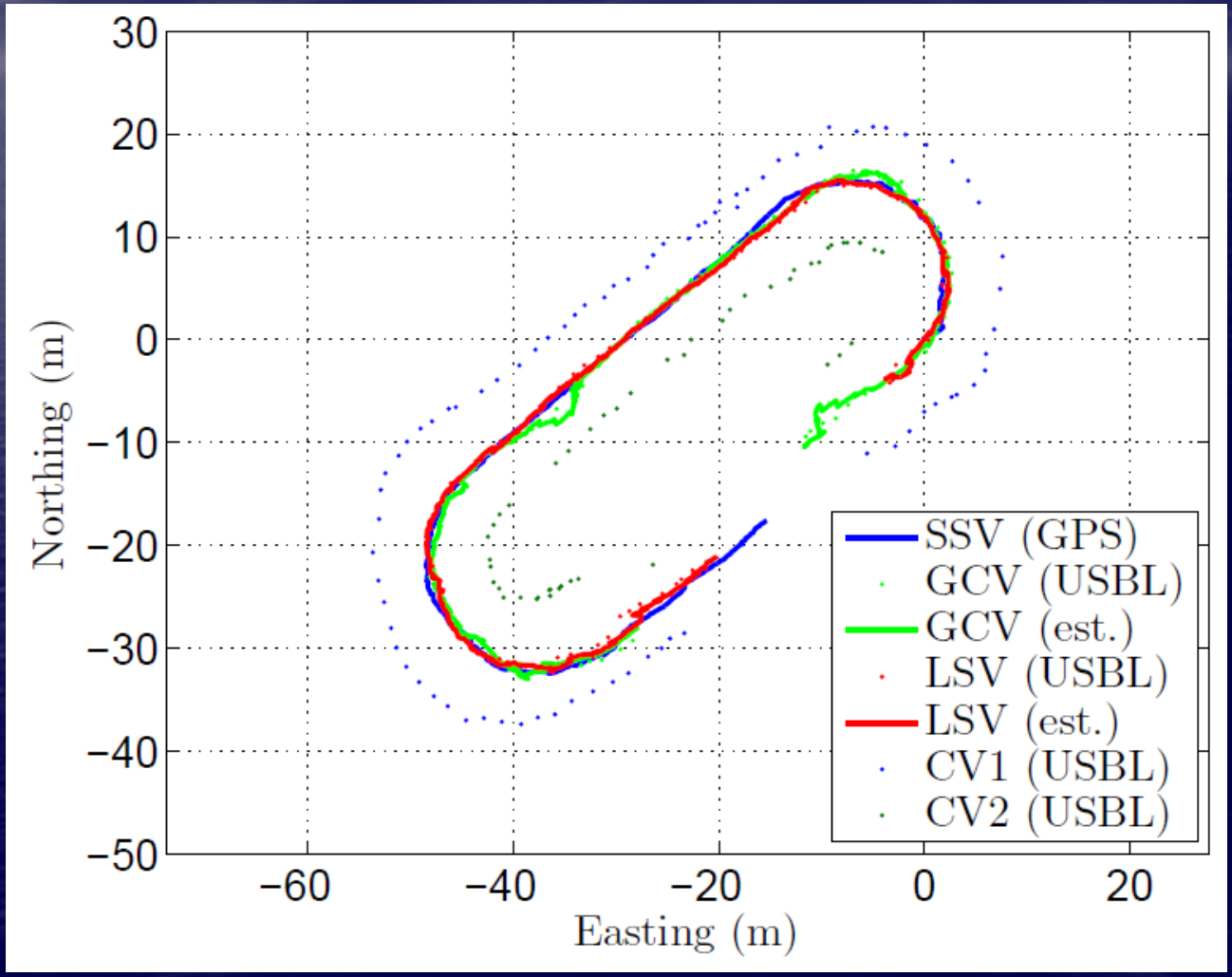


Upper segment trajectories: Full mission



Upper segment errors: one

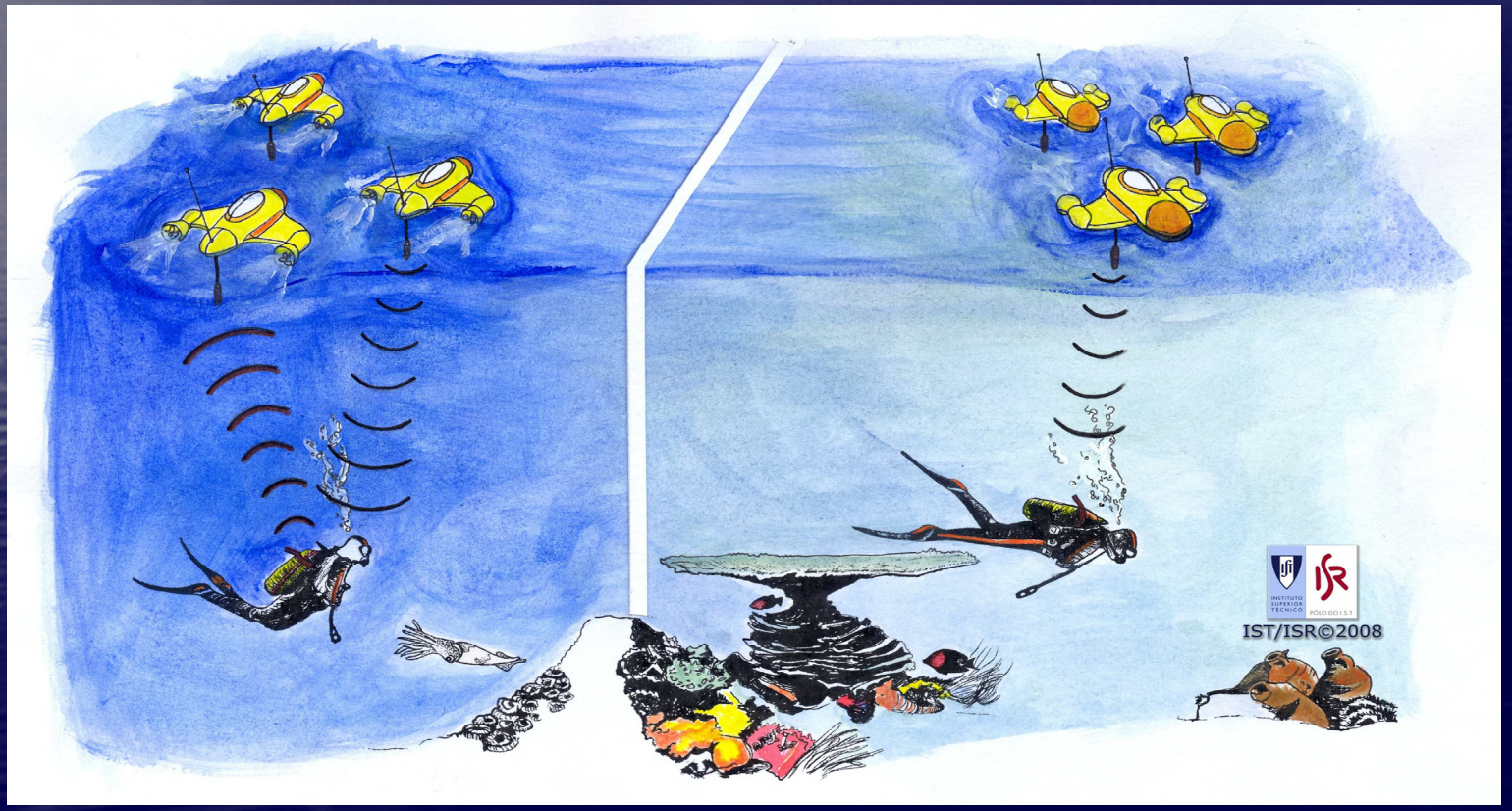
Results: Azores (2)



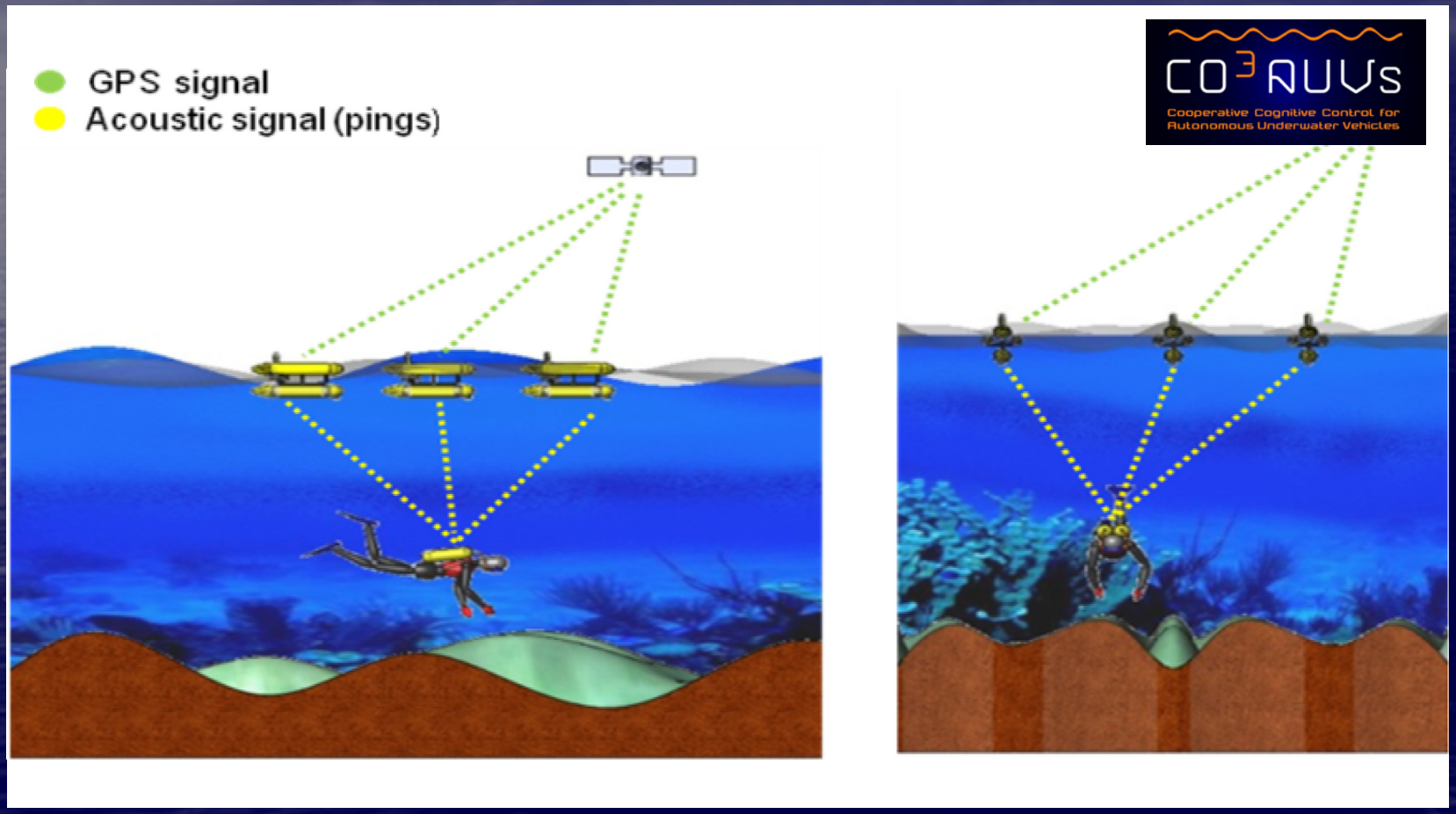
Upper and lower segment trajectories: one loop

“Leaning against the wall”

Robots and Humans in the Loop



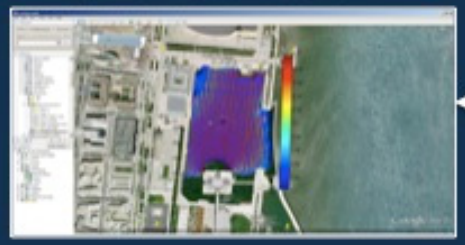
Visions of the Future (robots and humans in the loop)



CO3AUVs
Cooperative Cognitive Control for Autonomous Underwater Vehicles

Mission programming and visualization

Mission Control Segment



Wi-Fi Network

Cooperative control and diver tracking (GPS and acoustic ranges)

Autonomous Marine Vehicles Segment

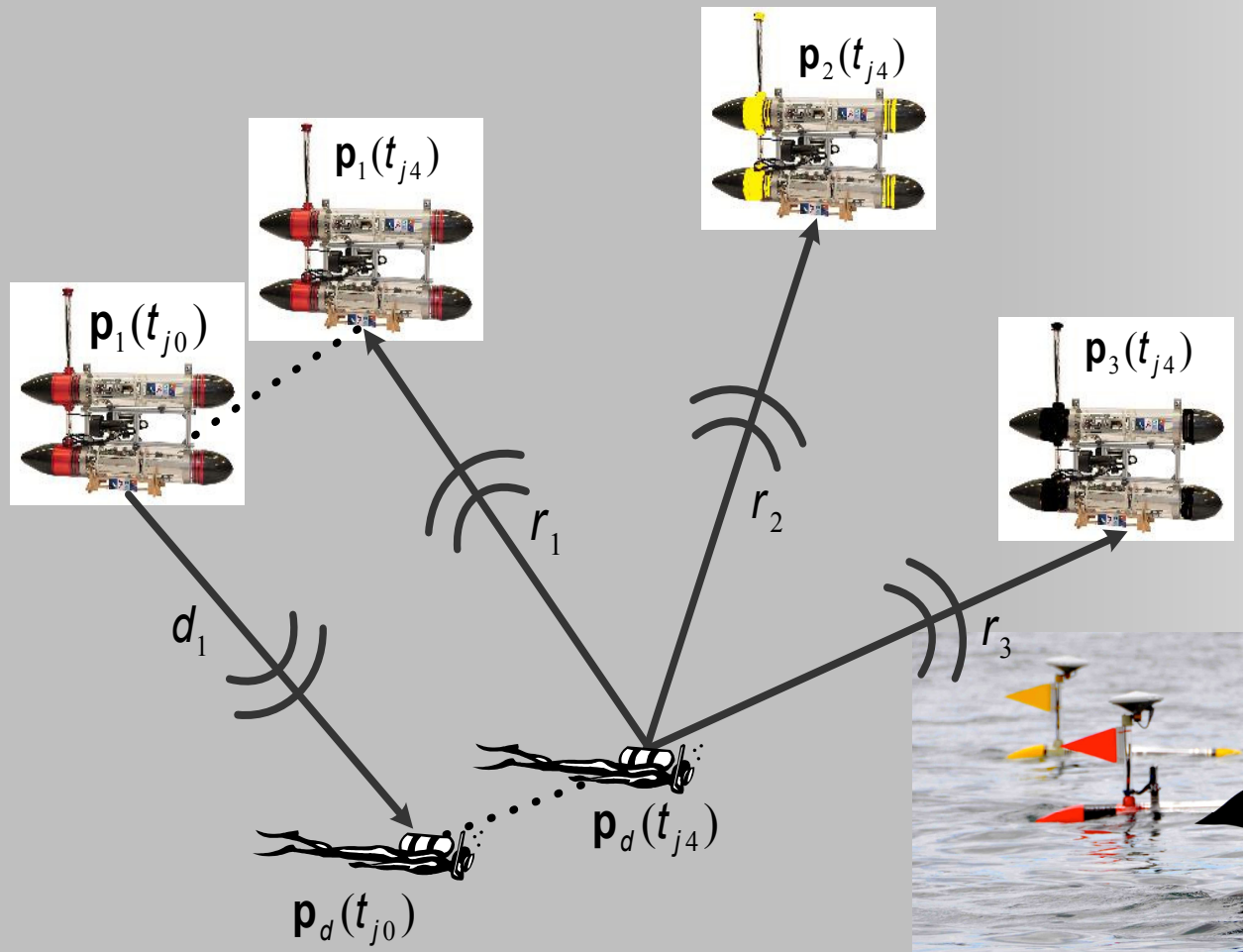
Acoustic Network

Diver guidance

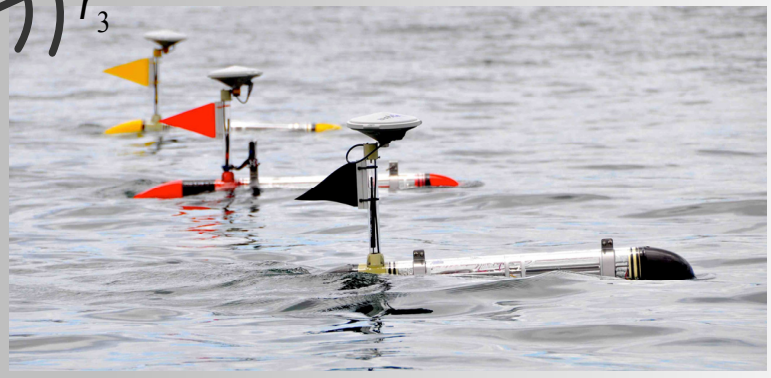
Diver Segment

Diver Assistance Unit (DAU)

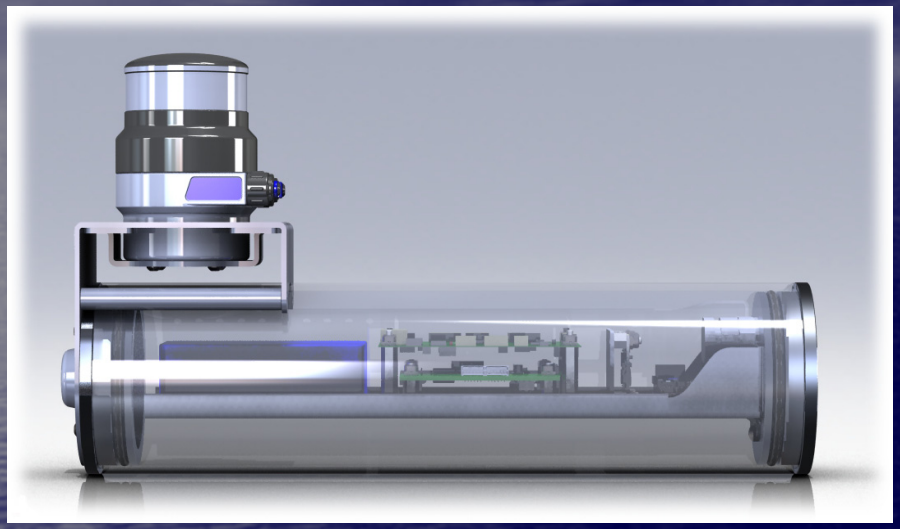
Key components: Diver Tracking System

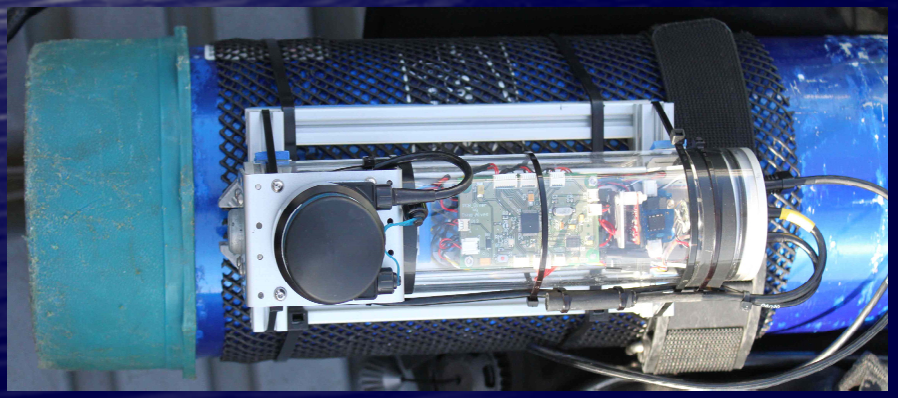


Tracking based on GPS and range data



Key components: the Diver Assistance Unit (DAU)



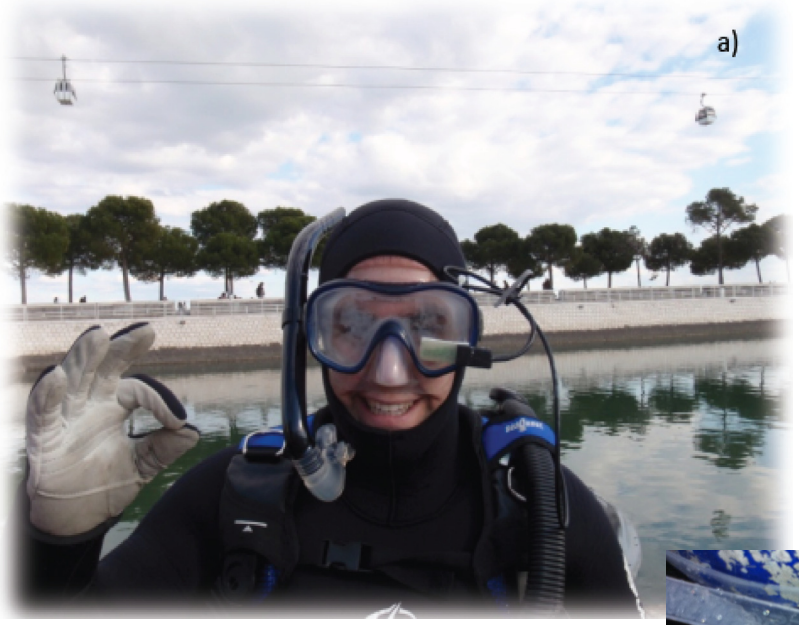


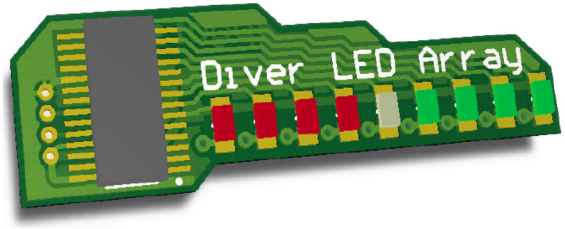
Goggles with LED array for diver guidance

Microprocessor and Attitude Unit

Acoustic modem and ranging device

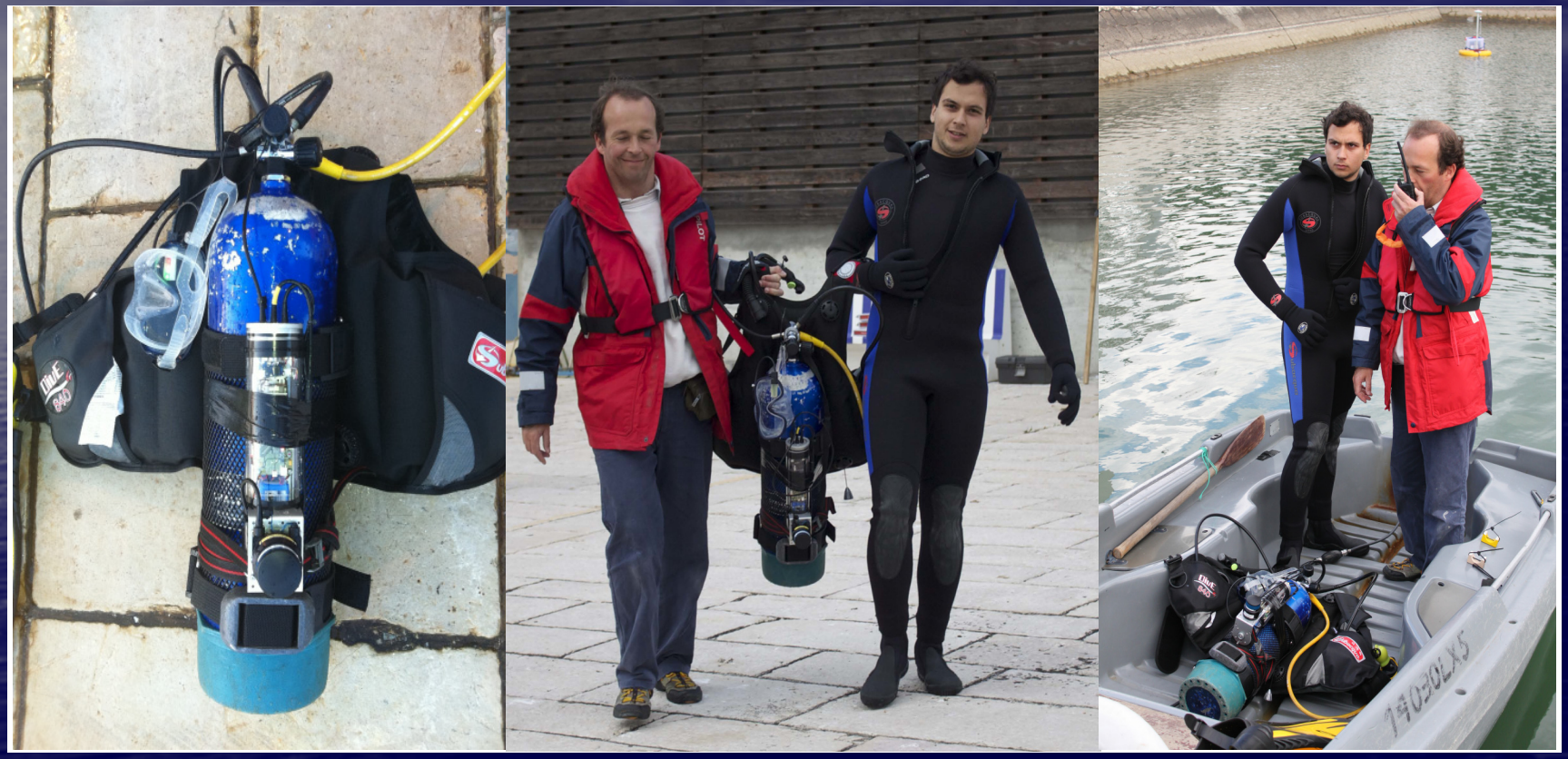
Key components: the Diver Assistance Unit (DAU)





