Marine Systems & Robotics
Cooperative Marine Robotic Systems: Theory and Practice – Part 2

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

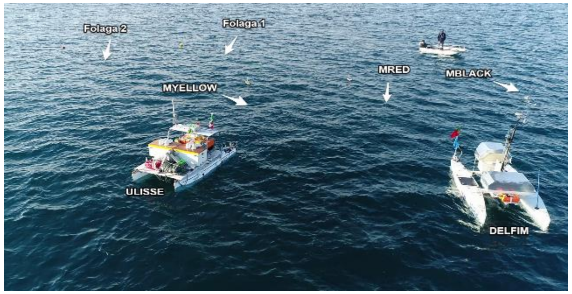
The WiMUST Coop. NC Architecture

Objectives

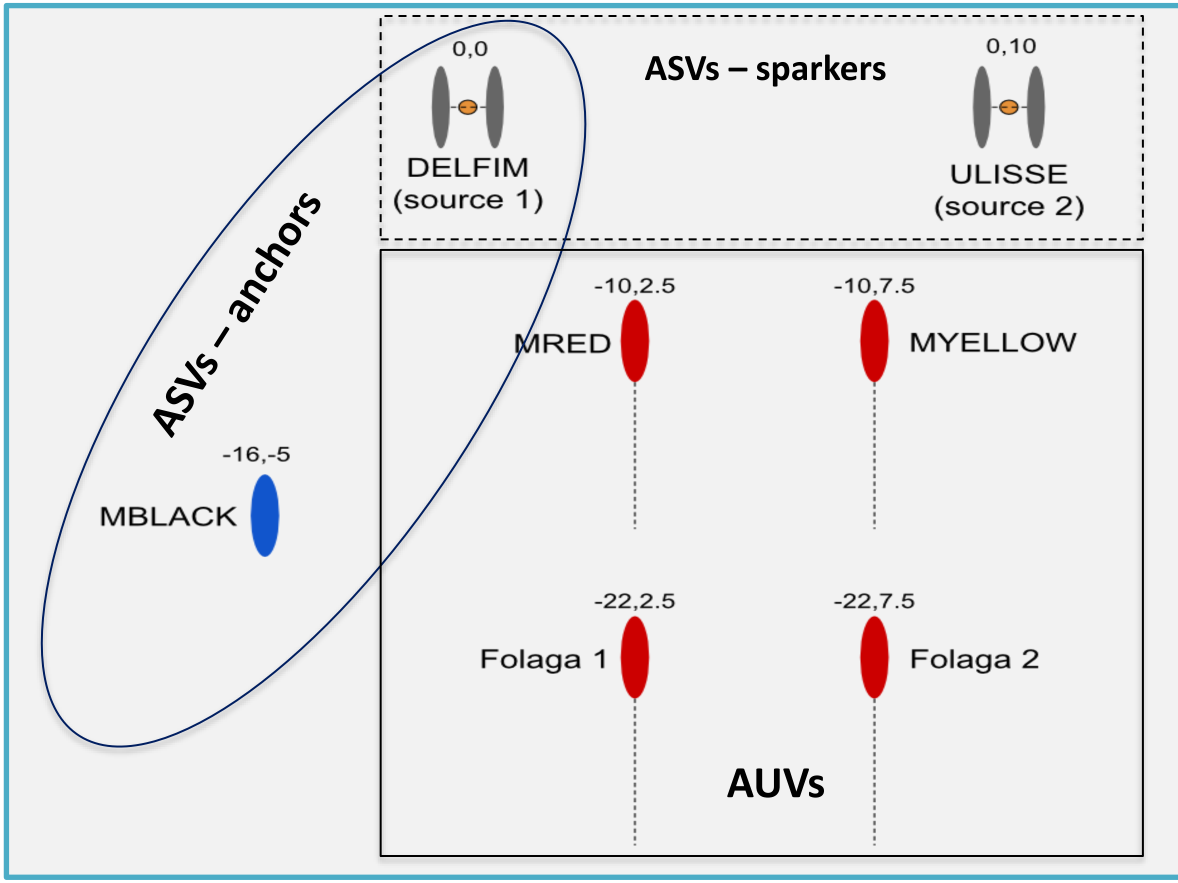
Design and performance analysis of the systems required to afford the WiMUST fleet the capability to execute cooperative missions for seismic data acquisition.

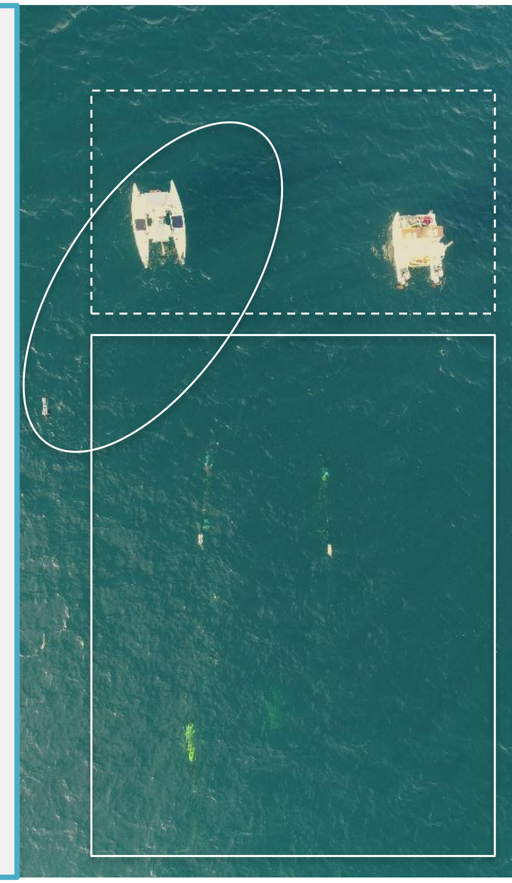
Tasks

- Cooperative Navigation
- Cooperative Motion Control
- Cooperative Motion Planning



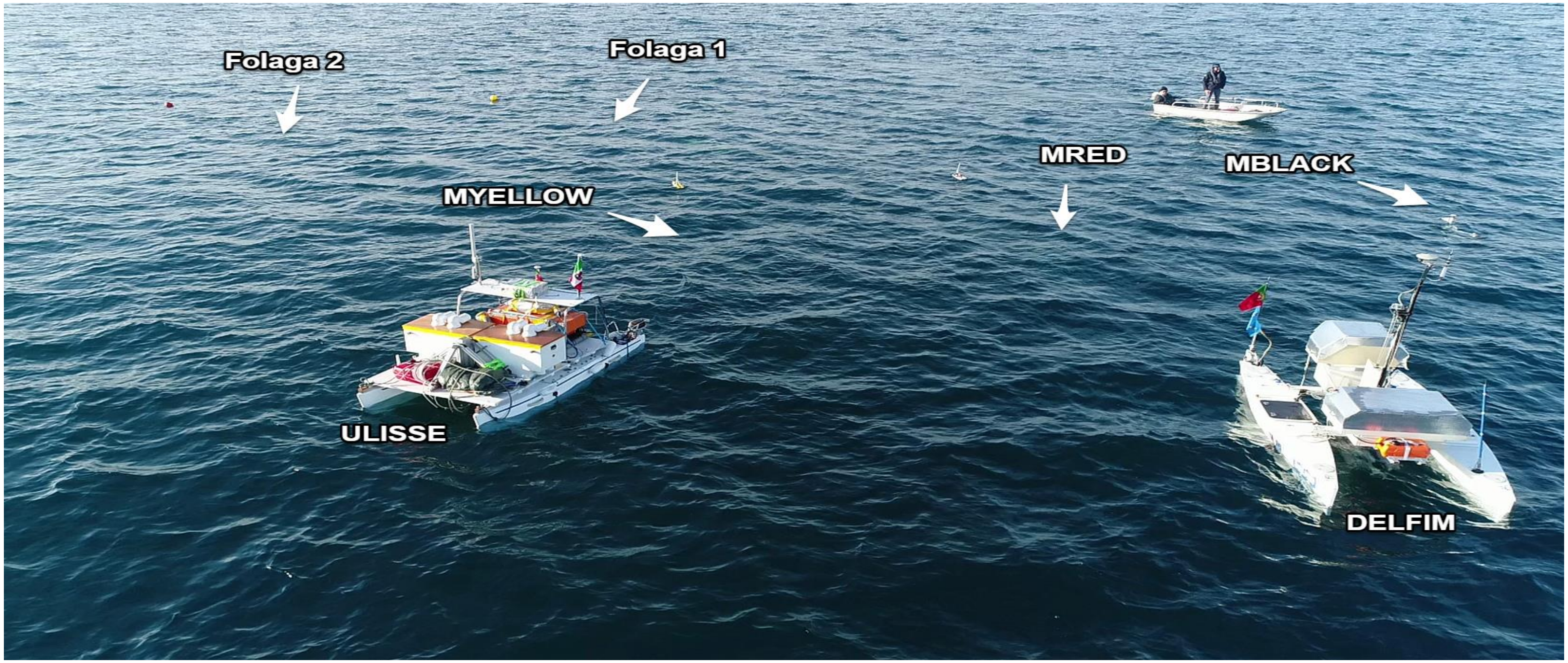
Multiple Vehicle Formation Control





Key practical objective: multiple vehicle formation for automated seismic surveys

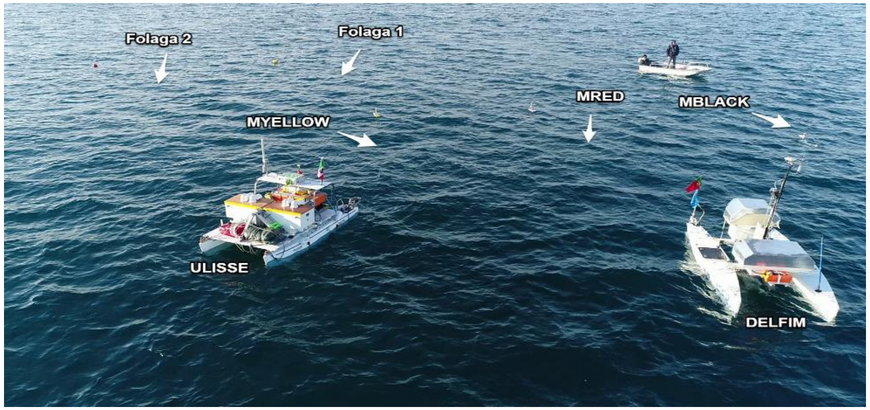
Basic Building Blocks

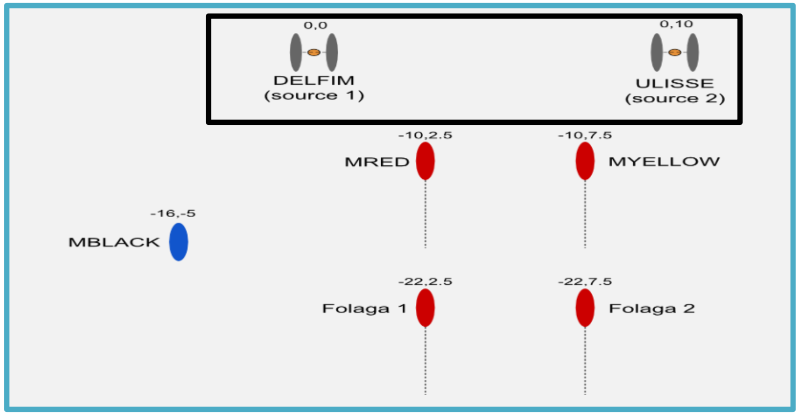


Basic building blocks

- 2 **Acoustic sources**: **Delfim and Ulisse ASVs**
- 2 **Anchors** and **Distributed acoustic receiver array**: Delfim and Medusa Black ASVs, **Folaga 1** and **Folaga 2 + Medusa Red** and **Medusa Yellow AUVs**

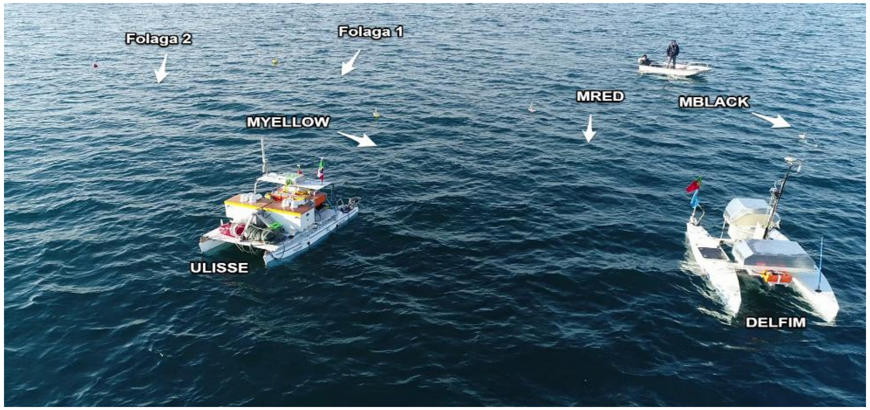
Enabling Multiple Vehicle Primitives

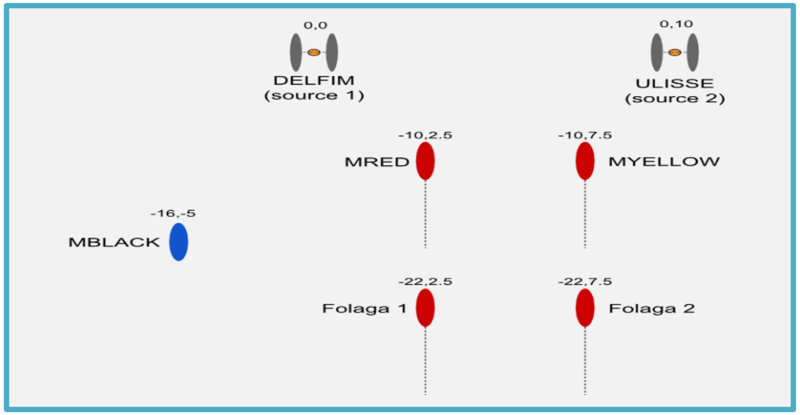




- DEFIM and ULISSE "set the pace" for the group of ASVs and follow pre-specified paths alongside, executing a **Cooperative Path Following (CPF)** maneuver.
- **Delfim is the reference vehicle:** it transmits it successive positions to the AUVs and to the Medusa Black ASV.

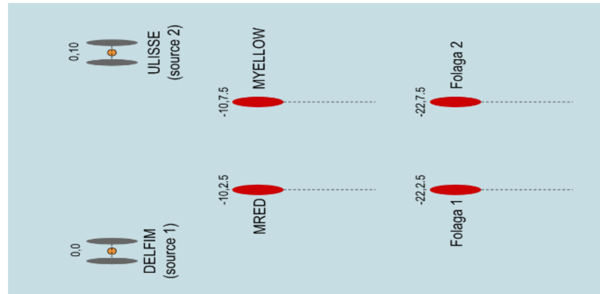
Enabling Multiple Vehicle Primitives

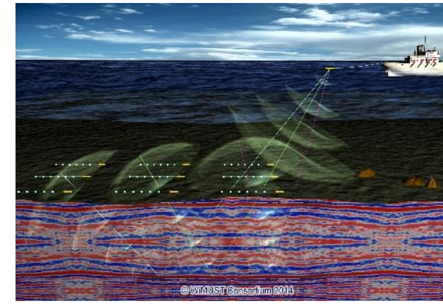




- The AUVs and Medusa Black track spatially “shifted replicas” of the DELFIM trajectory by executing a **Coordinate Trajectory Tracking (CTT)** maneuver.

Cooperative Navigation





Objective

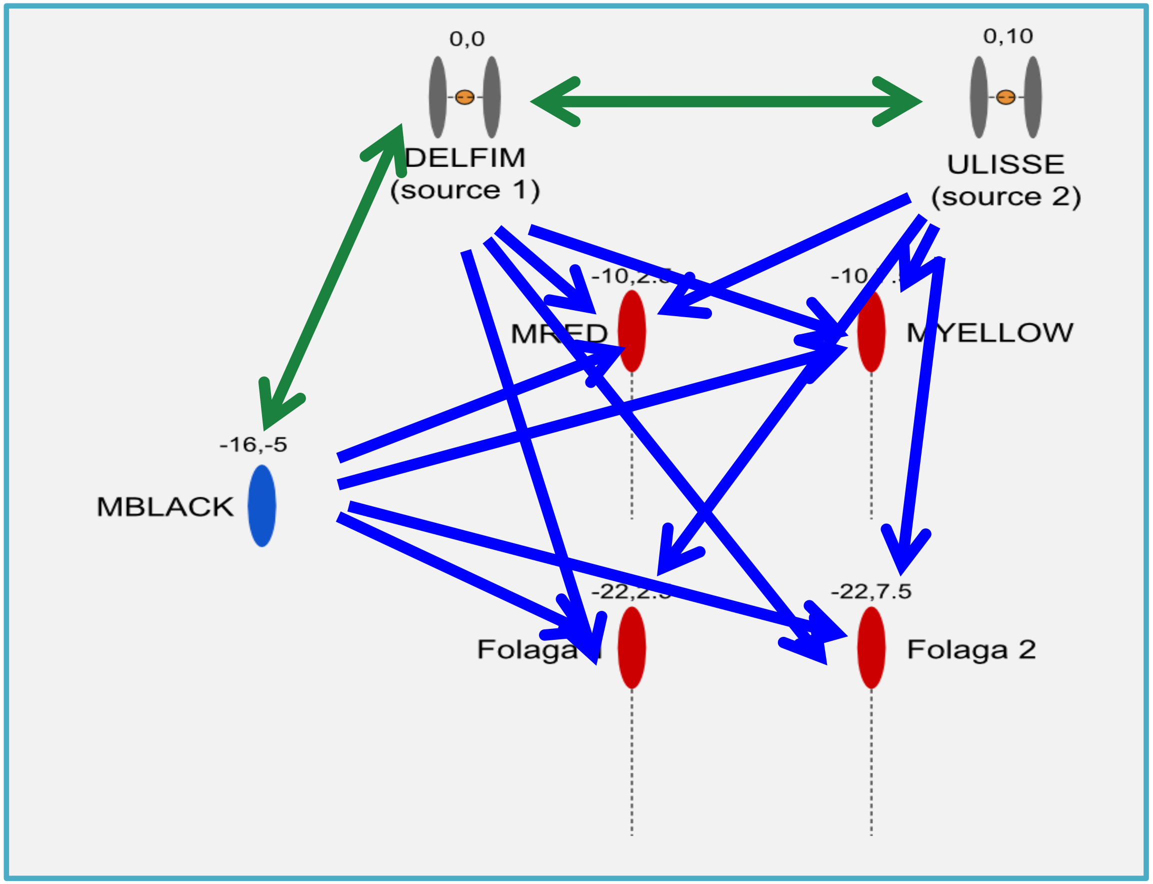
Geo-reference the vehicle fleet and the streamer hydrophones

Where are the vehicles? Where are the hydrophones?

Practical constraints

- Rely strongly on acoustic inter-vehicle ranging devices and internal motion sensors
- Avoid expensive inertial-like navigation units

Communications and Positioning Network



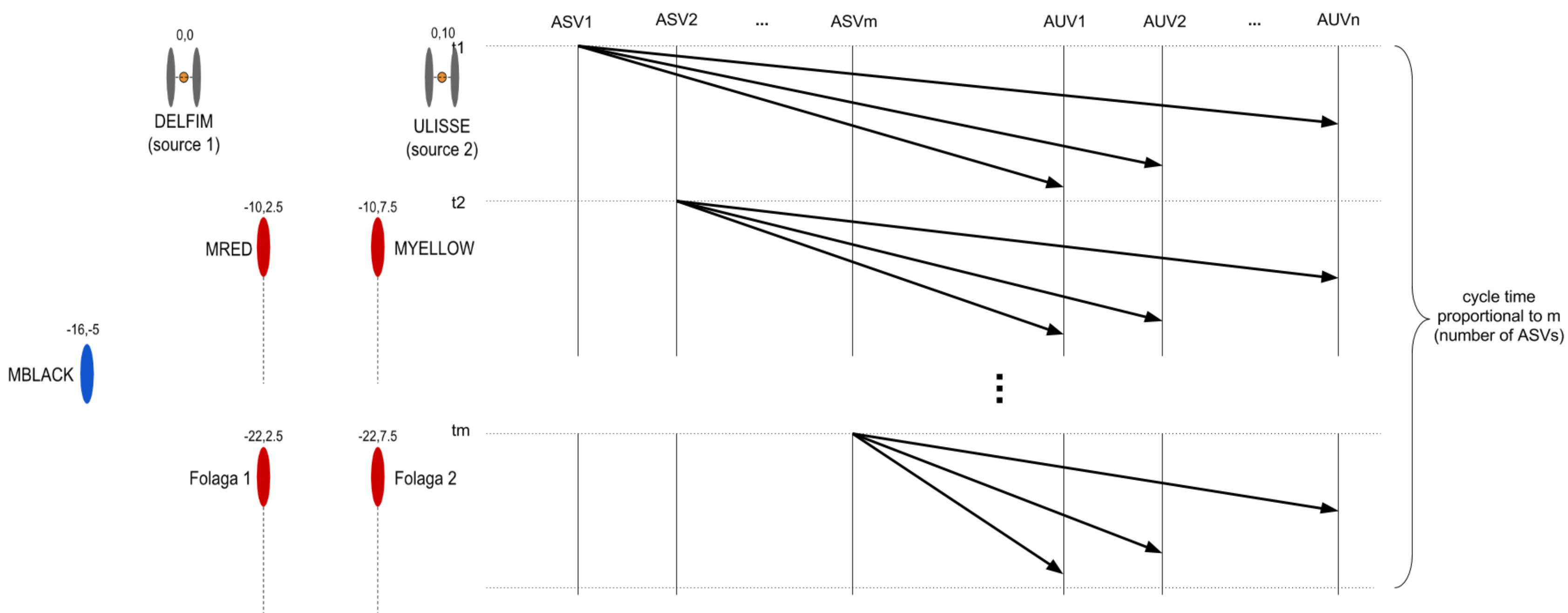
Acoustic Comms and Range measurements

Aerial Comms

Units with synchronized atomic clock: hardware of EvoLogics (GER)

Cooperative Navigation

Vehicle positioning: Acoustic Navigation Architecture

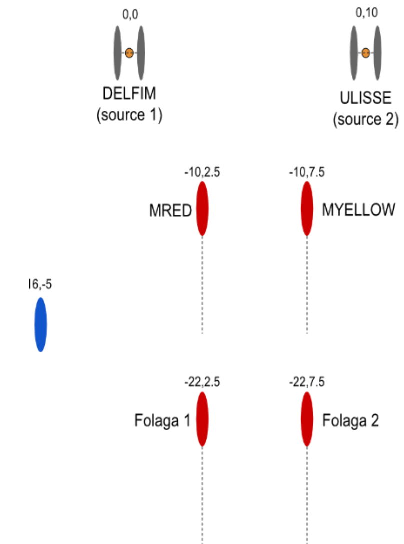


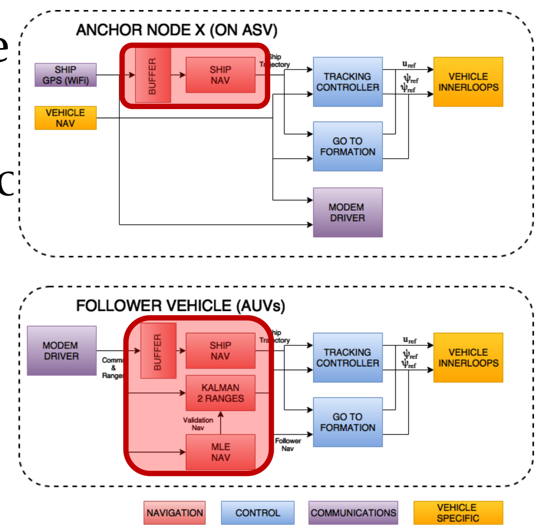
Anchors: agents capable of transmitting their global position via acoustic modems. Their placement should be favorable for localization purposes.

Cooperative Navigation

Vehicle positioning: Acoustic Navigation Architecture

- Each AUV obtains **ranges to the anchors and their global positions**
- **Scalable navigation**:
  - Acoustic cycle depends only on the number of anchors
  - For navigation, a minimum of two anchors are required
  - Navigation performance increases with the number of anchors
- Less dependence on high-end inertial navigatic units
- Extendable to **large numbers of AUVs**



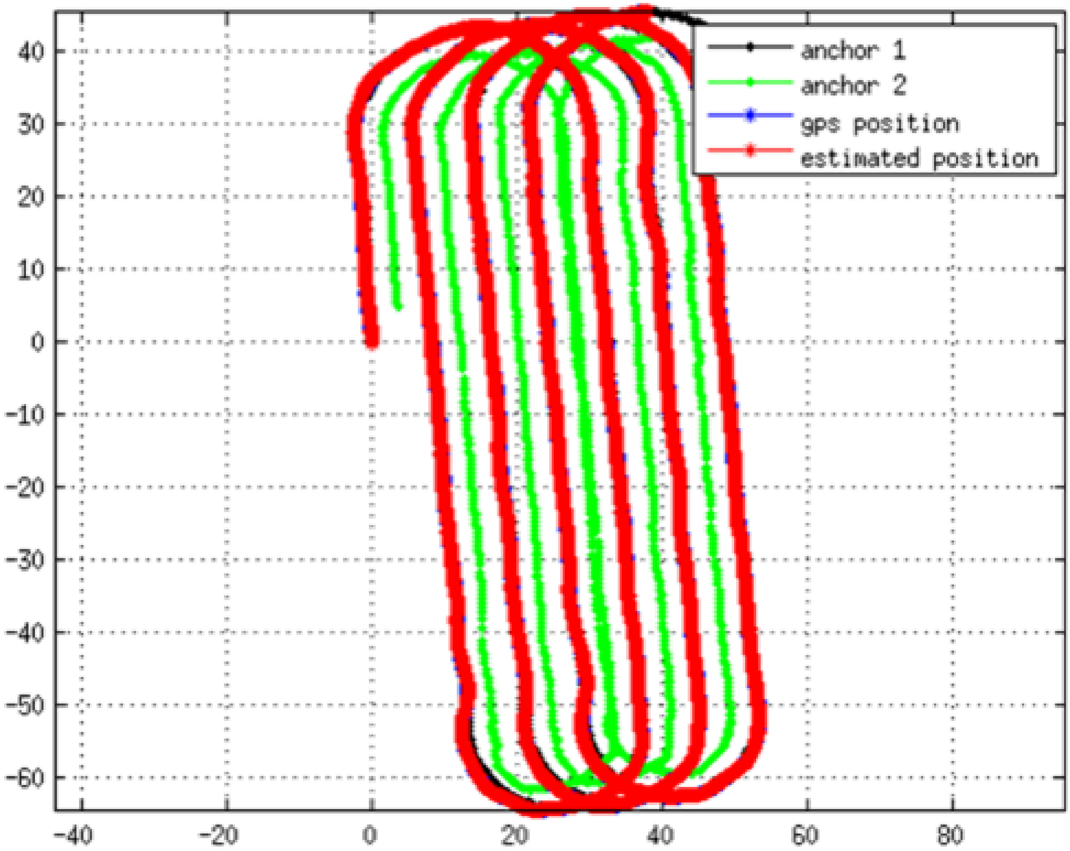


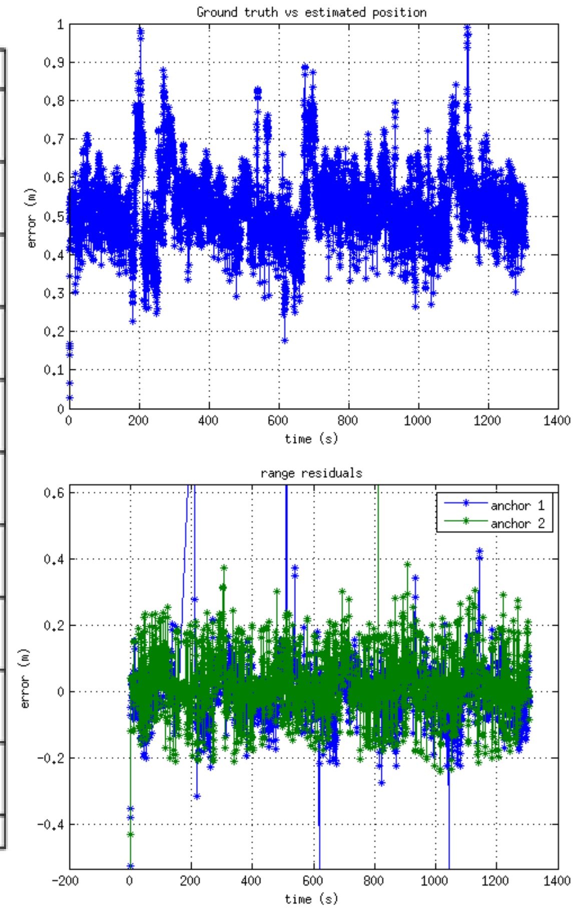
Theoretical Set-up:
Maximum Likelihood Estimation

Cooperative Navigation

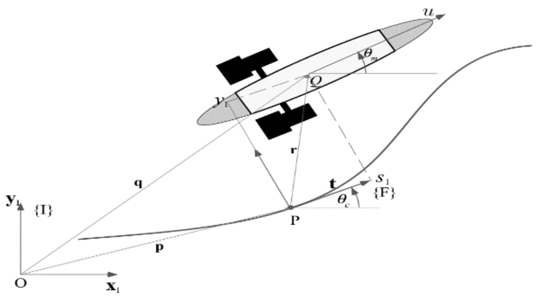
Extended Kalman filter for multiple anchor nodes

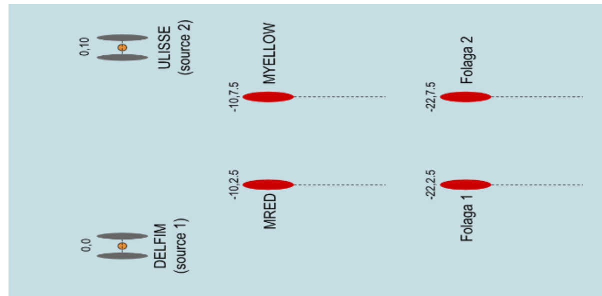
Sines Port Trials (2016/11/24) - Results

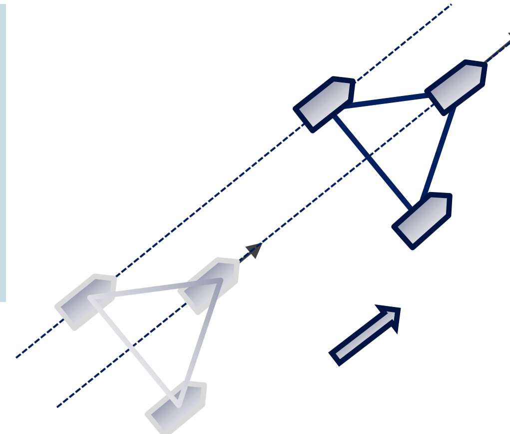




Cooperative Motion Control







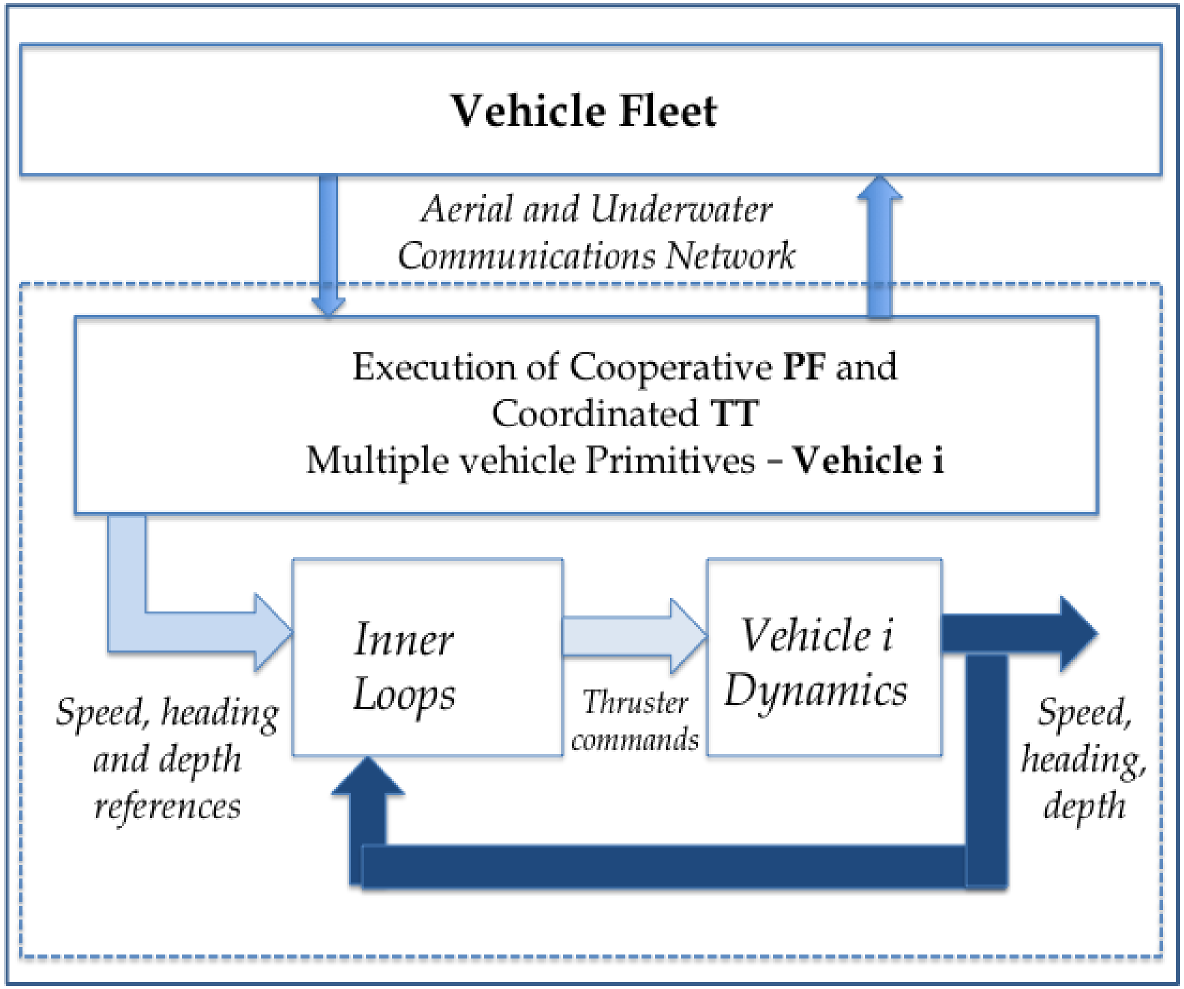
Objective

Lead the fleet to a desired geometric formation and change the geometry according to external commands

Practical constraints

- Heterogeneous vehicle fleet
- No fast communications among the underwater fleet

Cooperative Motion Control



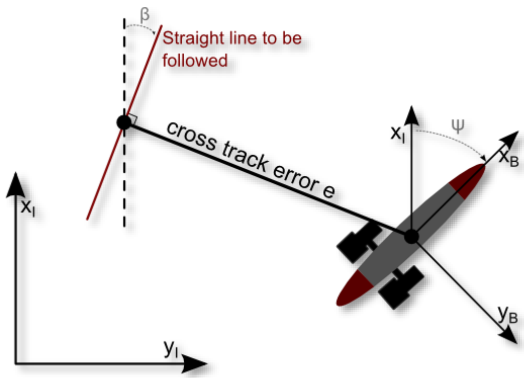
Multiple Vehicle Primitives

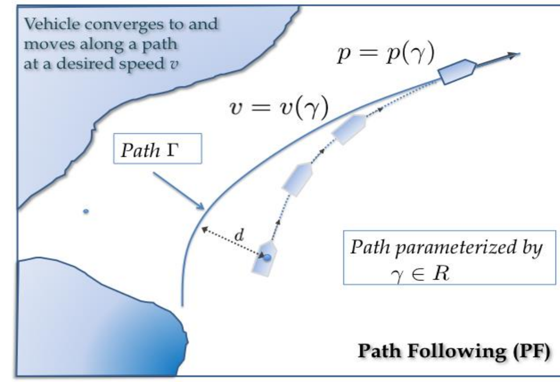
Single Vehicle Primitives

Single Vehicle Primitives

- **Inner-loop controllers**: track surge speed, heading and depth references
- **Waypoint**: go to point with specified coordinates, then hold position
- **Path Following**: converge to and follow a spatial path at a given speed profile
- **Trajectory tracking:** track a desired spatial curve parameterized by time

Path Following



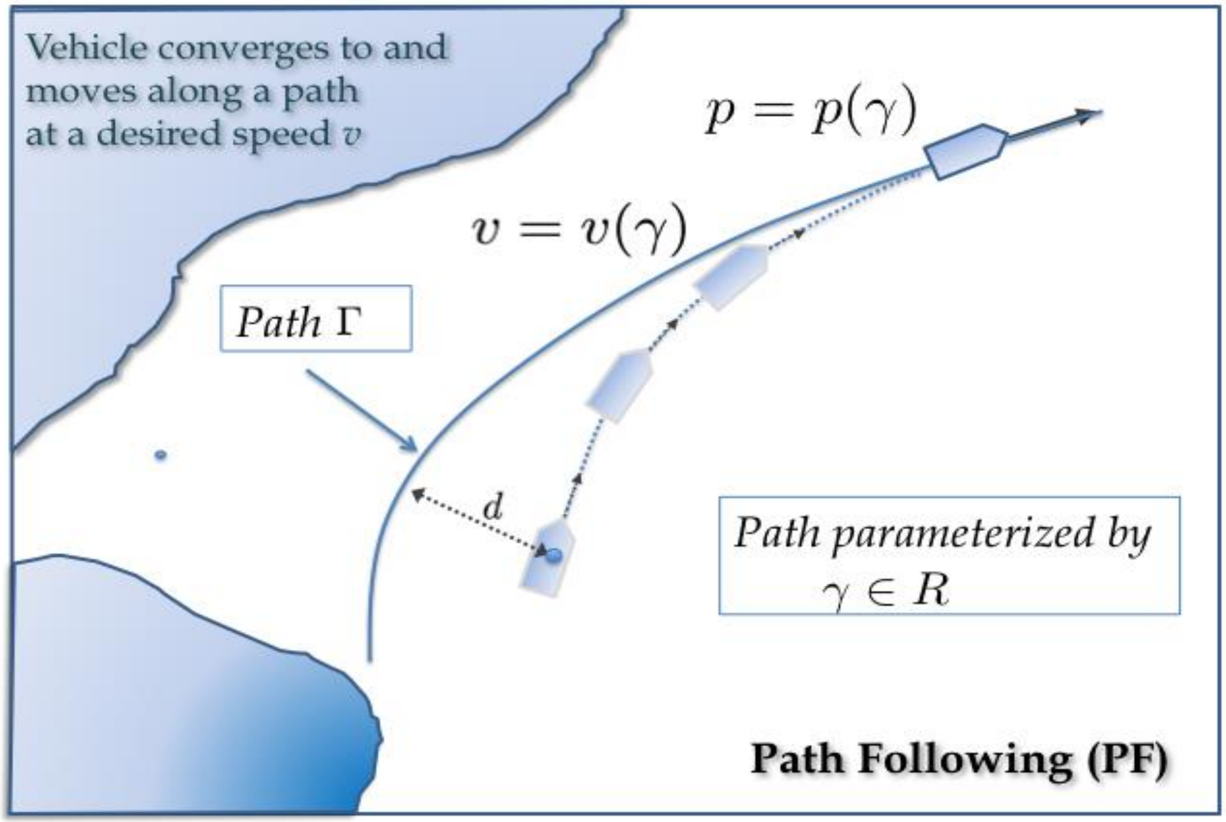


- Vehicle follows a path at a speed that may be path dependent (no explicit timing law)

- **Control strategy**

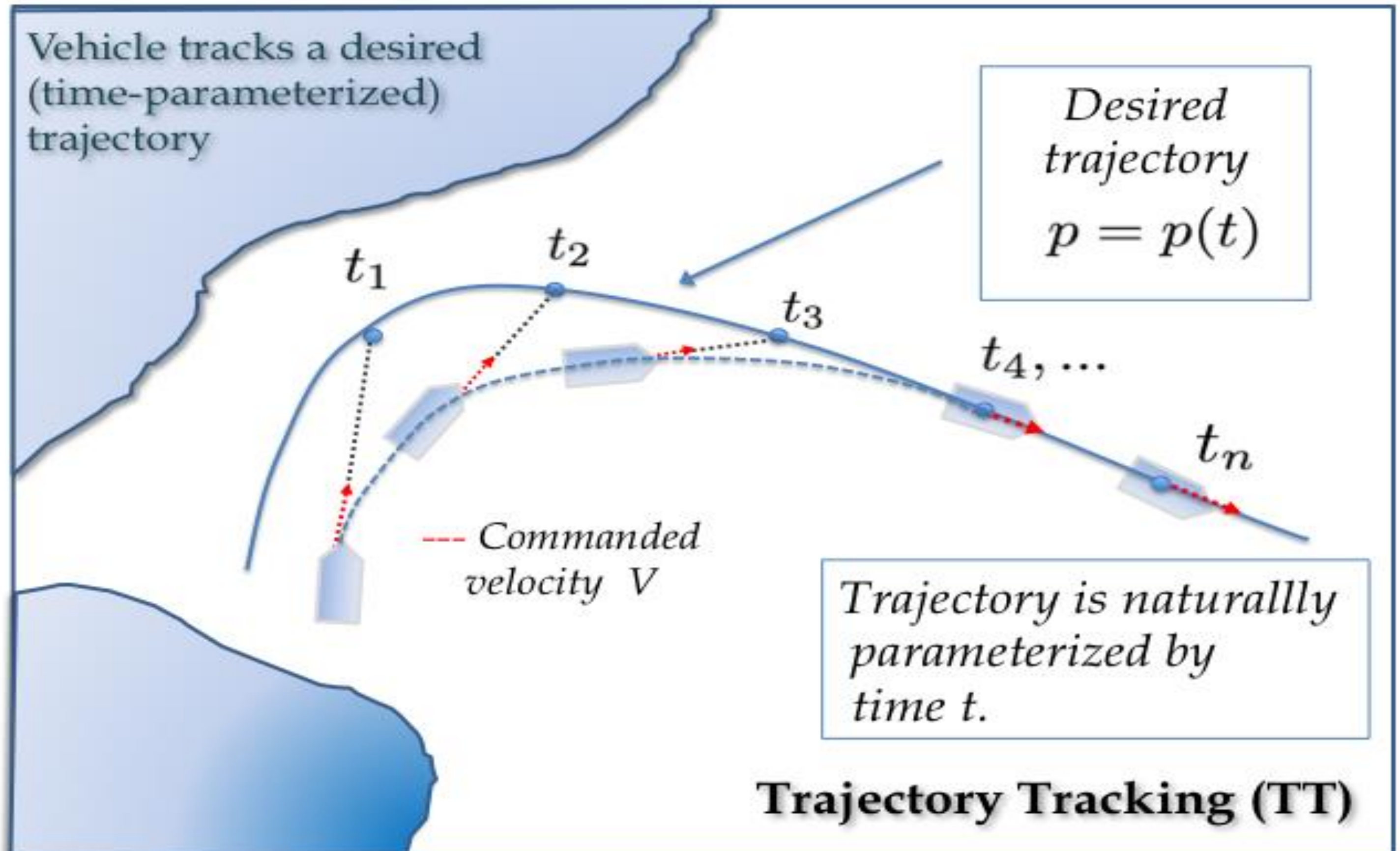
  - set longitudinal speed to prescribed value
  - set heading command to the direction of the path + correction for cross-track error

Path Following



Vehicle moves along a path at a desired speed. Path following algorithm issues speed and heading commands to the vehicle´s inner loops.

Trajectory Tracking

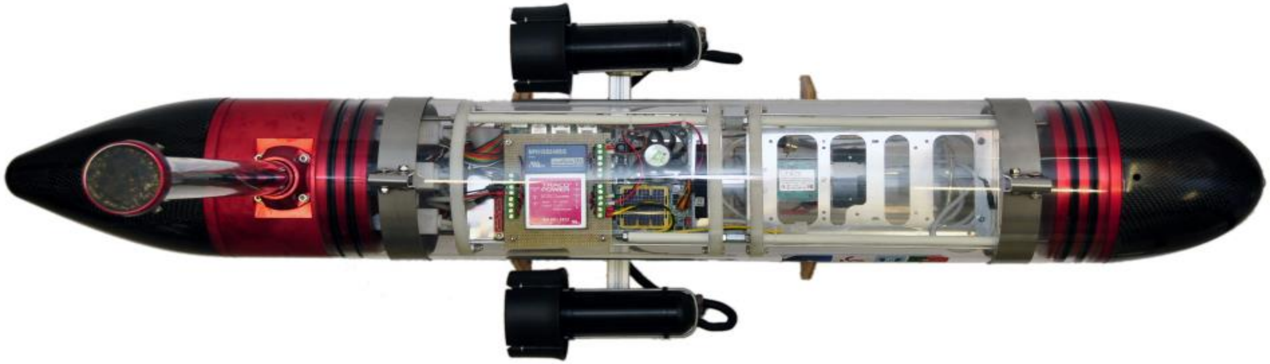


Vehicle tracks a desired trajectory

Single Vehicle Primitives

The DELFIM AUV –
Azores and Lisbon, PT

The MEDUSA class of AMVs

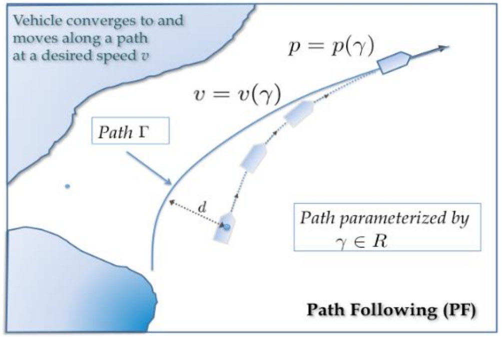


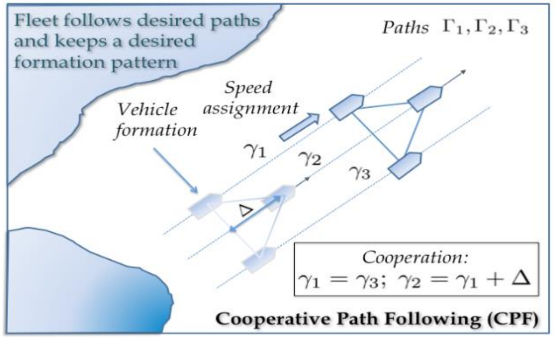
The MEDUSA HYBRID ASV/AUV – LISBON, PT

Path Following

WiMUST Cooperative N&C

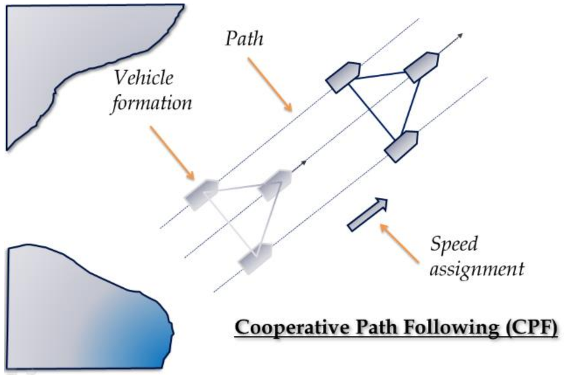
Multiple Vehicle Primitives

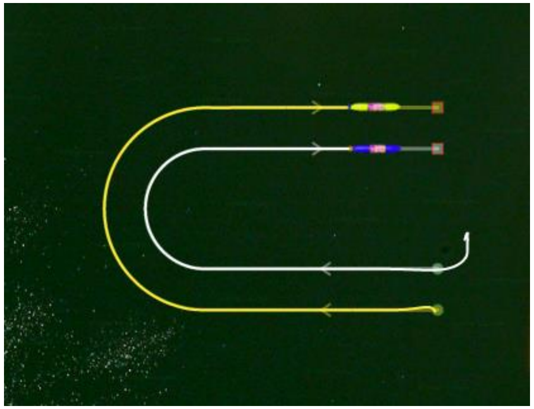




- Cooperative Path Following
- Coordinated TrajectoryTracking
- Cooperative Formation Control

Coperative Path Following

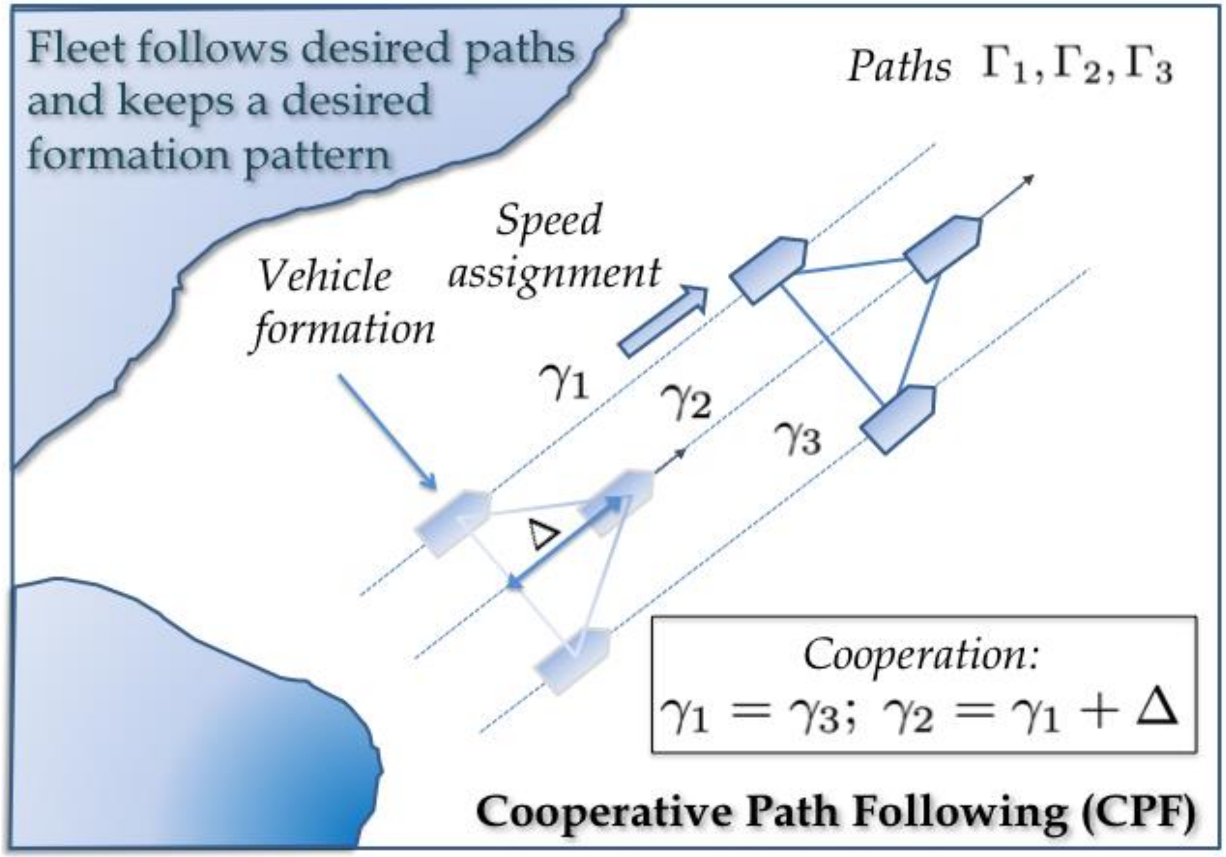




- Multiple vehicles following different paths
- *Define* normalized along-path coordinate γ for each path/segment (i.e. starting point γ =0, end point γ =*1*)
- At each cycle, each vehicle:
  - Broadcasts its current γ, receives γ*'s* from other vehicles
  - Computes average of all γ*'s* received, denoted γav
  - Adjust speed based on its $\gamma error = \gamma - \gamma av$

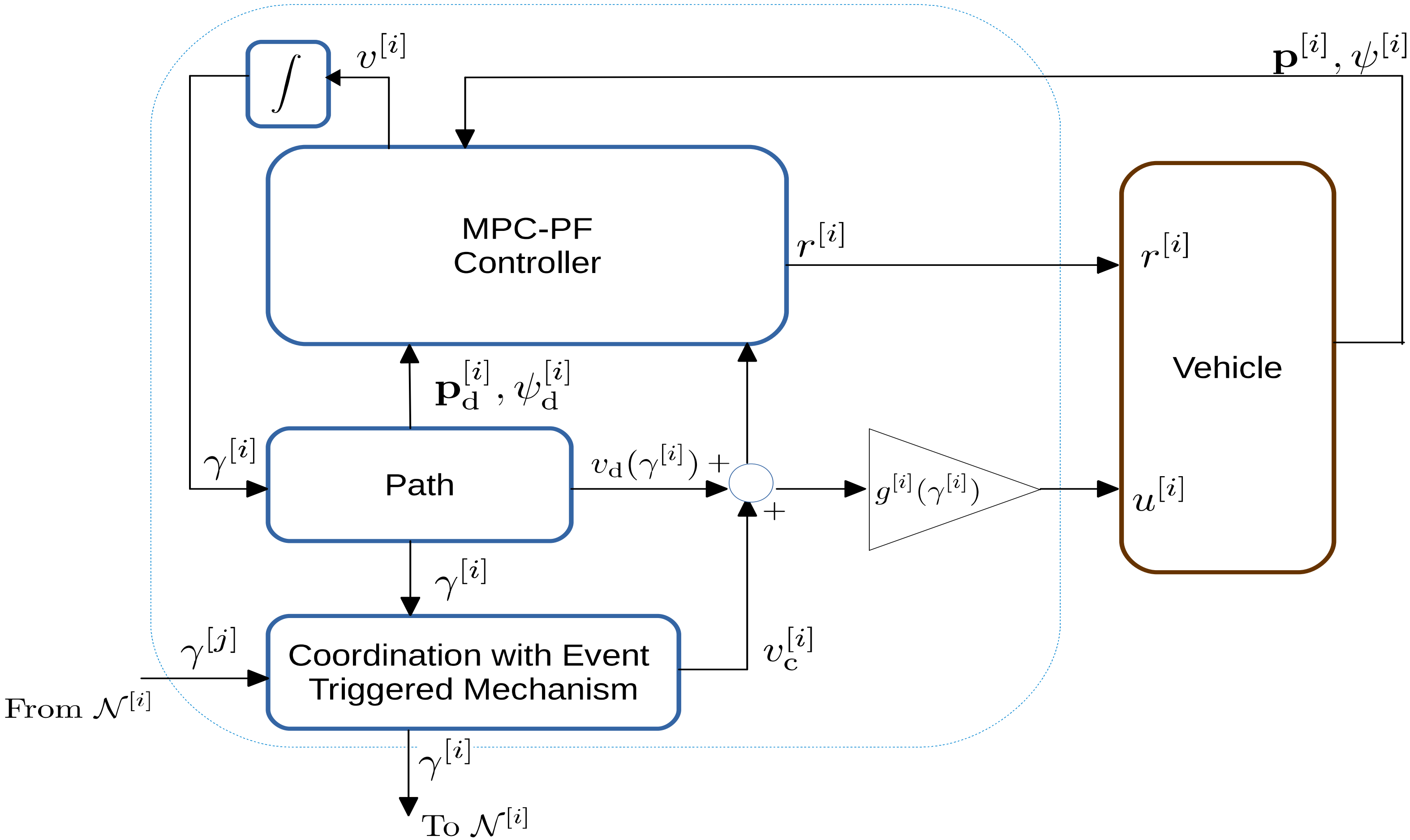
Vehicles reach consensus on path parameter γ!