Goggles with LED array for diver guidance

Robots/Diver operations

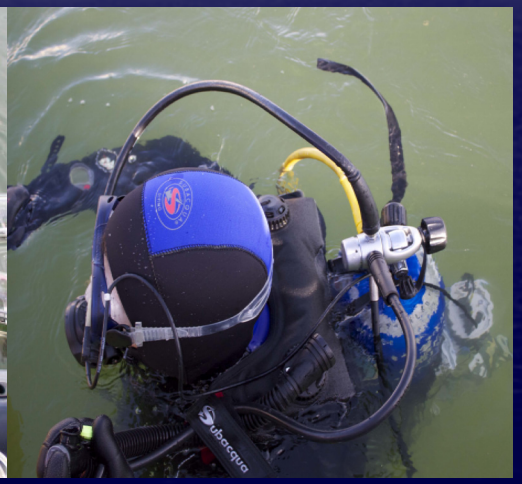


Phase 1. Diver preparation

Robots/Diver operations

Goggles with LED array

Checking the
acoustic comms network



Diver ready

Phase 2. Systems initialization

CO3 AUVs
Cooperative Cognitive Control for Autonomous Underwater Vehicles

Scenario | Vehicle | Variables | 39%

192.168.2.1 Server X = 8, Y = 124 Xj -1 Xk -1
Clear WPClear Point Zoom In Zoom Out WayPoint Yj -1 Yk -1

```
BAT_Cell5=3602.000000
BAT_Cell4=3572.000000
BAT_Cell3=3563.000000
BAT_Cell2=3536.000000
BAT_Cell1=3496.000000
BAT_Cell0=3483.000000
BAT_Current=1665.000000
MATLAB_Value4=0.694071
MATLAB_Value3=0.317212
MATLAB_Value2=0.352560
MATLAB_Value1=136.000000
Thrusters_OFF=0.000000
BAT_Cell6=3656.000000
Modem_Heading=83.000000
Modem_Depth=0.000000
Modem_Distance=10.269280
GPS_MODE=3.000000
LEAK2=0.000000
LEAK1=0.000000
```

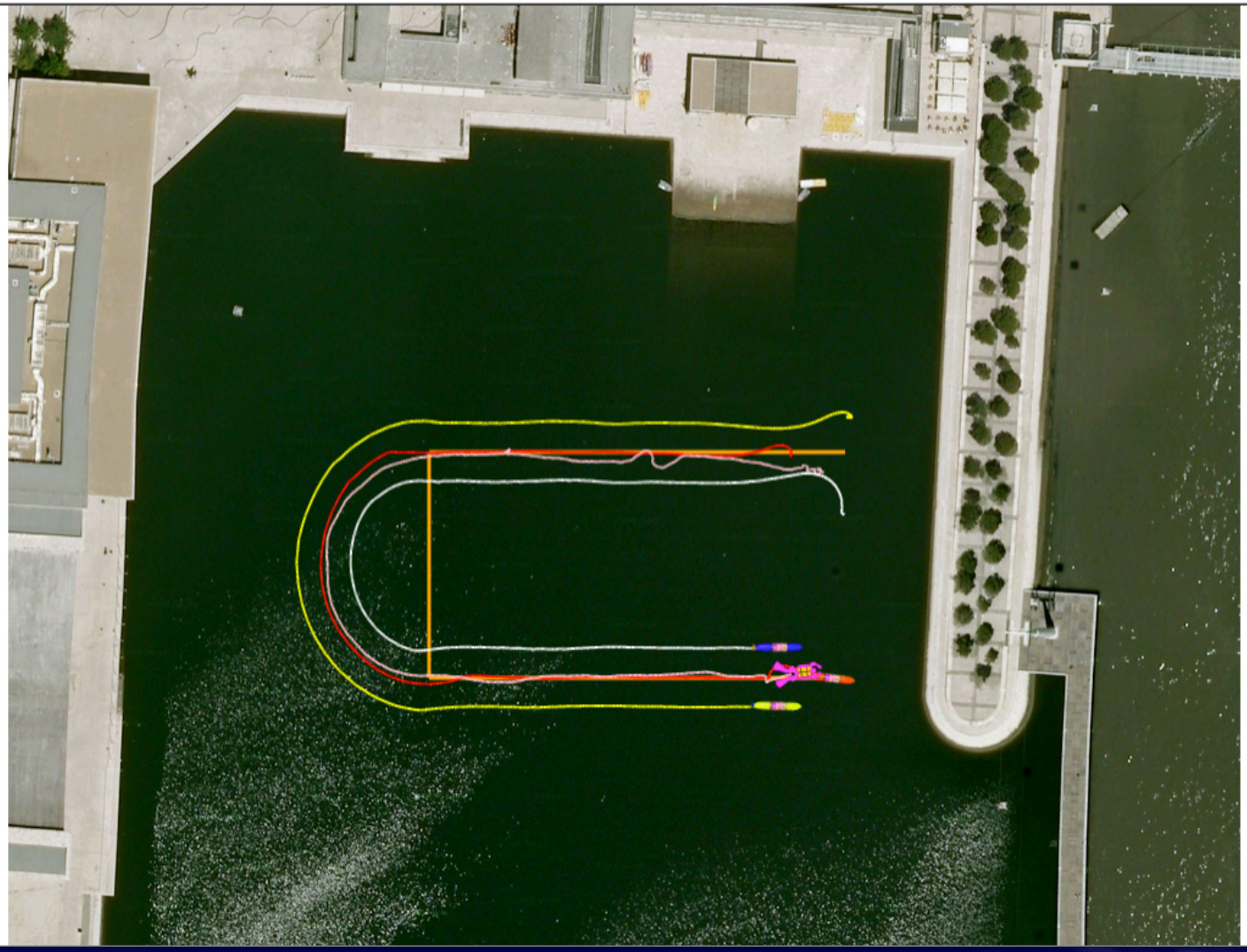
X Desire -1 HoldPos
Y Desire -1 Stop
RED BLACK YELLOW
DIVER

Upper Leak | Lower Leak | RTK FIXED

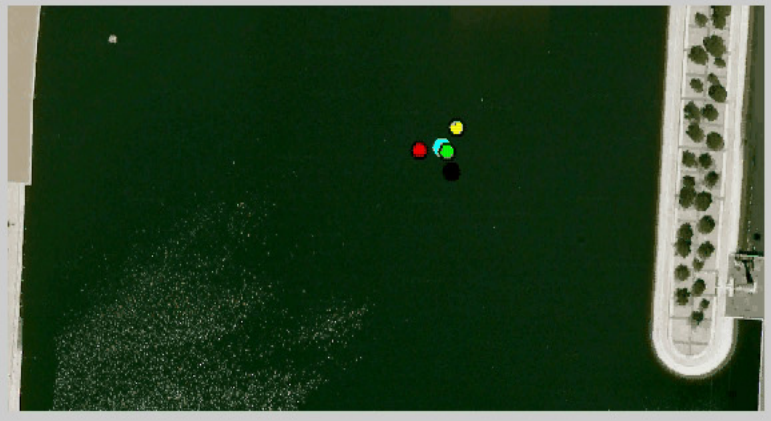
STOP VEHICLE!

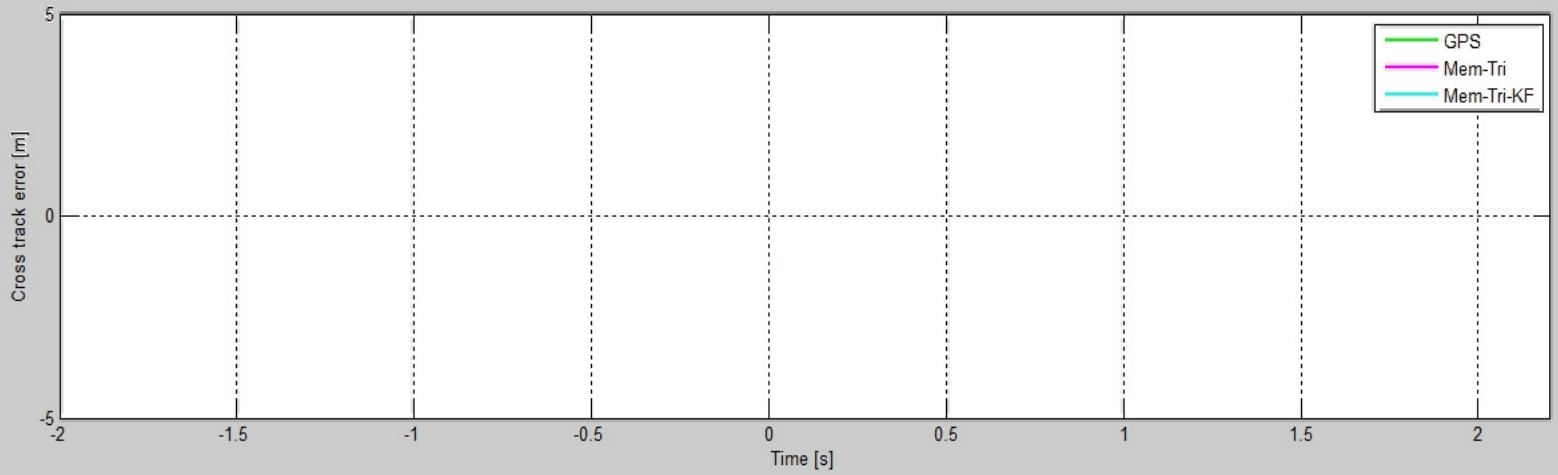
Click to Load Drop Mission

Draw Mission



Diver Assistance Mission 2 (Diver submerged)

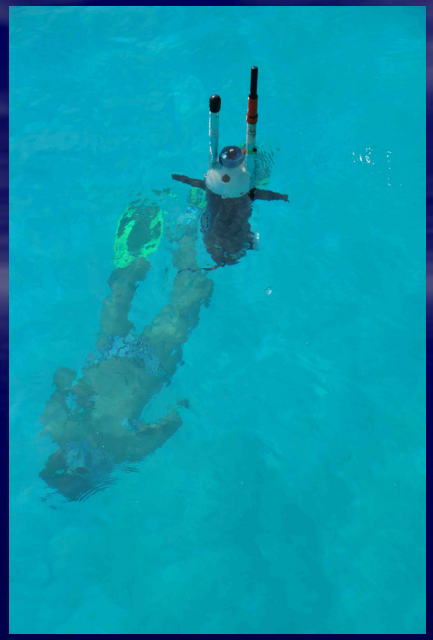




NIO

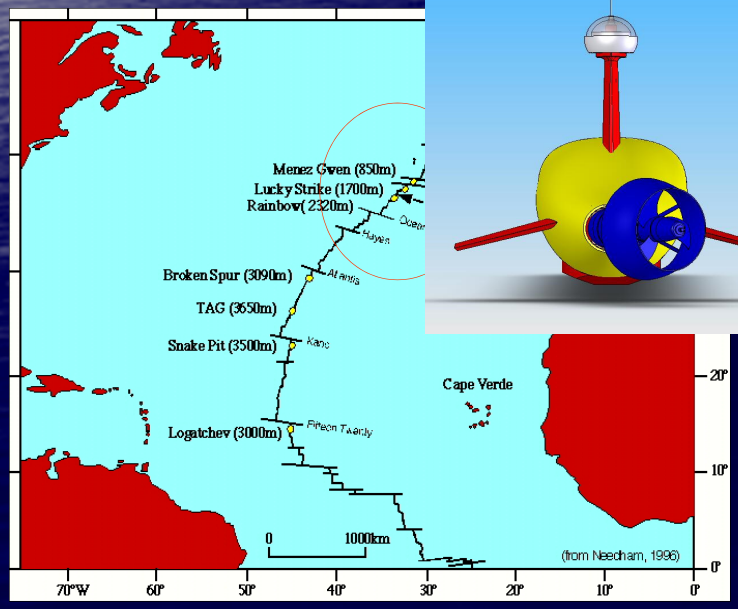
INSTITUTO SUPERIOR TÉCNICO

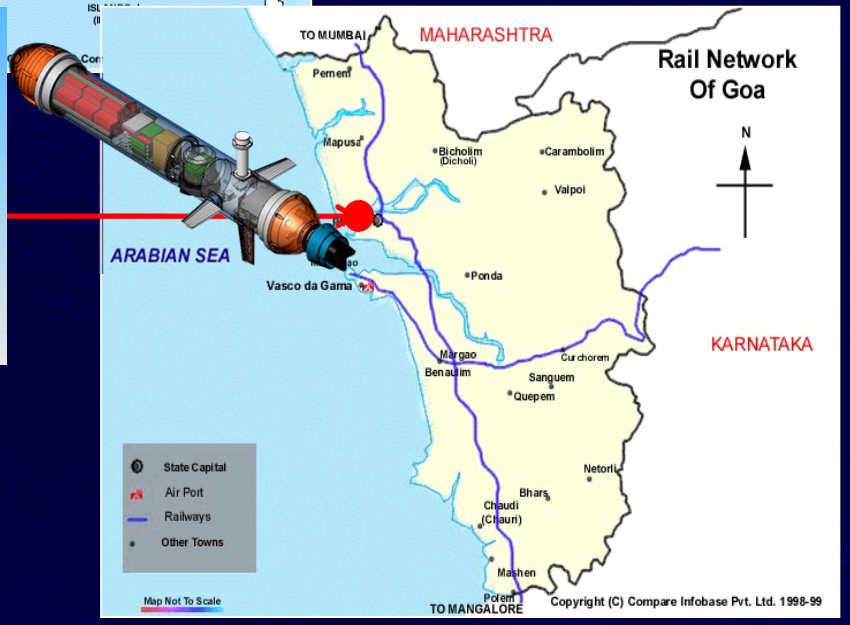
DSOR
dynamical systems and ocean robotics LAB



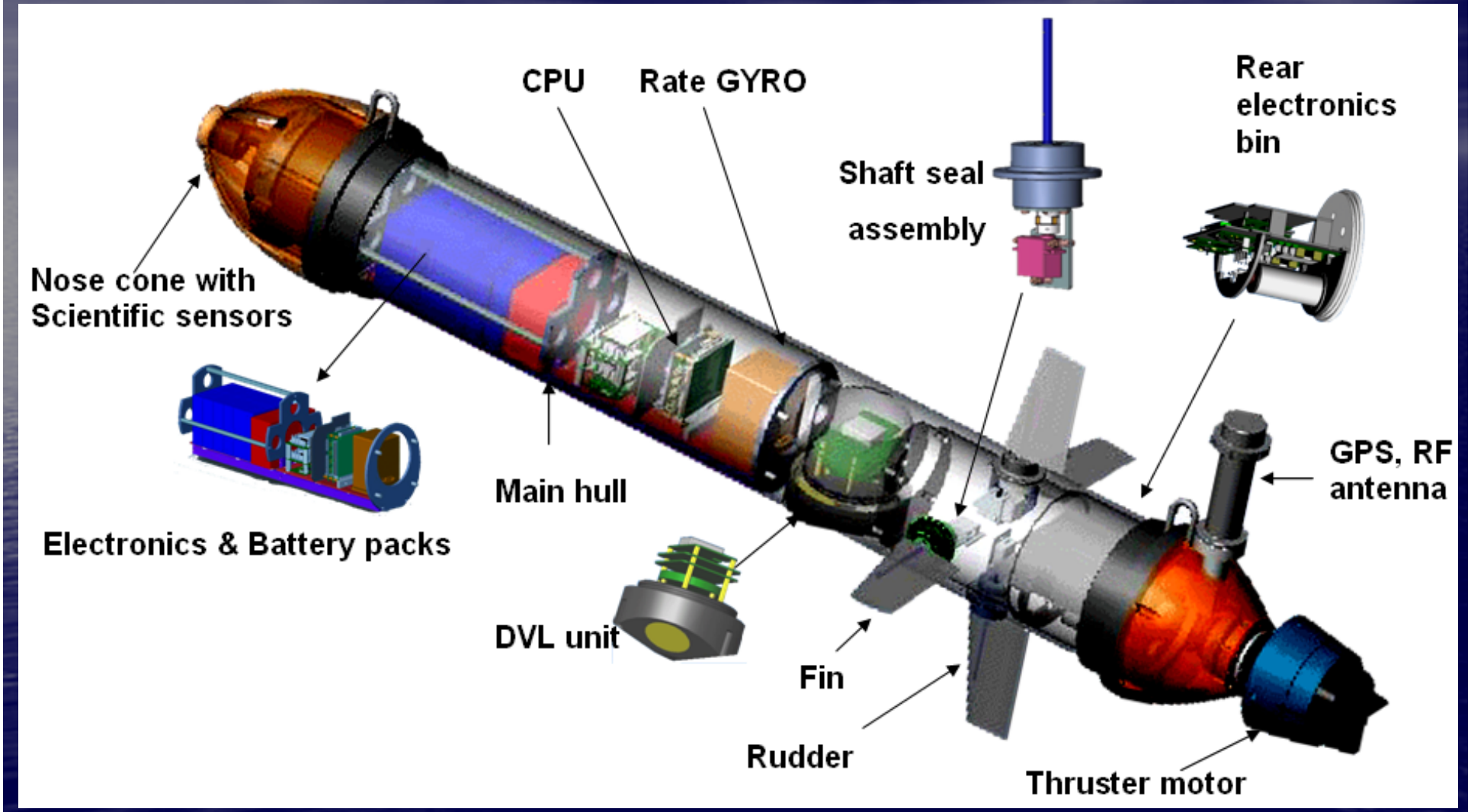
A New Step: India- Europe

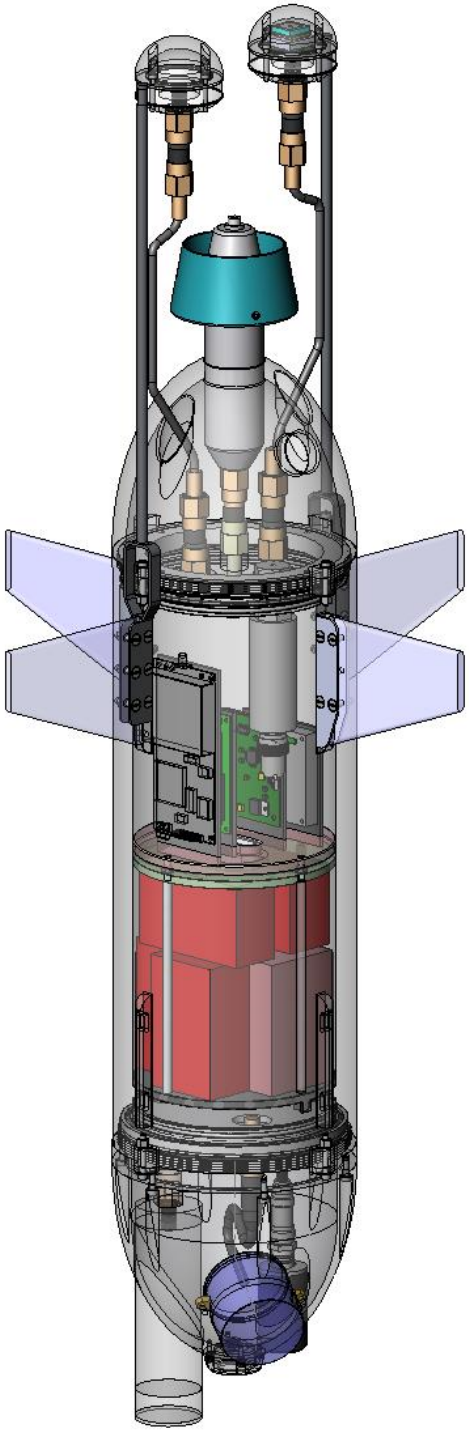
Meeting with Índia (1999)





Design of Maya





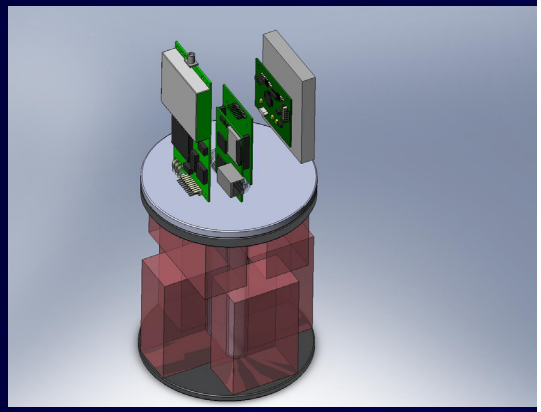
Autonomous Vertical Profiler (AVP)

Features:

- Delrin hull
- Weight: ~20 kg
- Length: 880 mm
- Dia: 180 mm
- Propulsion: 24V thruster
- Energy: Li Poly batteries
- sensor loaded nose
- +vely buoyant

sensor loaded nose

electronics, batteries

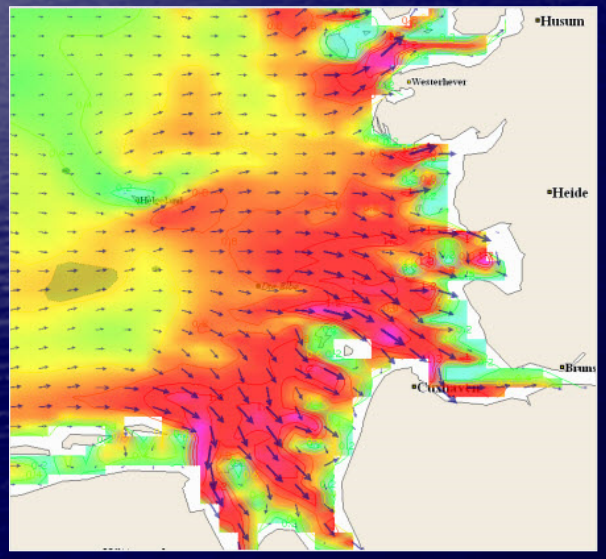


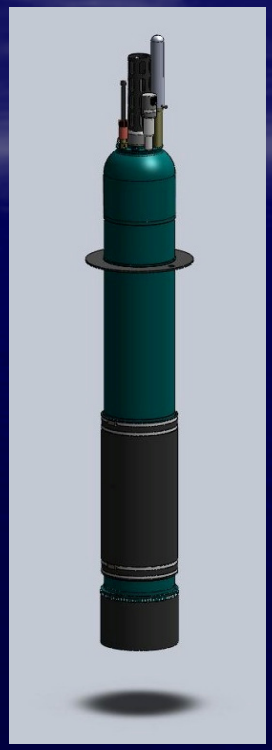
Jerome Jouffroy, MCI, jerome@mci.sdu.dk

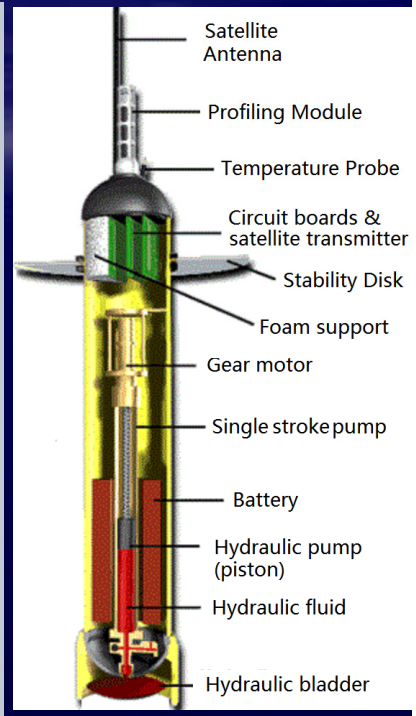
Selective Tidal-Stream Transport for Lagrangian profilers

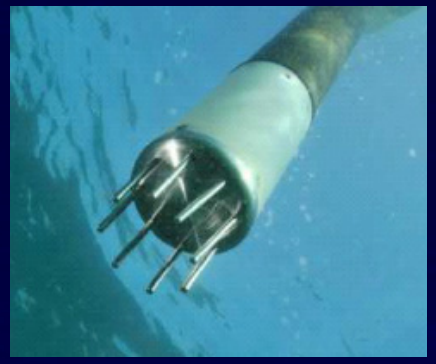
Lagrangian profiler/profiling float:

- Horizontally passive: follow ocean currents
- Used mostly in a deep water environment





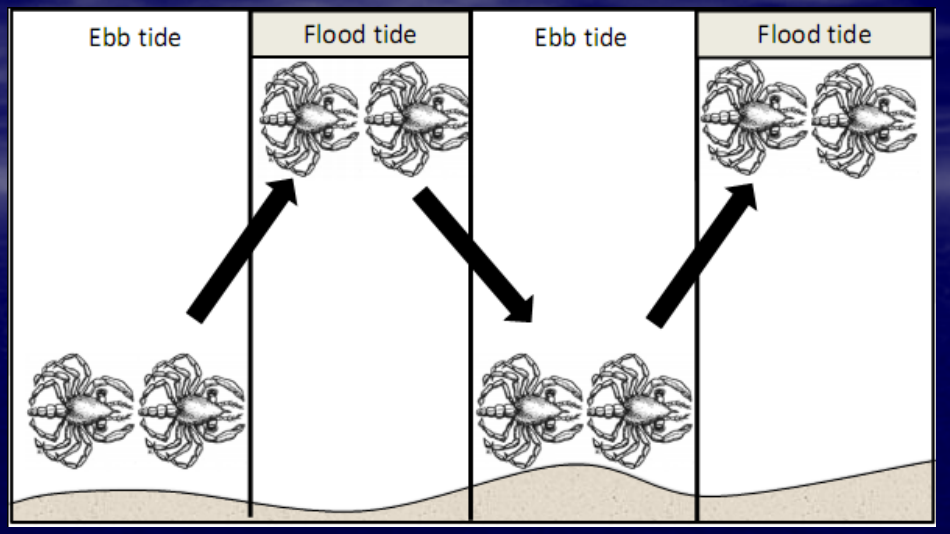


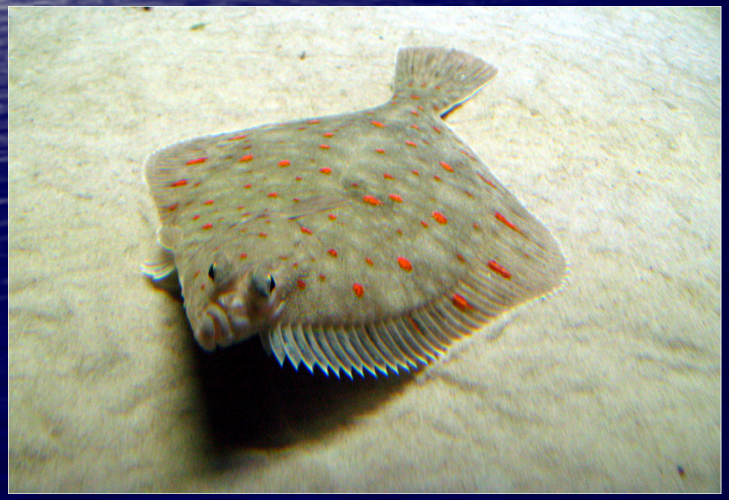


Can a profiler use
tidal currents actively?
(for recovery, re-deployment, …)

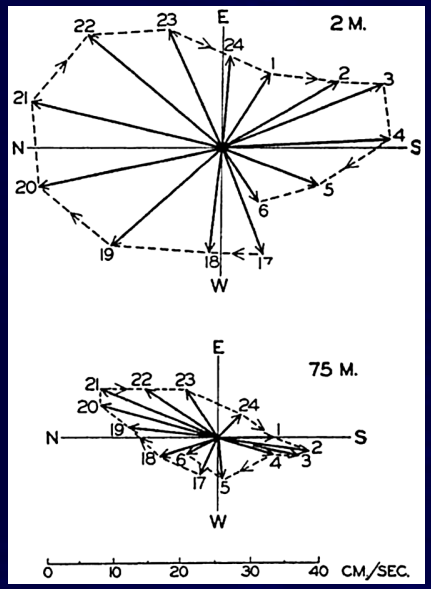
STST in the animal world


Blue crab megalopa





Adult Plaice

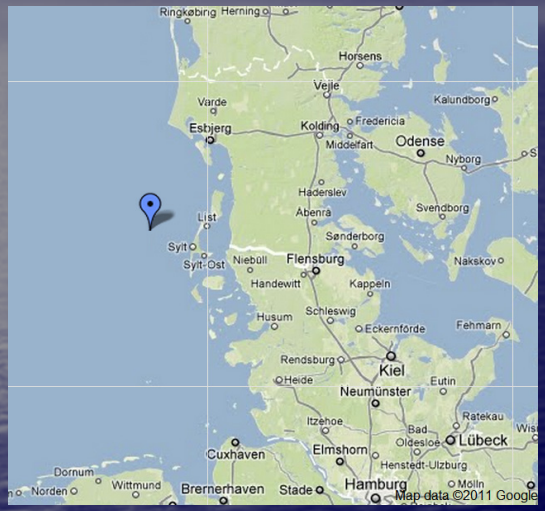


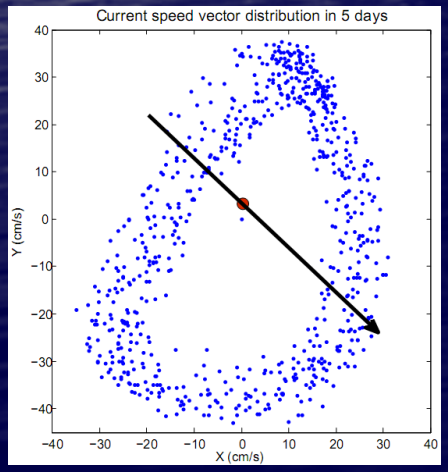
Jerome Jouffroy, MCI, jerome@mci.sdu.dk

Jerome Jouffroy, MCI, jerome@mci.sdu.dk

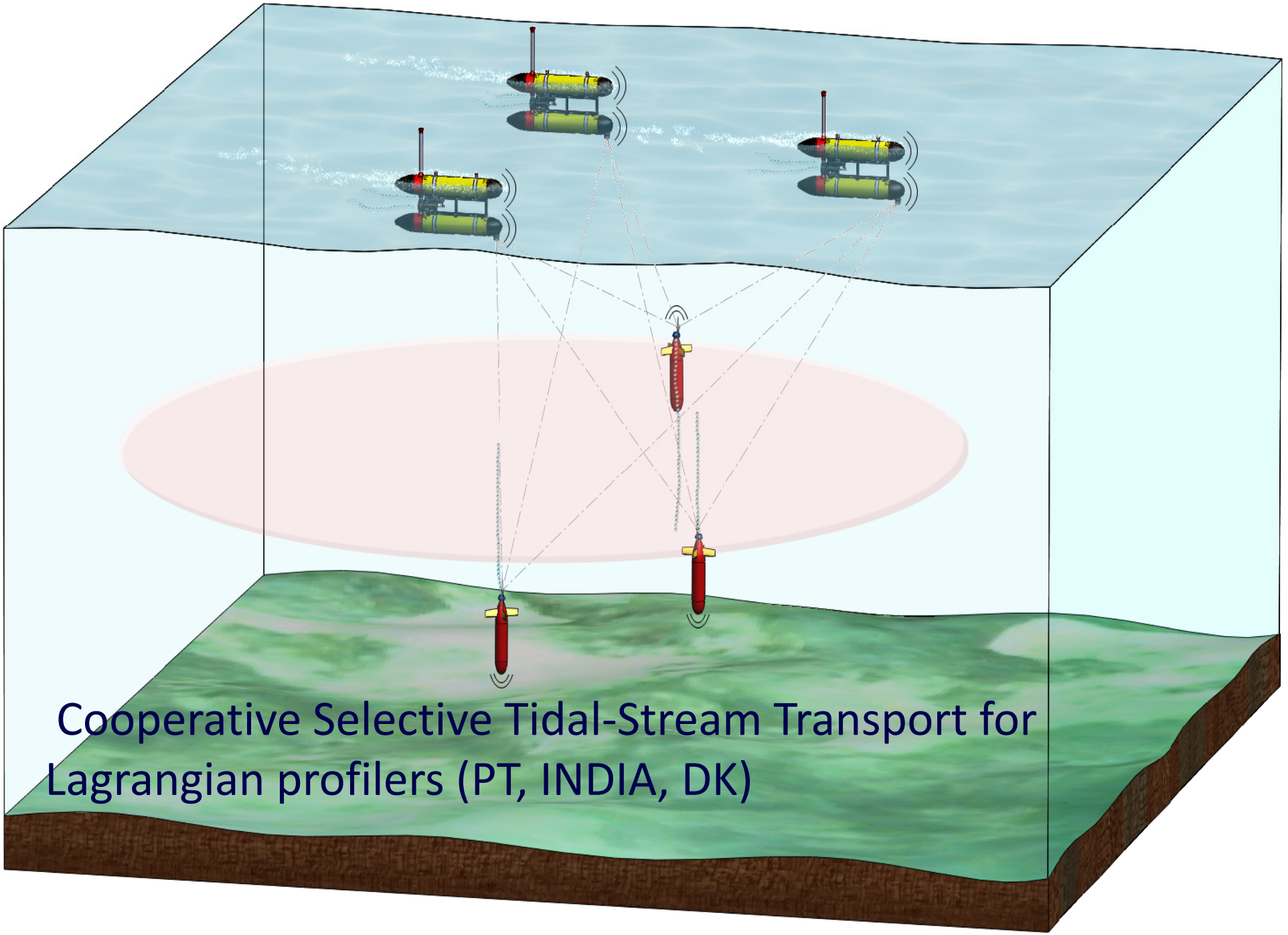
Test results in a re-deployment scenario

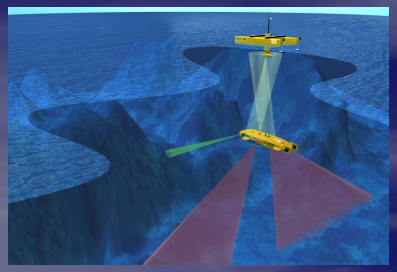
Current data profiles from the North Sea

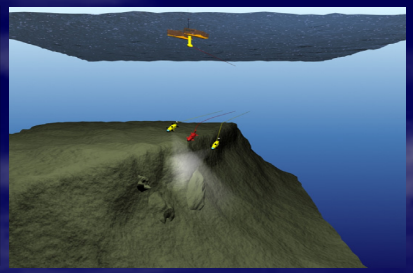




Mean current: 3.2cm/s


Cooperative Selective Tidal-Stream Transport for
Lagrangian profilers (PT, INDIA, DK)






Mission specification

Cooperative motion planning

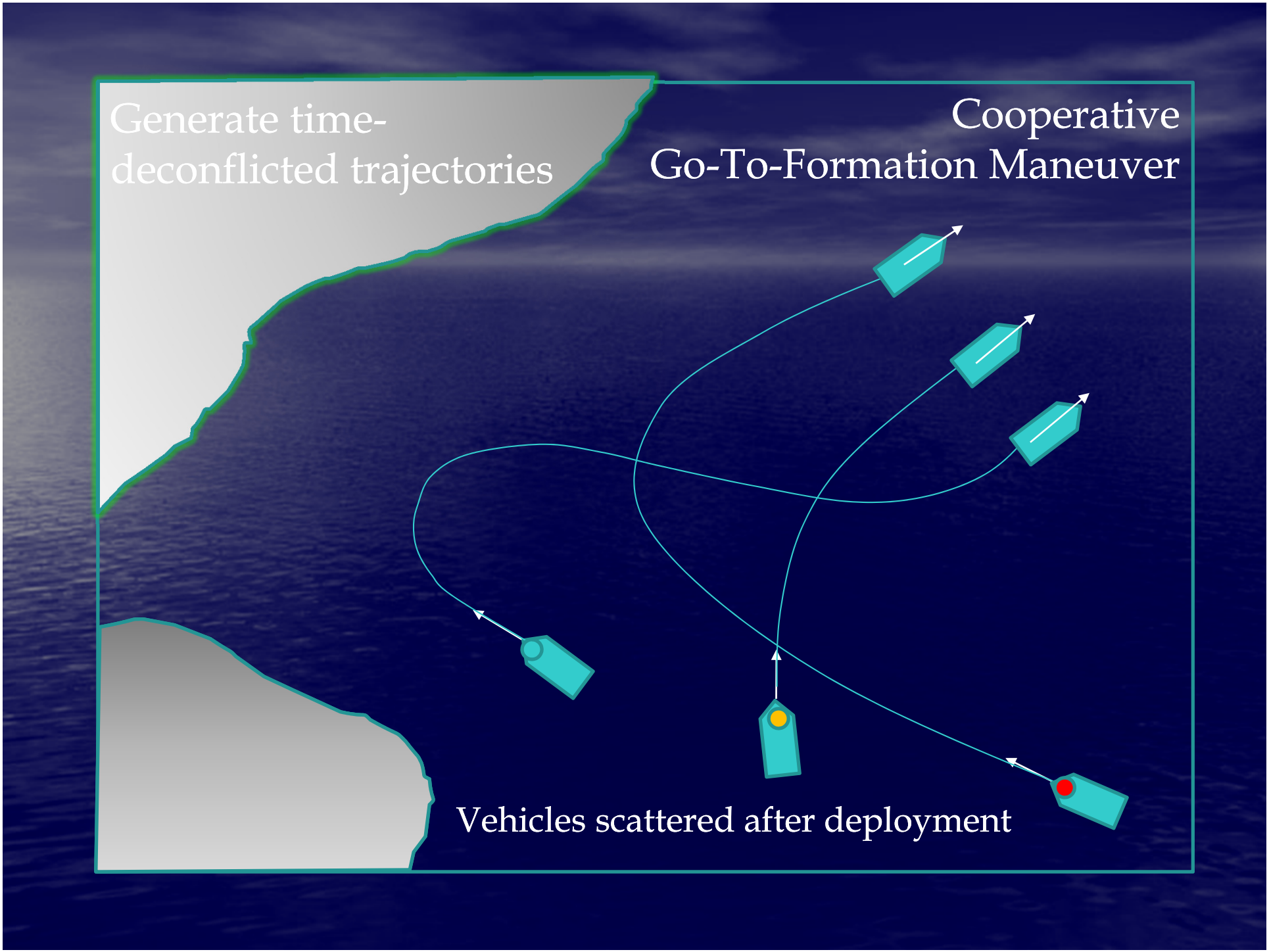
Nominal trajectories & desired vehicle formation

Cooperative motion control

Global and local, relative vehicle positions

Cooperative navigation

Cooperative systems: key blocks required

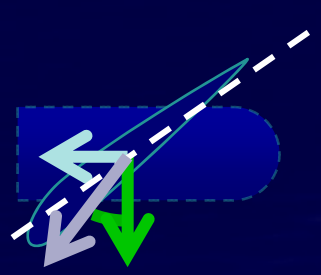

Generate time-deconflicted trajectories
Cooperative Go-To-Formation Maneuver
Vehicles scattered after deployment

Key issues

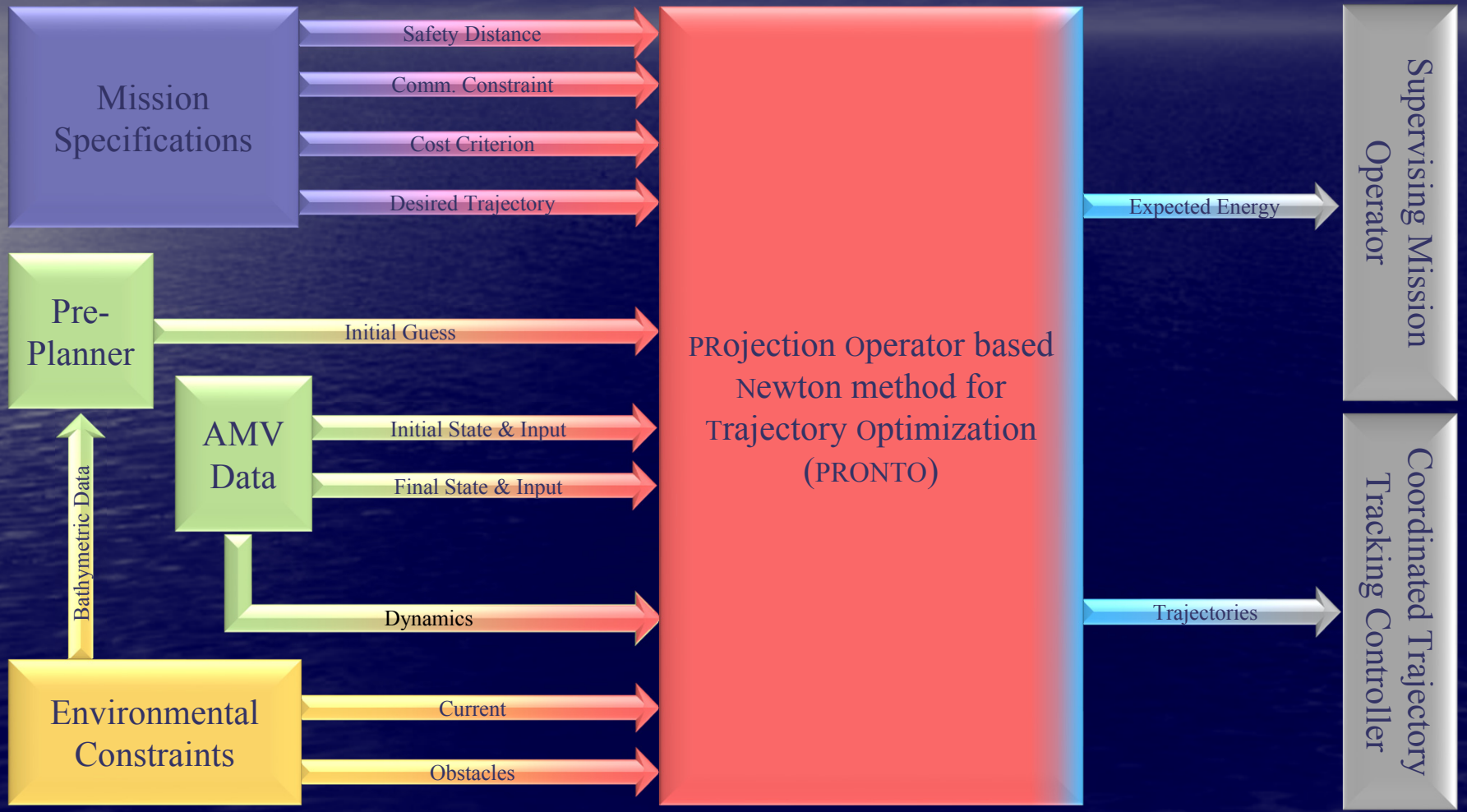
. Explicit incorporation of *nonlinear vehicle dynamics*

. 4-quadrant thruster model for energy consumption computations

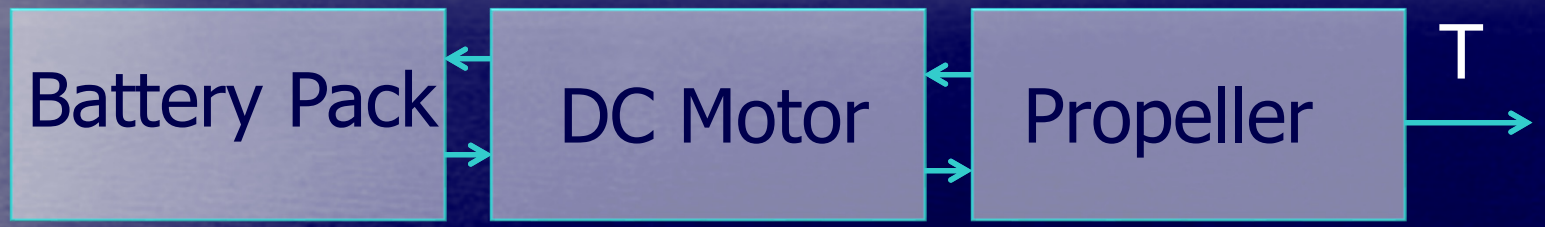
. Fast descent method to solve constrained continuous-time optimal control problems (PRONTO tool)



Trajectory Planning Framework



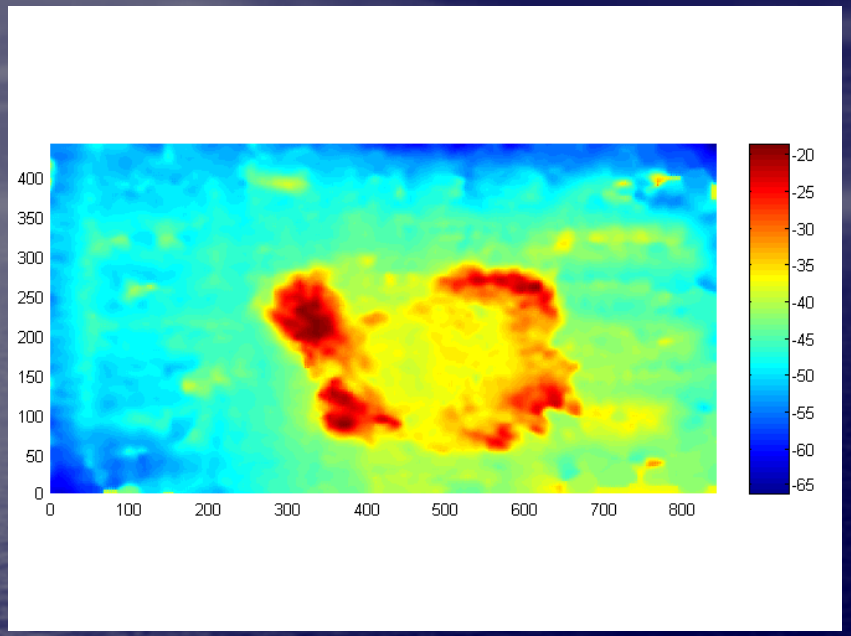
How is energy computed?