Coperative Path Following



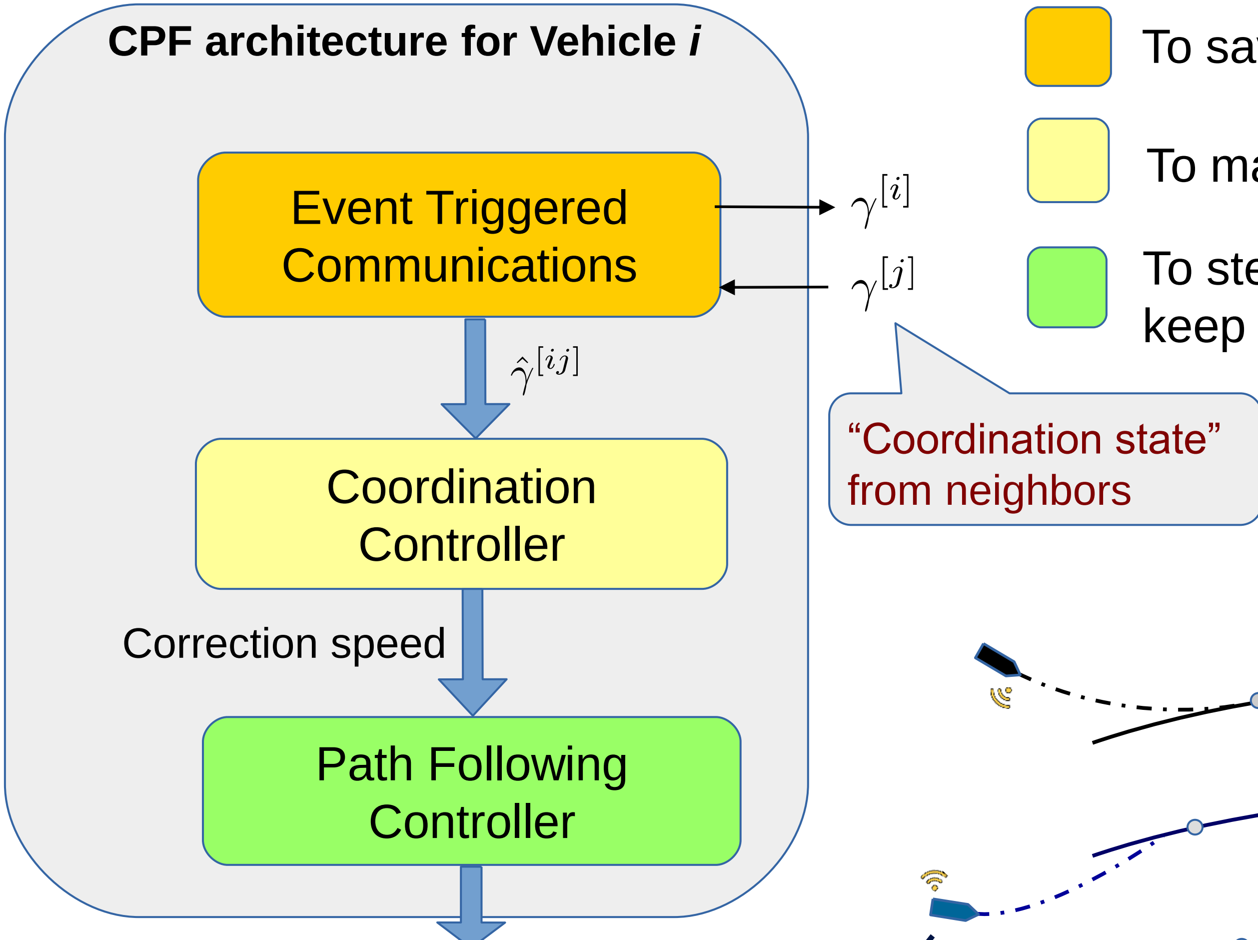
N vehicles converge to and follow N assigned at a common, desired normalized speed, while adopting a given geometric pattern

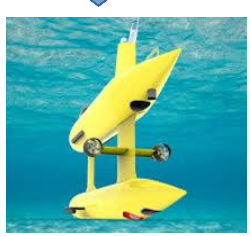
Coperative Path Following

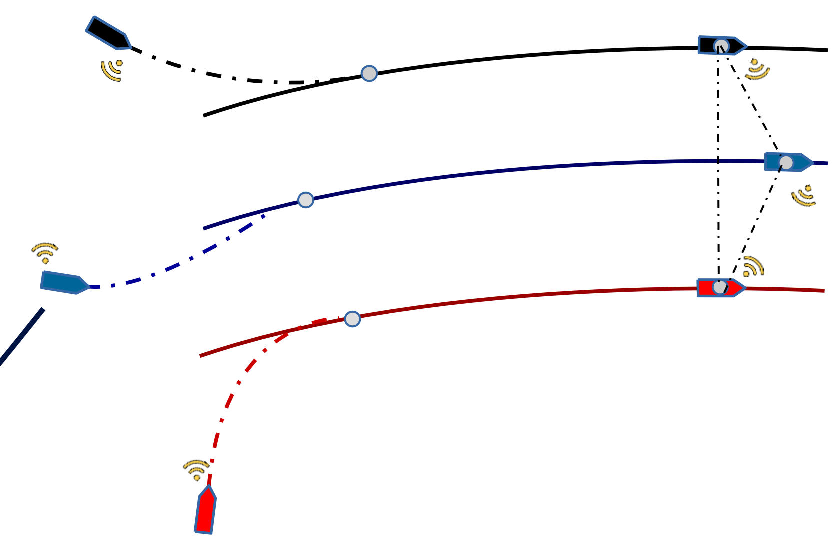


Rooted in: MPC-PF (**Model Predictive Control**), **Cooperative Control**, and **Event-Triggered Communications** (Hung and A. Pascoal, 2018)

Coperative Path Following



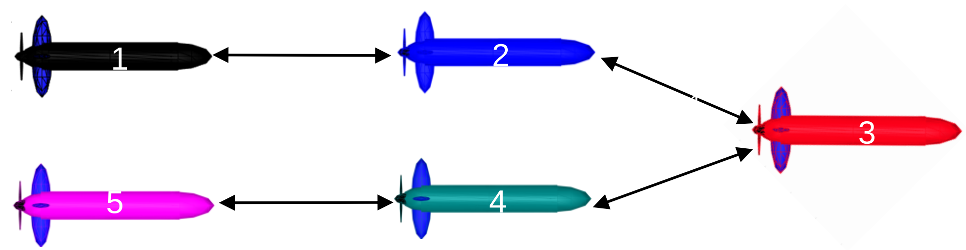


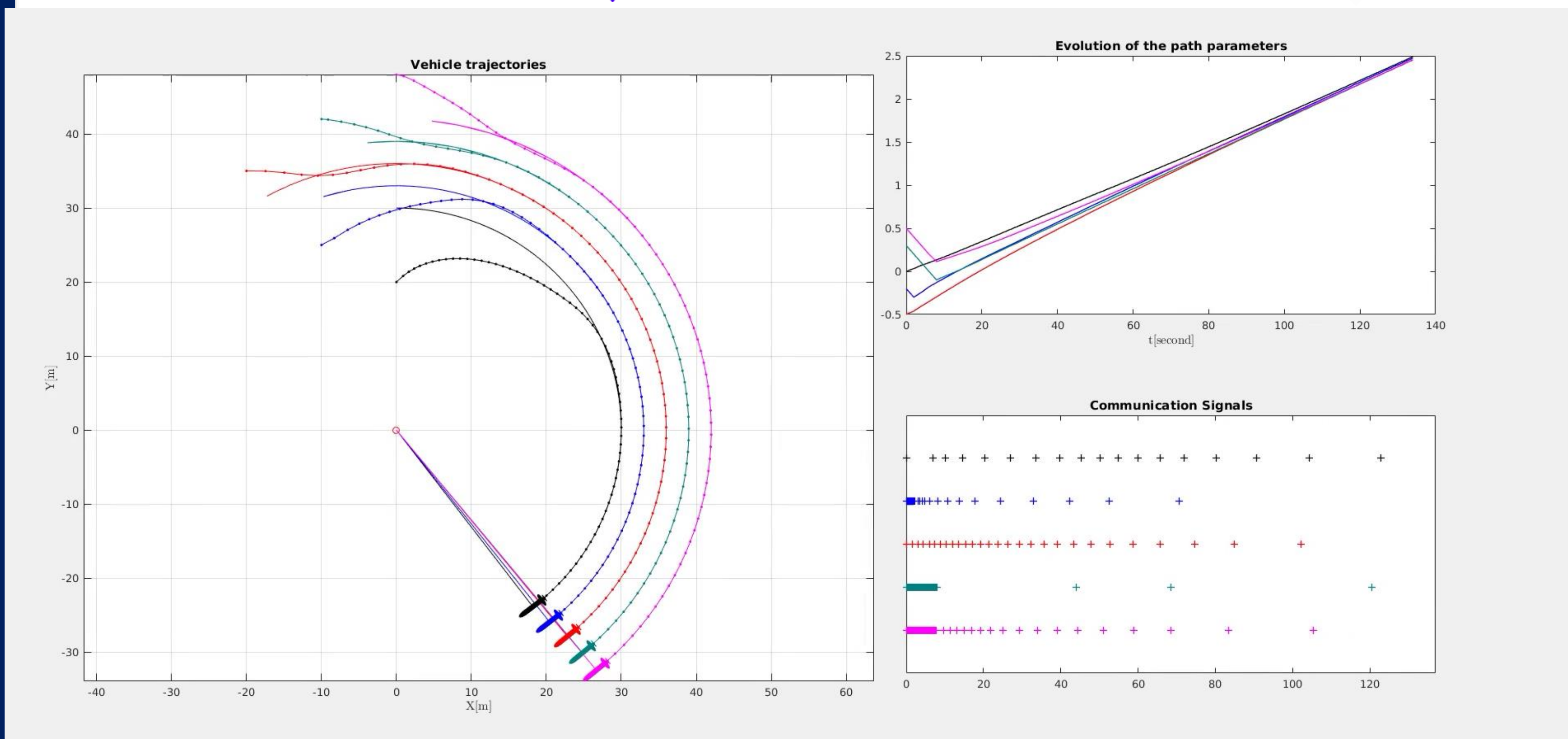


- To save communications
- To make vehicles coordinated
- To steer vehicles to and keep follow desired paths

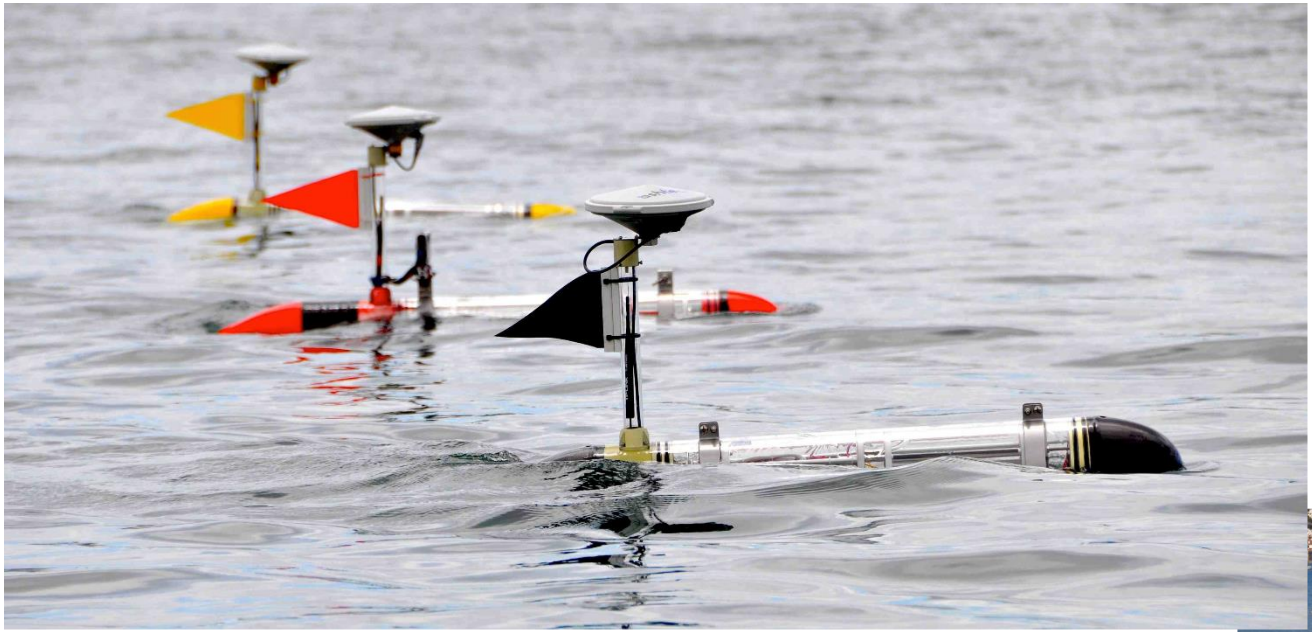
Coperative Path Following

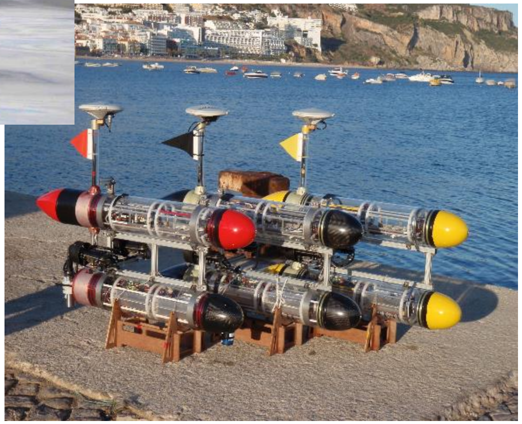
Circular formation





Key components: the MEDUSA ASVs



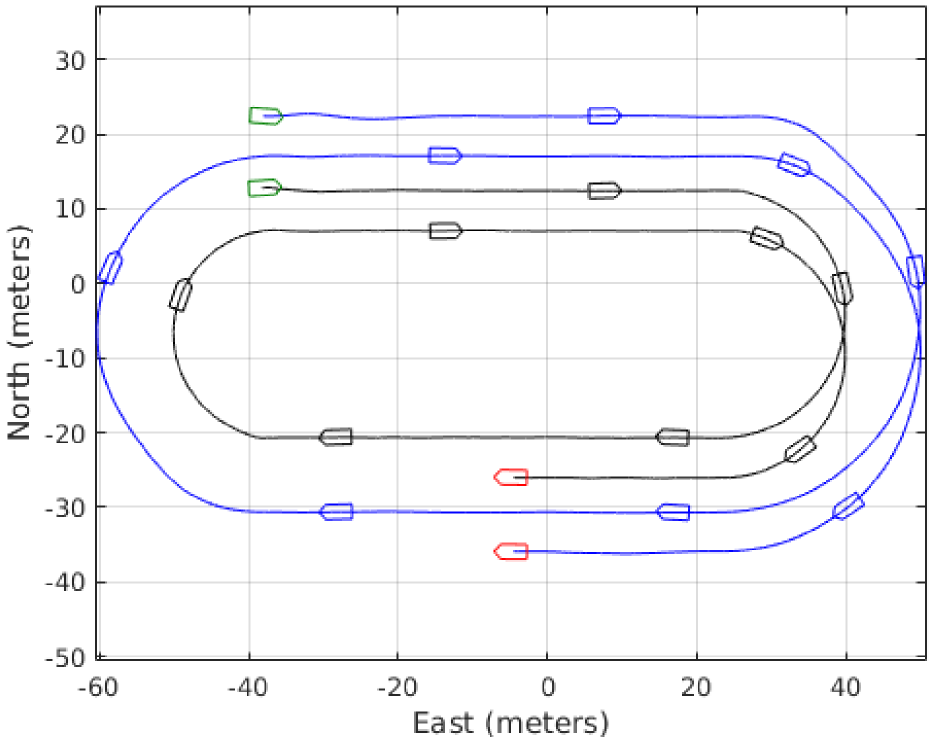


. *3 autonomous vehicles (cooperative motion control capability)*

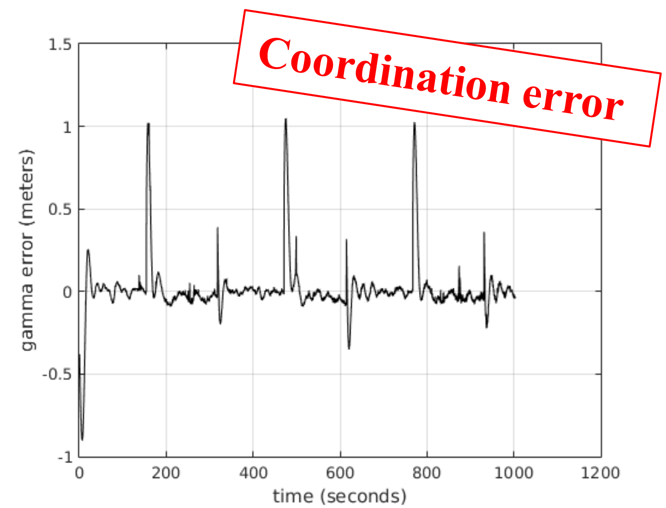
. *Acoustic network (Tritech micromodems)*


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

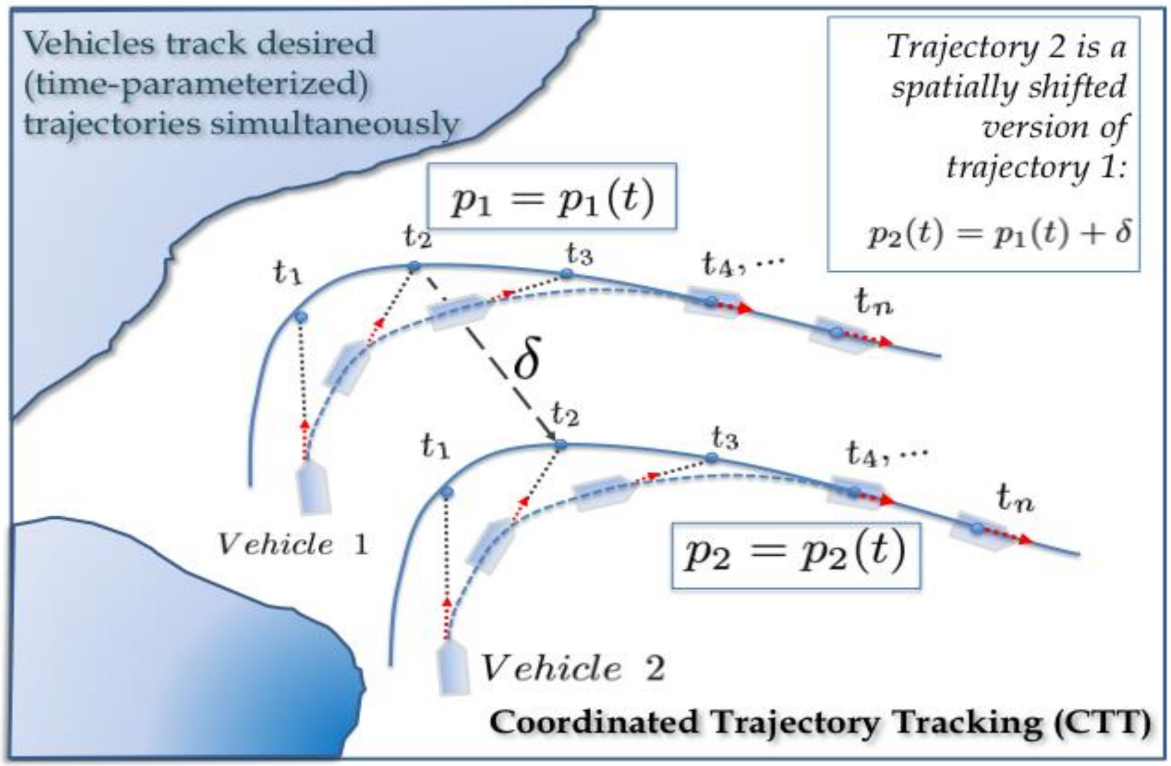
Coperative Path Following- Experiments



Lisbon Trials (2017/11/29) - Results



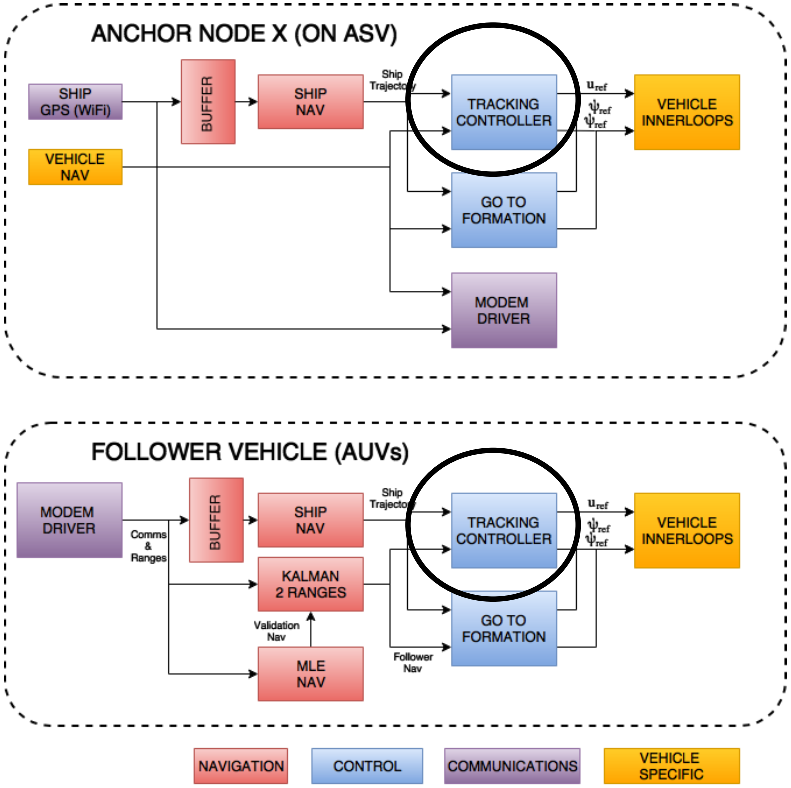
Coordinated Trajectory Tracking

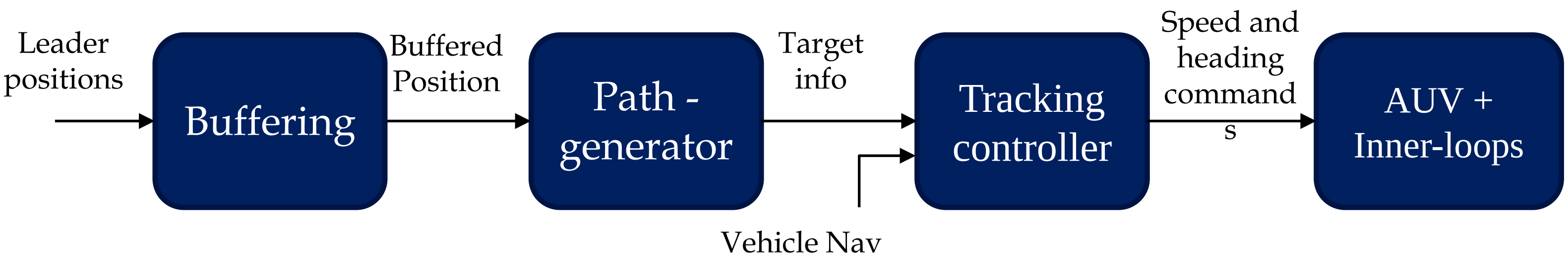


The Delfim ASV transmits periodically its position to all the AUVs. The AUVs build a sliding buffer of constant size with the positions received (using a last-in, first-out procedure), fit smooth trajectories to them, and track the resulting trajectories

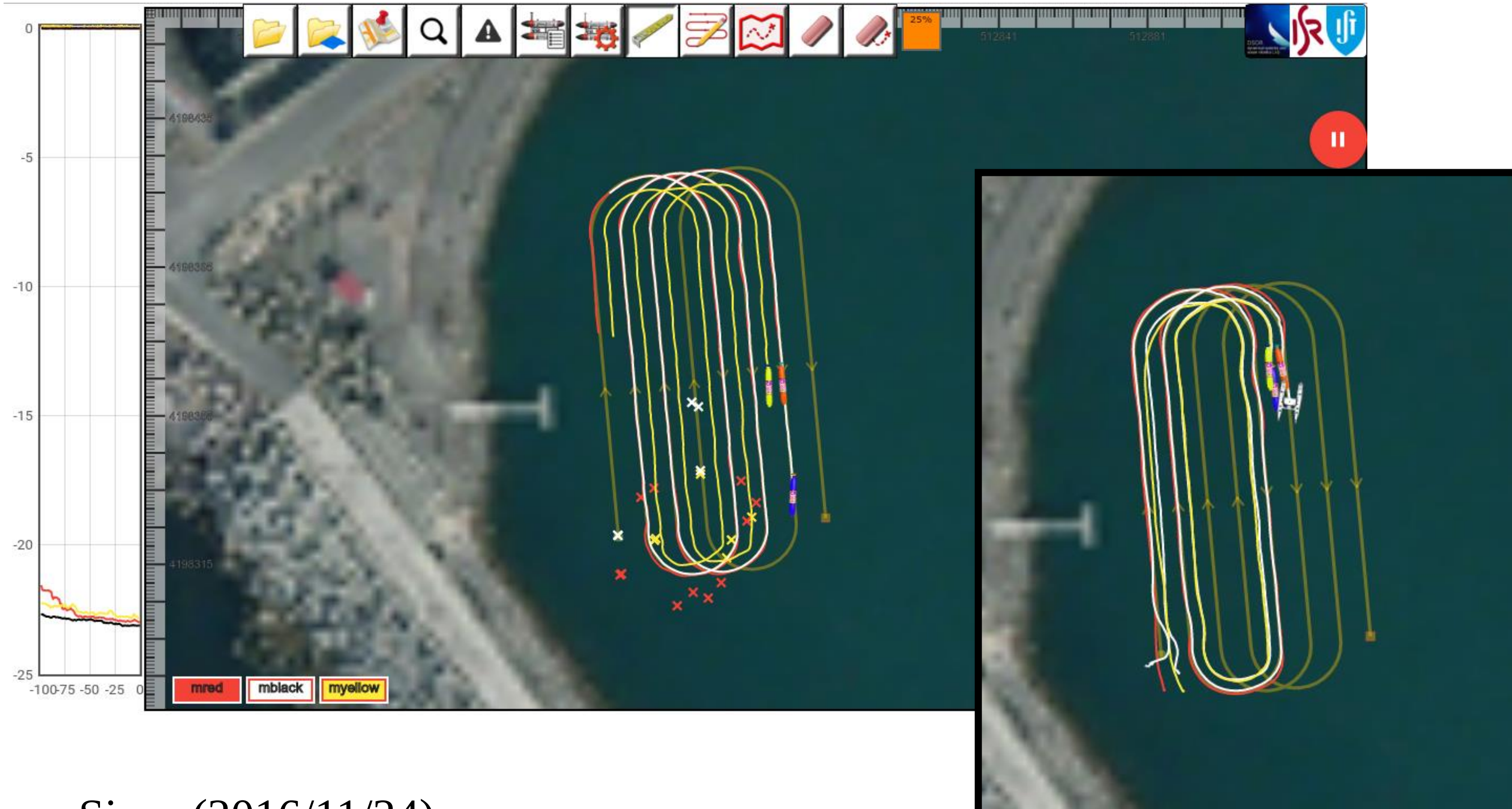
Coordinated Trajectory Tracking – Implementation

- Leader-follower strategy, *no a-priori knowledge of the path traversed by the leader*
- Advantages: simple, requires little information exchange through the acoustic network
- Limitation: over-reliance on a single vehicle



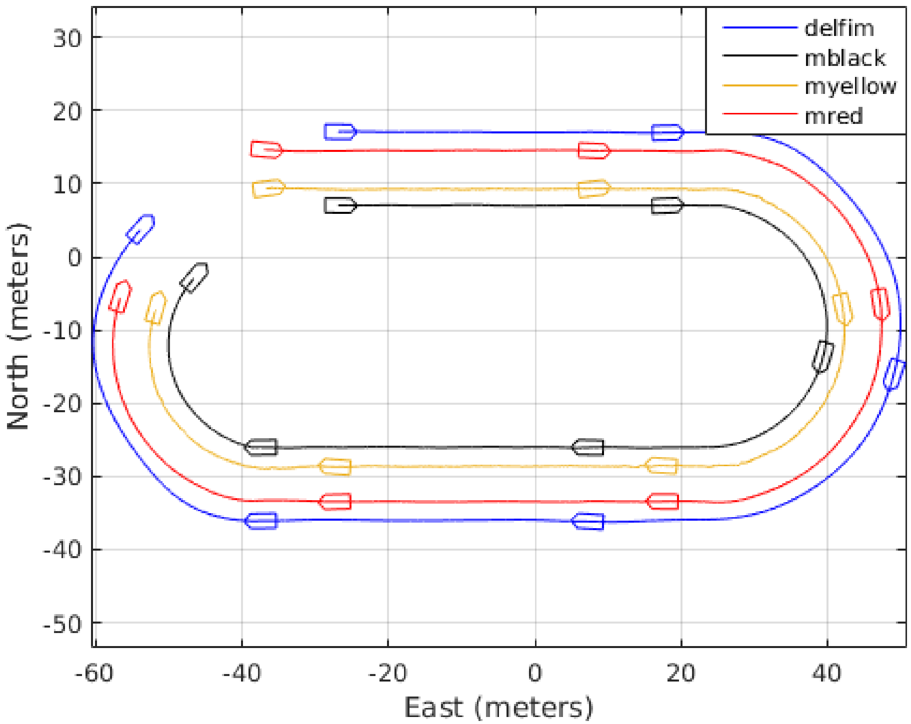


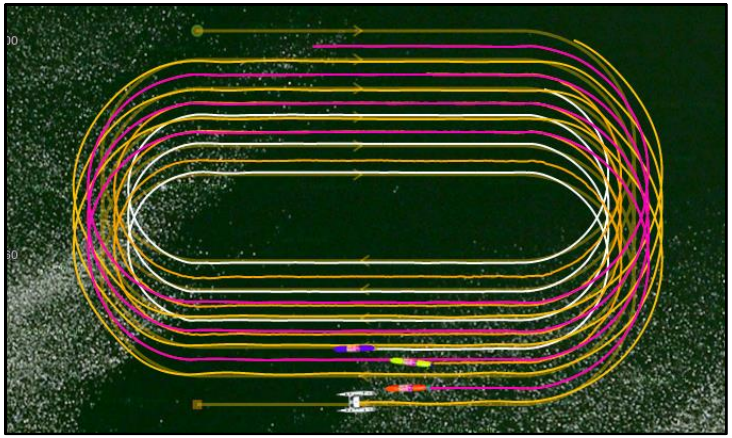
Coordinated Trajectory Tracking (CTT) - Experiments

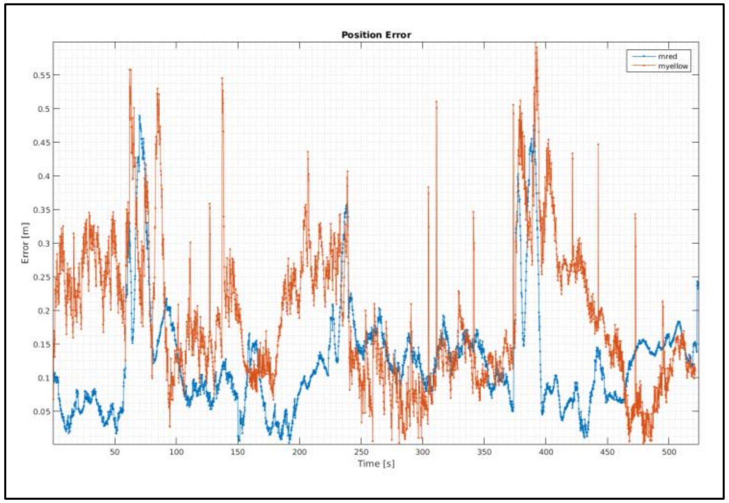


Sines (2016/11/24)
Medusa Black or Delfim Catamaran
as Leaders

Coordinated Trajectory Tracking (CTT) - Experiments



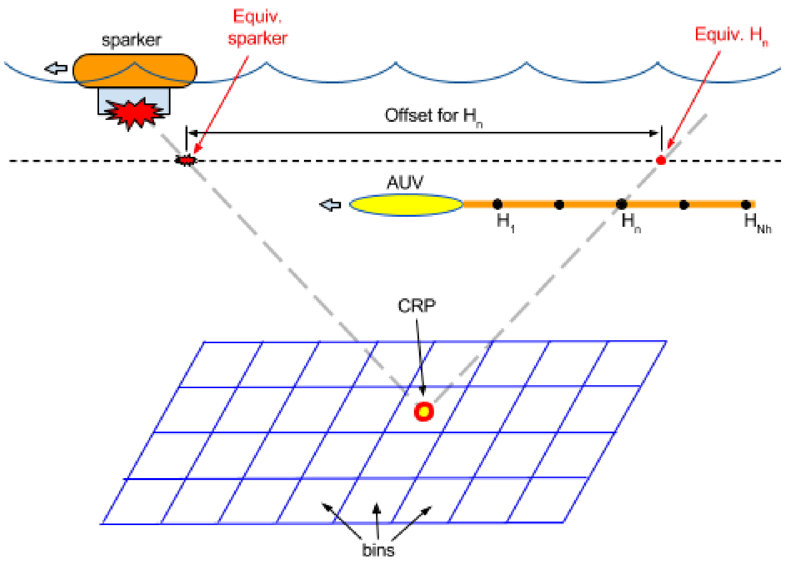




Lisbon Trials
(2017/11/27)
2 followers

Cooperative Trajectory Tracking
Fold preview using real navigation data – Sines Port

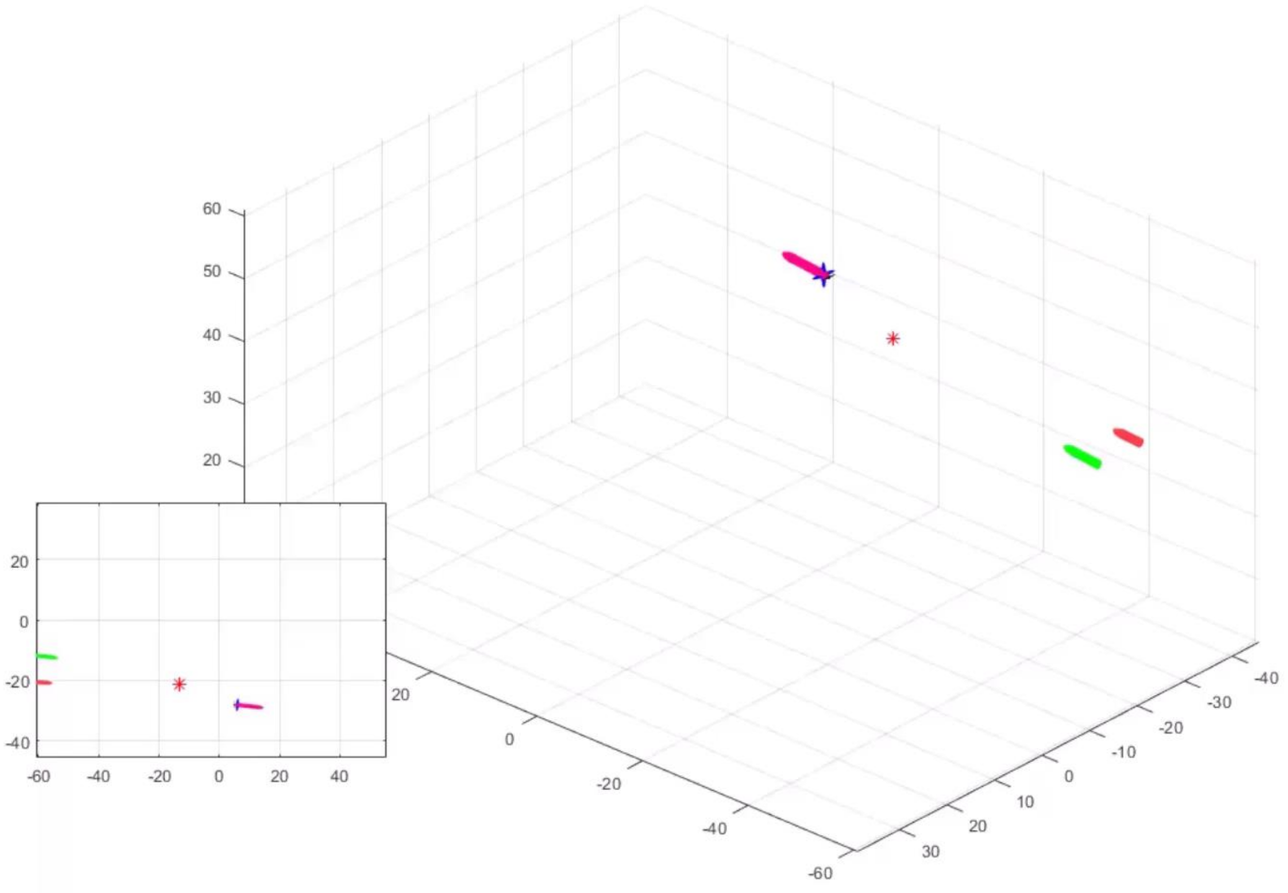
- 1 sparker on a moving platform and another stationary;
- 2 Medusa vehicles carrying streamers;
- Streamer with 8m length and 8 elements;
- Bin(cell) size of 4m ;



- Assumption: streamer motion is "similar" to that of the towing vehicle

Coordinated Trajectory Tracking

Fold preview using real navigation data – Sines Port



Full system implementation and final mission at sea

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Technical Highlights & Seismic Data Acquired

Full system implementation and final mission at sea

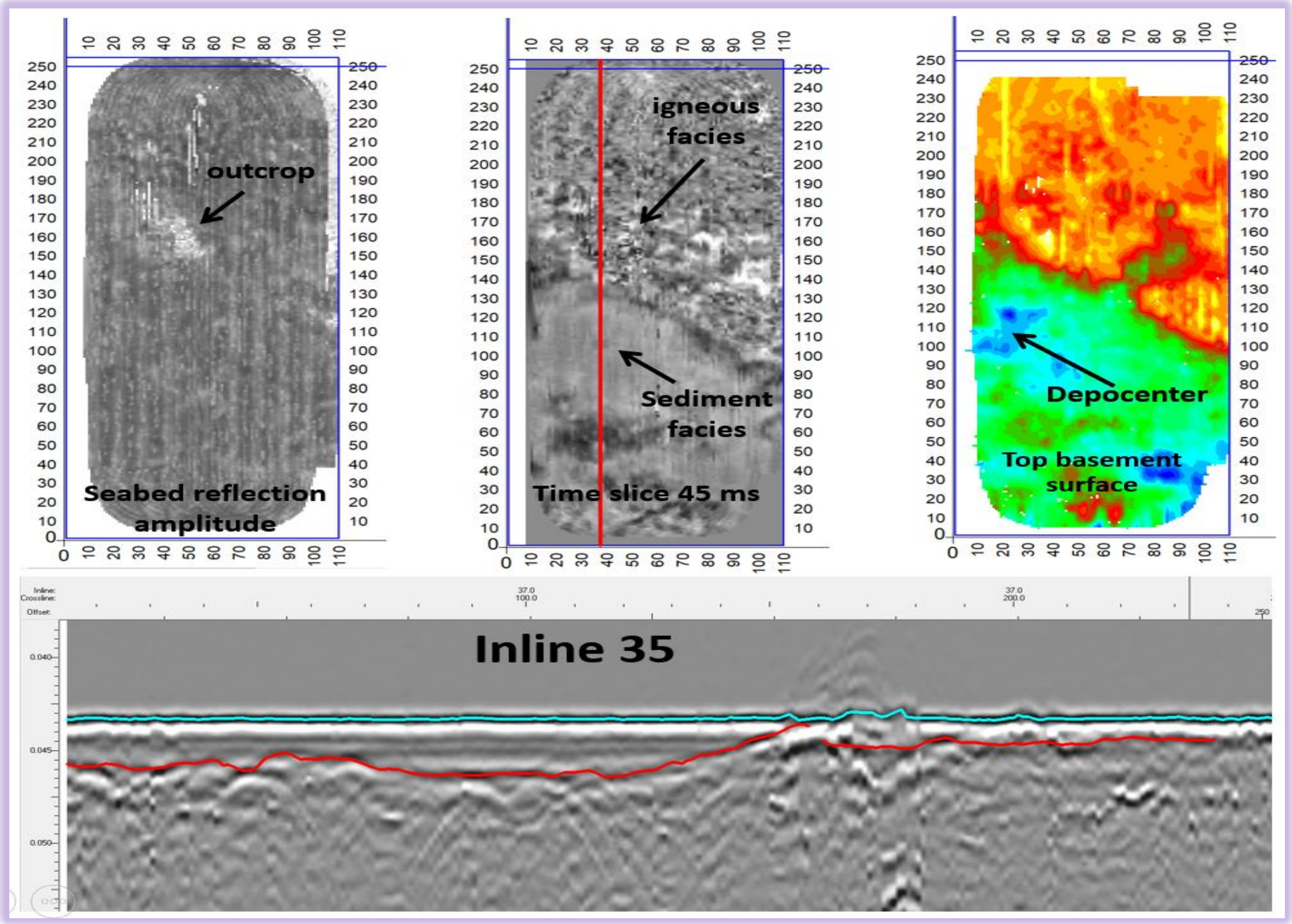
1:07 and 2:00

Cooperative Motion Planning and CTT in WiMUST

WiMUST
Widely scalable Mobile
Underwater Sonar Technology

Go-To-Formation Maneuver – U. Hertfordshire, UK

Full system implementation and final mission at sea



Technical Highlights & Seismic Data Acquired

Towards Cooperative Geotechnical Surveying in Shallow Water

MARINE SURVEY SYSTEMS (NL)

GeoSurveys geophysical consultants

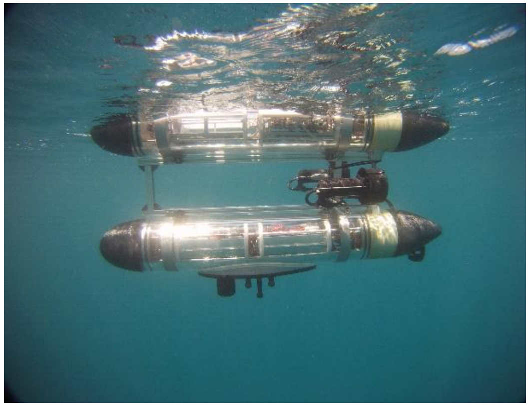
Aveiro (PT)

ISR PÓLO DO I.S.T

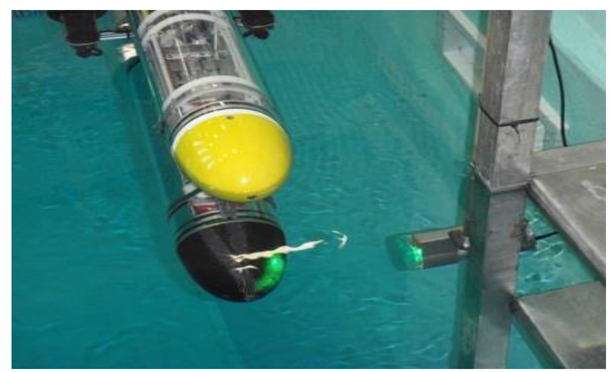
LARSyS

TÉCNICO LISBOA

Hybrid Acoustic-Optical Communication Networks

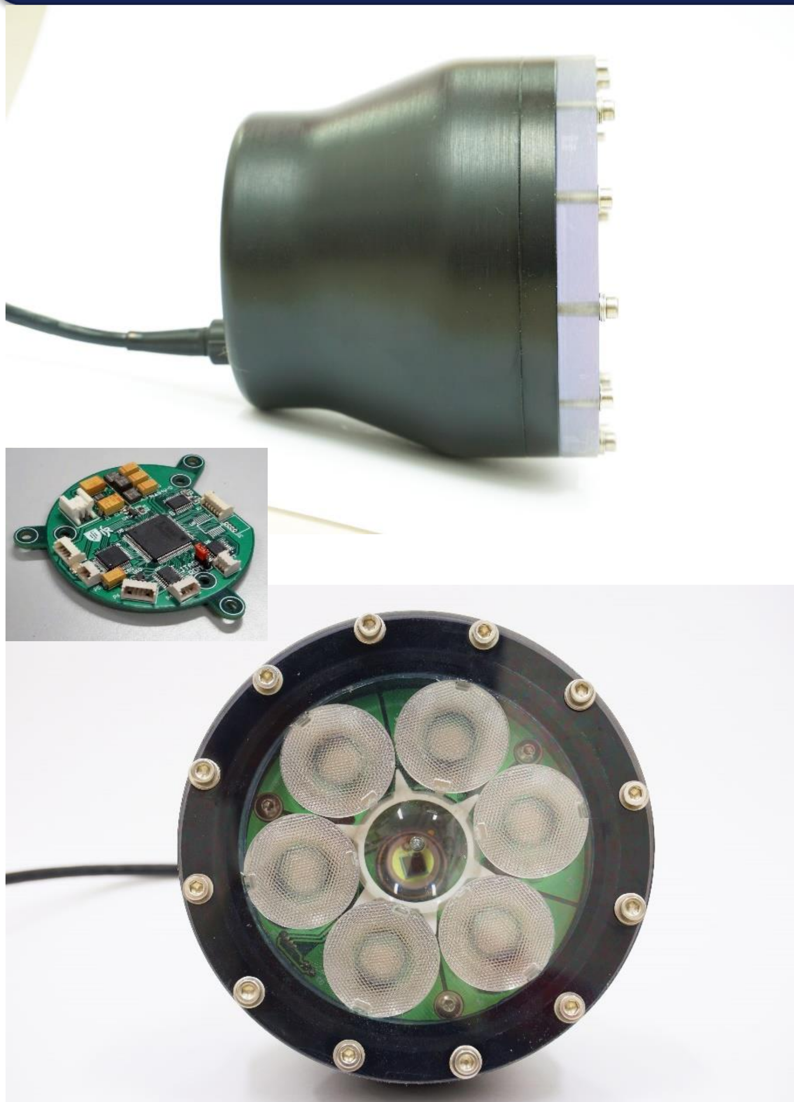


Acoustic Networking. **High frequency 42-65 kHz modem and USBL units:** data transfer rates up to 31.2 kbit/s over a 2000 m range



The BlueRay optical modem developed at IST

The BlueRay Optical Modem (IST)

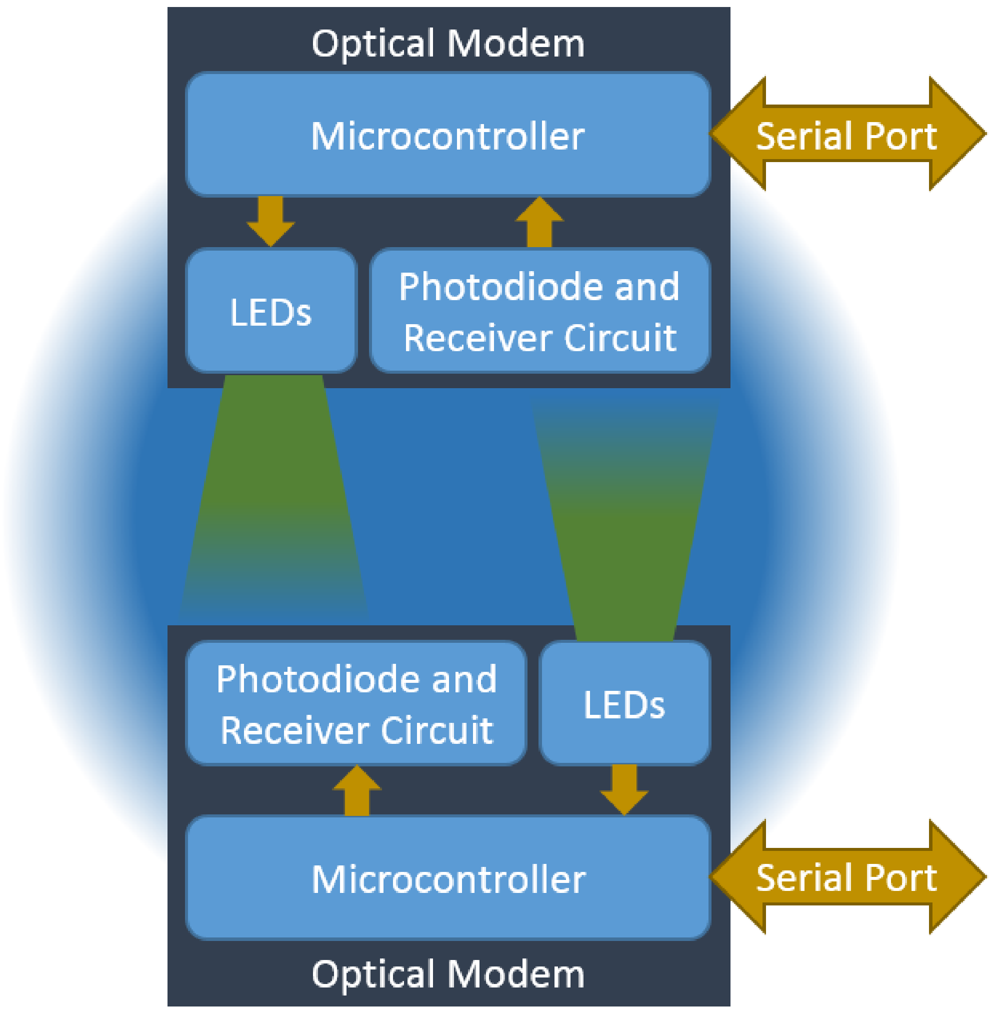


Specifications

Range sea water	12m
Range harbour water (visibility 1m)	3,5m
TX Power	12W
Beam divergence	12º
Receiver Aperture	45º
Data rate	20kbit/s
Modulation	OOK
Encoding	Manchester
Price	~150€
Dimensions	D = 105mm L = 100 mm
Obs.	Robust to high background light

New units capable of transmission rates in the range from **200kbit/s** up to **1Mbit/s** will become available soon.

The BlueRay Optical Modem (IST)



Receiver

- Photodiode
- Transimpedance amplifier scheme
- Hardware filters

Transmitter

- High power LEDs
- Direct drive with MOSFETs

Other features

- Clock synchronisation between modems jitter < 50us

Cooperative Control using Optical Comms

TÉCNICO LISBOA

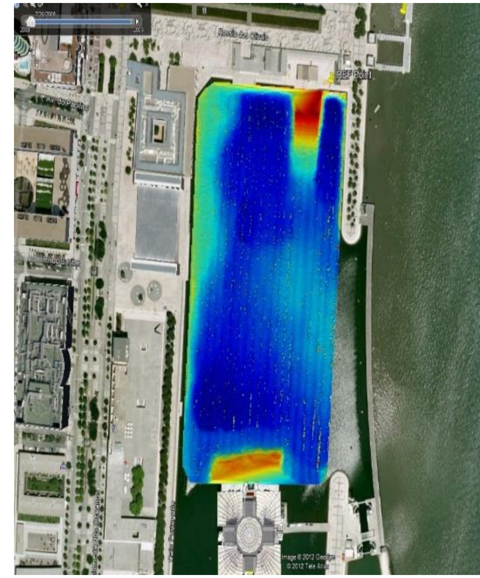
Institute for Systems and Robotics | LISBOA

1:33

Recent exciting results: Range-BasedTarget localization

Set-up

- A tracker with a GPS
- A target at a depth of 1[m]
- Target moving at a constant speed of 0.2[m/s]
- Range measurements every 1.5[s]
- “Open water” experiments

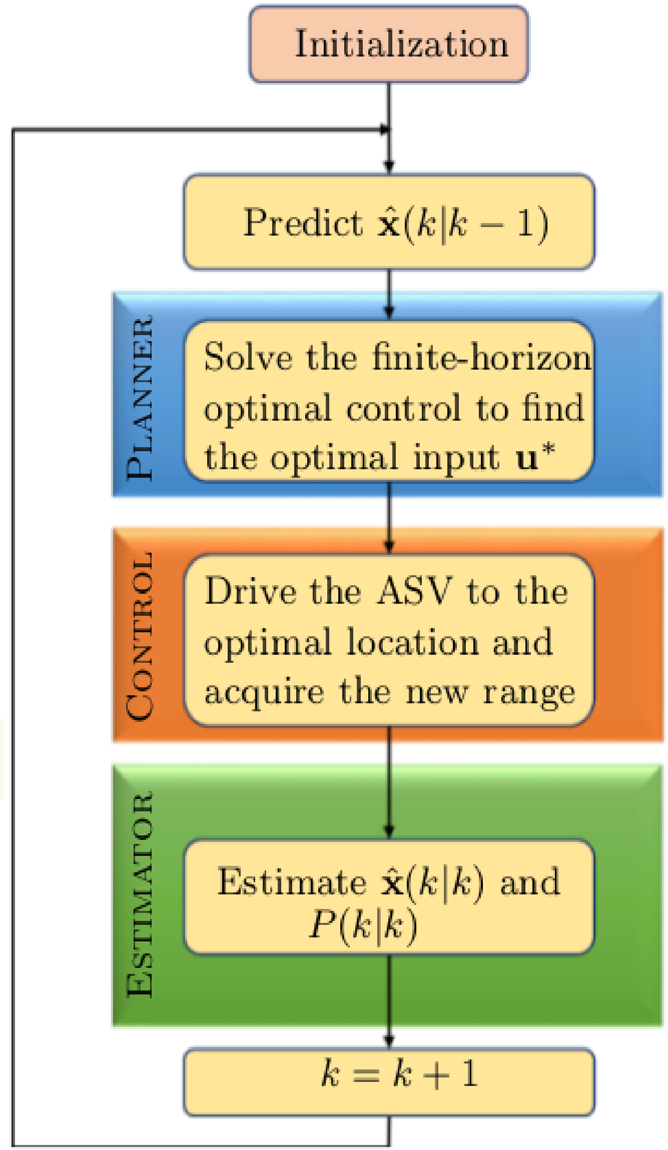


Key assumptions

- Target position was unknown
- No currents
- Transmit velocity vector information

MEDUSA vehicles

Integrated Motion Planning, Control, and Estimation



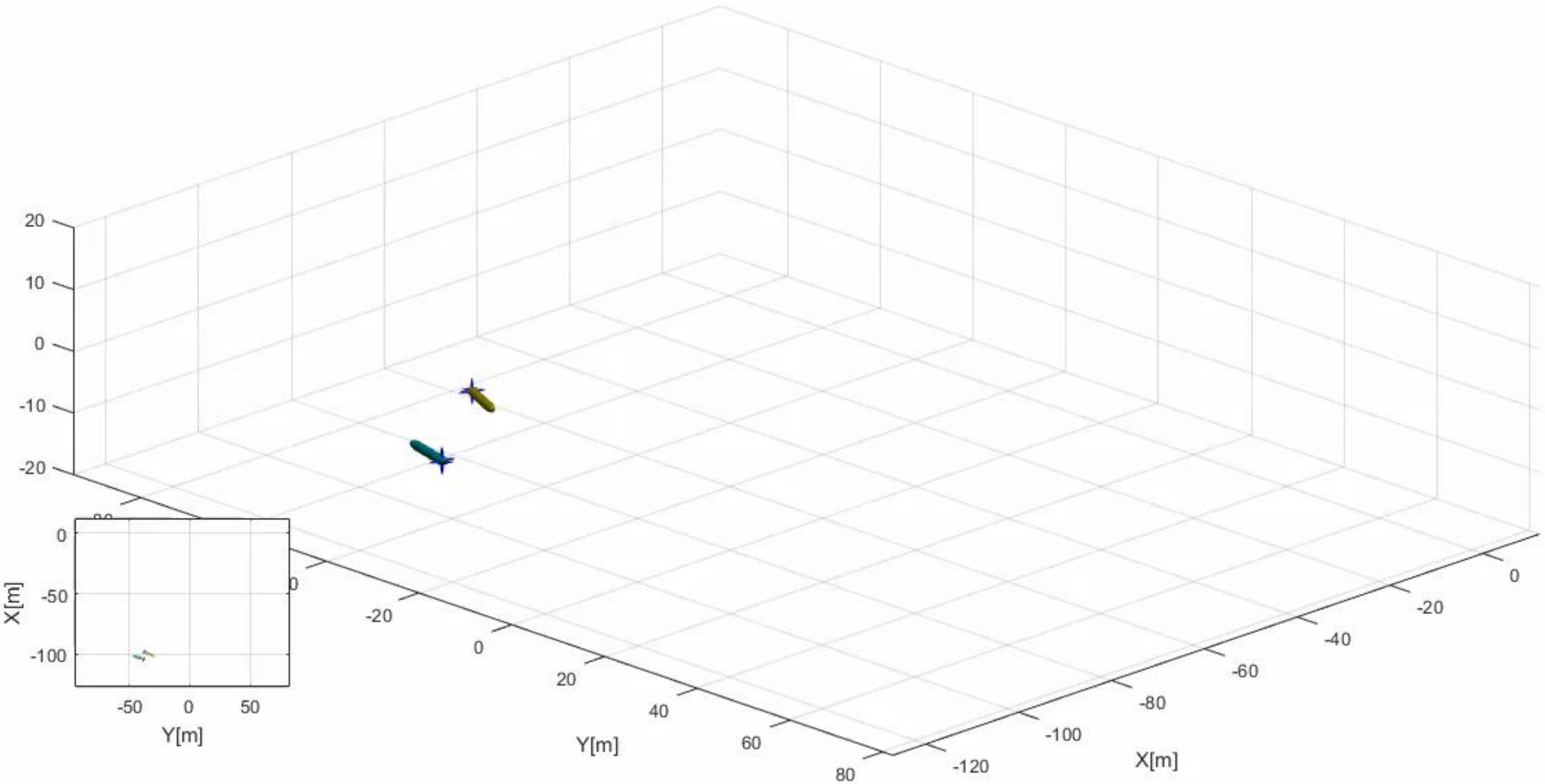
Predict target parameters (e.g. speed, position, etc.)