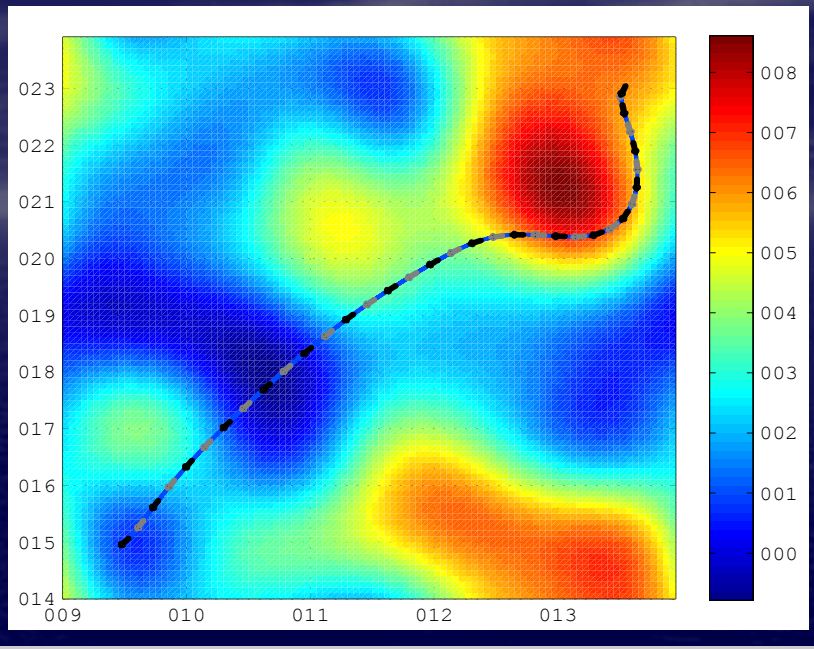


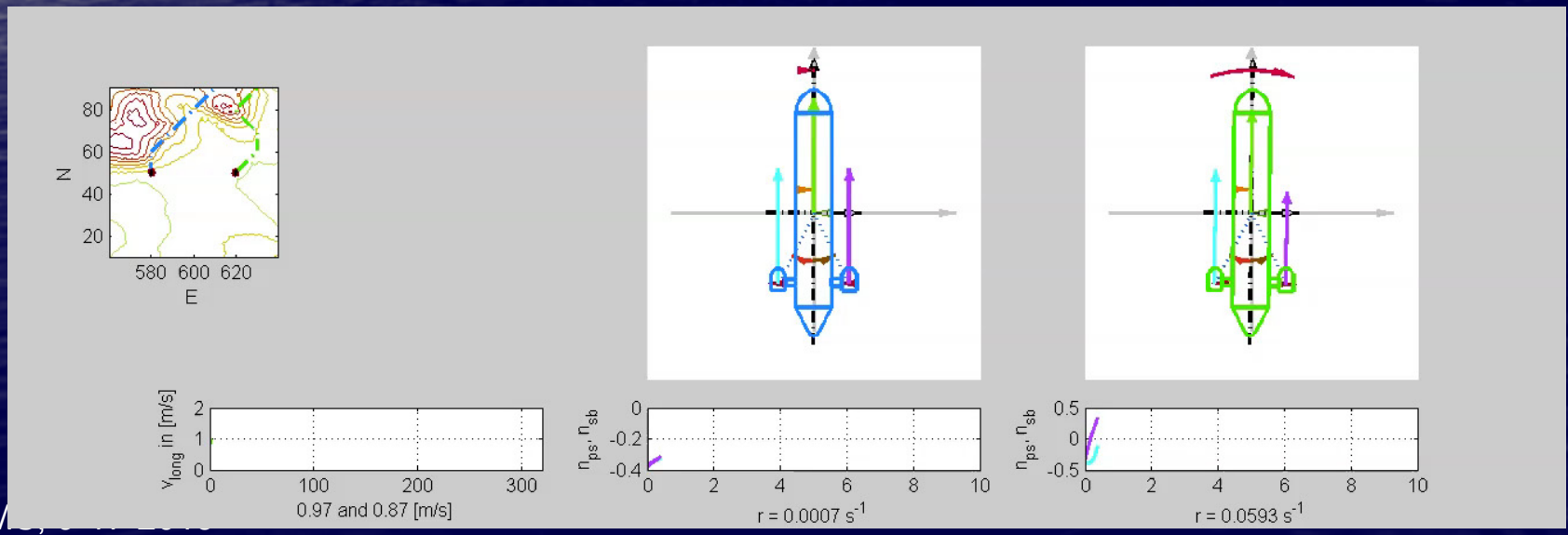
Electrical Power= Voltage x Current

ENERGY expenditure= integral of Power

Cooperative Motion Planning
Temporal, Energy, and Geophysical Constraints)



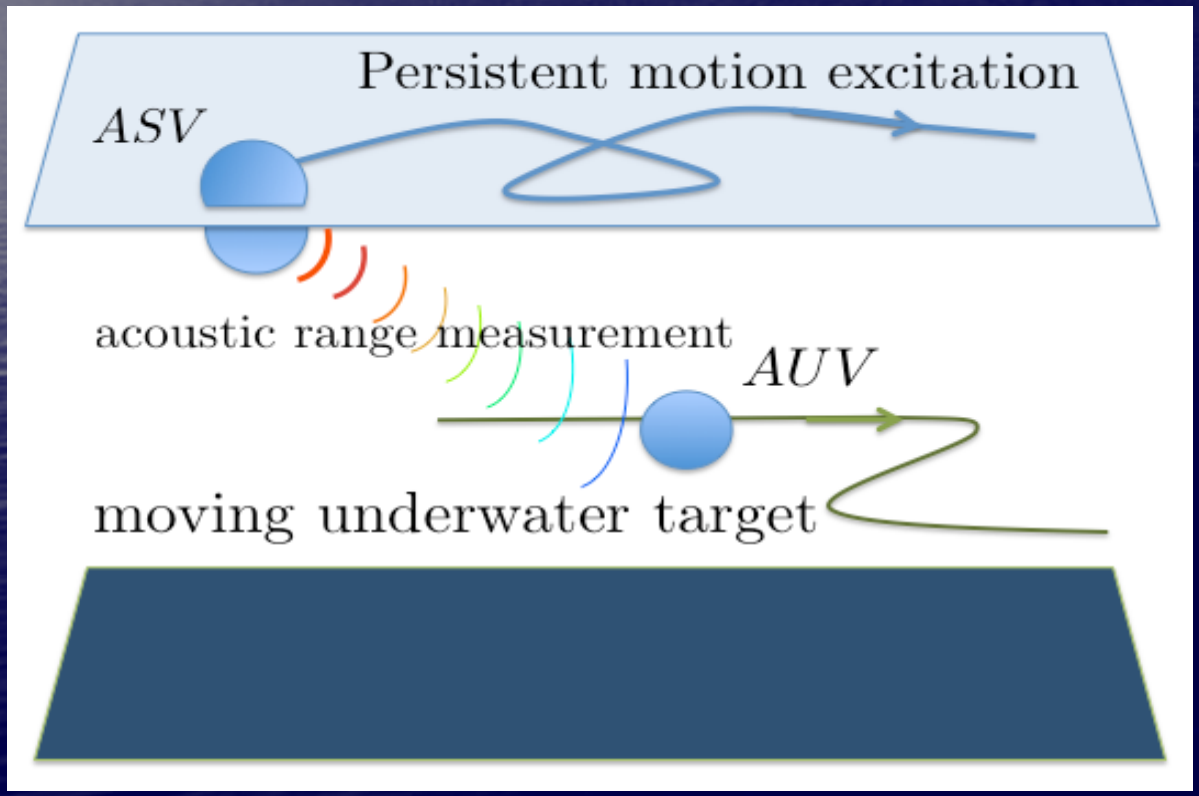


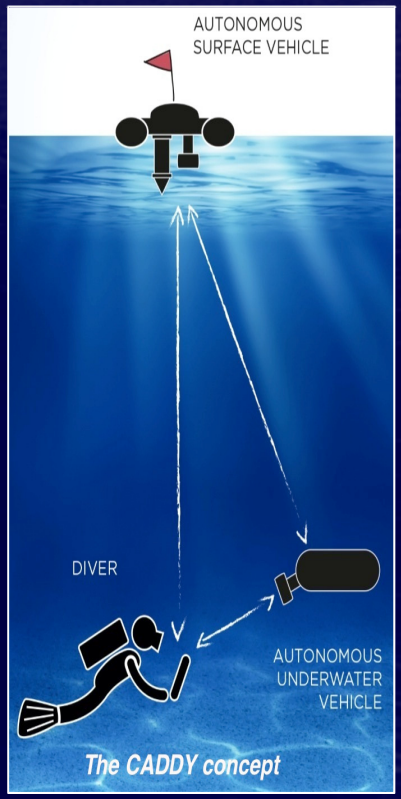


Range-Based AUV Tracking

CADDY

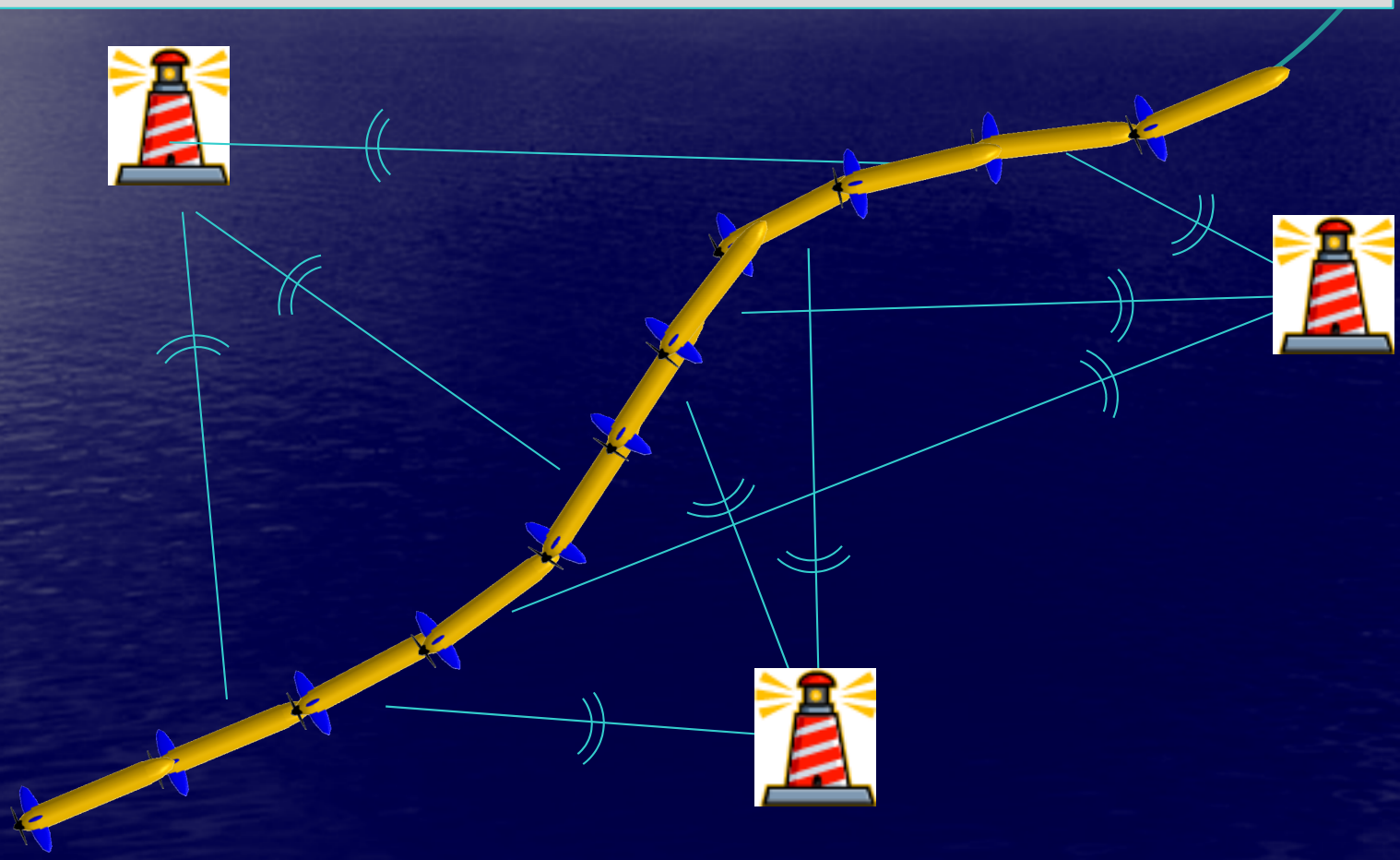
Cognitive Autonomous Diving Buddy



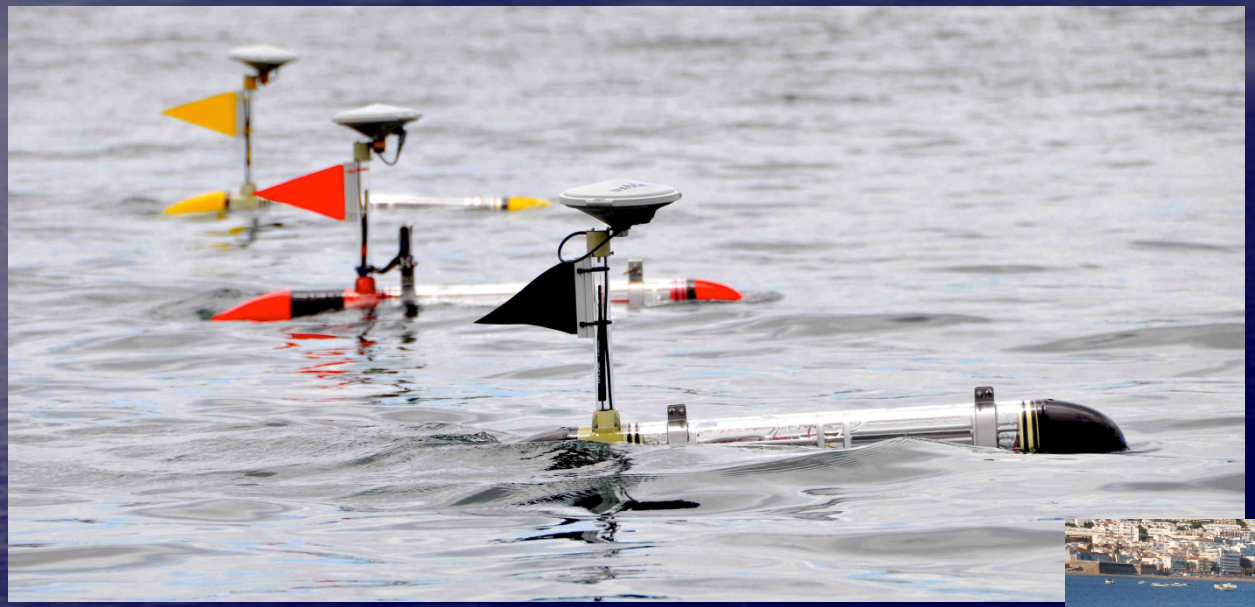


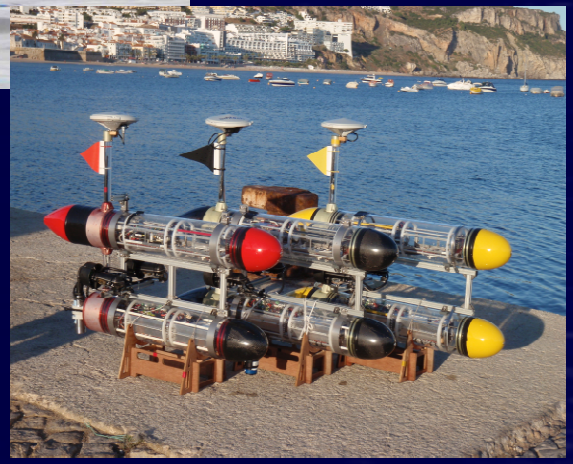
AUV Range-Only Localization

- Under what ***conditions*** can we reconstruct the initial state of the system (unknown beacon and/or vehicle location)?



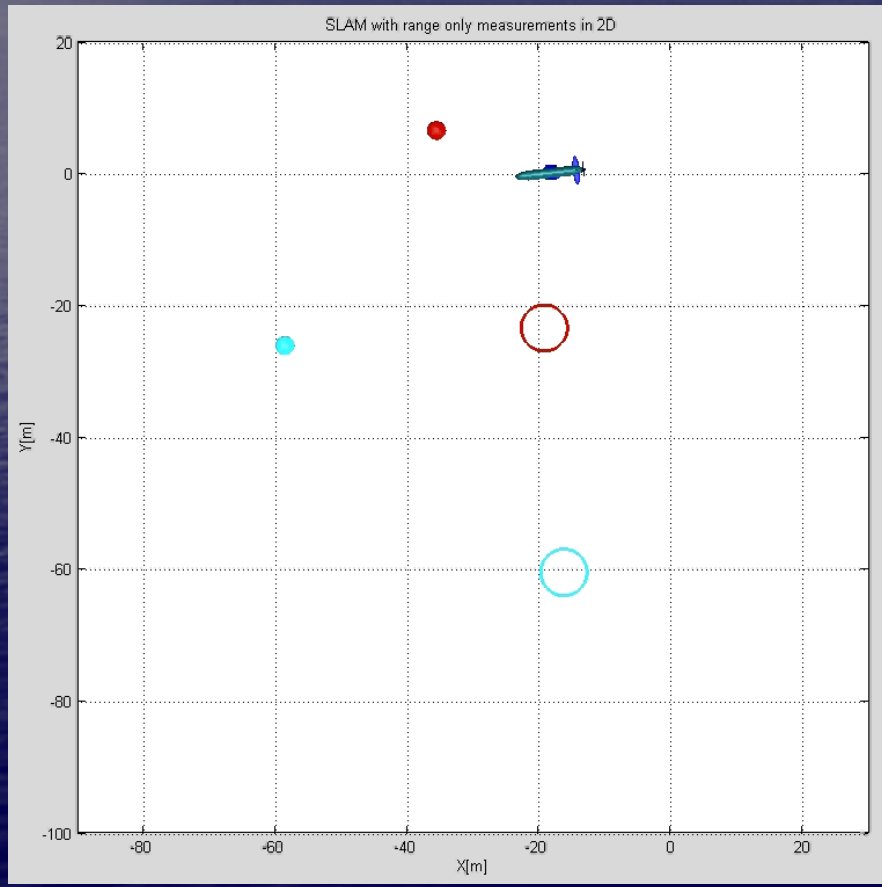
Experimental Results

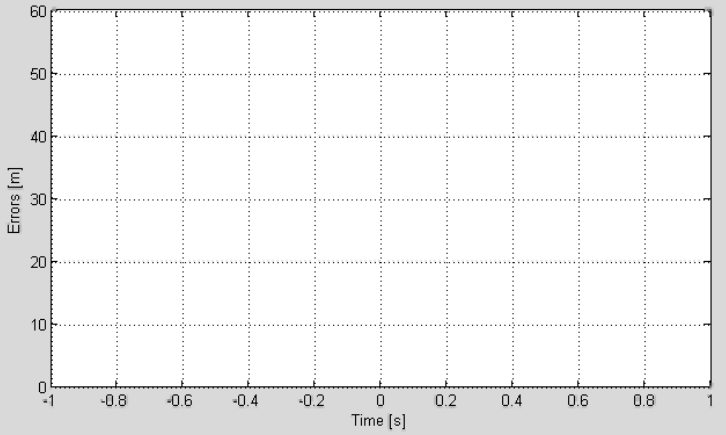




- ***Medusa*** *autonomous vehicles with cooperative motion control capabilities*
- *Acoustic* ***network***