Obtain tracker's optimal speed and optimal course rate

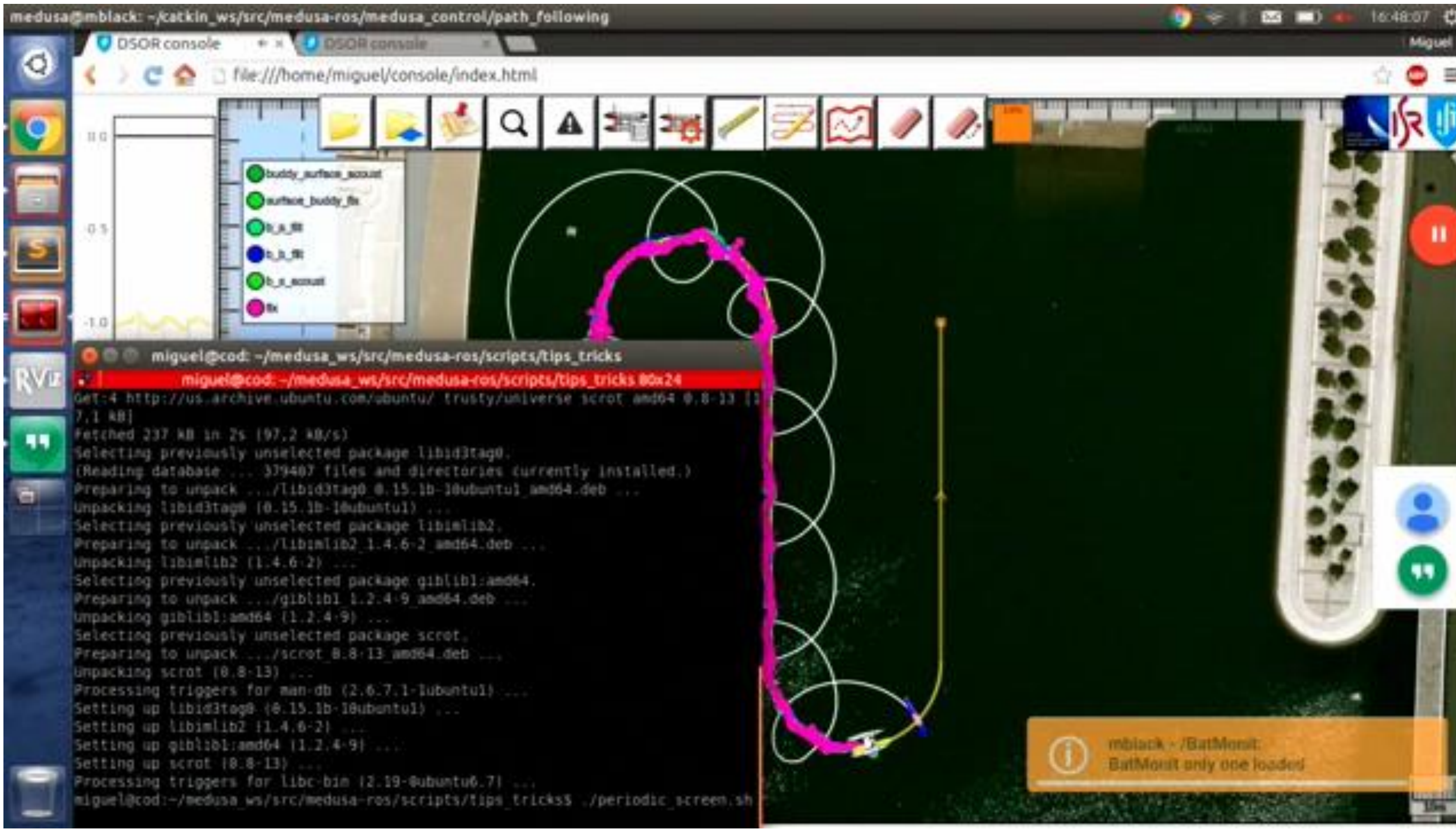
Implement the control law for the tracker

Estimate target position and the error covariance matrix

Recent exciting results: Range-BasedTarget localization



Recent exciting results: Range-BasedTarget localization



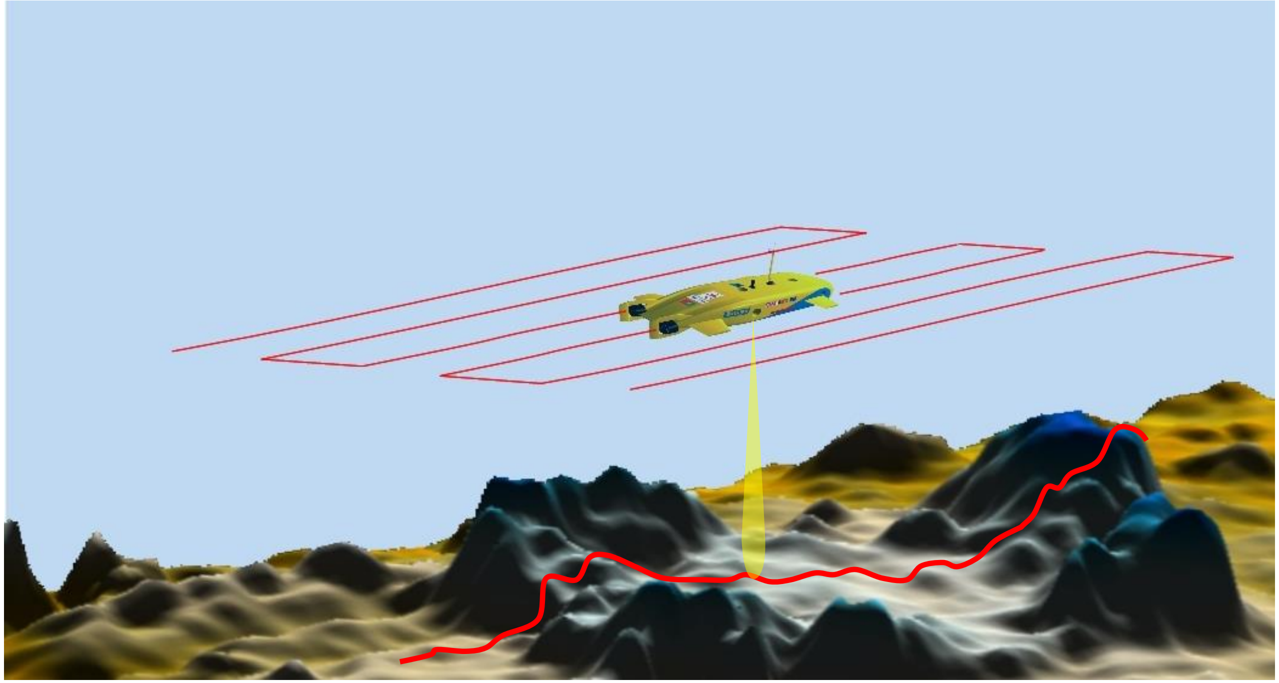
Mission Control Console on shore

Challenges: Navigation, Energy, Hybrid Vehicles

Long-range Geophysical Navigation

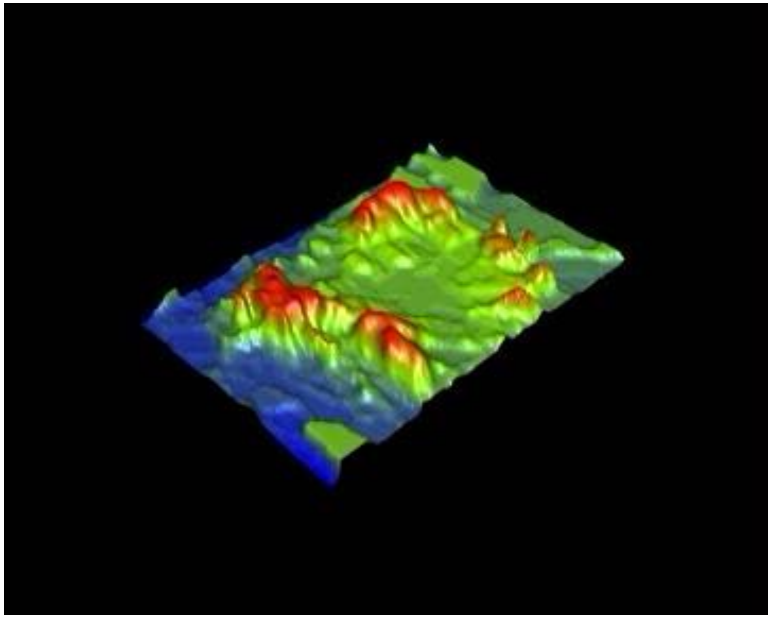
(using terrain and
Geomagnetic maps of the seabed)

Nonlinear Filtering
Monte Carlo Methods

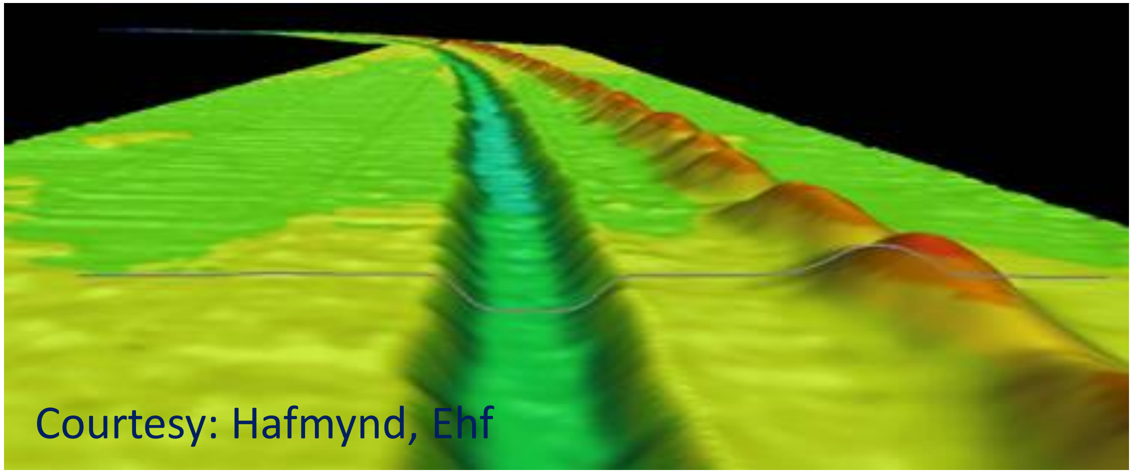


Geophysical Navigation

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

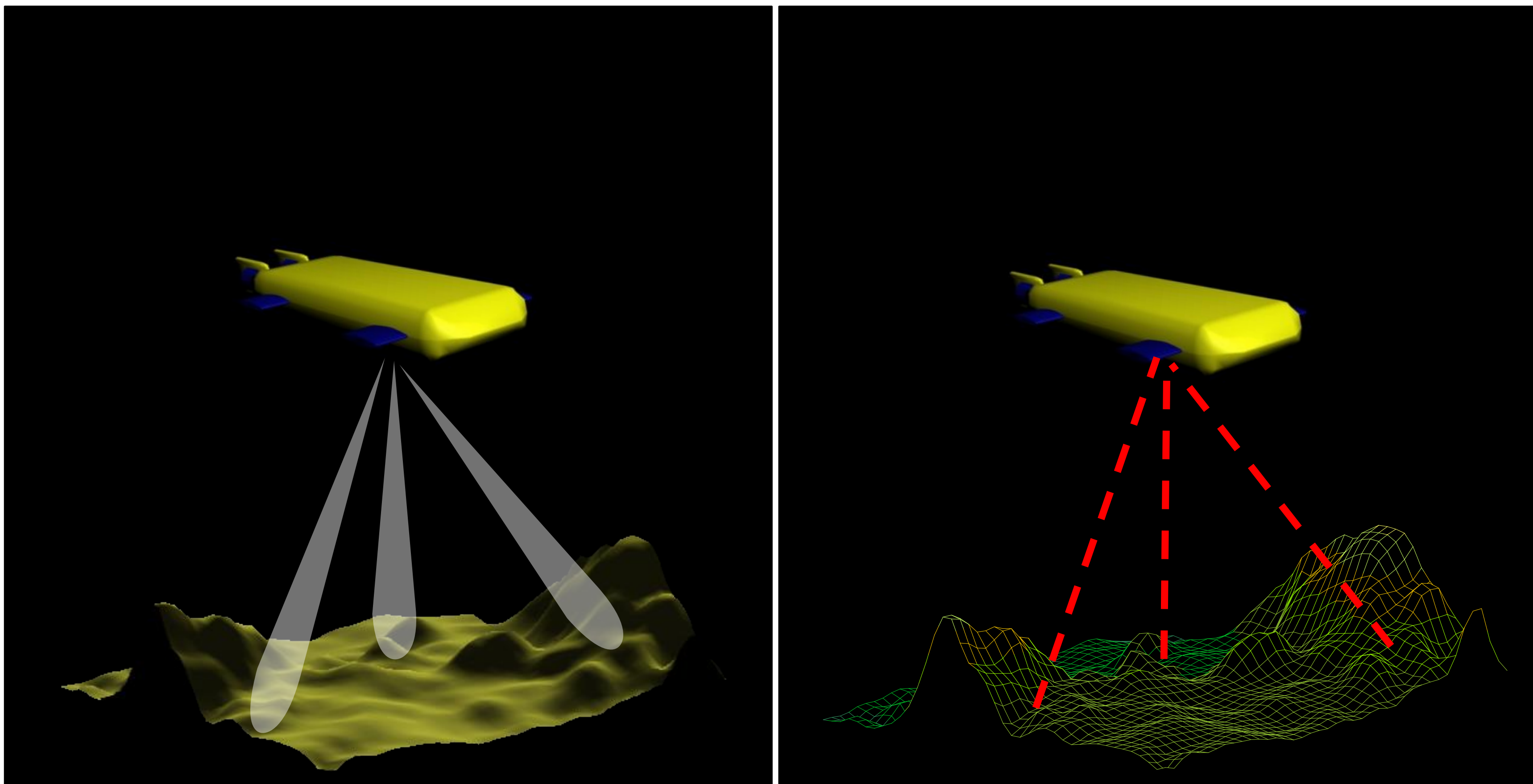


- **TAN**
- **SLAM**



Geophysical Navigation

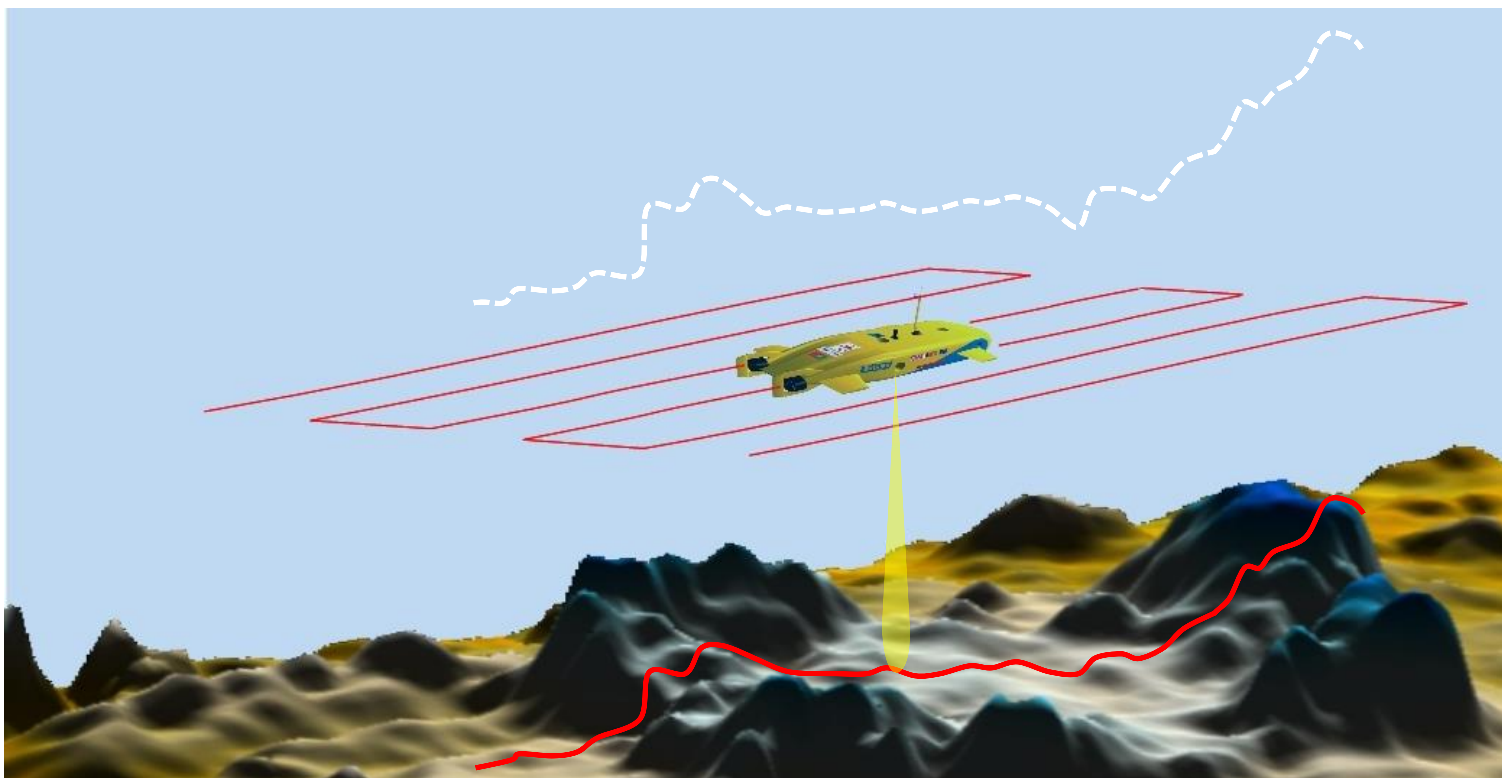
- **Terrain-Aided Navigation (TAN** a.k.a. TRN,TBN**)**
  - Use a **prior map** of the environment.
  - Make **observations** of the terrain
  - **Match observations** against the map to estimate position.



Geophysical Navigation

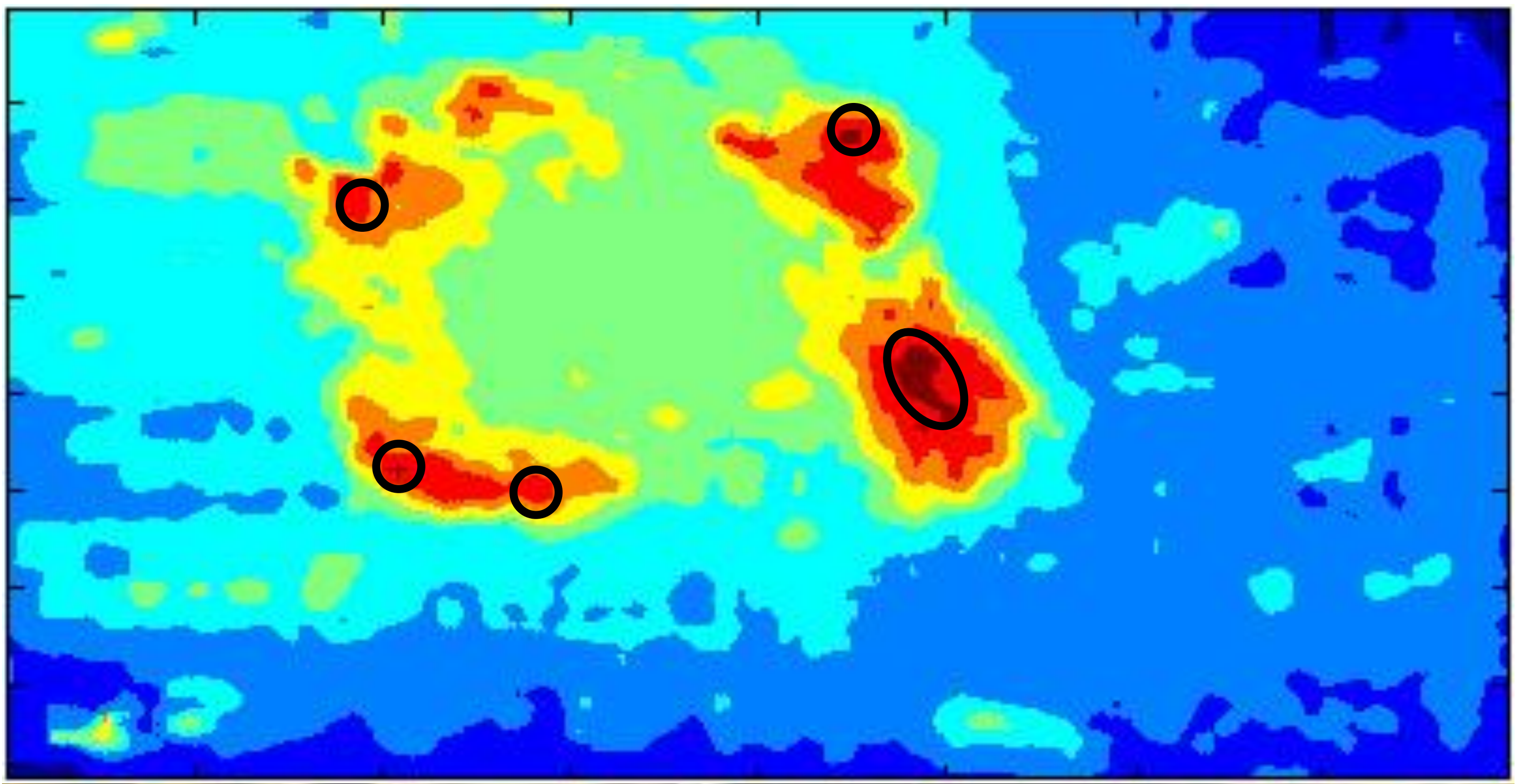
- **Map matching**

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

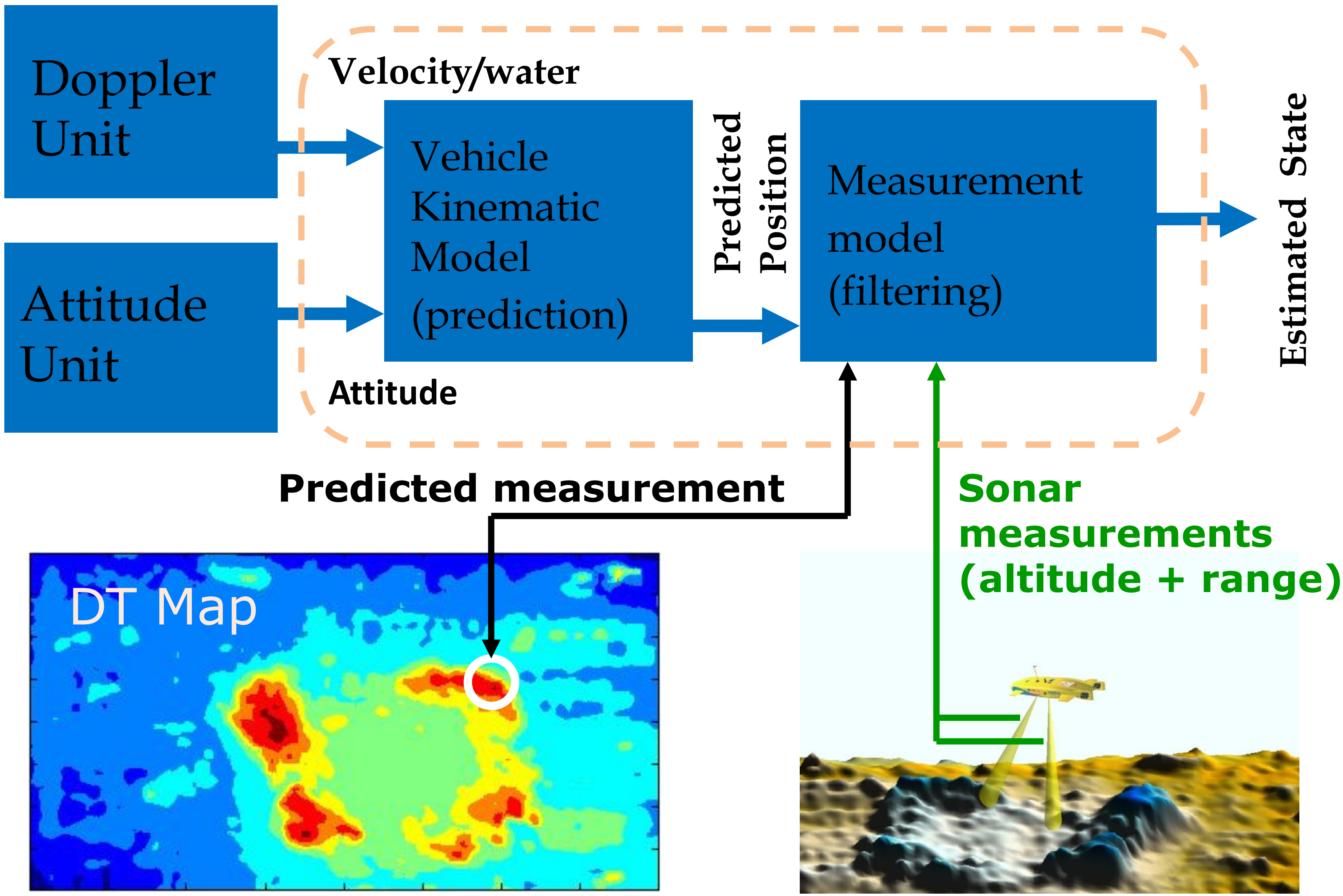


Simultaneous Localization and Mapping (SLAM)

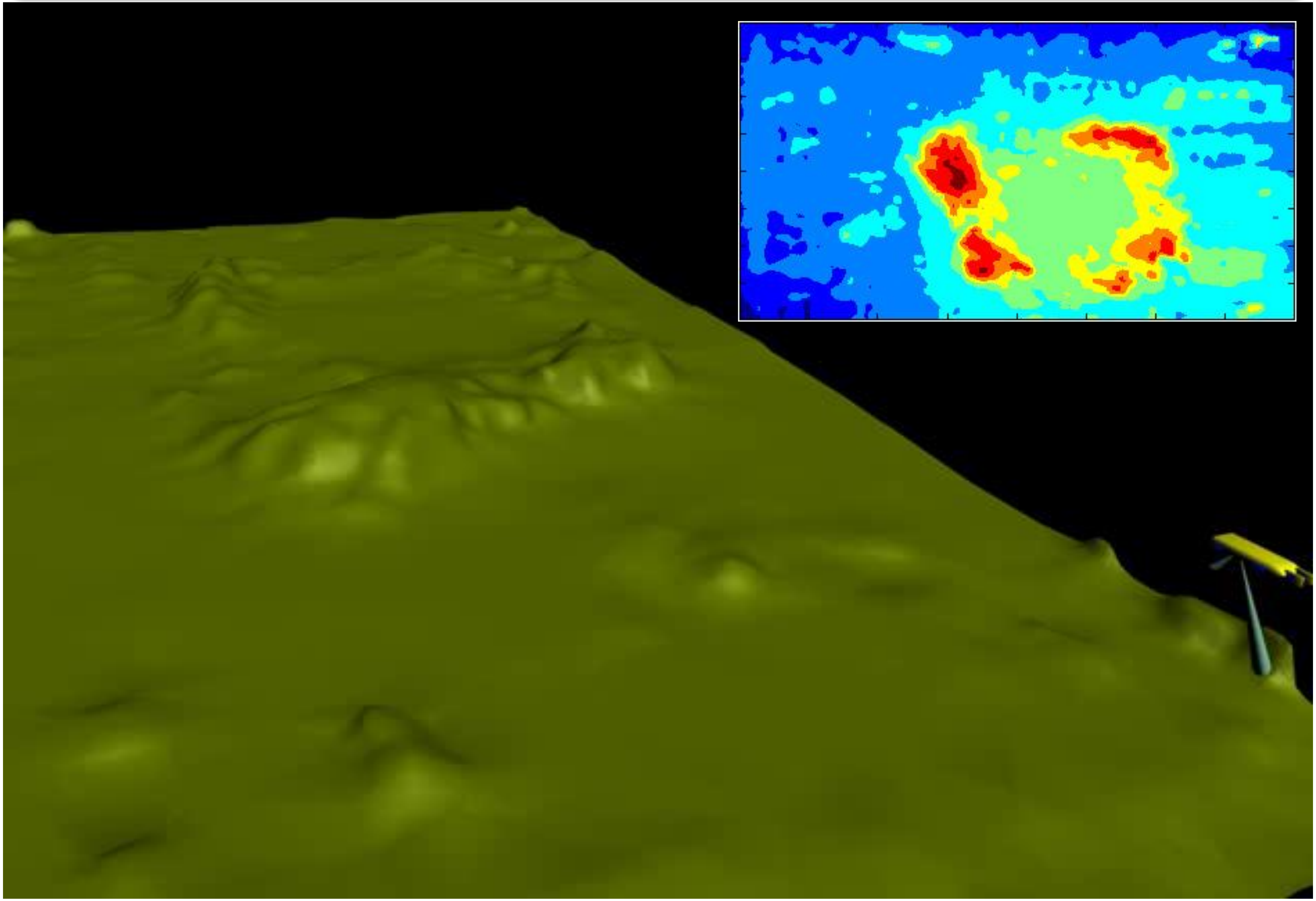
- **Sequentially acquire/refine a map of the terrain & simultaneously use this map for self-localization.**
  - Use sparse, metric or topological maps of the terrain.
  - Apply explicit feature extraction and data association.