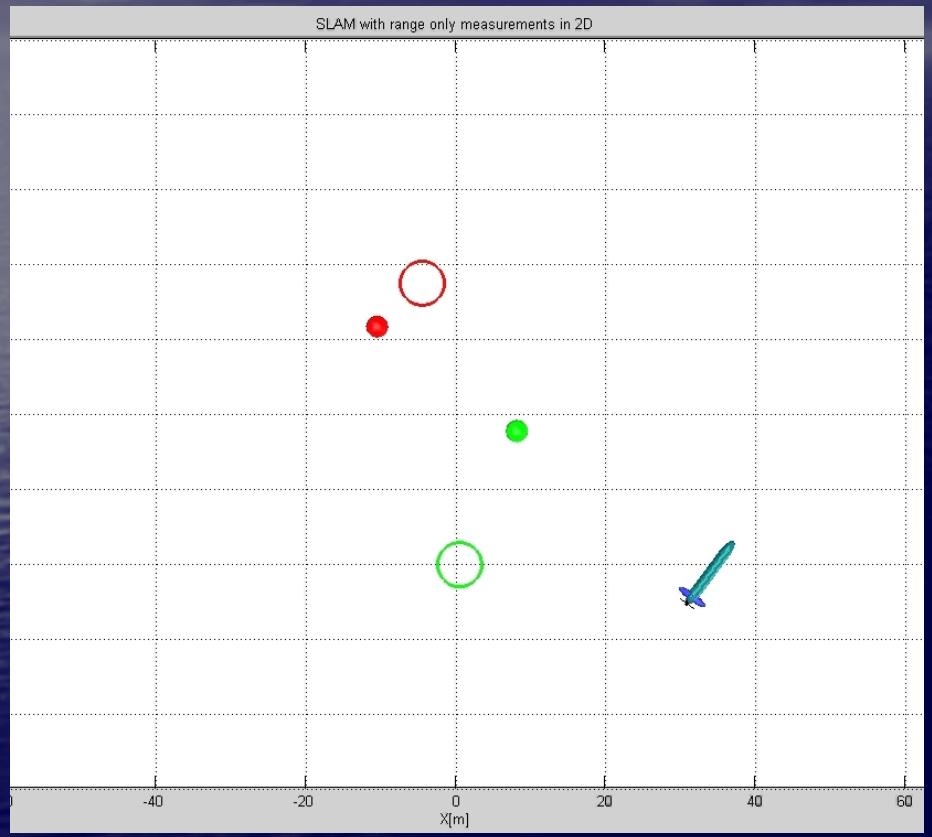
Experimental Results





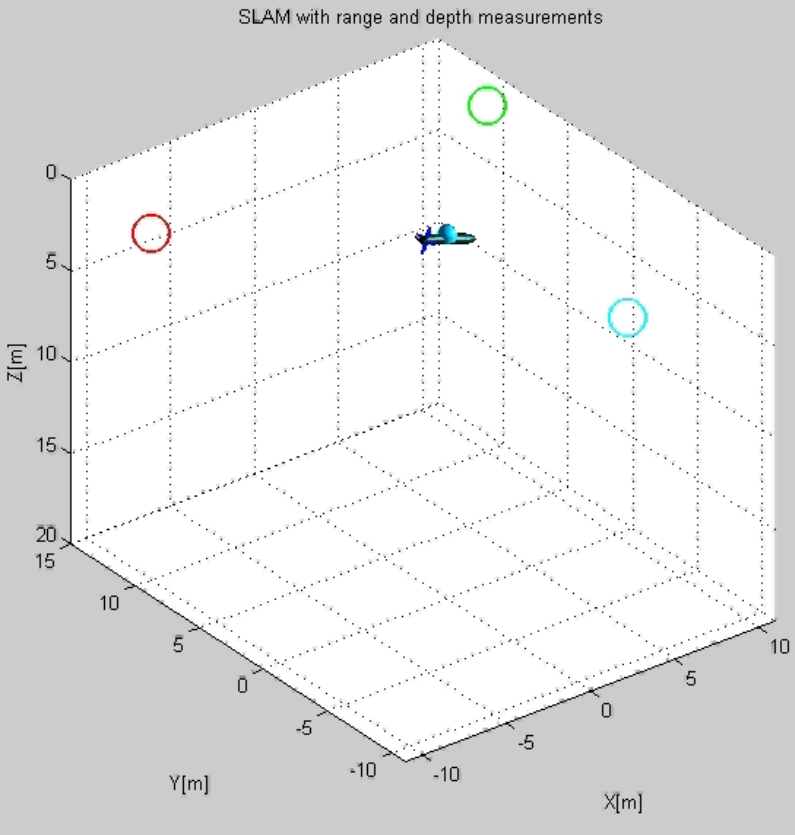
Experimental Results

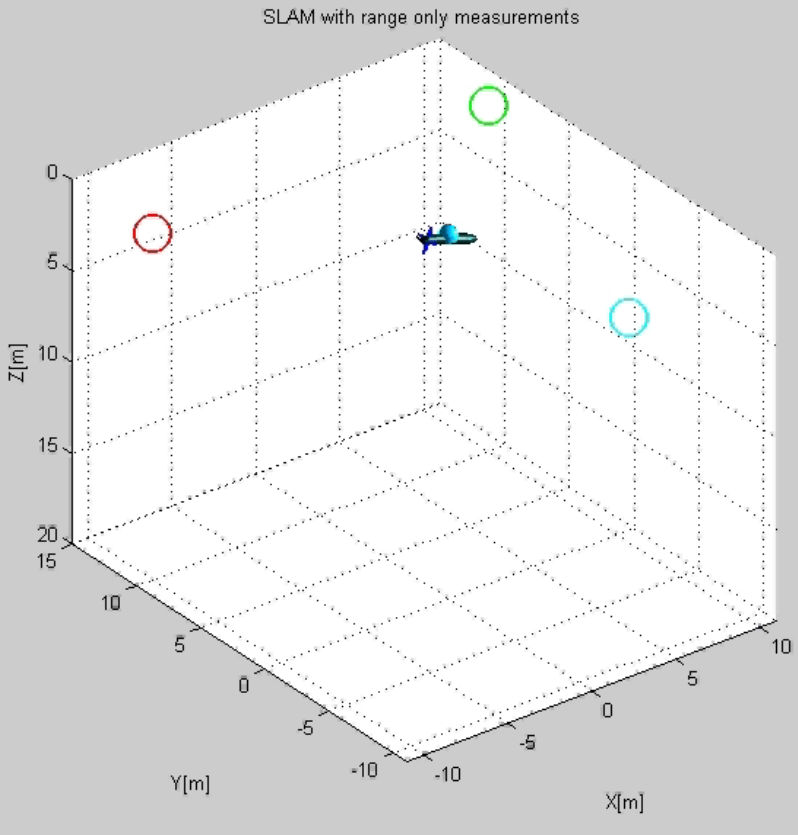
- Vehicle position and estimate



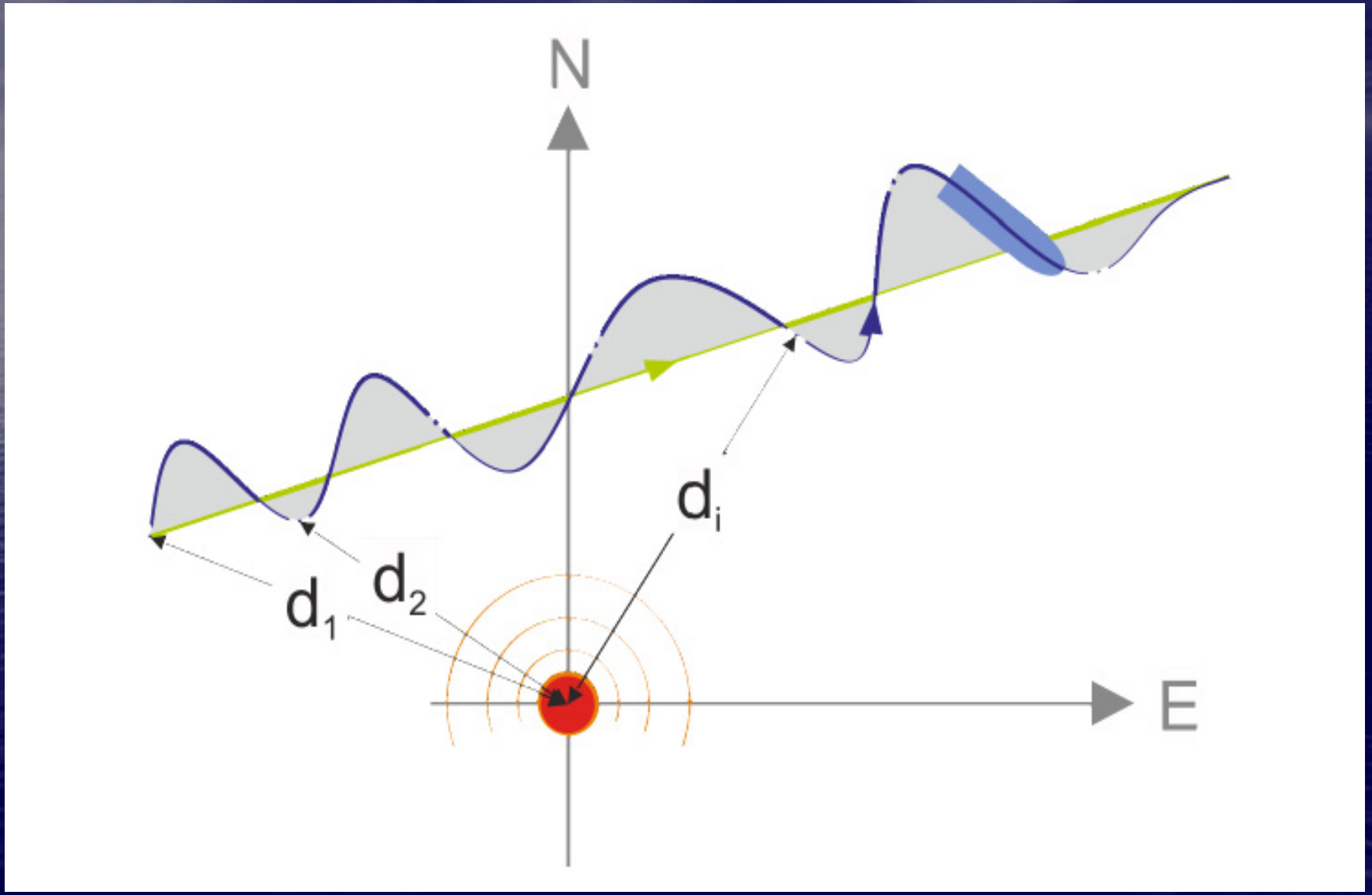
Transponder positions and estimates

3D Multiple Model Adaptive Estimation

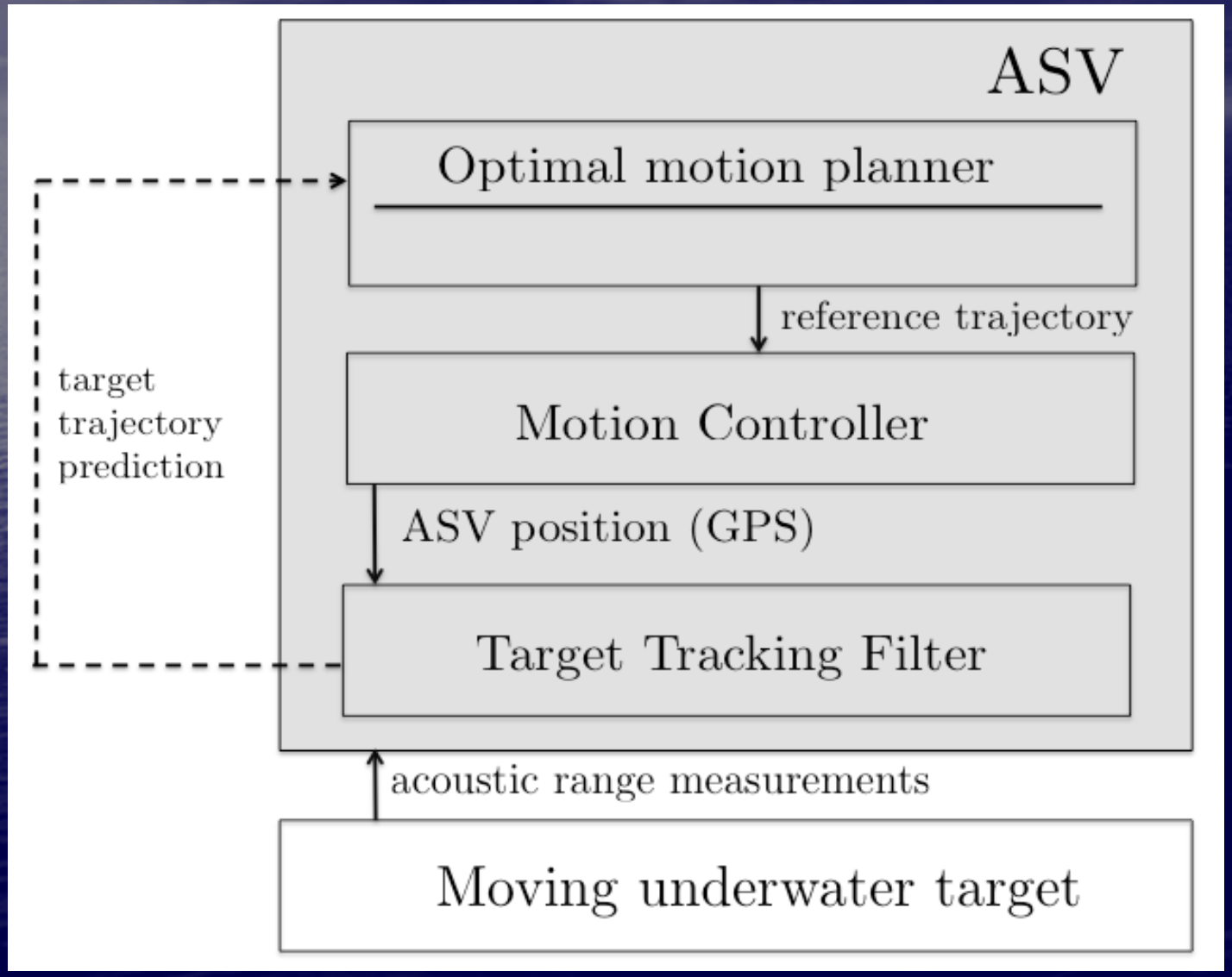




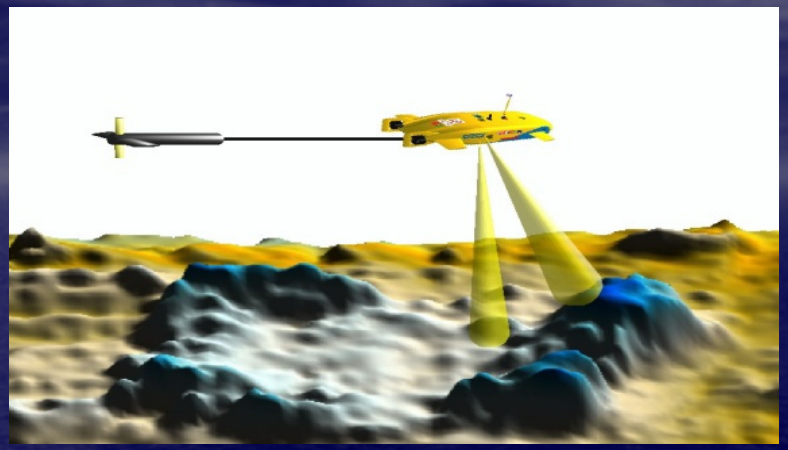
Motion Planning under Observability Constraints

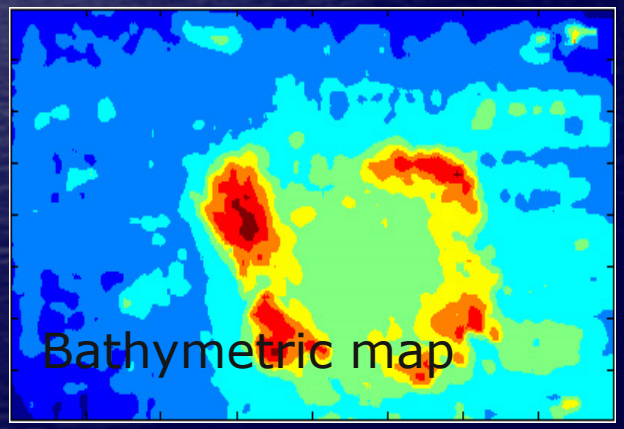


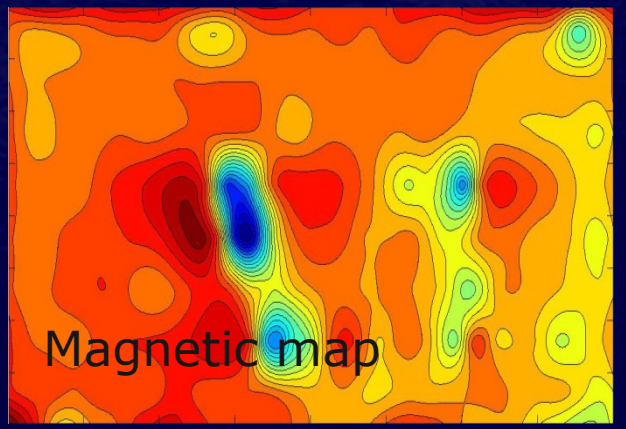
Range-Based AUV Tracking: put it to work!



Geophysical-Based Navigation





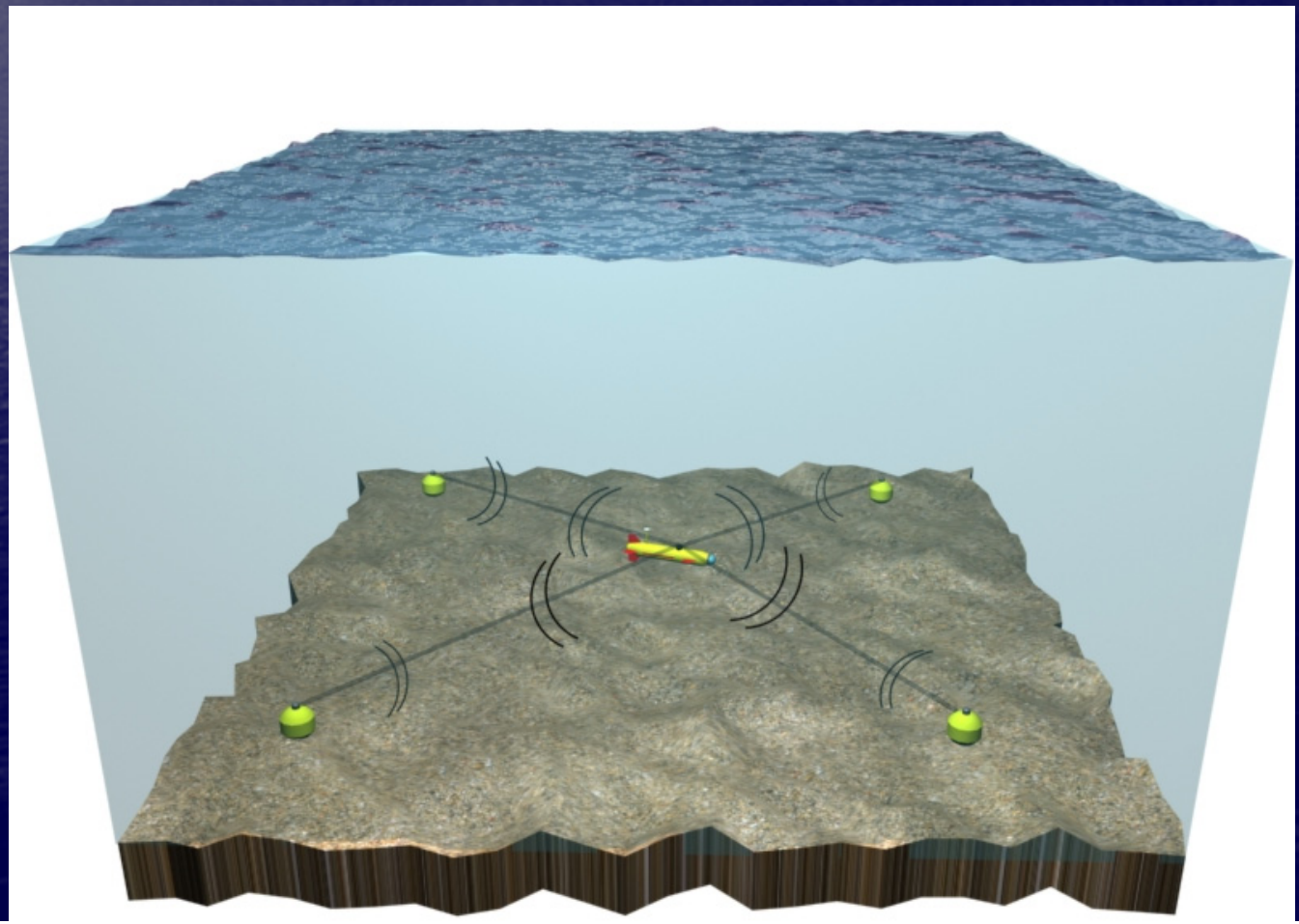


(IST-PT, UAveiro-PT,NIO-Goa, India;
New project KAIST (Jinwhan Kim) –IST (Francisco Curado and Antonio Pascoal), funded by ADD)

Conventional Navigation Solutions

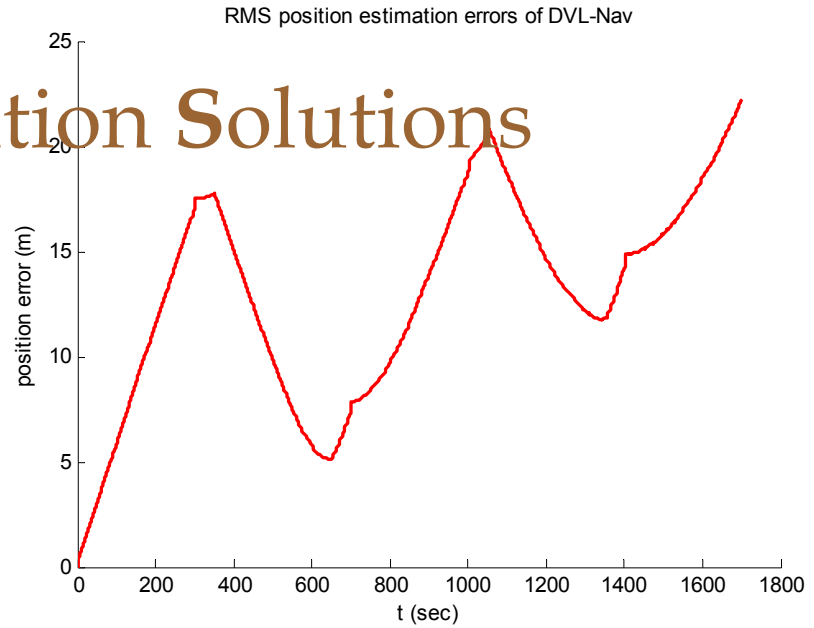
Conventional equipment

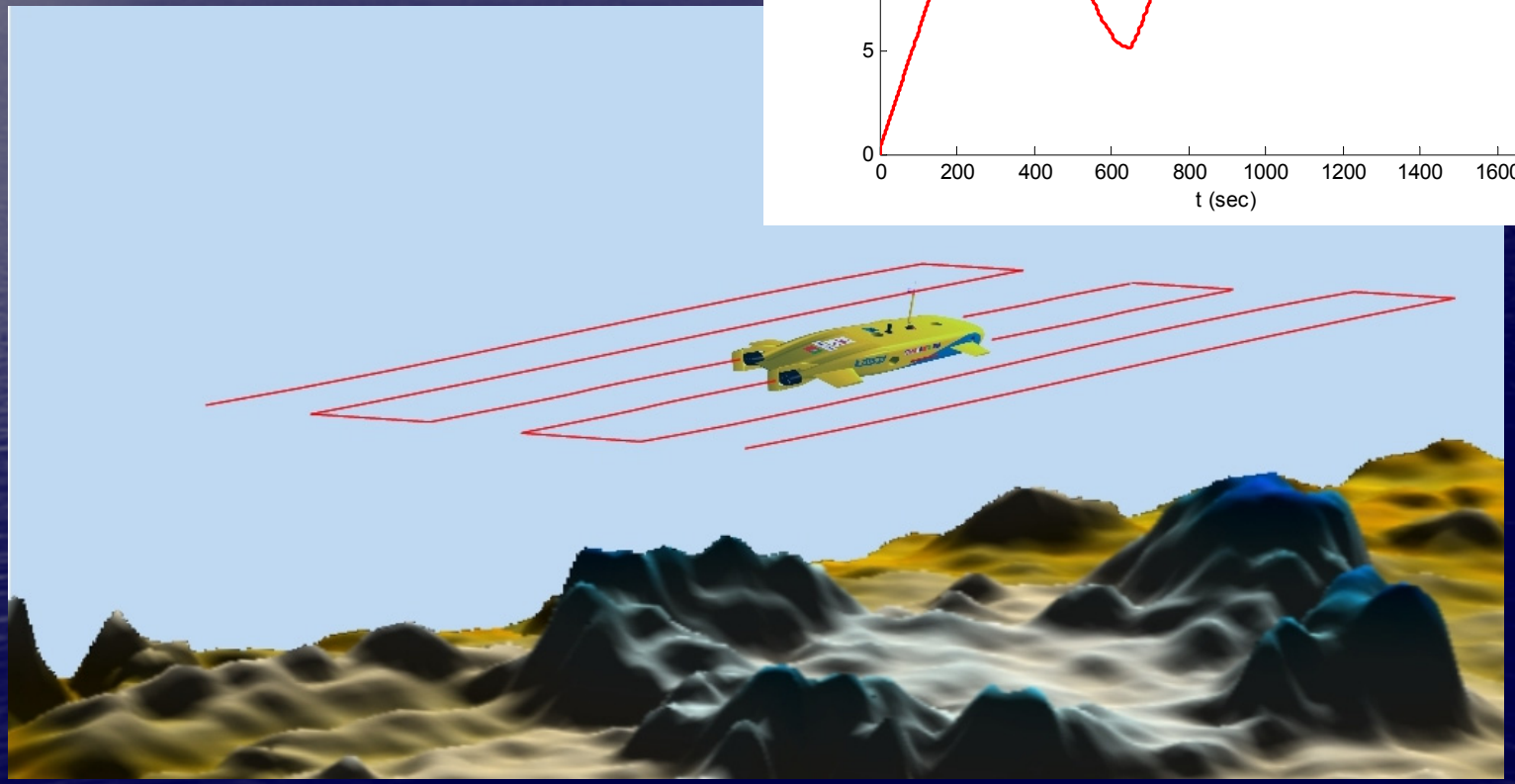
- Inertial navigation systems (INS): **proprioceptive sensors**
- Odometry sensors (DVL): **exteroceptive sensors**
- Long acoustic baselines (LBL): **artificial beacons**



Conventional Navigation Solutions

- INS/DVL limitations

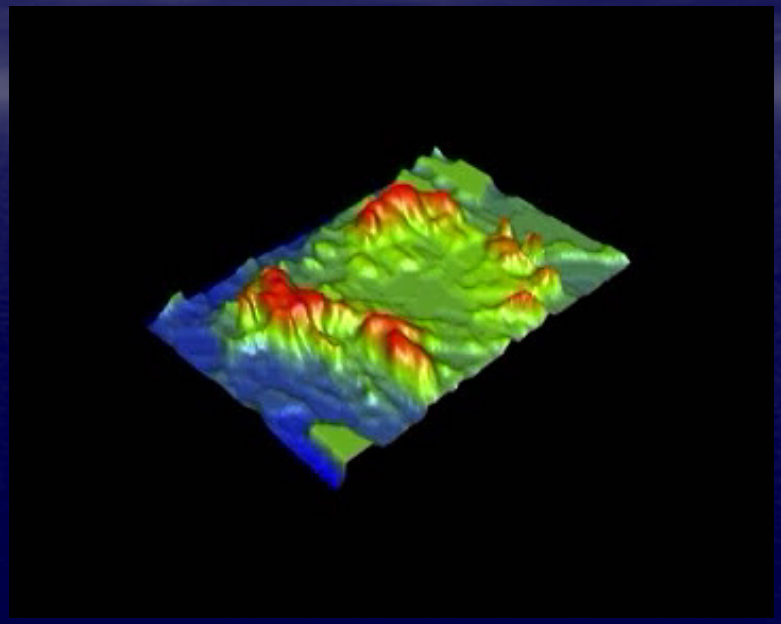




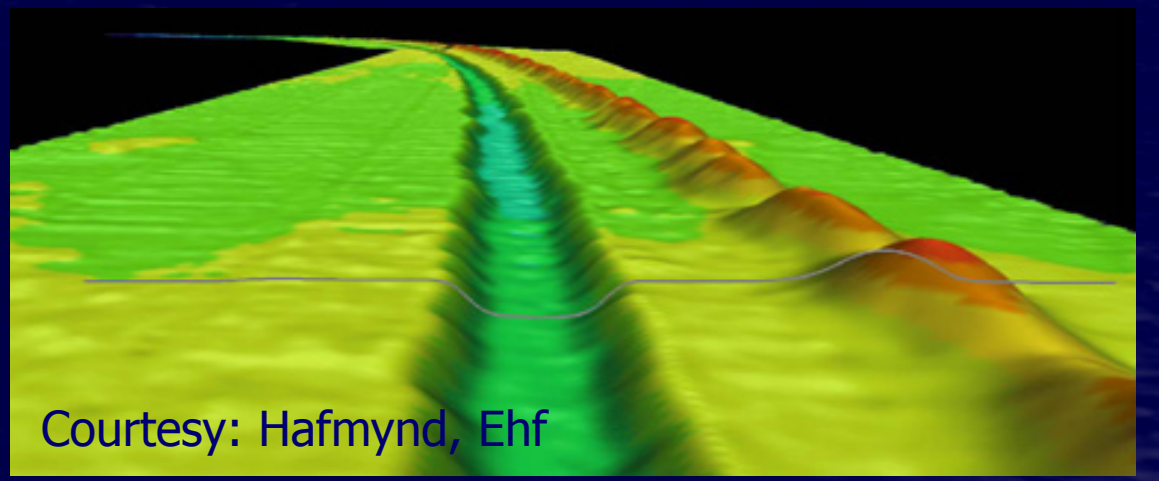
- LBLs are expensive and complex to deploy

Non-conventional Navigation Solutions

- **Exploit information from the environment for self-localization**
  - Natural features: elevation; reflective properties…
  - Artificial features: submarine cables or trenches; moorings; ship wrecks…