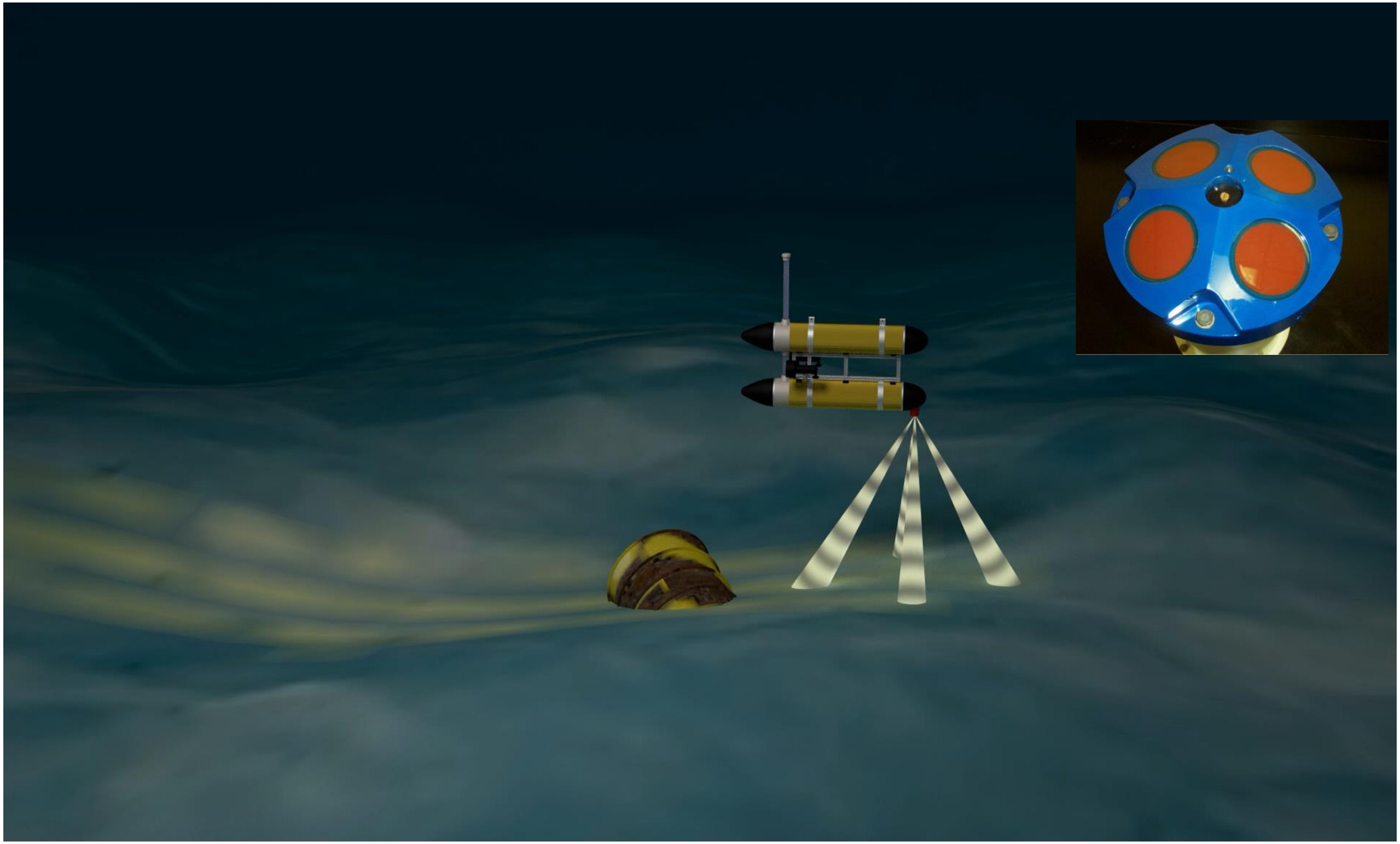
Terrain Aided Navigation (TAN) Filters



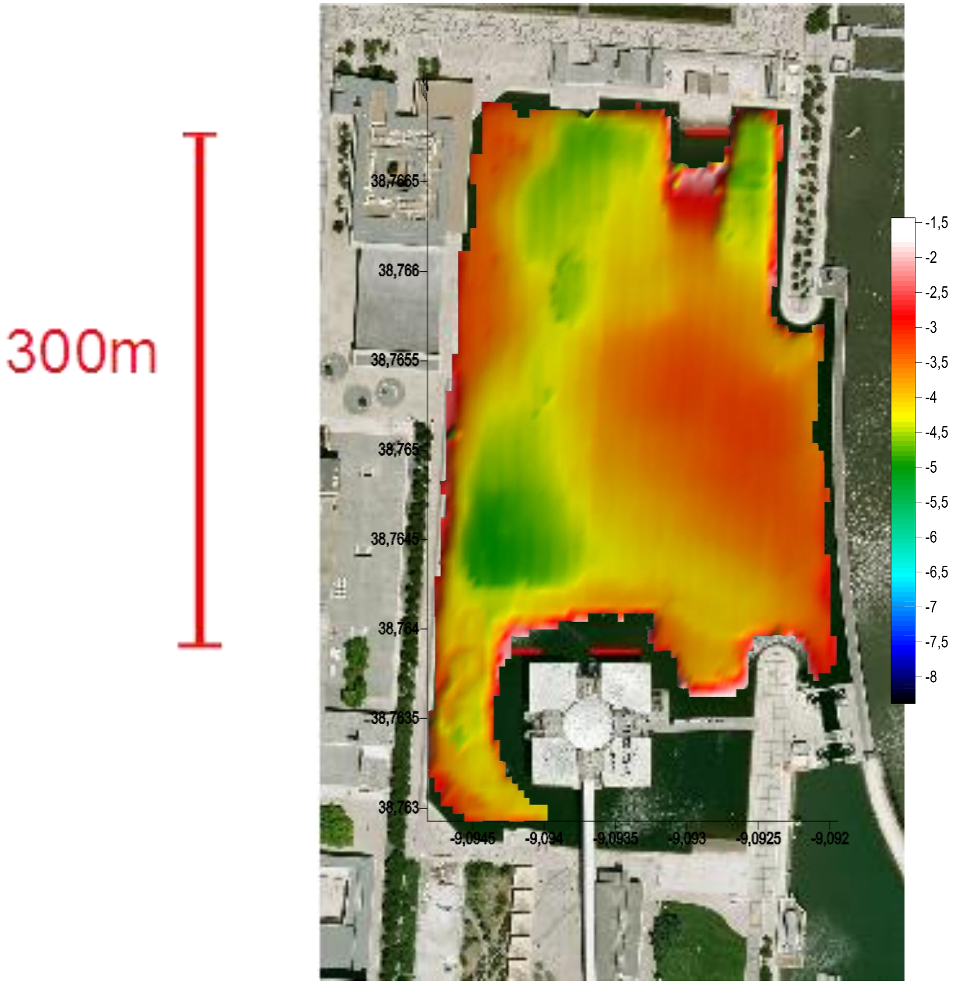
TAN – Monte Carlo Methods (Particle Filters)

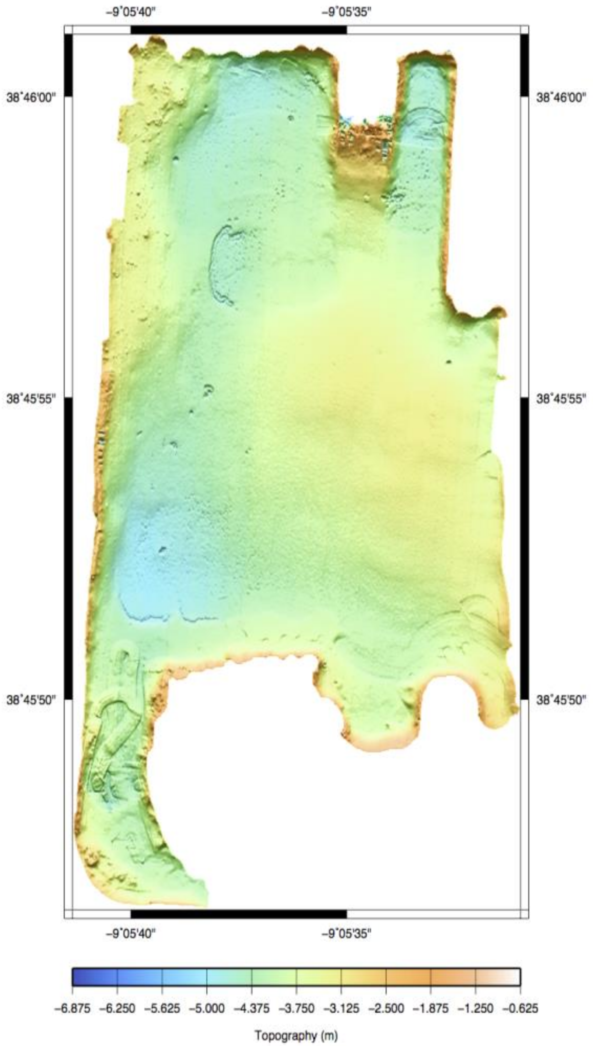


TAN – DVL Implementation



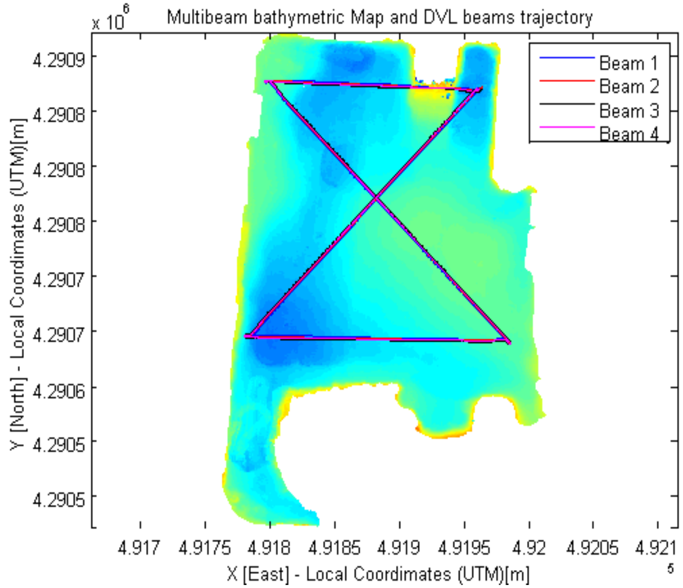
TAN – DVL Implementation

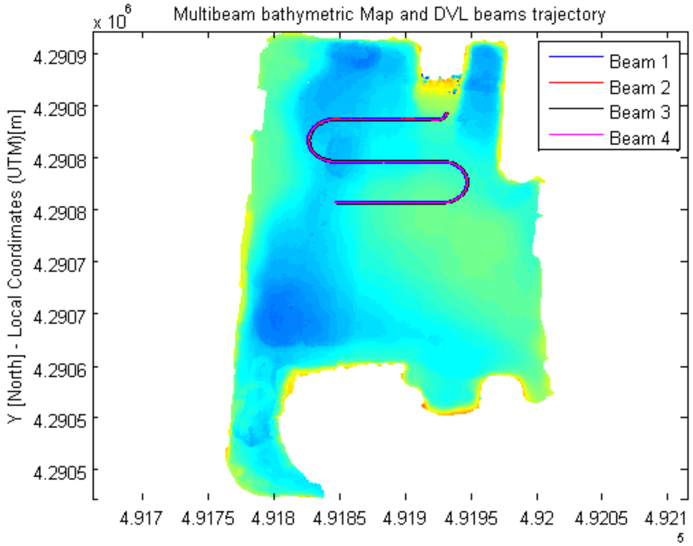




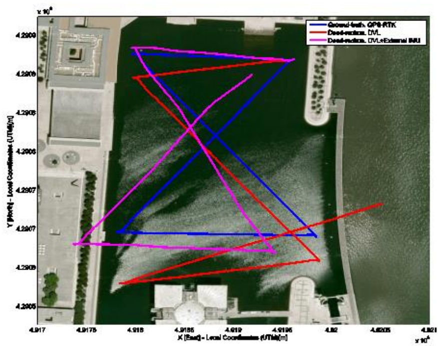
Test site, Lisbon, Portugal

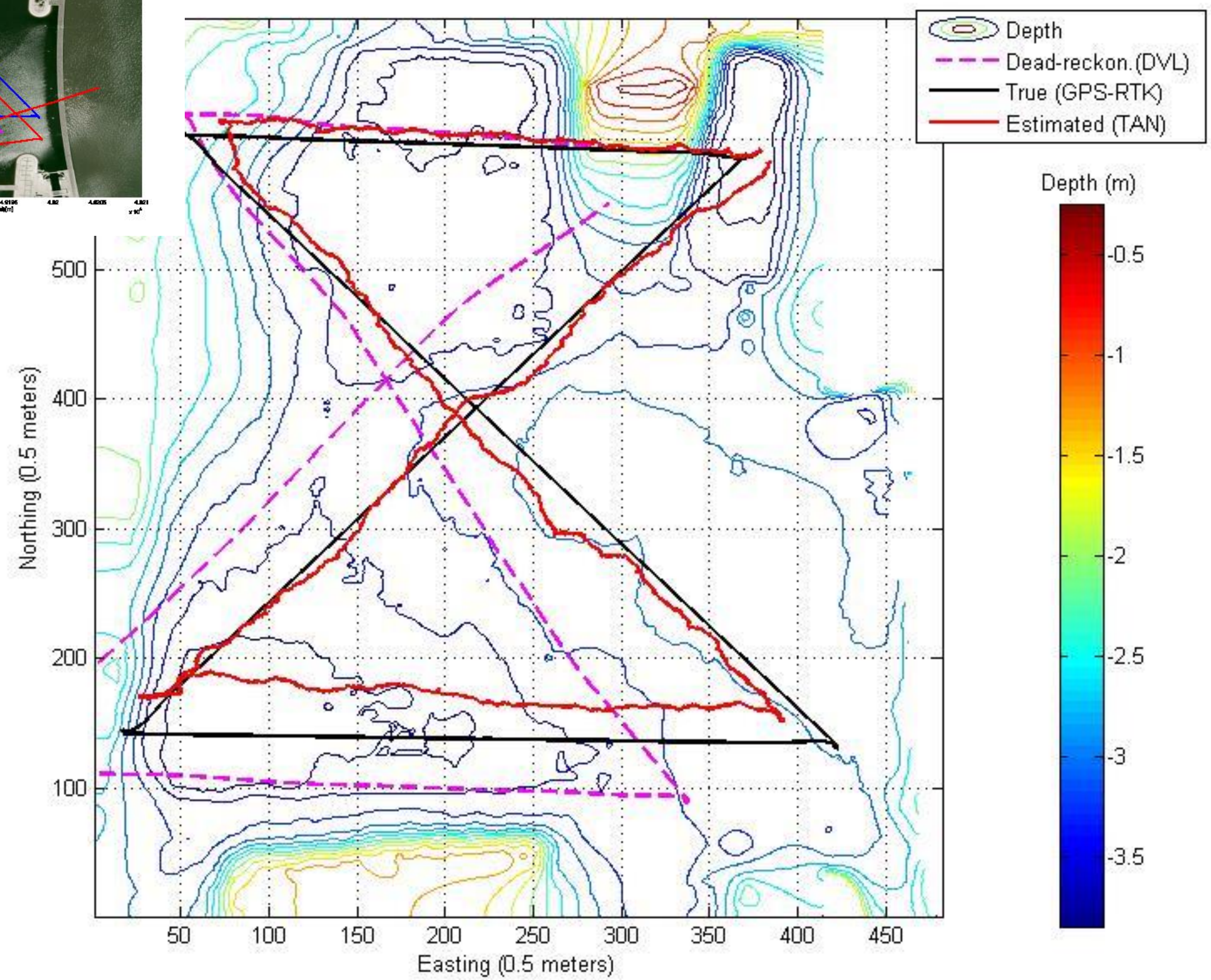
TAN – DVL Implementation





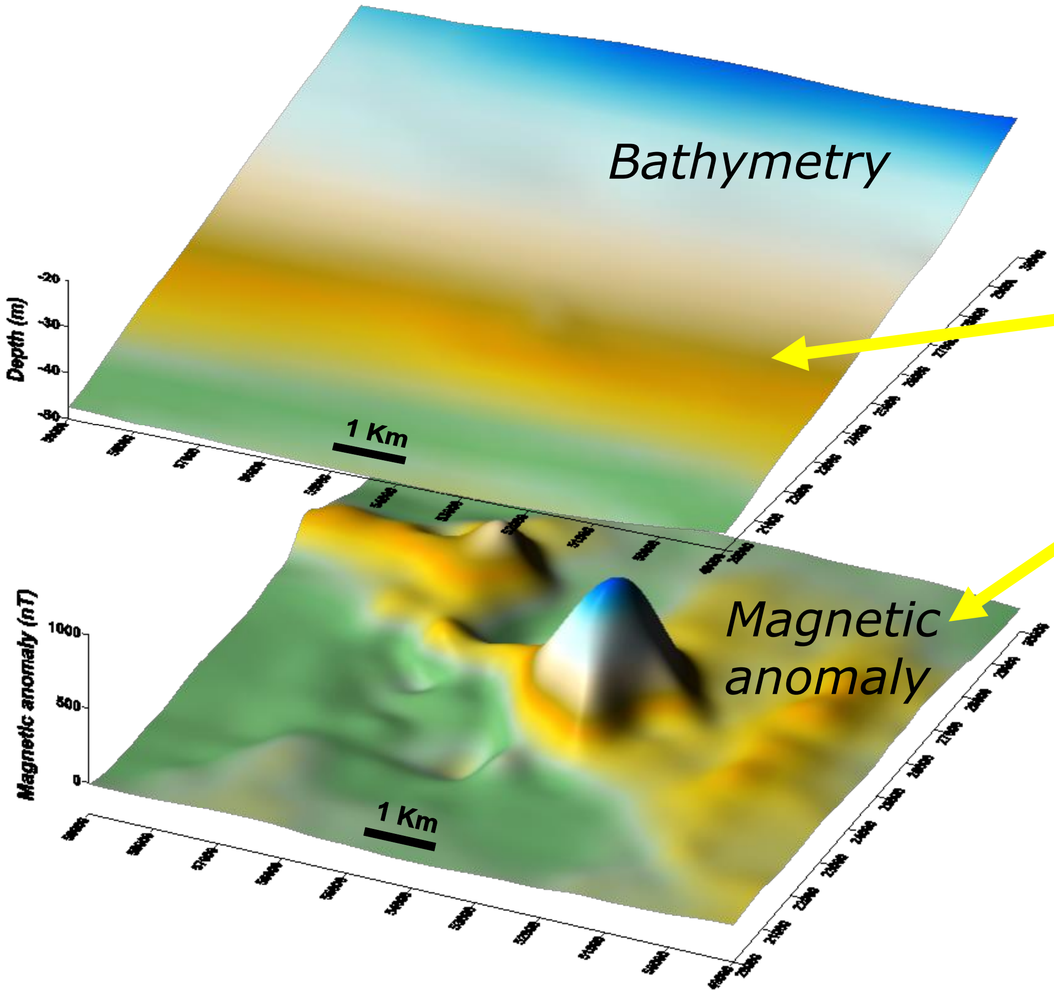
TAN – DVL Implementation

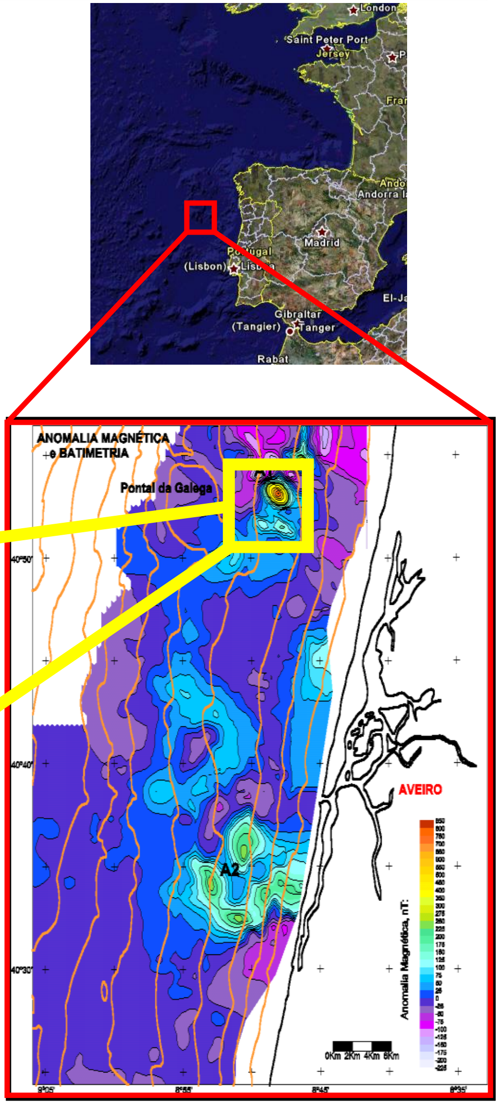




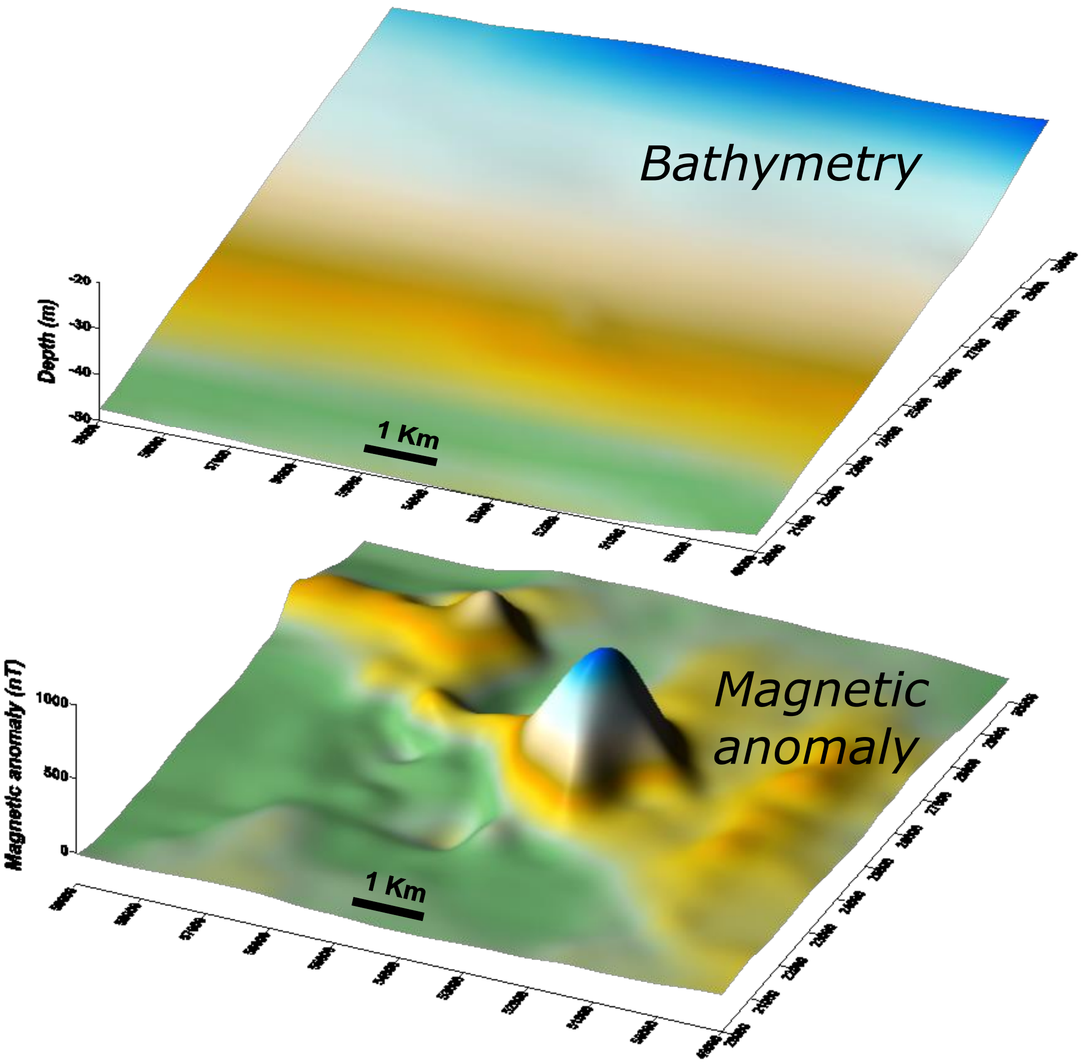
Geomagnetic Navigation

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





Geophysical Navigation

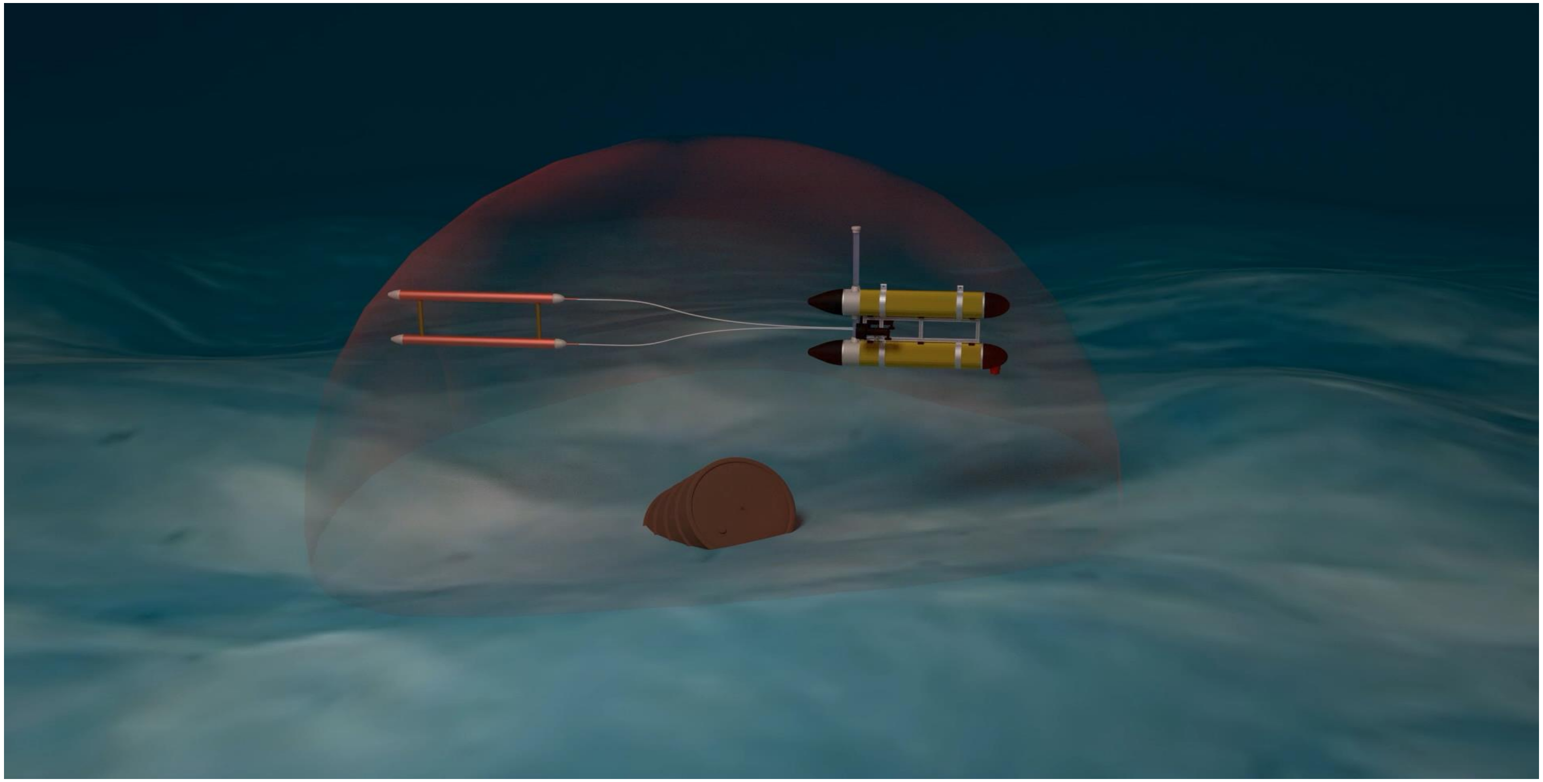


Terrain and Geomagnetic-Based Methods

Geomagnetic Navigation

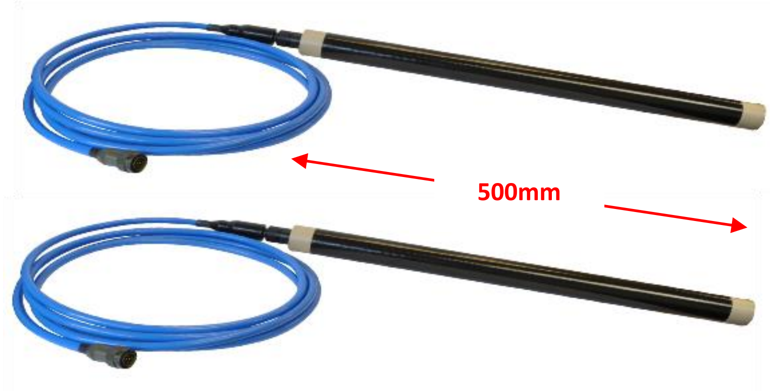
The problem of ambient and vehicle noise suppression