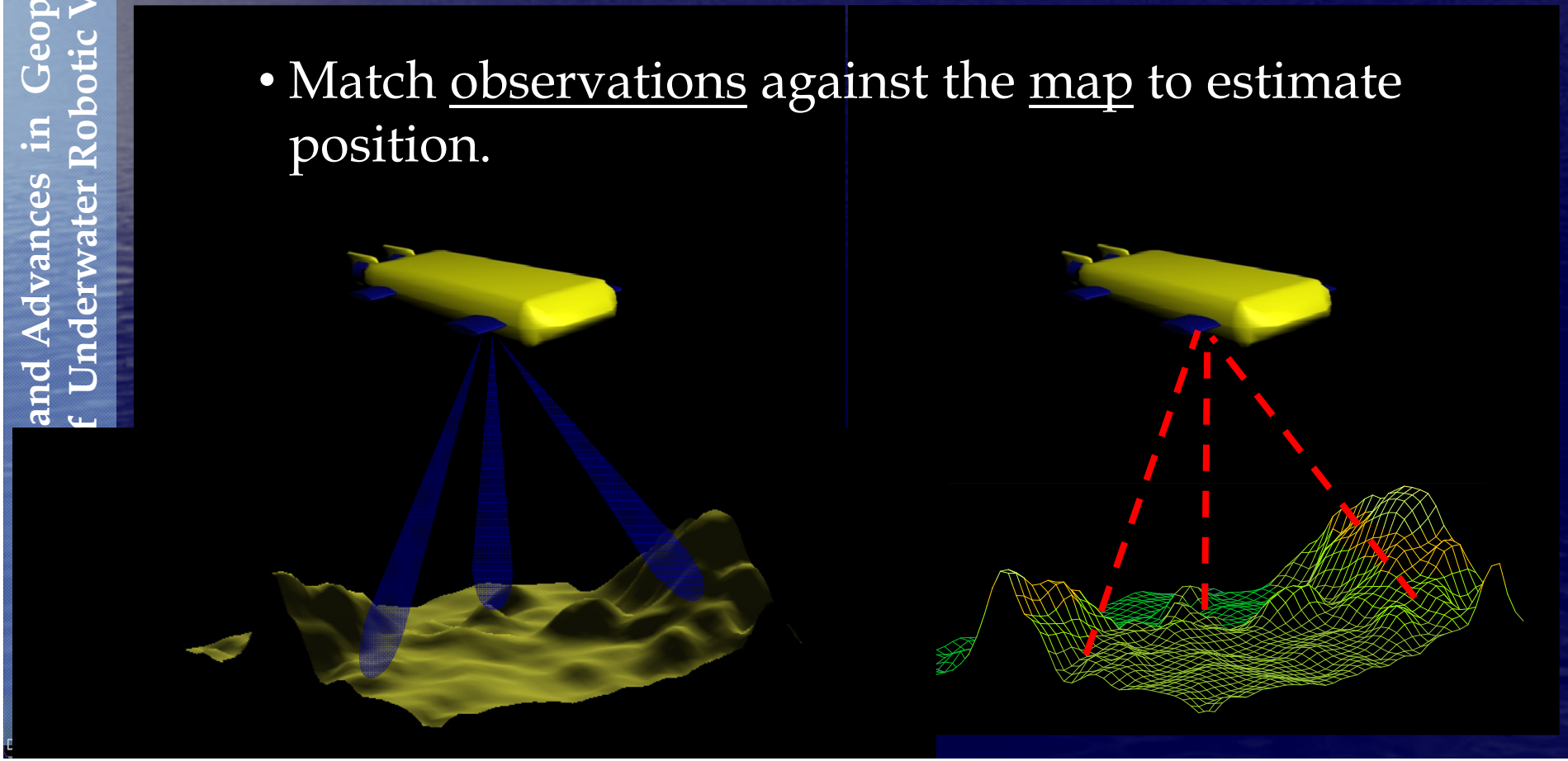


- **TAN**
- **SLAM**

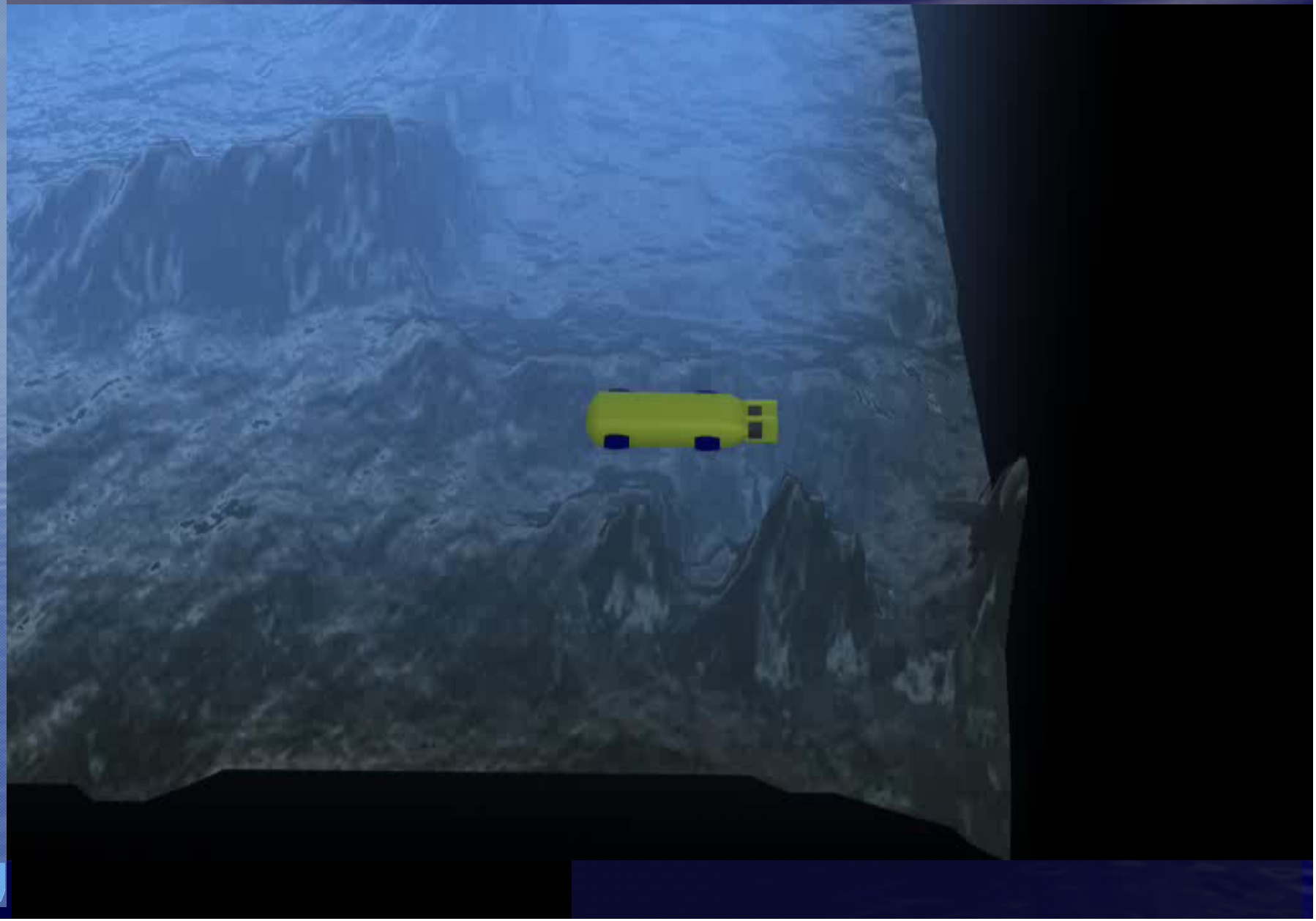


Non-conventional Navigation Solutions

- **Terrain-Aided Navigation (TAN** a.k.a. TRN,TBN)
  - Use a prior map of the environment.
  - Make observations of the terrain
  - Match observations against the map to estimate position.

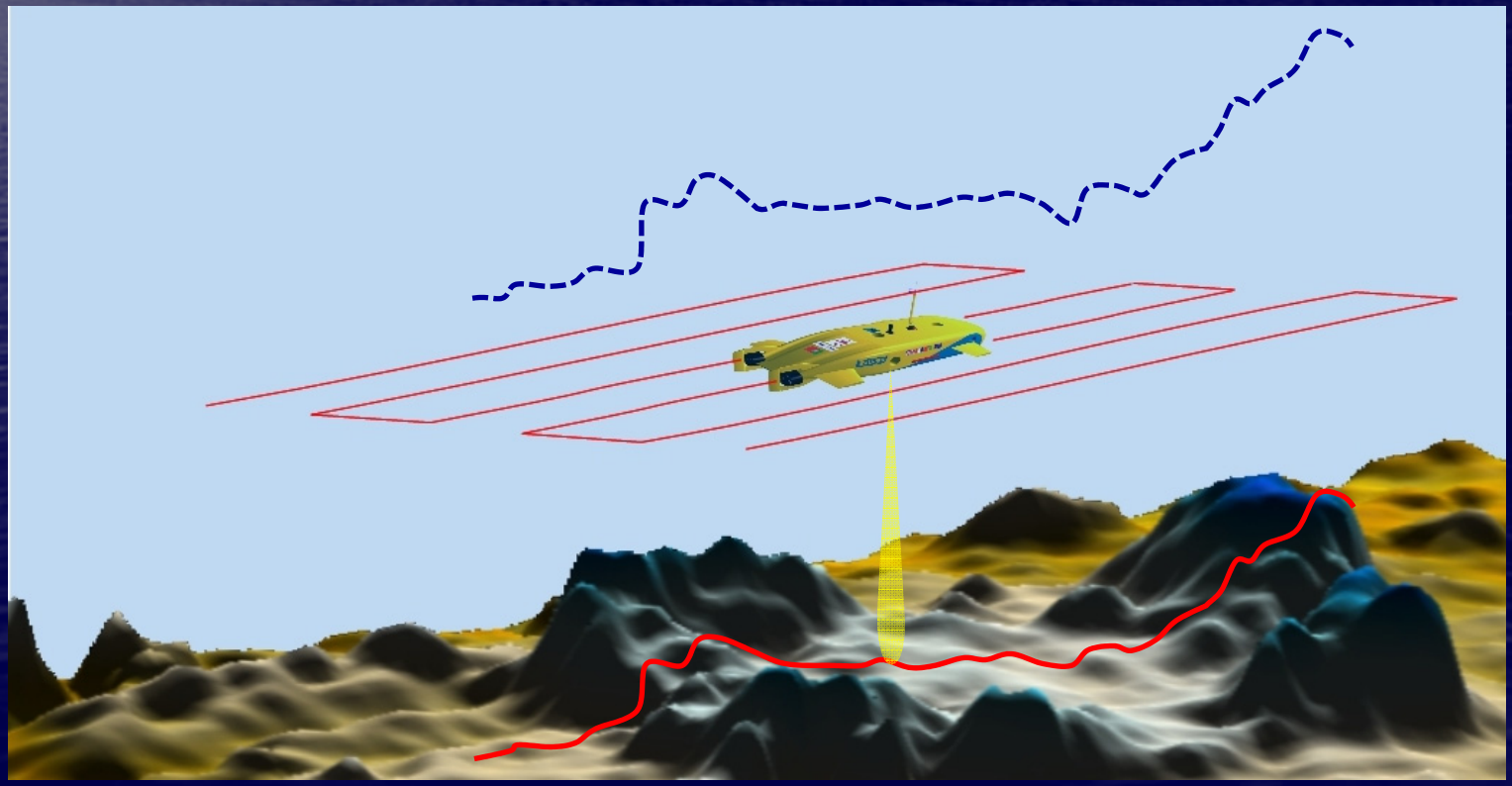


Non-conventional Navigation Solutions



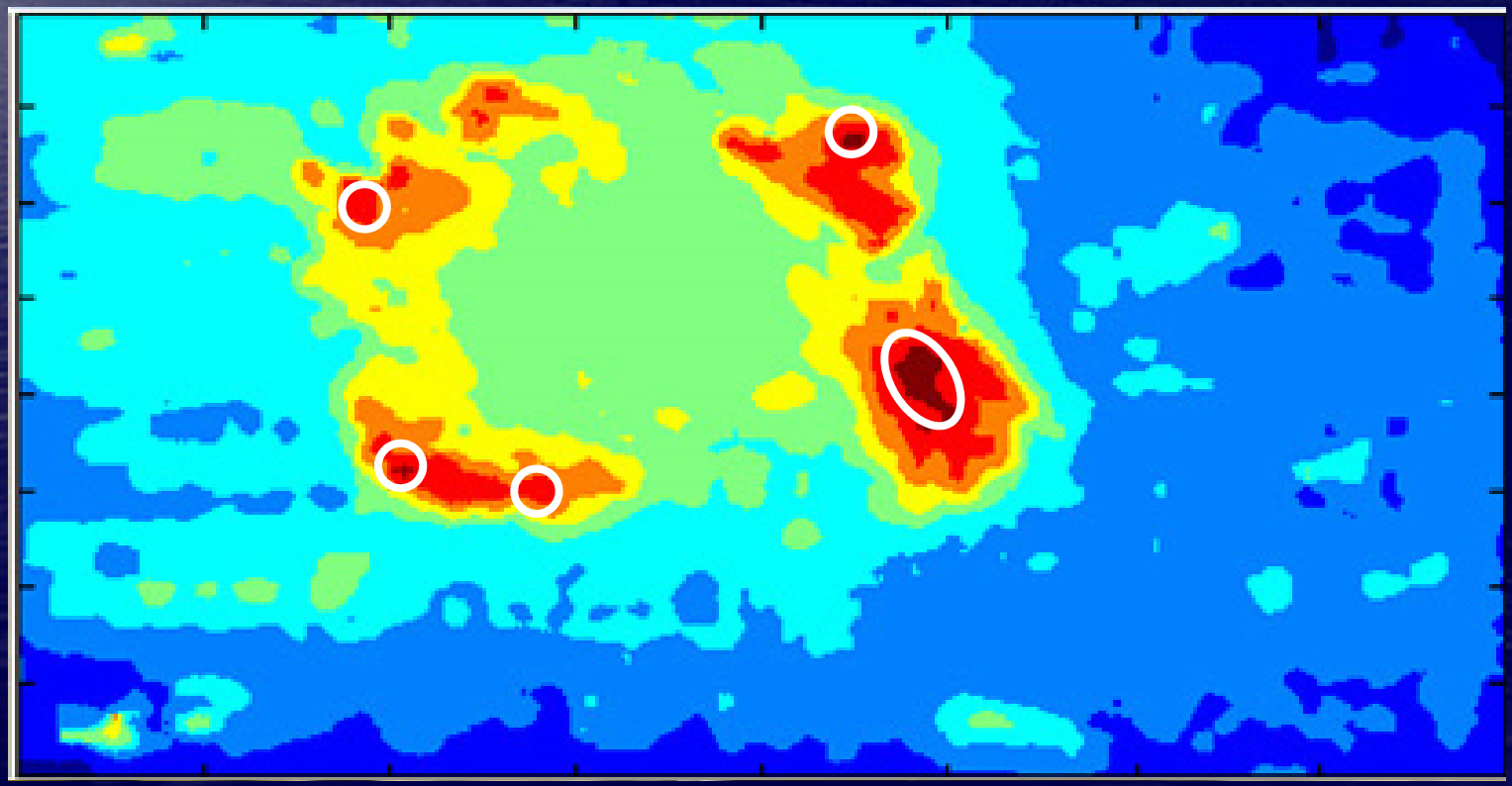
Non-conventional Navigation Solutions

- **Map matching**
  - Can be done sequentially or in batch without explicit feature extraction and data association/registration.



Simultan. Localization And Mapping (SLAM)

- **Sequentially acquire/refine a map of the terrain & simultaneously use this map for self-localization.**
  - Use sparse, metric or topological maps of the terrain.
  - Apply explicit feature extraction and data association.



TAN Filters

Doppler Unit

Attitude Unit

Velocity/water

Vehicle Kinematic Model (prediction)

Predicted Position

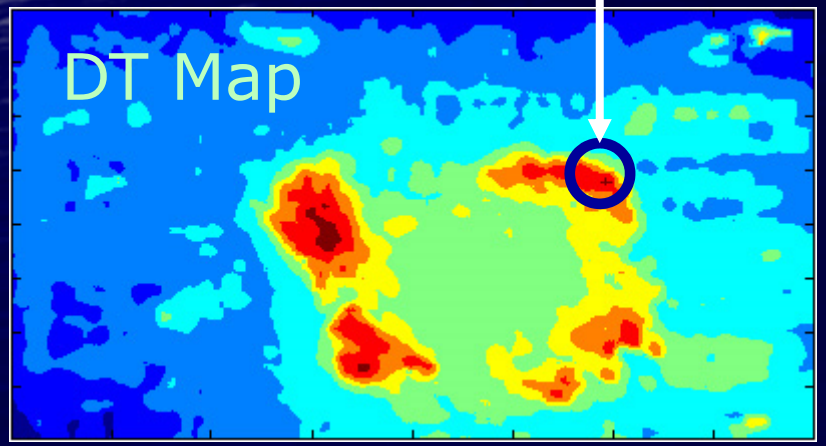
Measurement model (filtering)

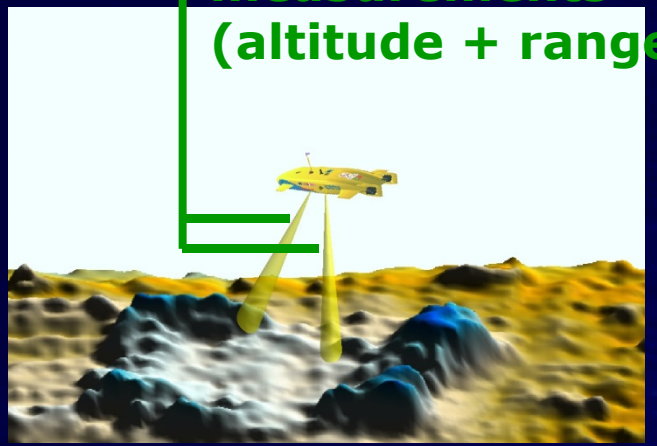
Estimated State

Attitude

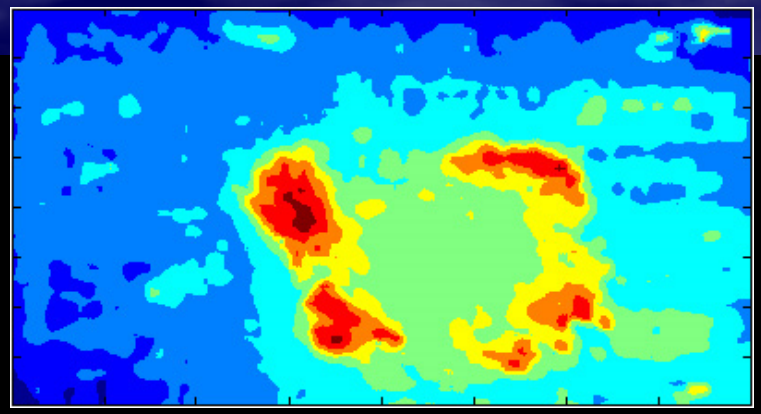
Predicted measurement

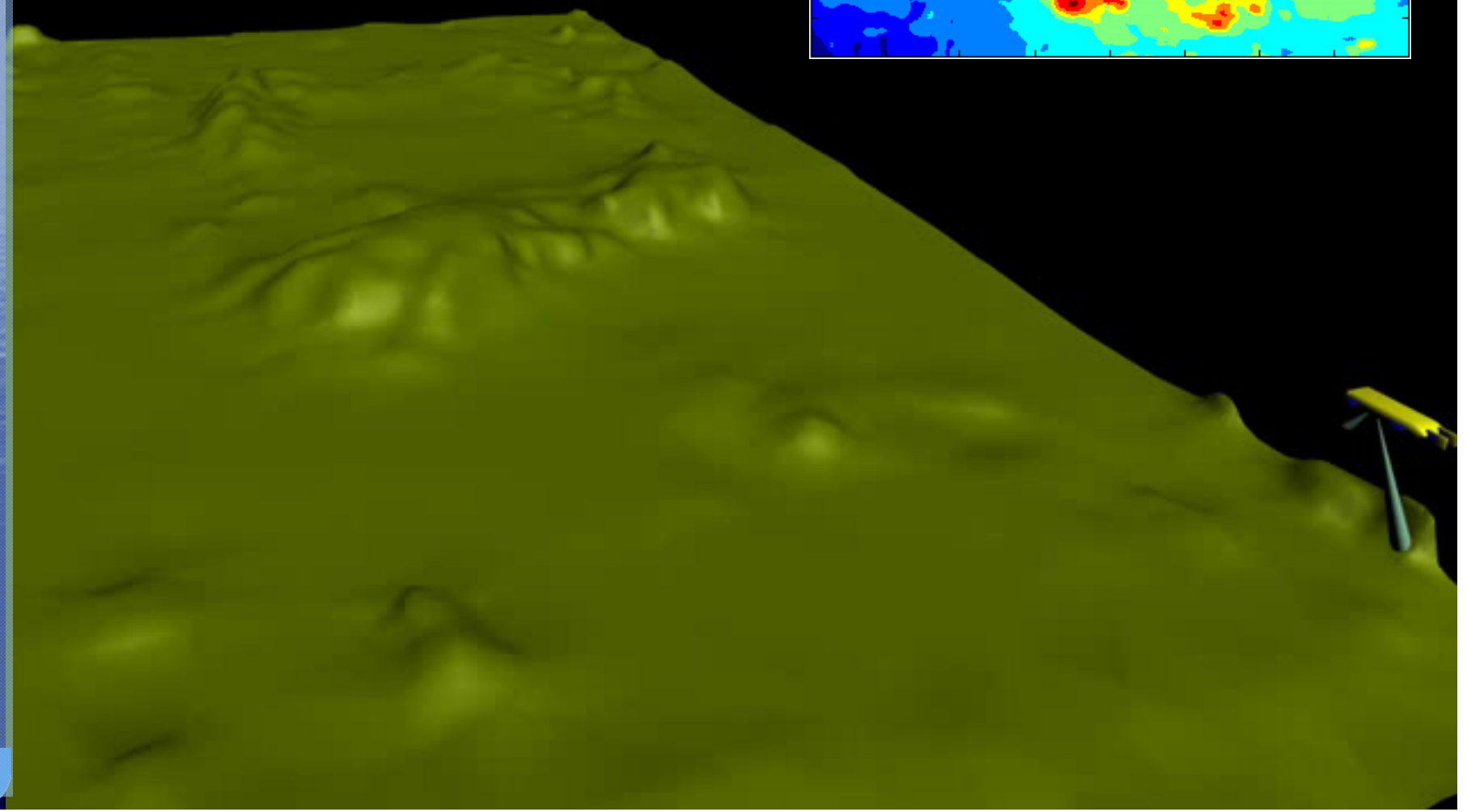
Sonar measurements (altitude + range)



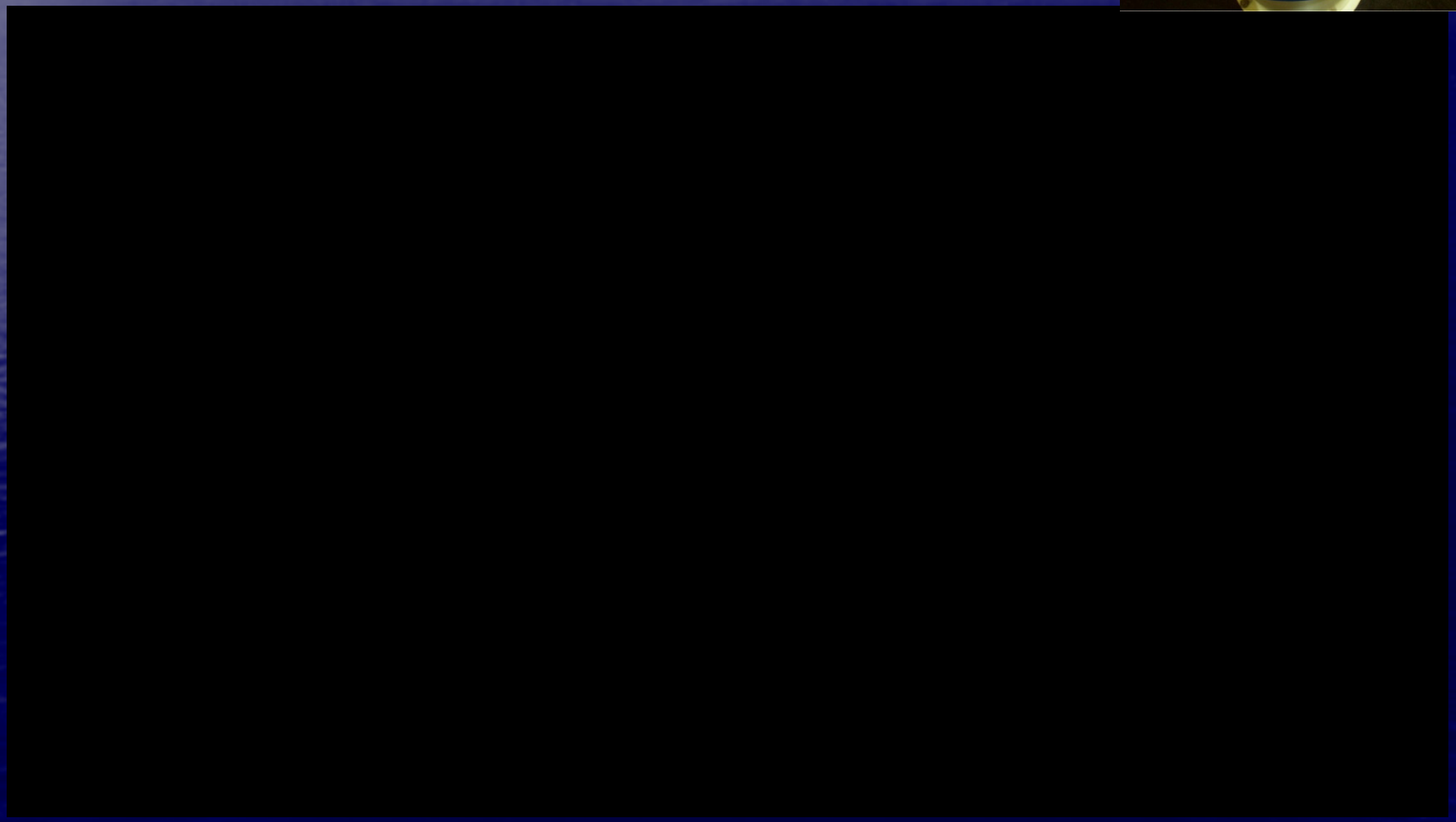


TAN Filters (Monte Carlo Methods – Particle Filters)