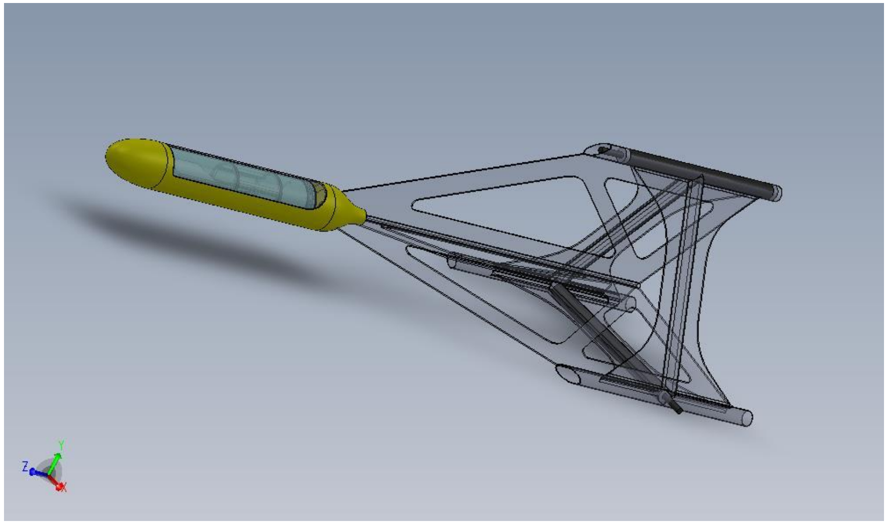
- *Tow the **magnetometer***
- *Use a mag. **gradiometer***

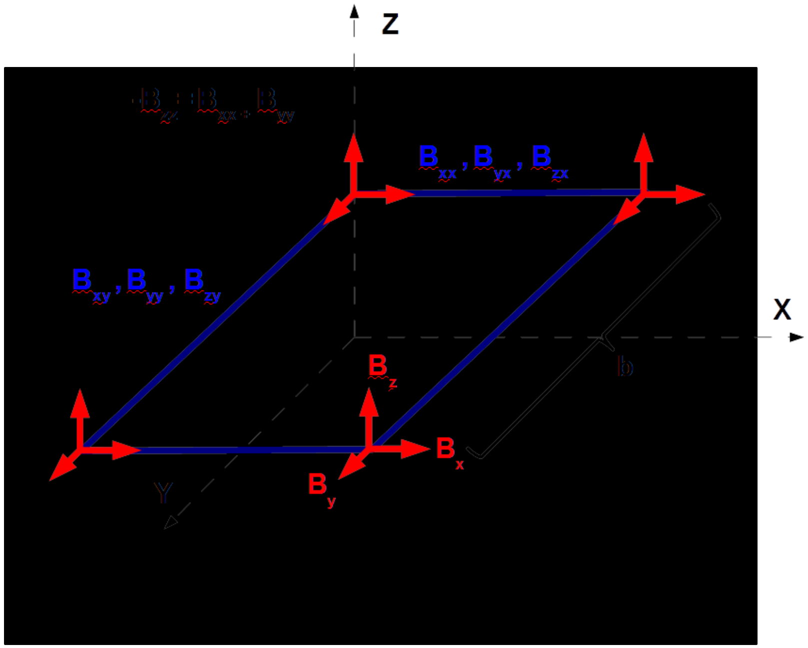


Geomagnetic Navigation

- **Sensors used (mags, gradiometers)**

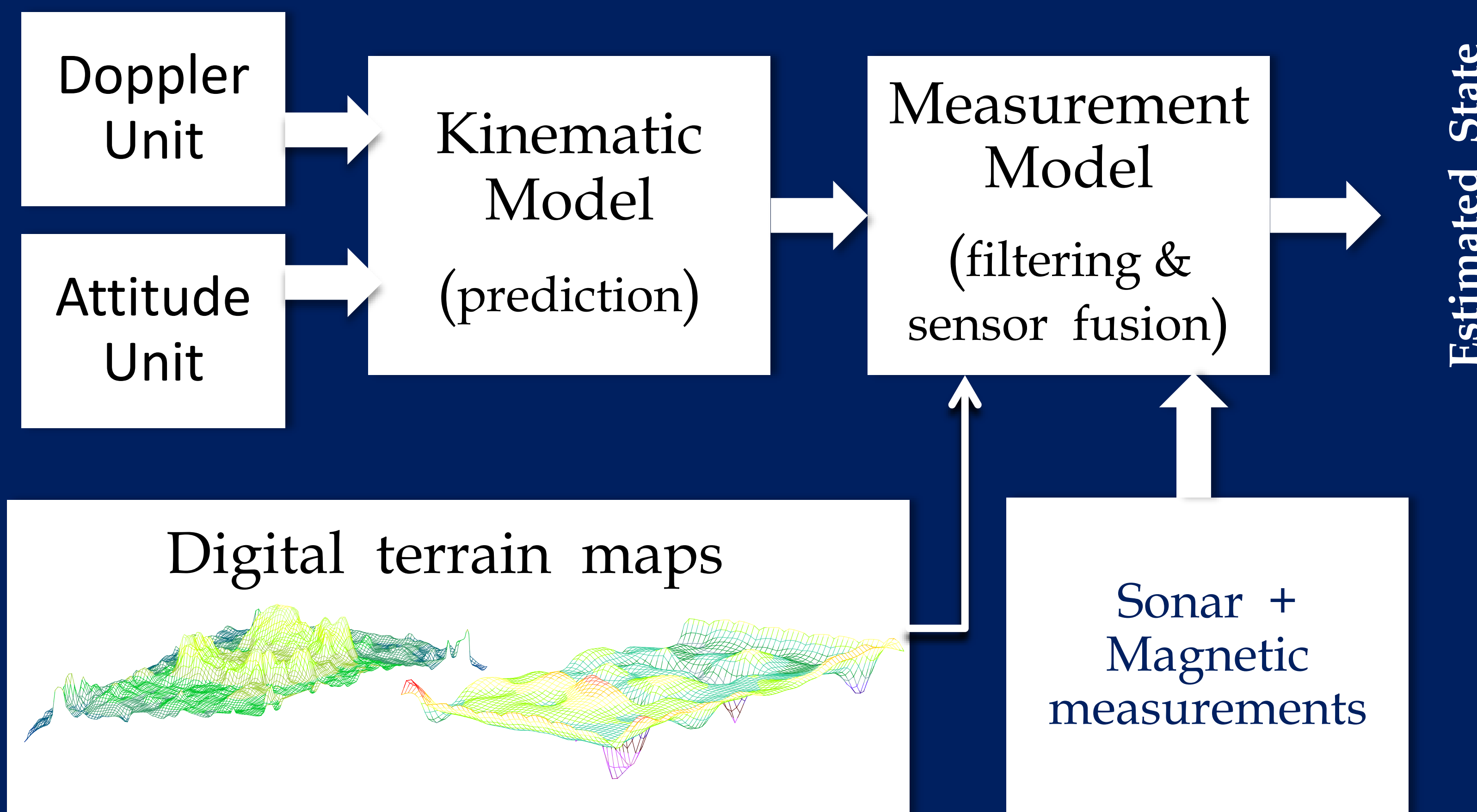






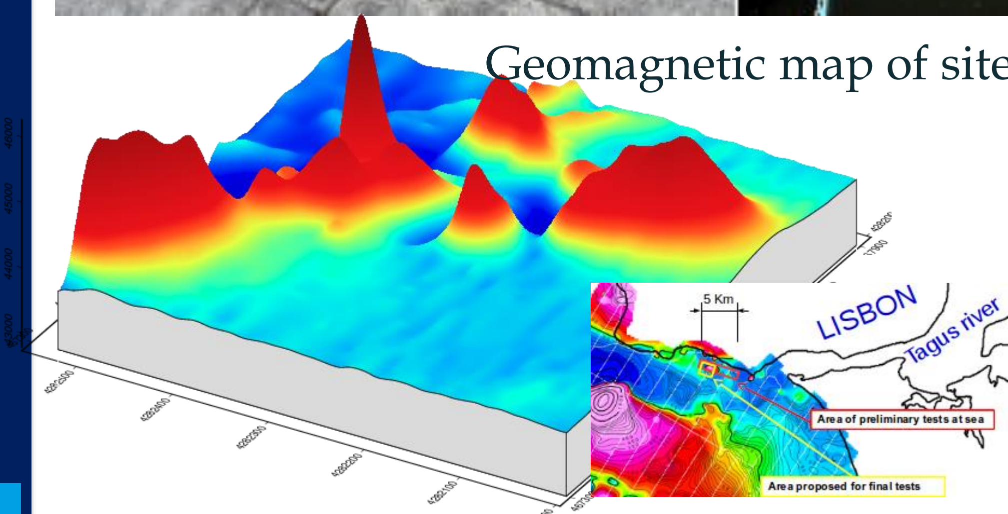
Geophysical Navigation

Integrating bathymetry and geomagnetics

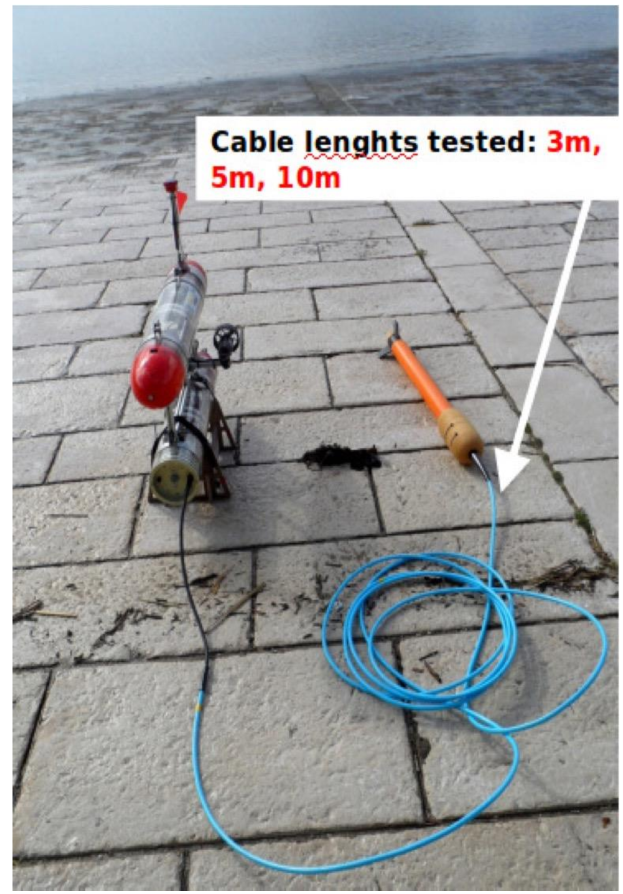


Geophysical Navigation Using Magnetic Data (MEDUSA GN System)

Gradiometer for geomagnetic map acquisition

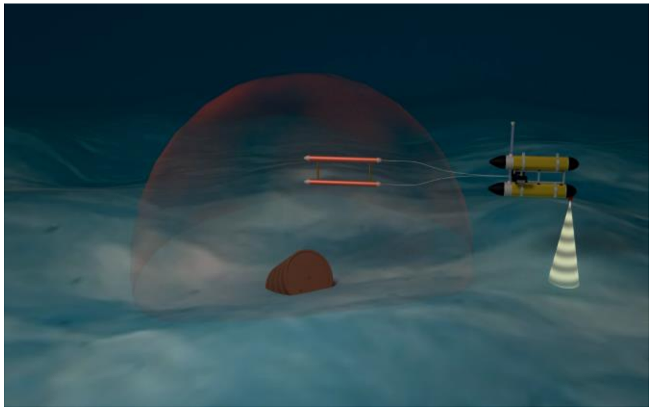


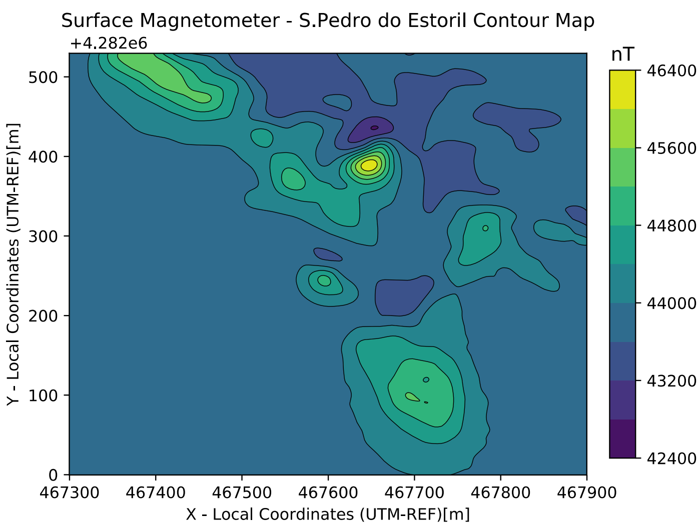
Geomagnetic map of site

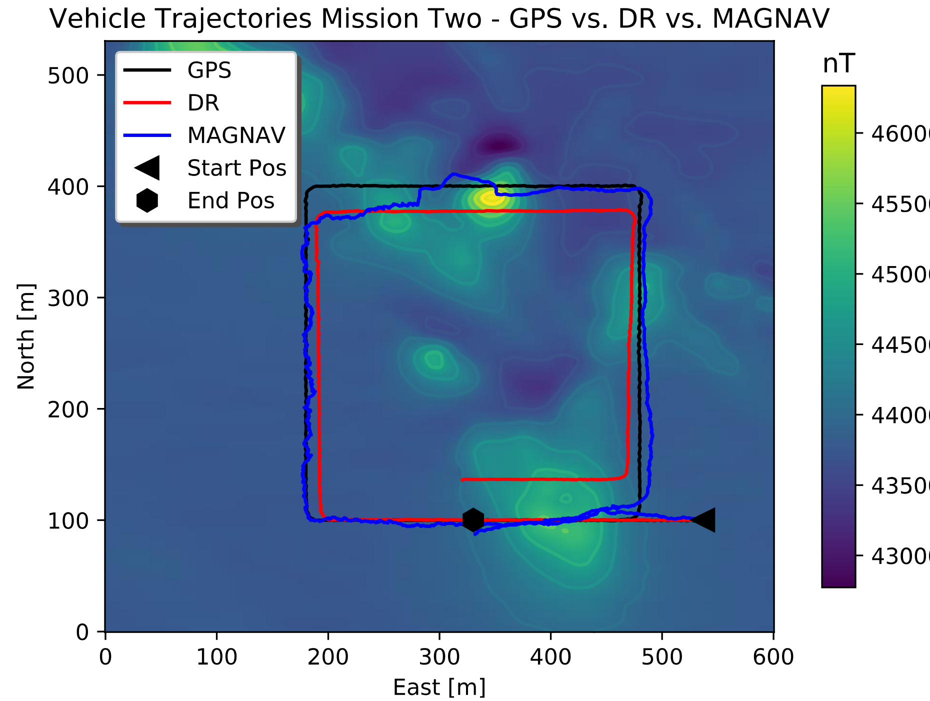


MEDUSA with magnetometer

Geophysical Navigation Using Magnetic Data (MEDUSA GN System)





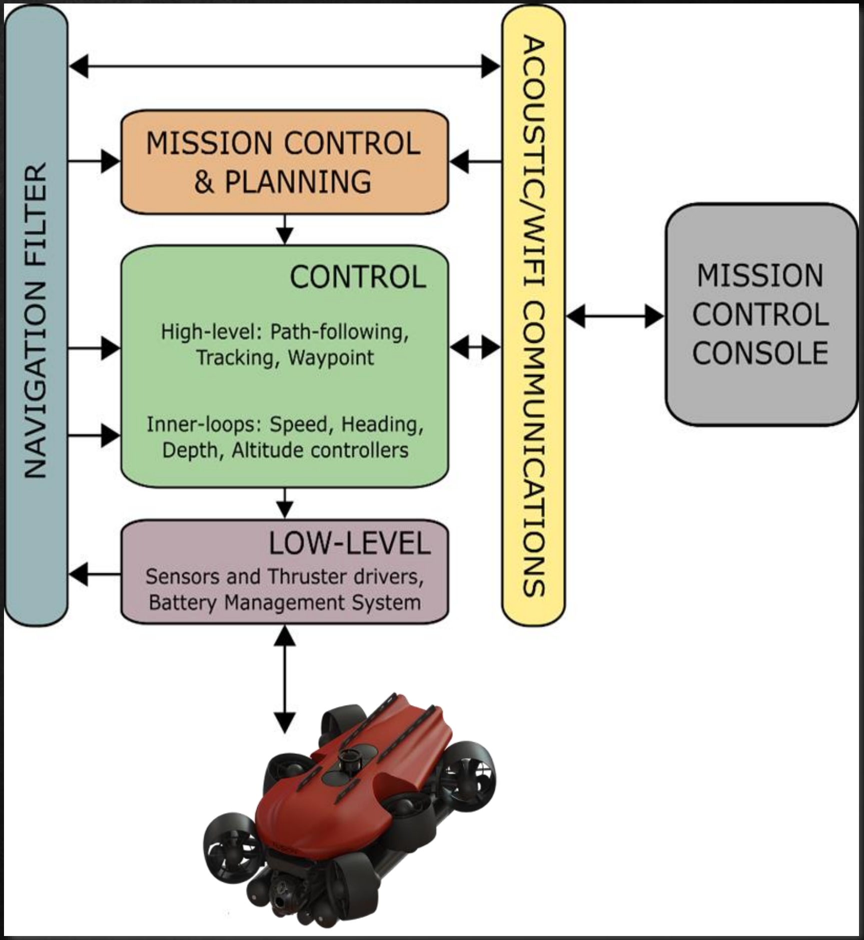


Real trajectory followed by the vehicle,
compared with the trajectory estimated by dead-recknoning and the
MAGNAV filter.

Hybrid Vehicles

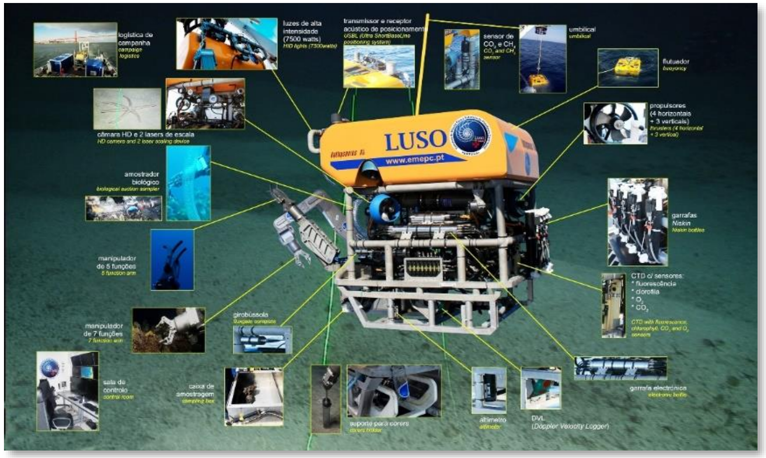
Hybrid Vehicles

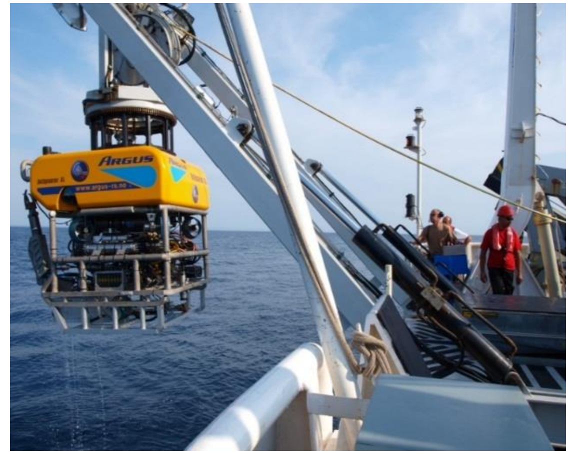
- Capitalizing on the know-how obtained from years of developing the MEDUSA Class AUVs
- IST main contributions:
    - Navigation and Control Systems
        - Development
        - Implementation
        - Optimization



Deep Going Ocean Vehicles

The Call of the ABYSS

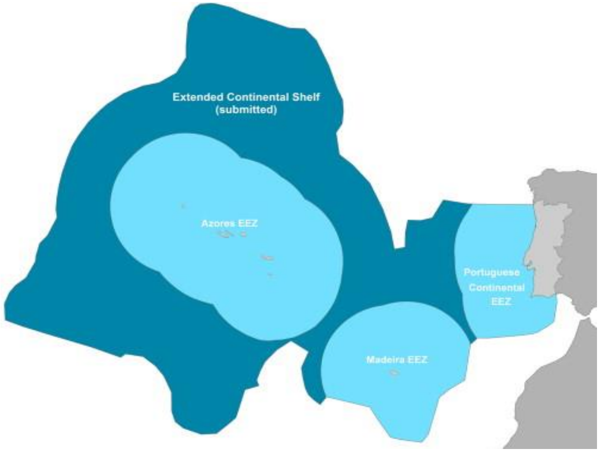




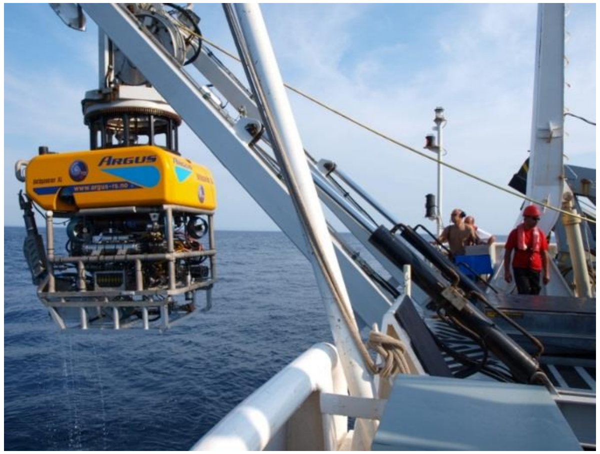
The LUSO ROV – 6000 m depth

The MEDUSA Deep Sea AUV
- 3000 depth

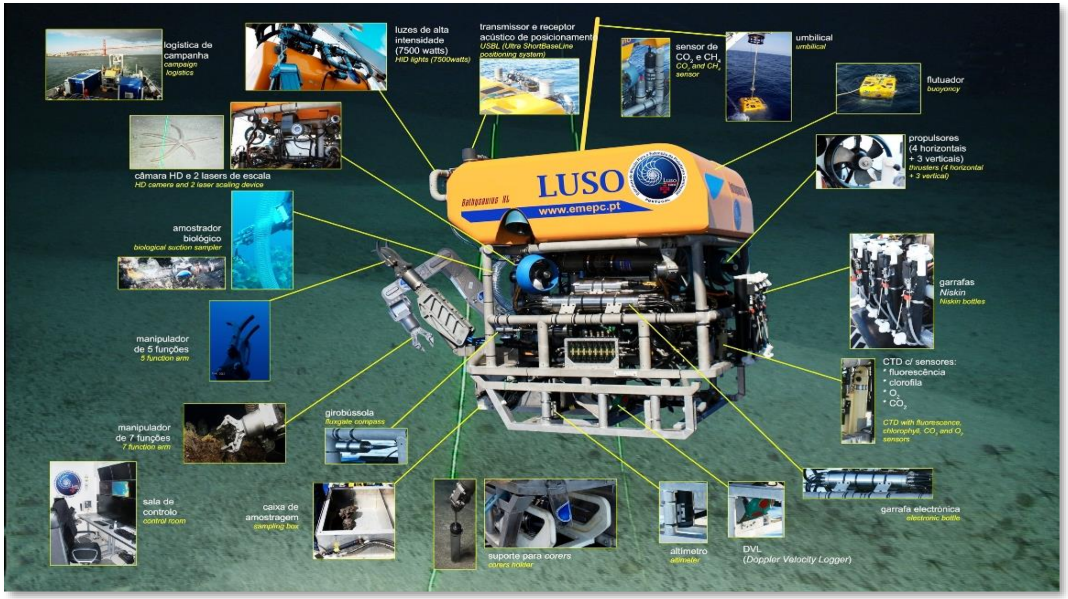
The LUSO ROV



Extended Continental Shelf
(submitted)
Azores EEZ
Portuguese
Continental
EEZ
Madeira EEZ



ARGUS

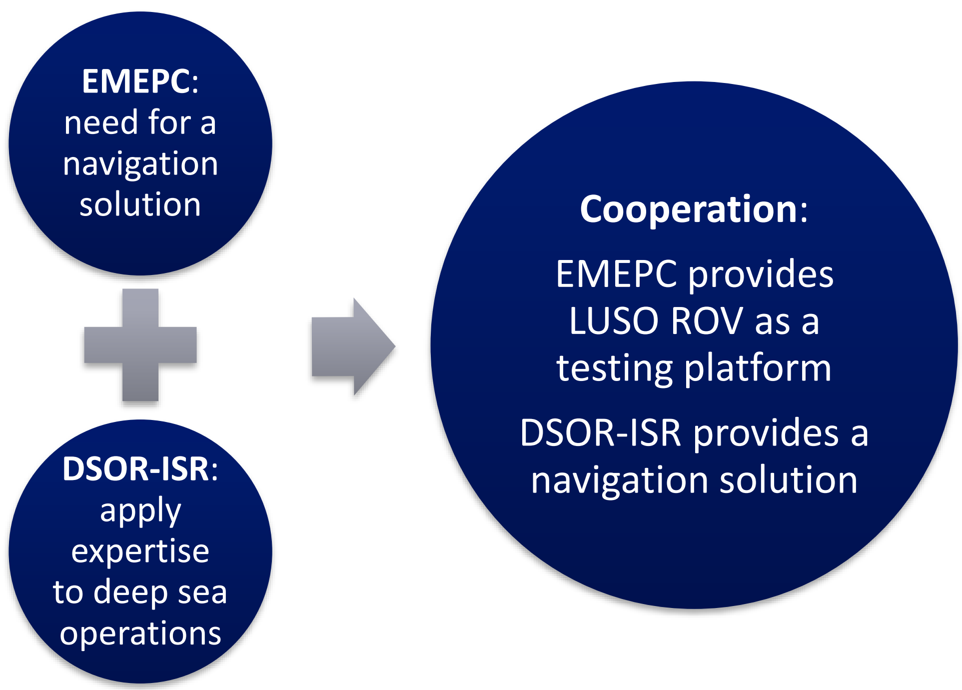


logistica de campanha
campaign logistics
luzes de alta intensidade (7500 watts)
HID lights (7500watts)
transmissor e receptor acústico de posicionamento
USBL (Ultra ShortBaseLine positioning system)
sensor de CO_2 e CH_4
CO_2 and CH_4 sensor
umbilical
umbilical
flutuador
buoyancy
câmara HD e 2 lasers de escala
HD camera and 2 laser scaling device
propulsores (4 horizontais + 3 verticais)
thrusters (4 horizontal + 3 vertical)
LUSO
Bathysaurus XL
www.emepc.pt
amostrador biológico
biological suction sampler
garrafas Niskin
Niskin bottles
manipulador de 5 funções
5 function arm
CTD c/ sensores:
* fluorescência
* clorofila
* O_2
* CO_2
CTD with fluorescence, chlorophyll, CO_2 and O_2 sensors
manipulador de 7 funções
7 function arm
girobússola
fluxgate compass
sala de controlo
control room
caixa de amostragem
sampling box
suporte para corers
corers holder
altímetro
altimeter
DVL
(Doppler Velocity Logger)
garrafa electrónica
electronic bottle

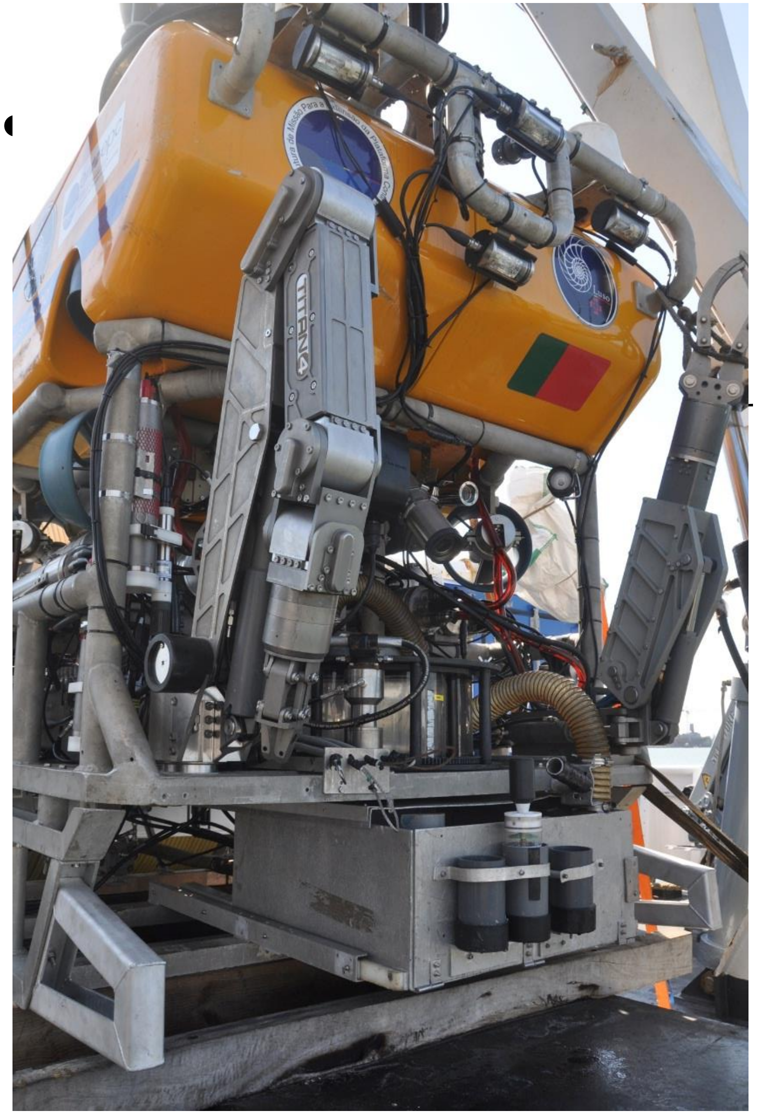
Estrutura de Missão Para a Extensão da Plataforma Continental
Luso
EMEPC
PORTUGAL