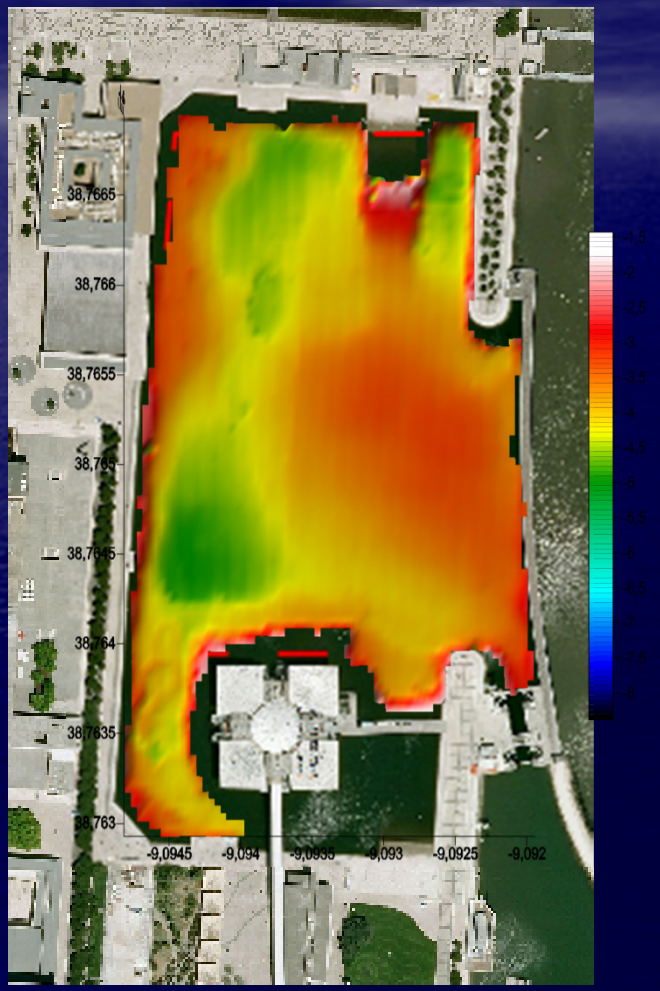


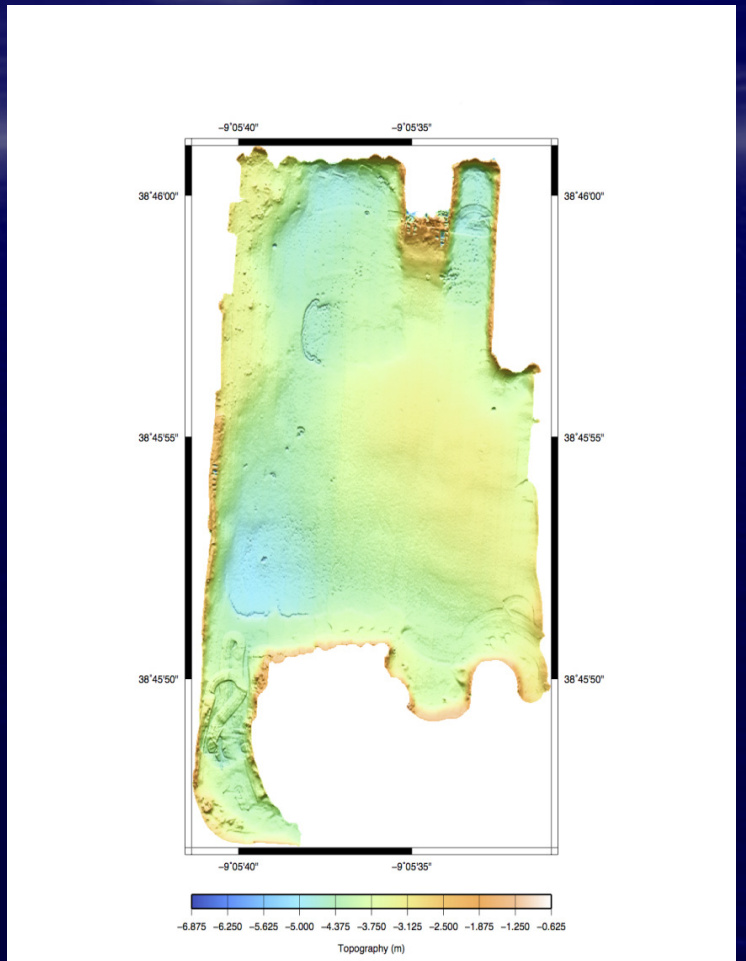
TAN /DVL Implementation



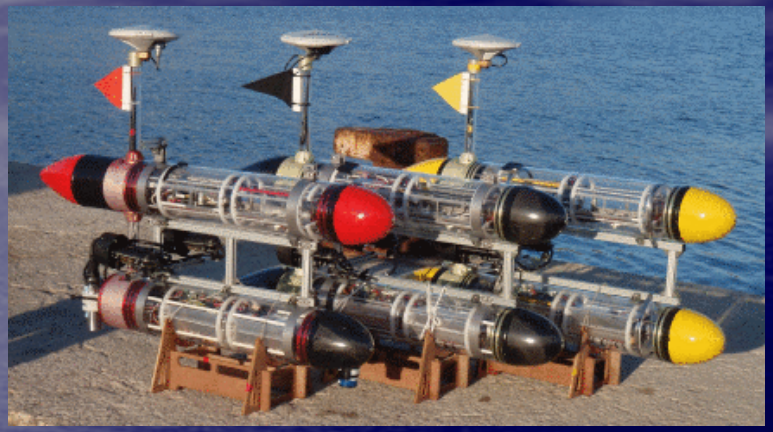
TAN /DVL Implementation

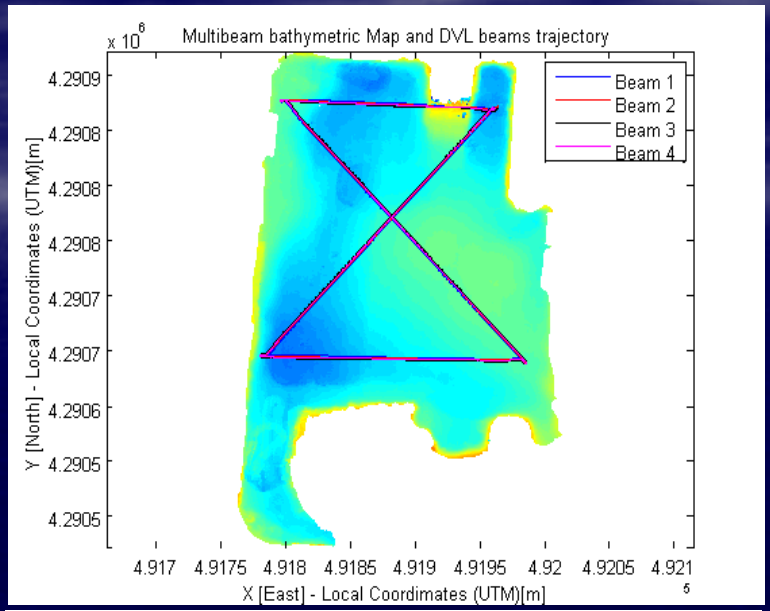
300m

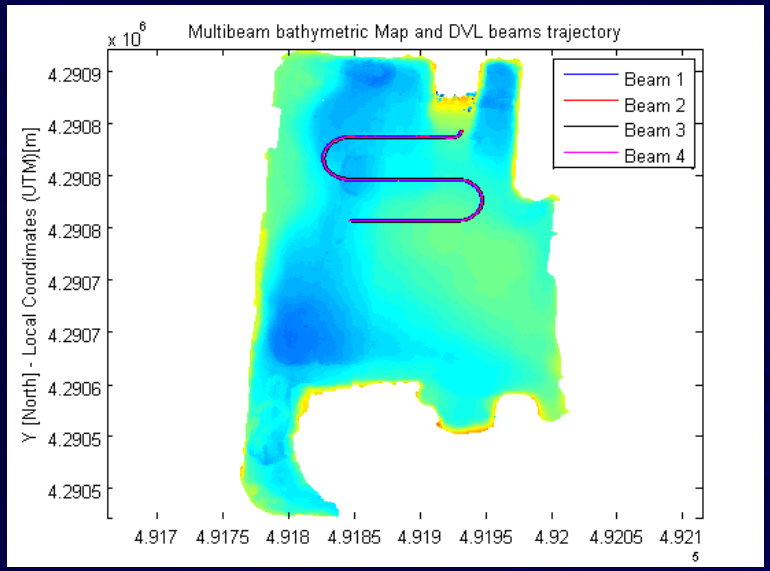




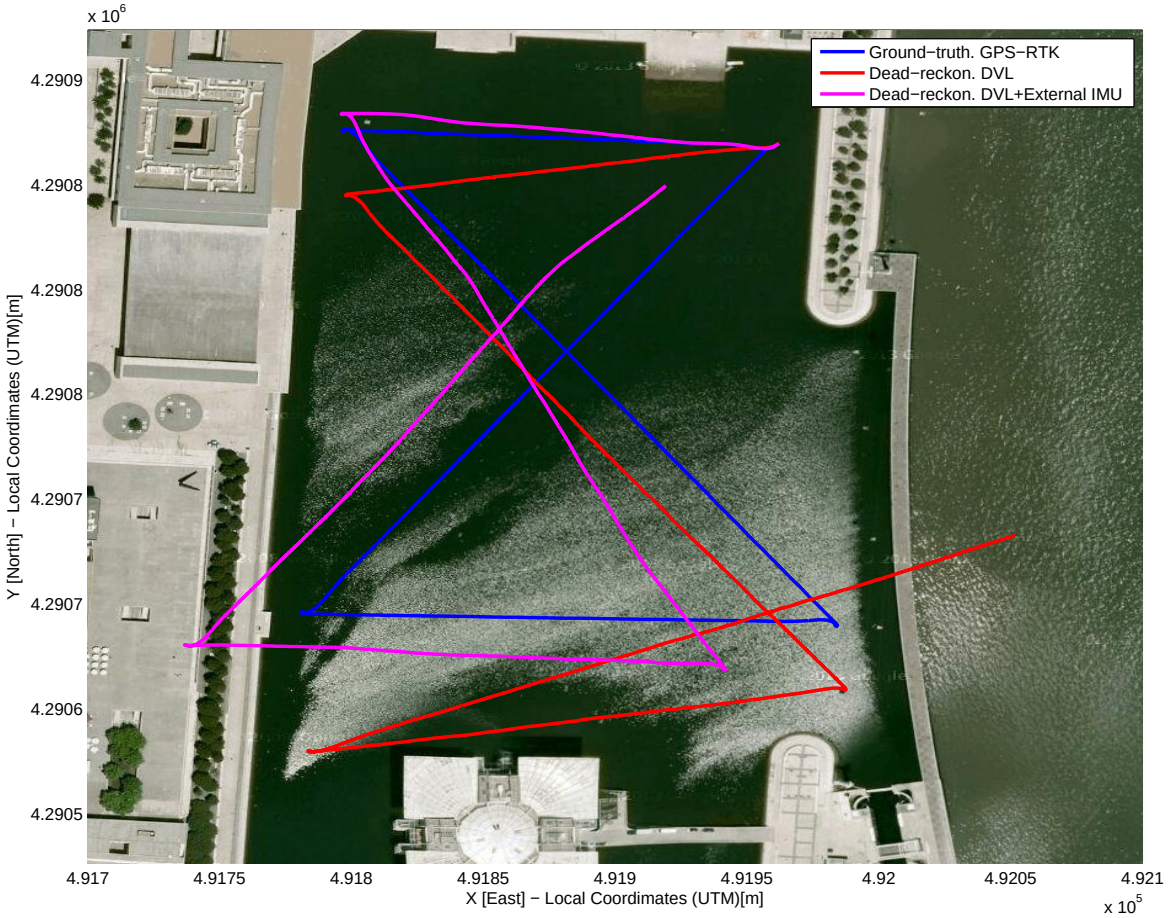
TAN /DVL Implementation



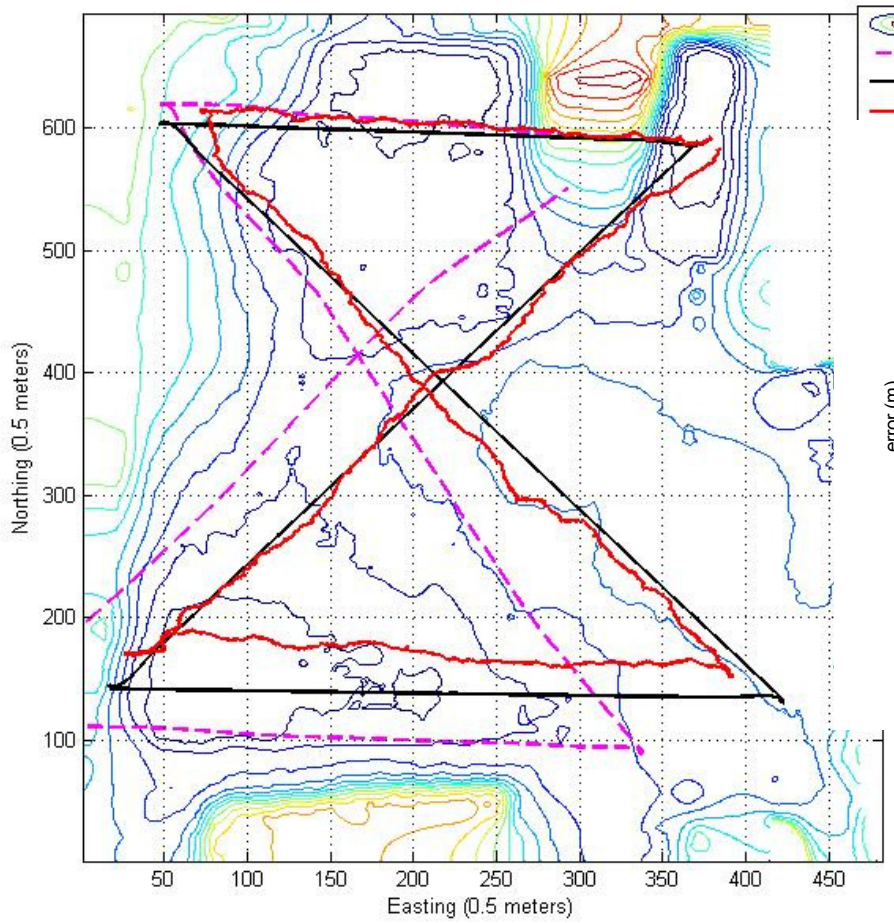


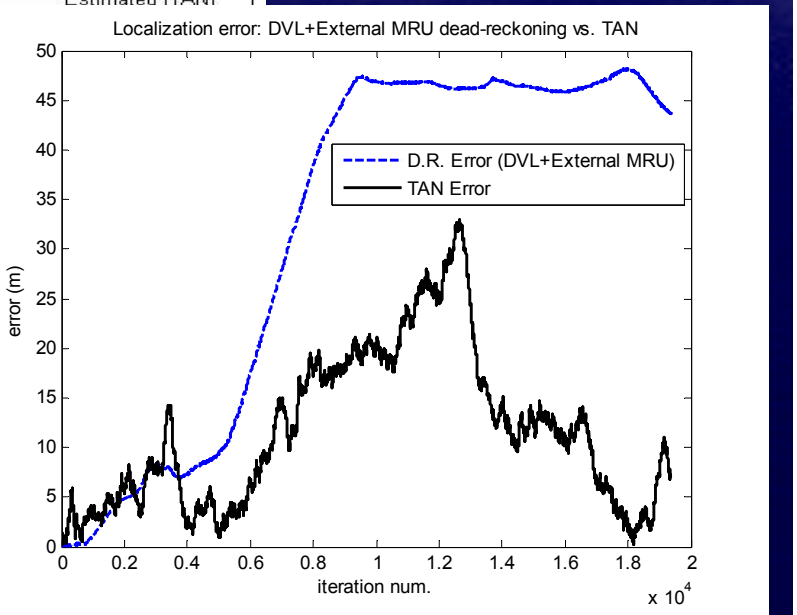


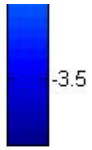
Deadreckoning /DVL Implementation



TAN /DVL Implementation

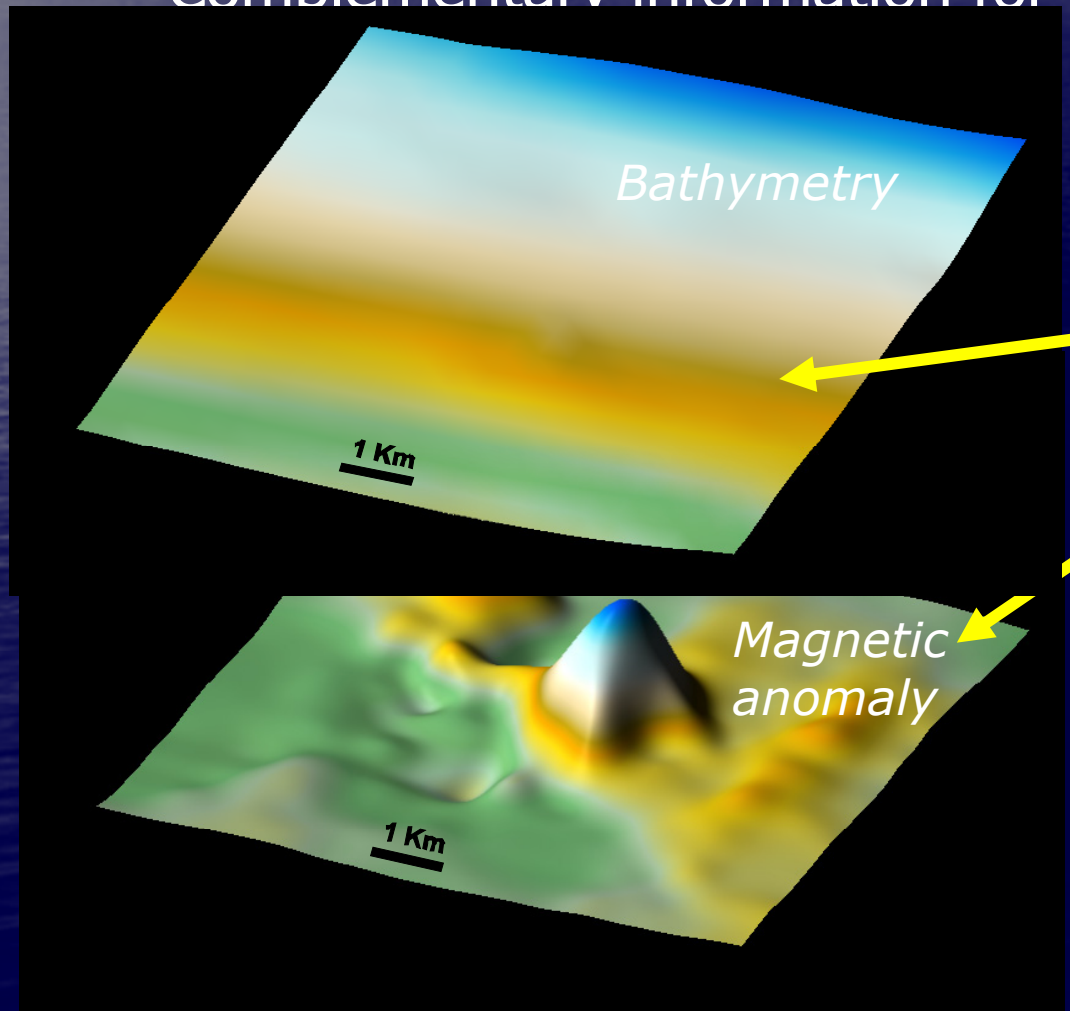


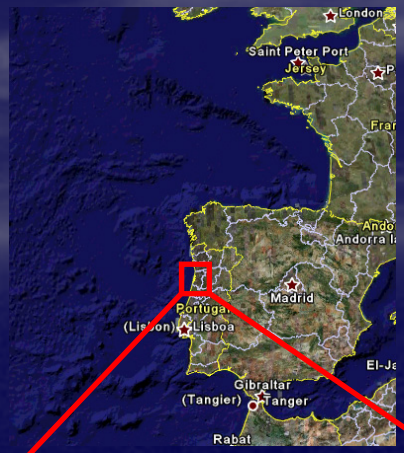


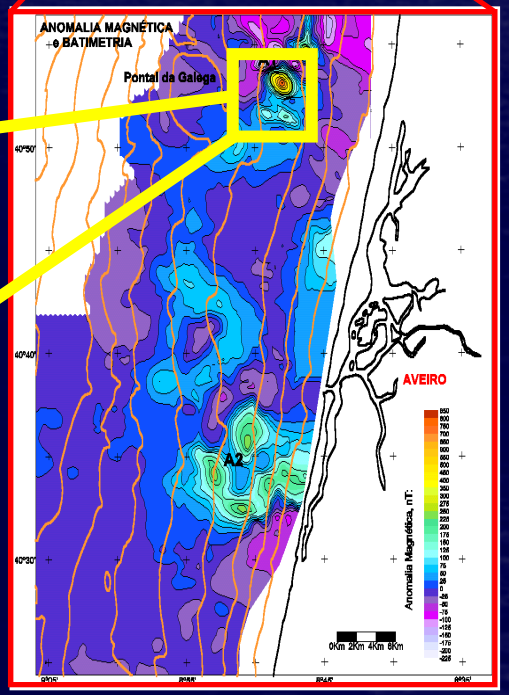


Magnetic Navigation (MN)

- **Main motivation**
  - Complementary information for TAN







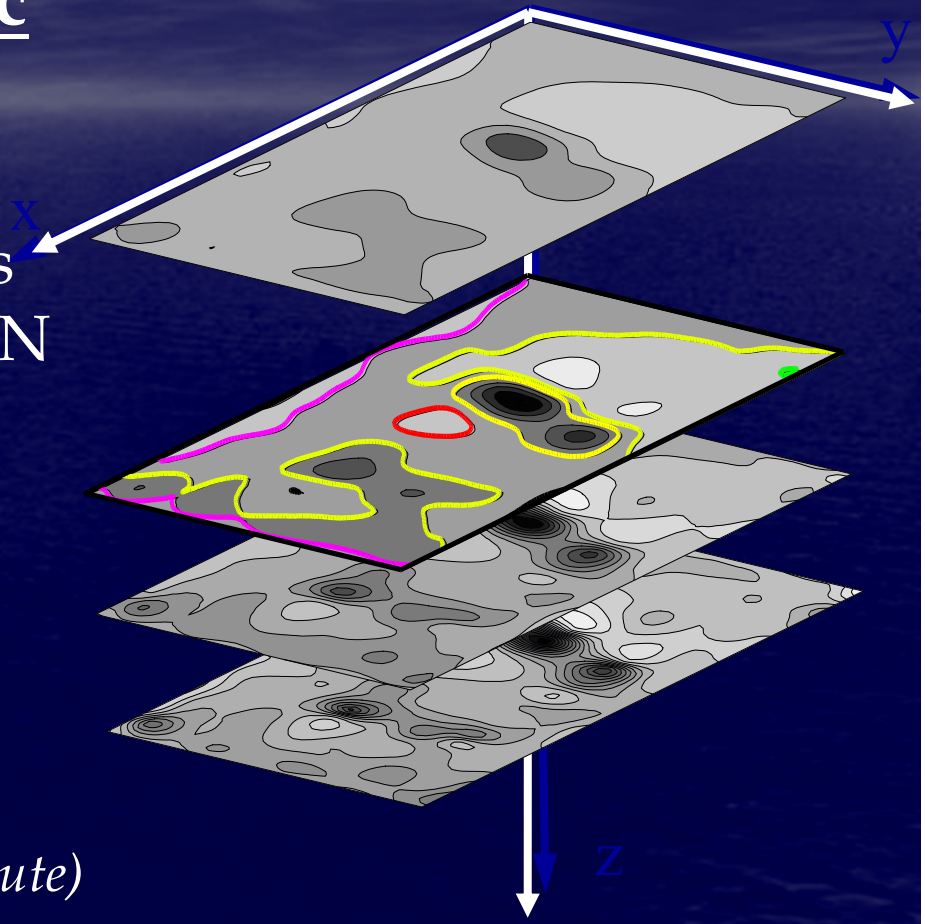
Magnetic Navigation (MN)

- **"Proof of concept"**
  - Used by animals for long-range navigation

Magnetic Navigation (MN)

MN with prior magnetic maps

- Maps based on 2D grids do NOT apply to 3D MN
- Nonlinear scaling of magnetic features with distance



Possible solution

- *Navigation at* ***constant*** *(absolute)* ***altitude***
- *Use* ***2D maps*** *for a given altitude*

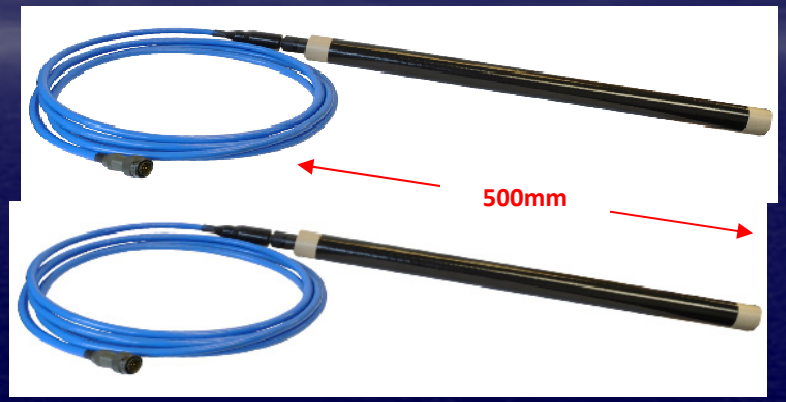
Magnetic Navigation (MN)

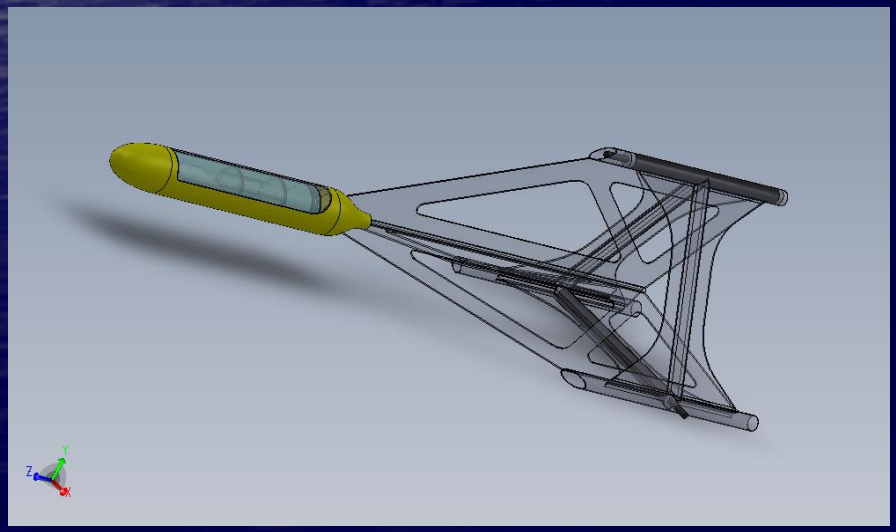
The problem of ambient and vehicle noise suppression

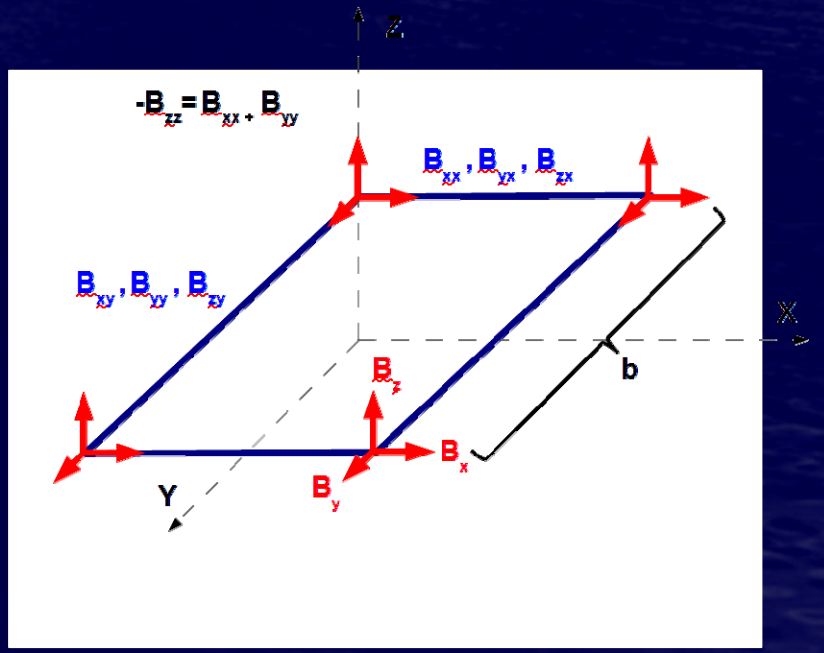
- *Tow the magnetometer*
- *Use a mag. gradiometer*

Magnetic Navigation (MN)

- Sensors used (mags, gradiometers)

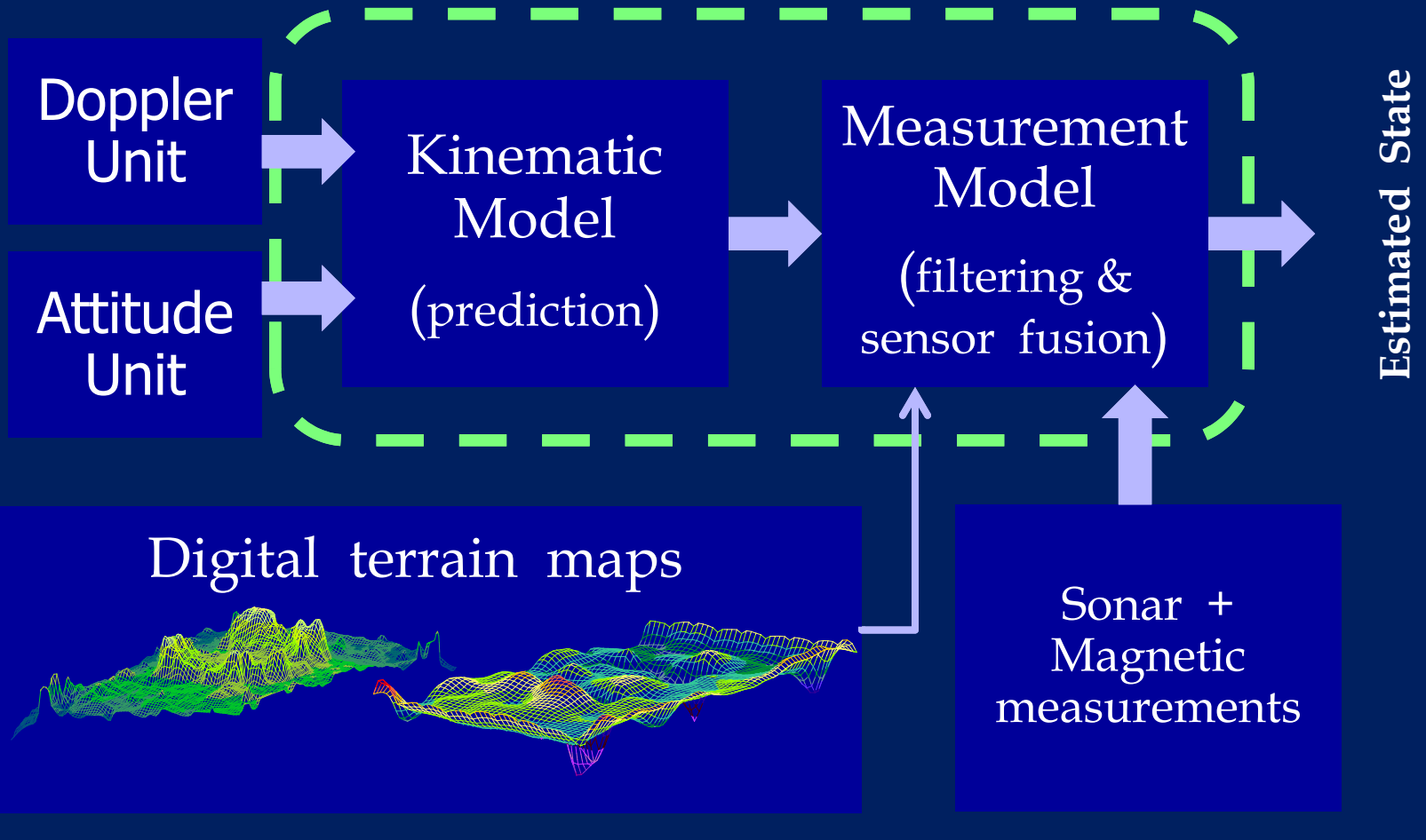




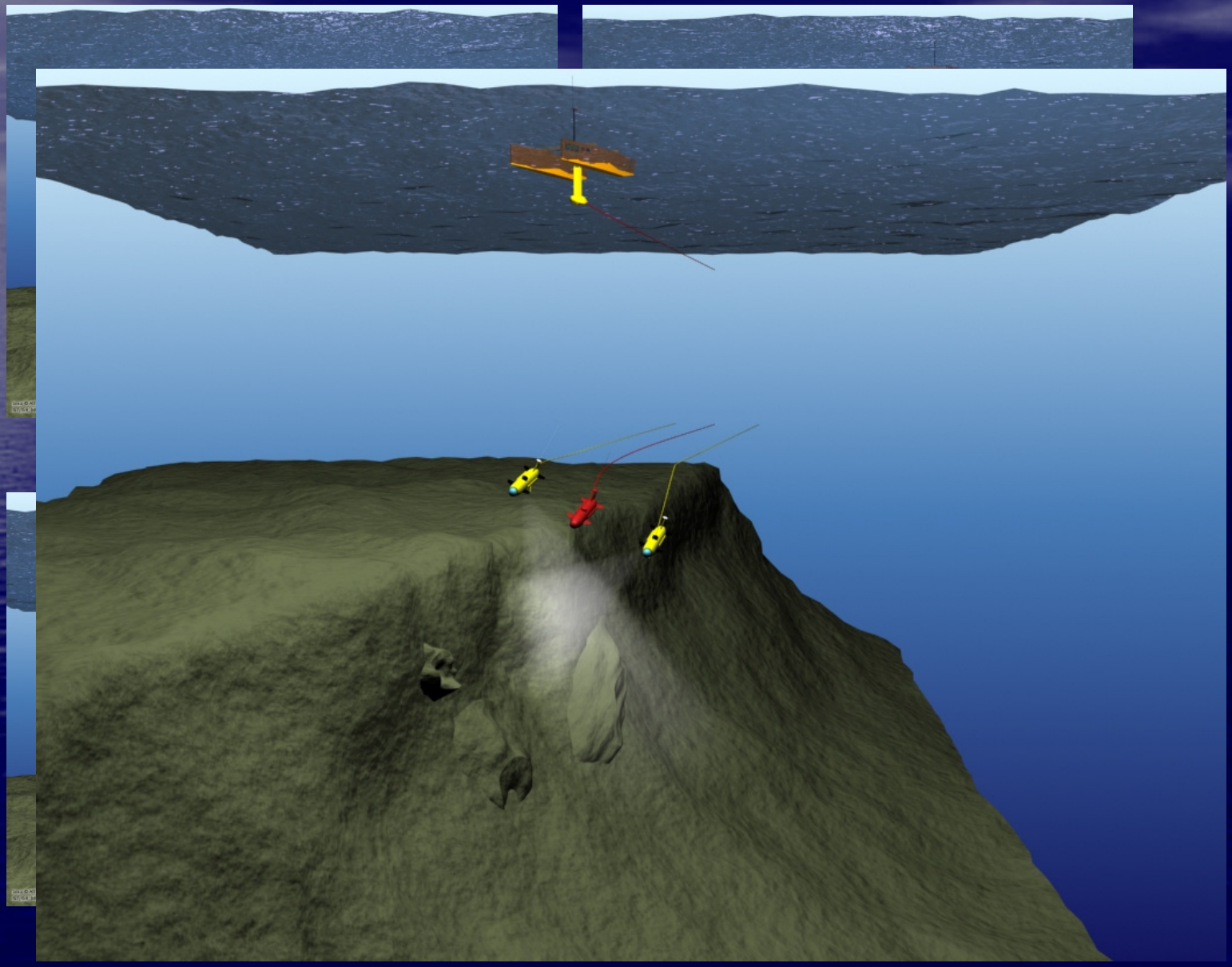


Magnetic Navigation (MN)

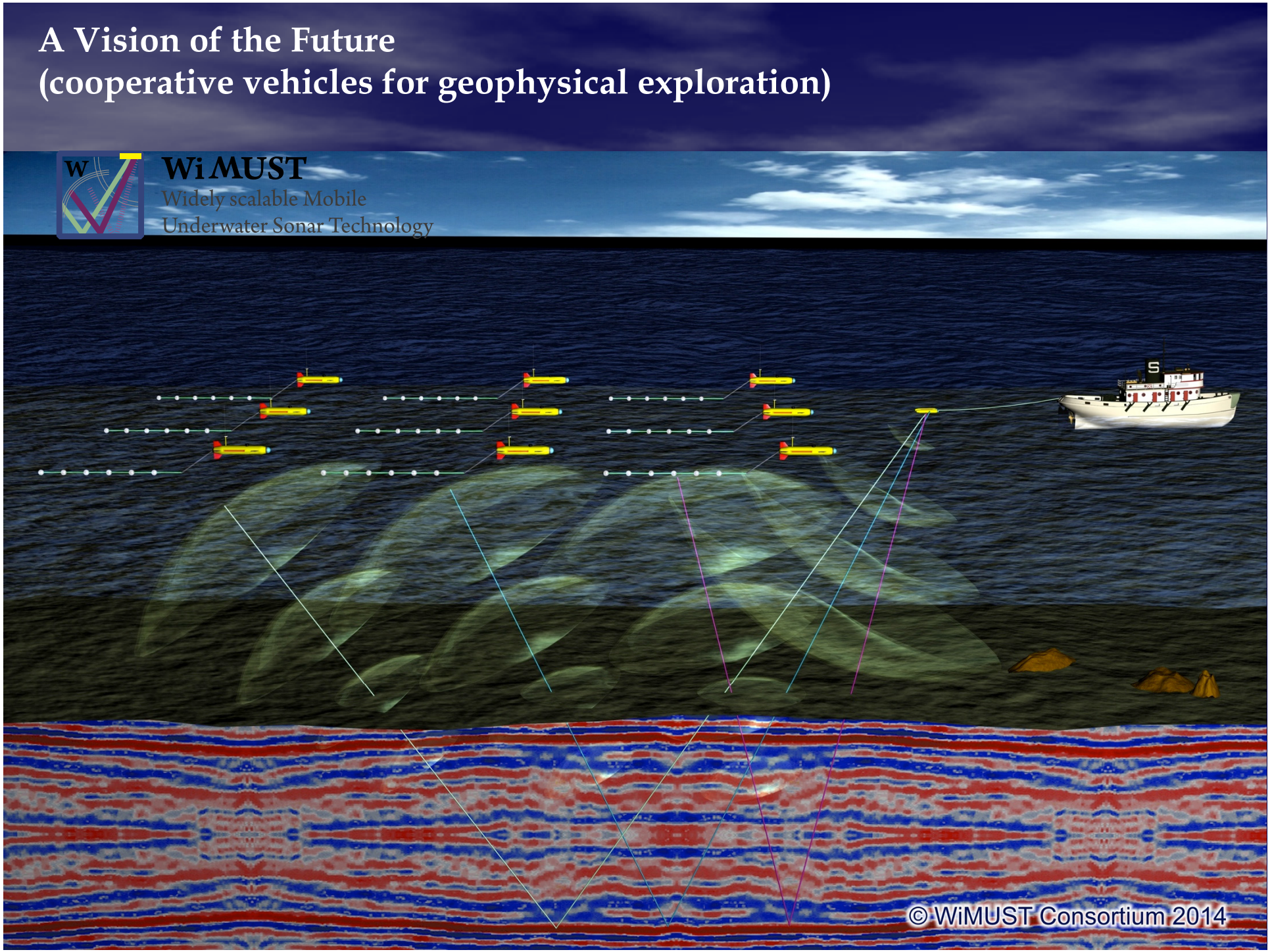
Integrating bathymetry and geomagnetics



The future: on-line reconfigurable vehicles



A Vision of the Future
(cooperative vehicles for geophysical exploration)



A Vision of the Future
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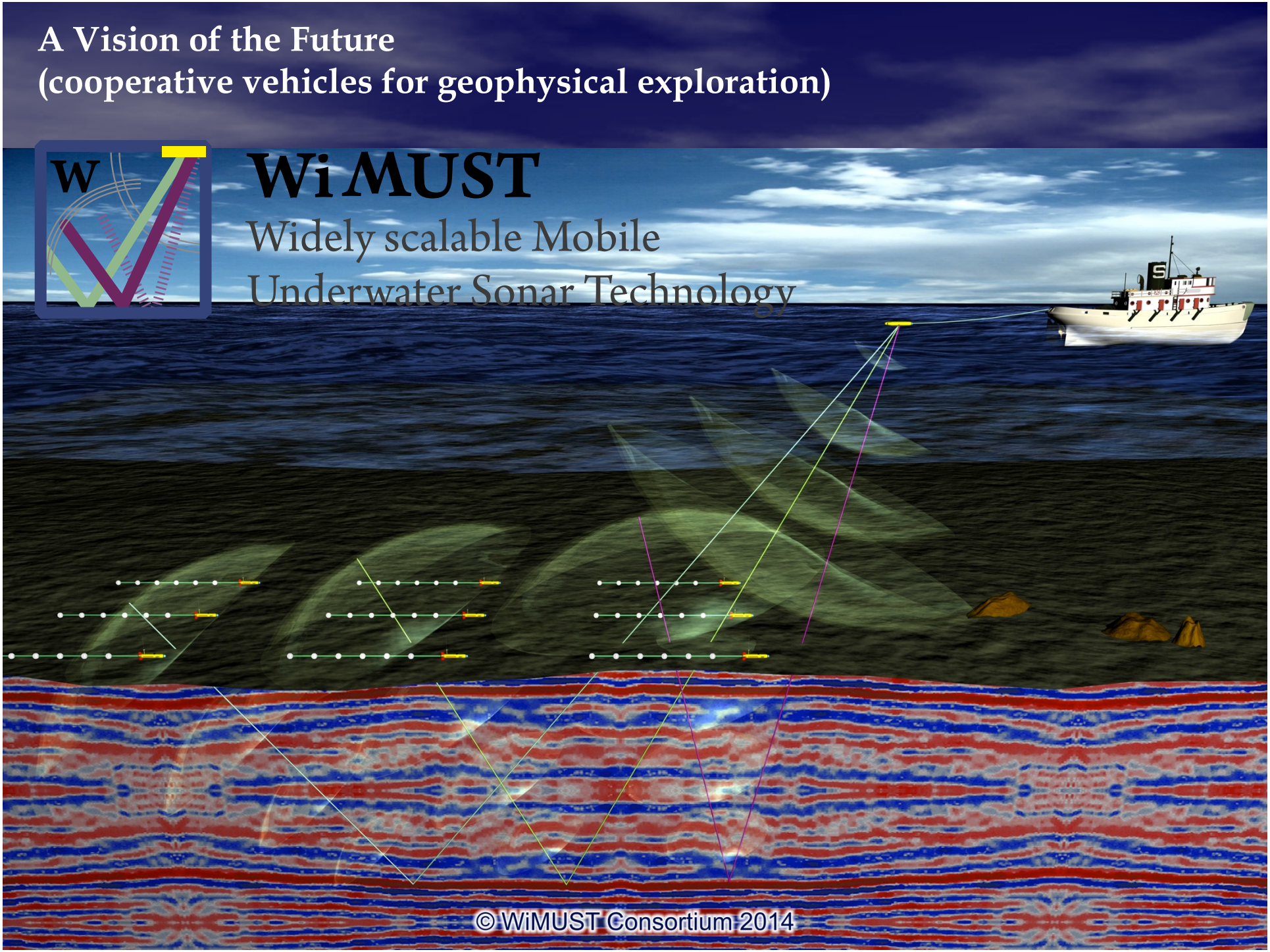
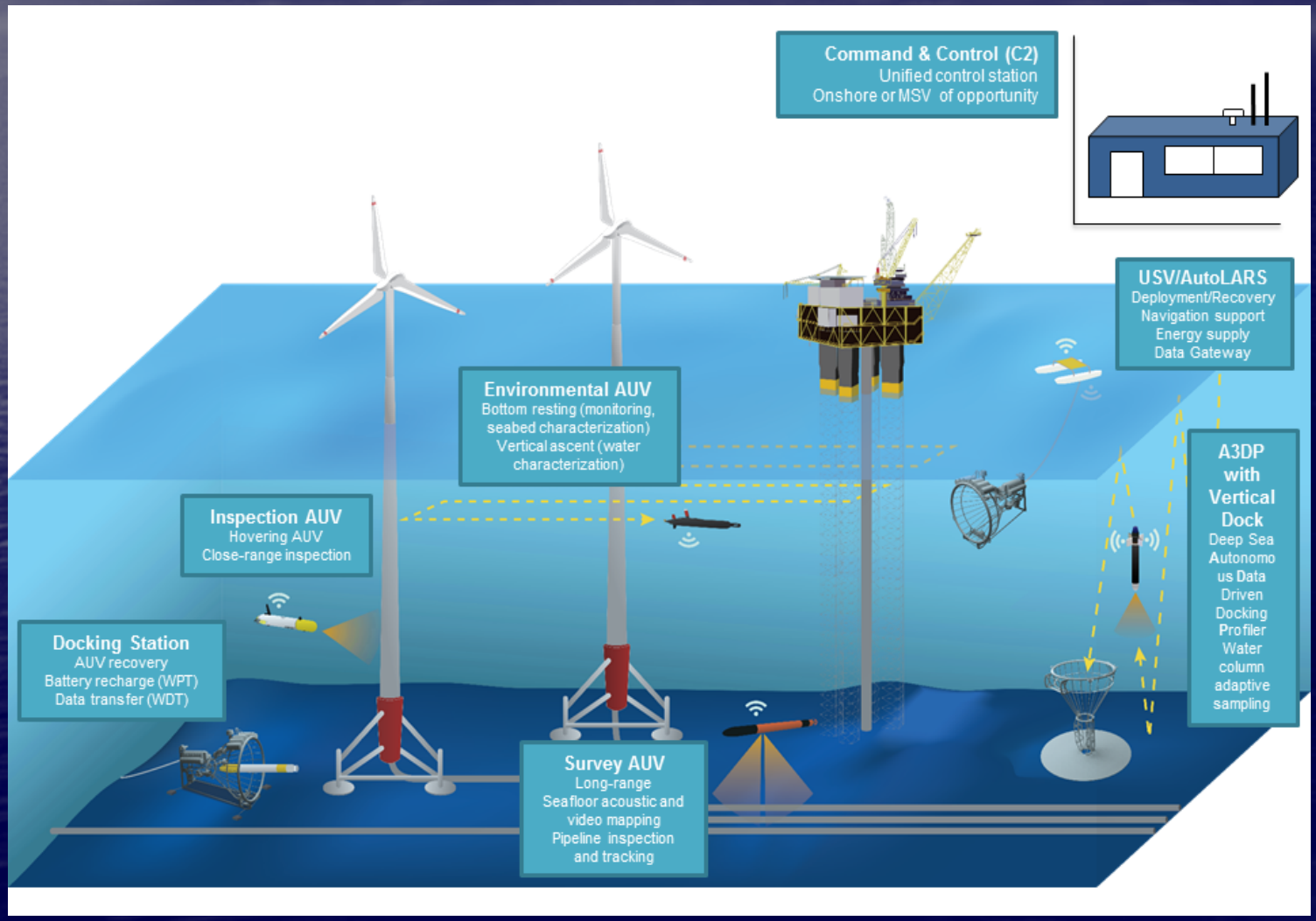


A vision of the future

Sustained presence in the Ocean (an European collaborative effort – Horizon 2020 proposal, 2014)



The future: Robots and humans in the loop & Cooperative robots for ocean resources E&E (e.g, oil exploration and deep sea mining)

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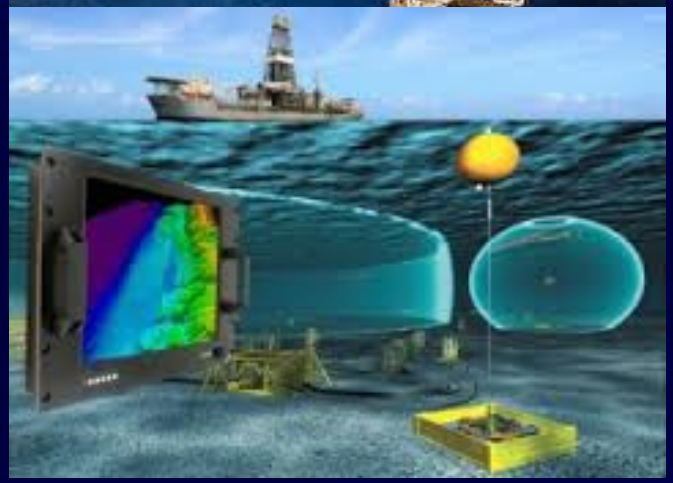

Estimated State

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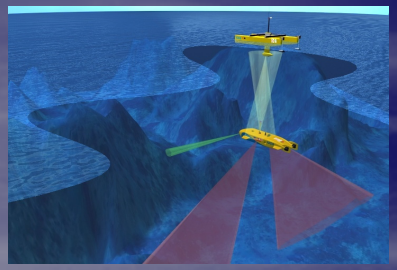

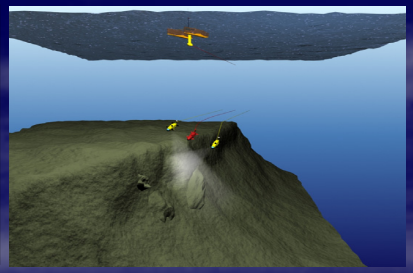


Cooperative Motion Planning, Navigation, and Control of Multiple Autonomous Marine Vehicles: Robots and Humans in the Loop

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