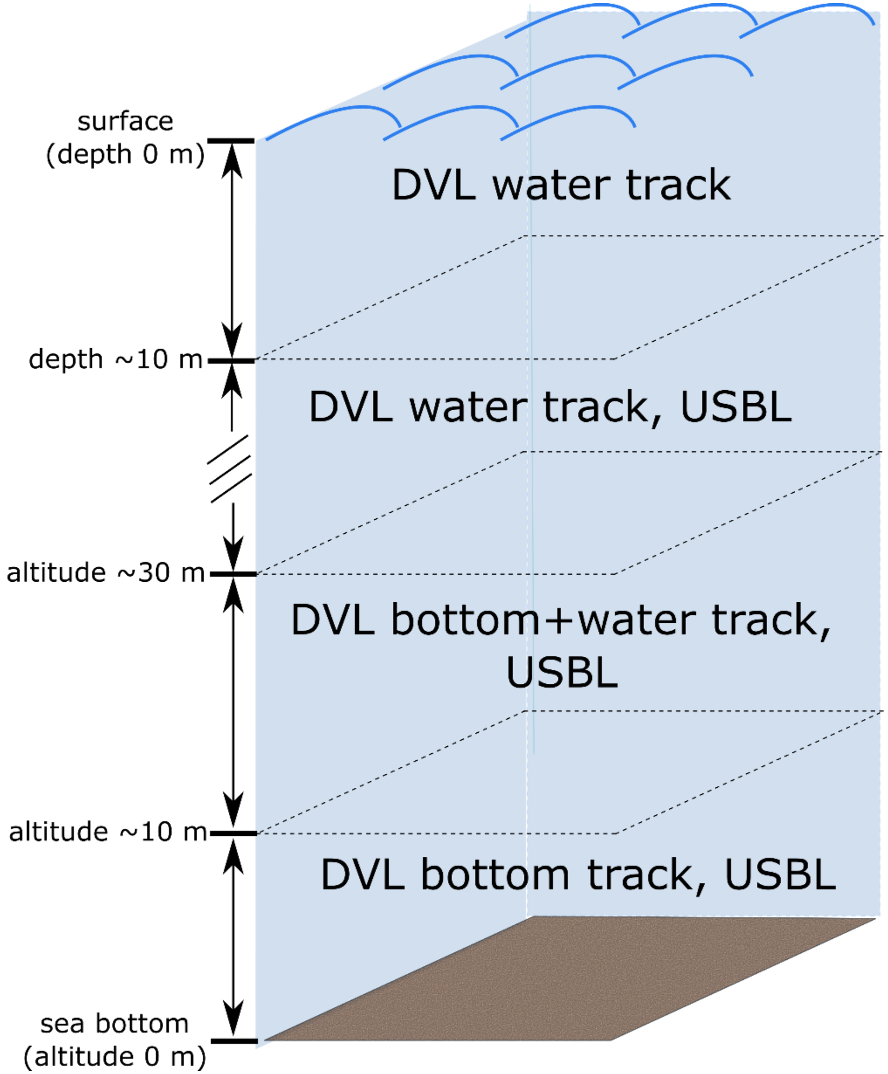
LUSO ROV Navigation

- Pilots depended on noisy, unreliable, infrequent **Ultra-Short Baseline (USBL) position fixes**
- A reliable, continuous-time estimate of the ROV position would allow for precise georeferencing and assist pilots
- Navigation should take advantage of other sensors, e.g. the **Doppler Velocity Log**

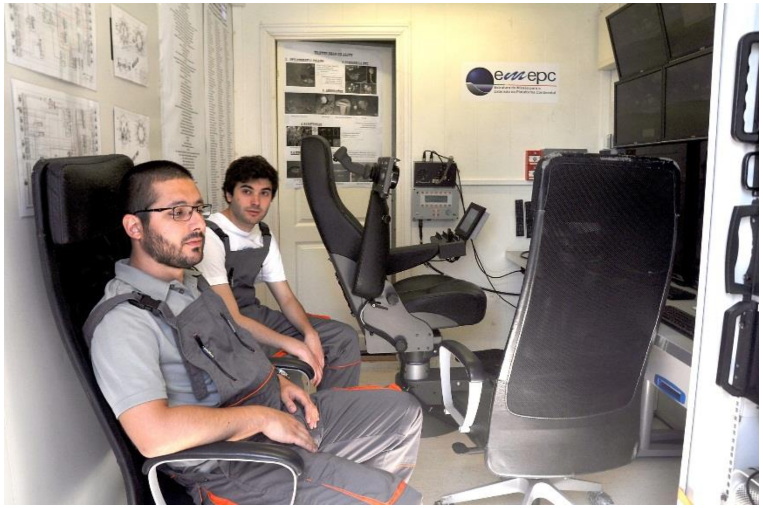


Measurements available

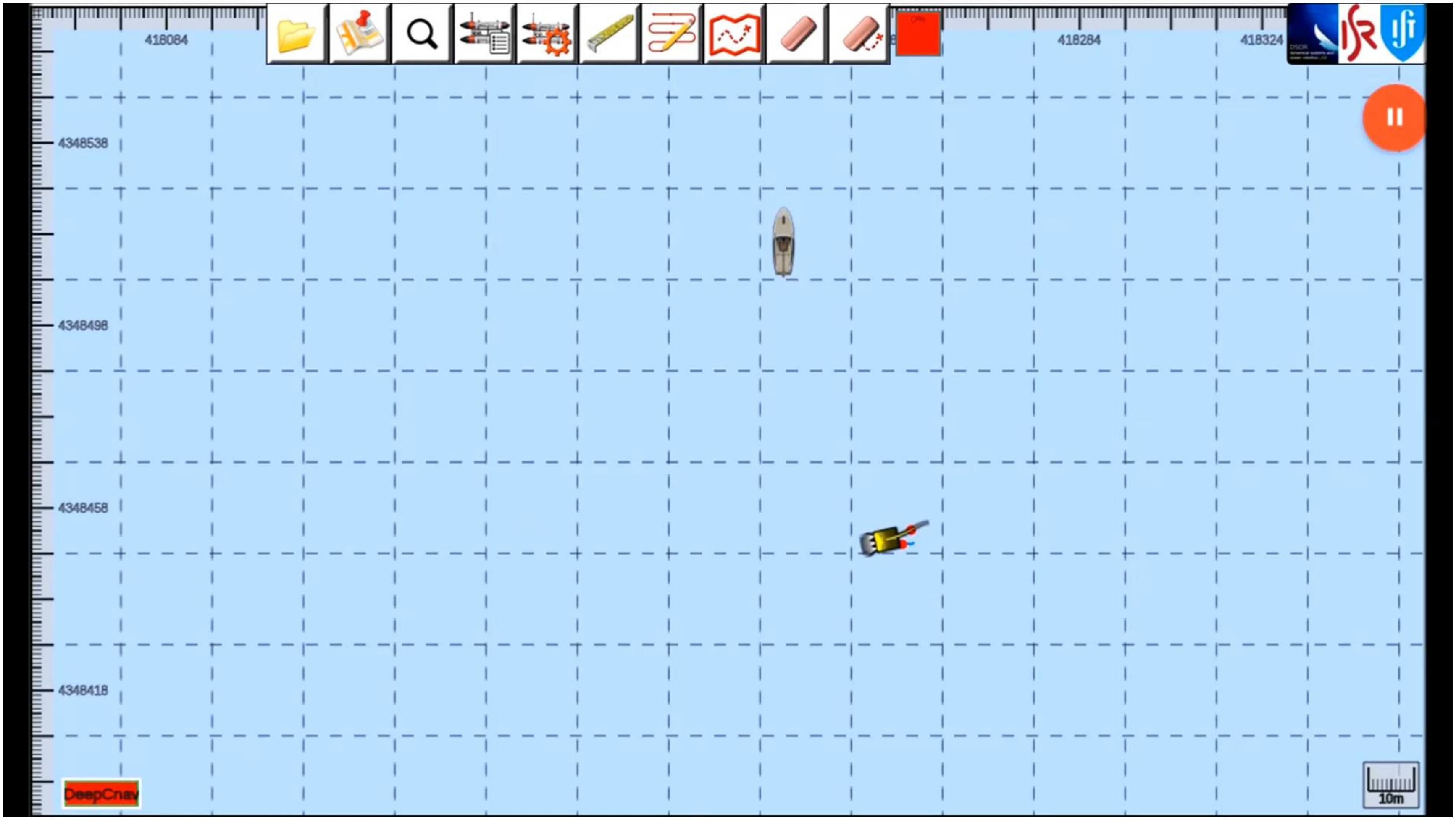




Test at Sea



Final setup & testing at sea

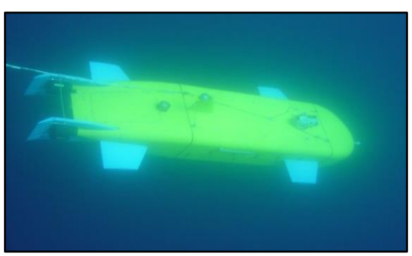


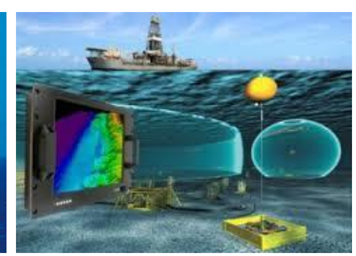
The big push forward

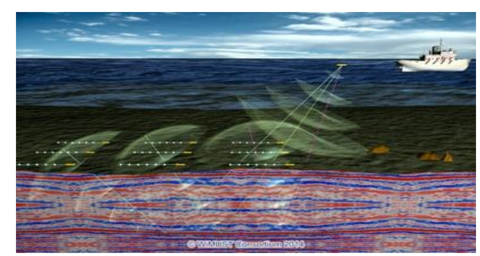
Bring about a true revolution in the marine technology area by:

- Focusing on challenging **flagship initiatives** driven by end-users (including aquaculture, renewable energies, fisheries, and ocean modeling)

- Merging innovation with core technologies for seamless access to the water column, critical infrastructures, and the **deep sea**.

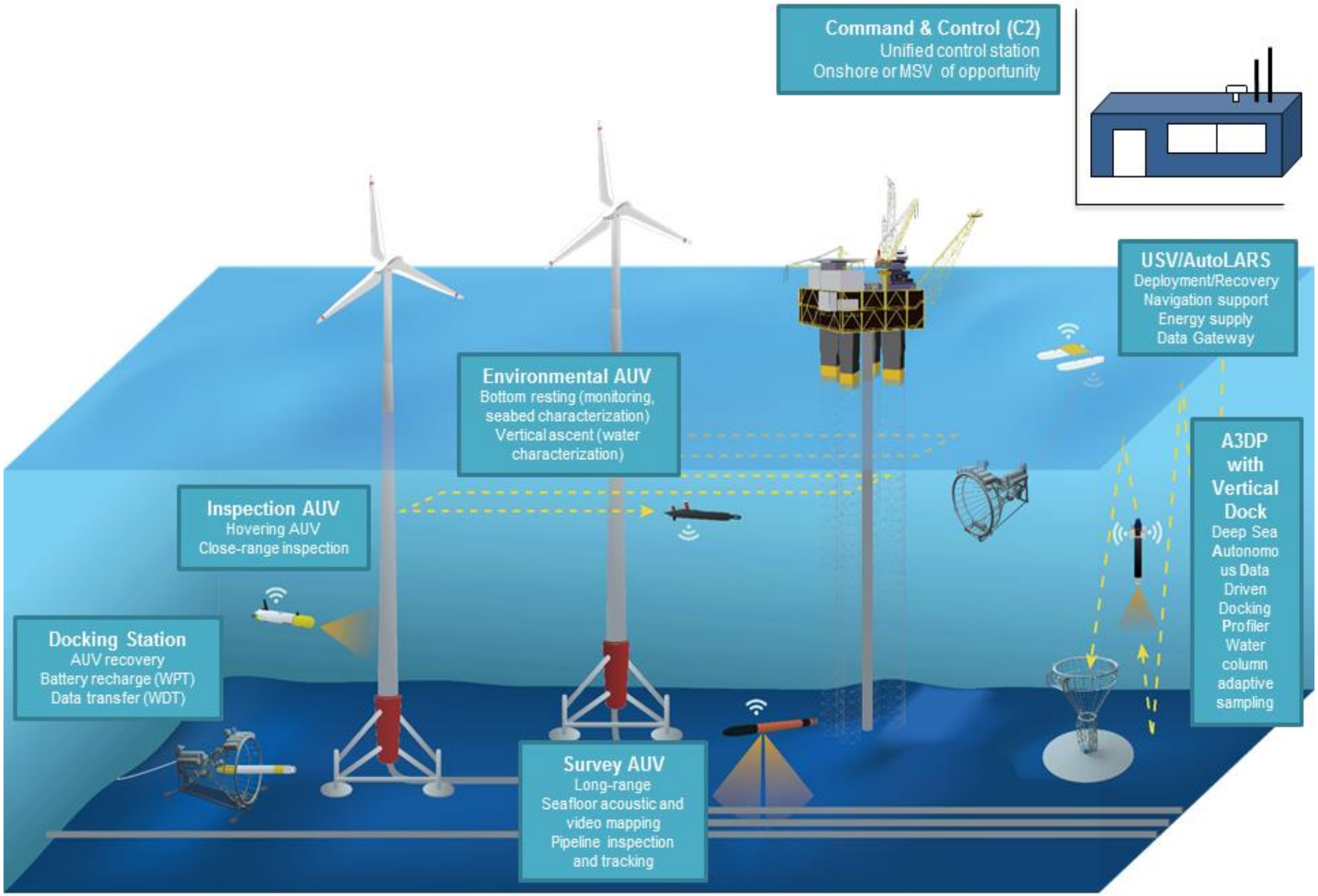






A Vision of the Future: the EC PASS intiative

Sustained presence at sea: offshore wave and wind energy harvesting, deep sea lab maintenance



SOS4ATLANTIC: A NEW MIT-PT INIATIVE

A Multi-Domain Atlantic Ocean-Space Observation System: Science, Technology, and Society

tekever SPACE

deimos ENGENHARIA

TÉCNICO LISBOA

TEKEVER

hidrográfico marinha · portugal

Massachusetts Institute of Technology

efacec Empowering the future

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

CERENA Centro de Recursos Naturais e Ambiente

spin.works

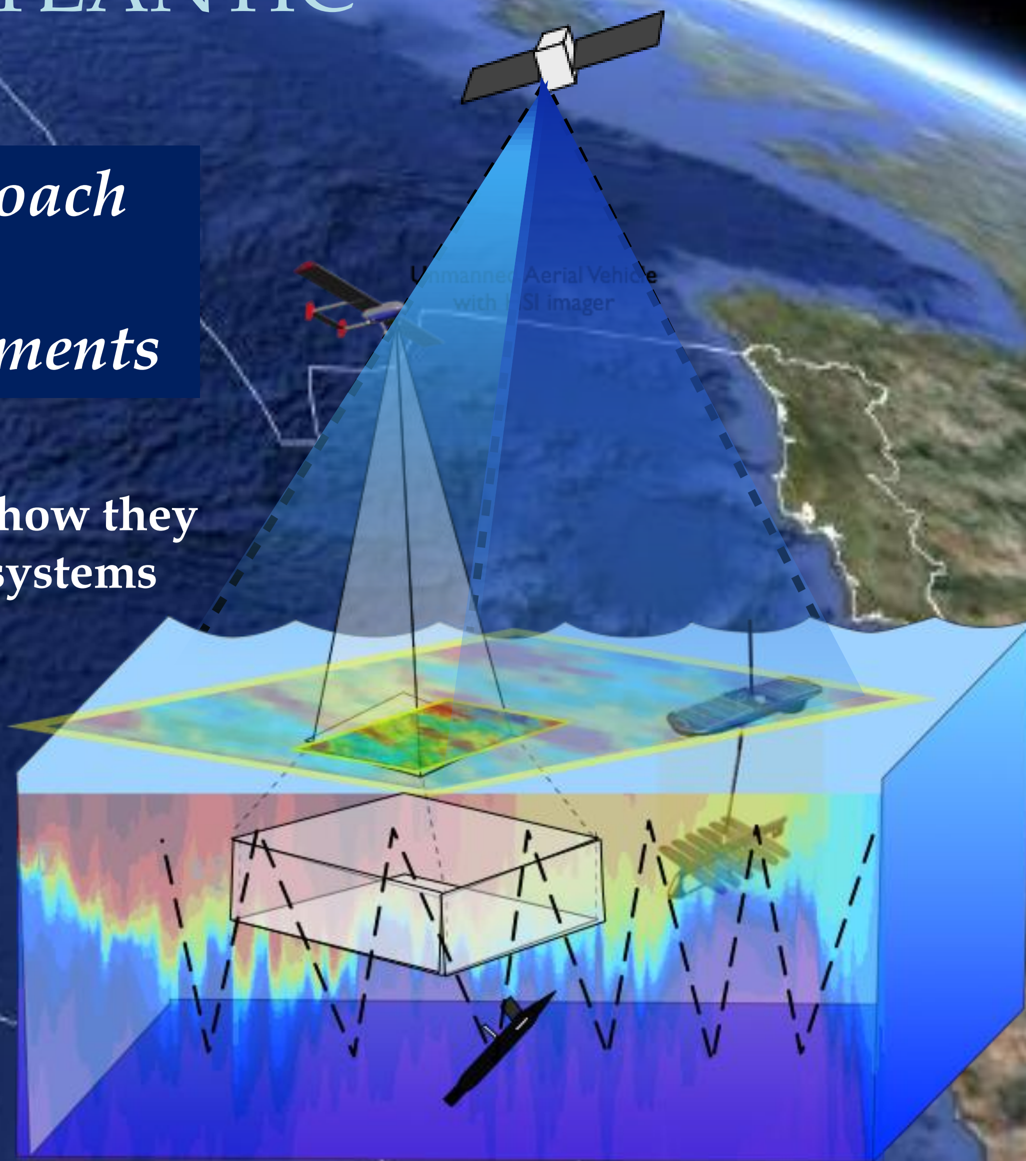
U.PORTO FC FACULDADE DE CIÊNCIAS UNIVERSIDADE DO PORTO

imar

CoLab +ATLANTIC

SOS4ATLANTIC

A System of Systems approach integrating
Space, Air, and Marine segments



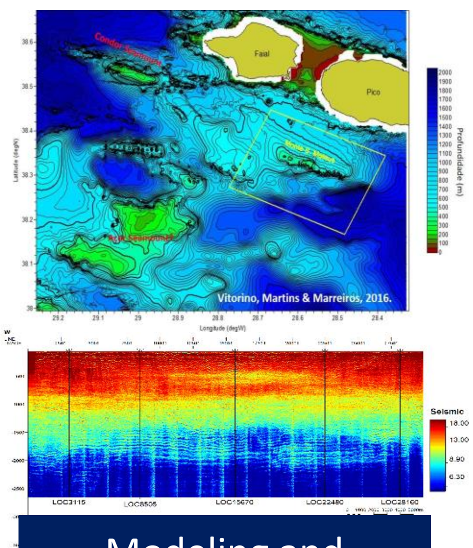
Target use-case:
Study of ocean front dynamics and how they impact on pelagic and deep sea ecosystems

Vision:
lay the foundations for an **Atlantic Ocean Observation Platform** with far reaching scientific, commercial, and societal impact.

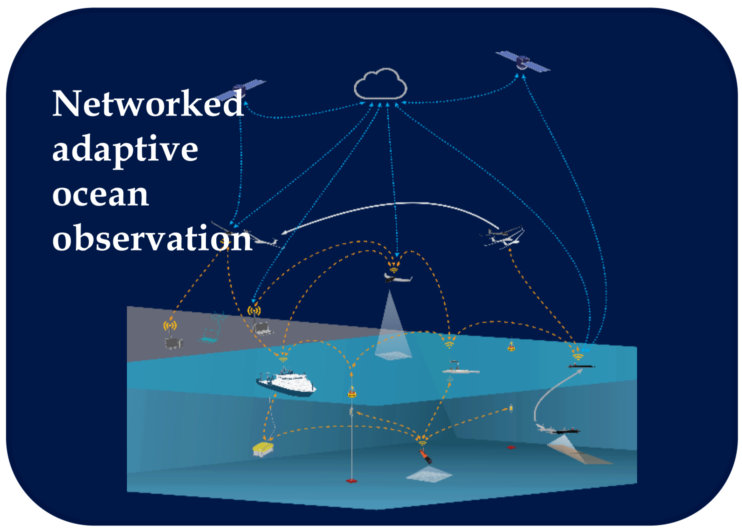
SOS4ATLANTIC

SOS4ATLANTIC

A System of Systems approach integrating Space, Air, and Marine segments for Ocean Science



Modeling and Forecasting



Multi-vehicle SOSystems

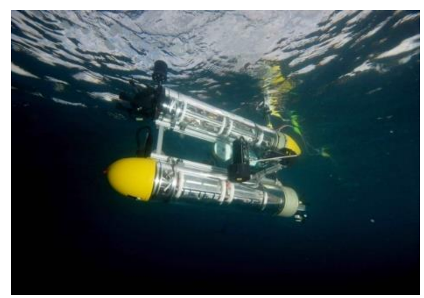
Ocean front and ecosystem studies

SOS4ATLANTIC

SOS4ATLANTIC

A showcase of technological assets for science and the industry

NRP D. Carlos class Oceanographic Vessel



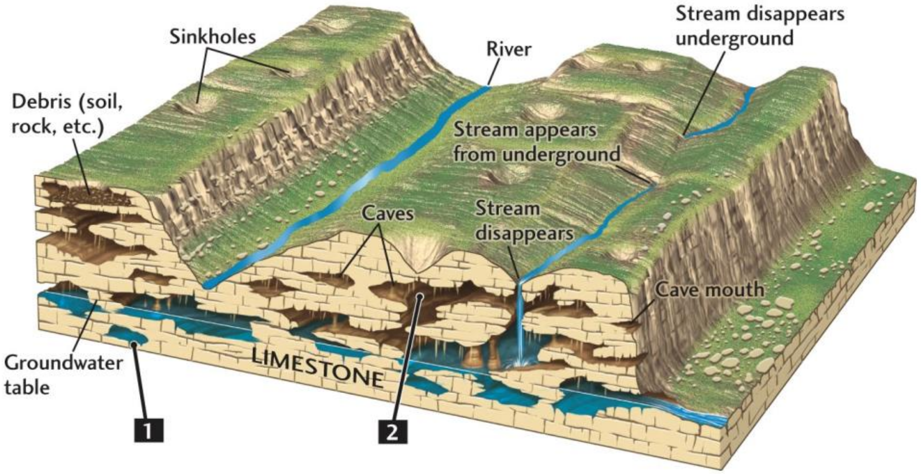
RV Águas Vivas

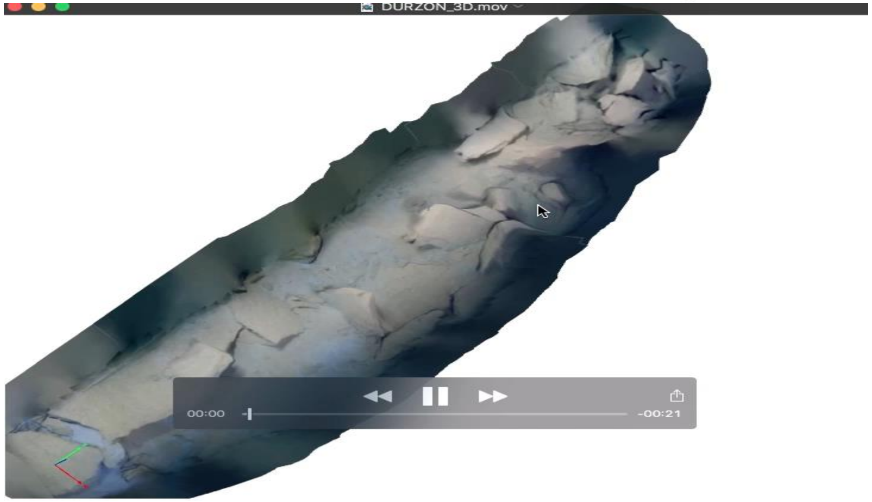
Fleet of 20 surface and underwater autonomous marine robots – FEUP, IST, MIT

10 unmanned air vehicles – FEUP & TEKEVER

EU - ANZAR

Karstic exploration using autonomous robots (water reservoir management)



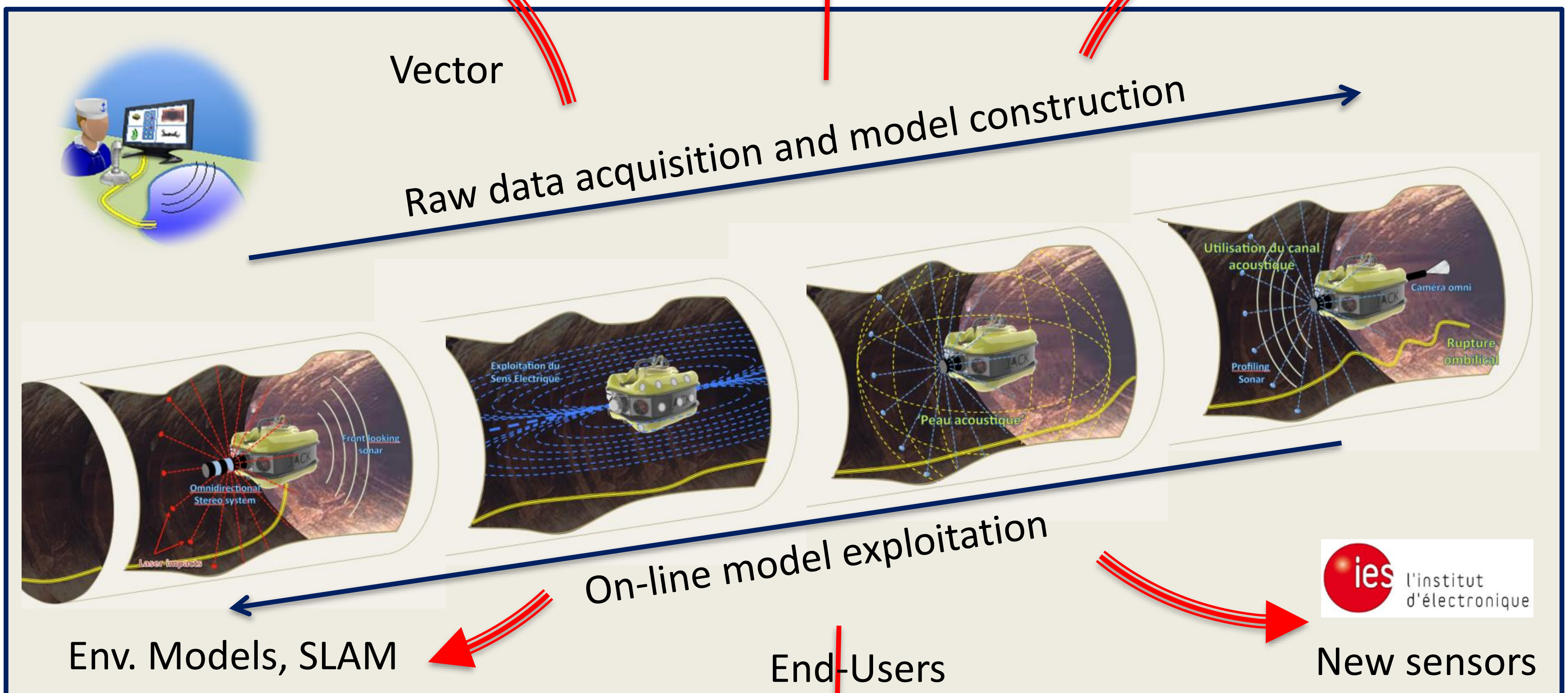


Near Future : The Anzar European Extension

LARSyS Laboratory of Robotics and Engineering Systems
LIRMM

LEM Lille Economics Management
MRM Montpellier Research in Management
Business

USJ 1875
brgm Géosciences pour une Terre durable
HSM
Environnement



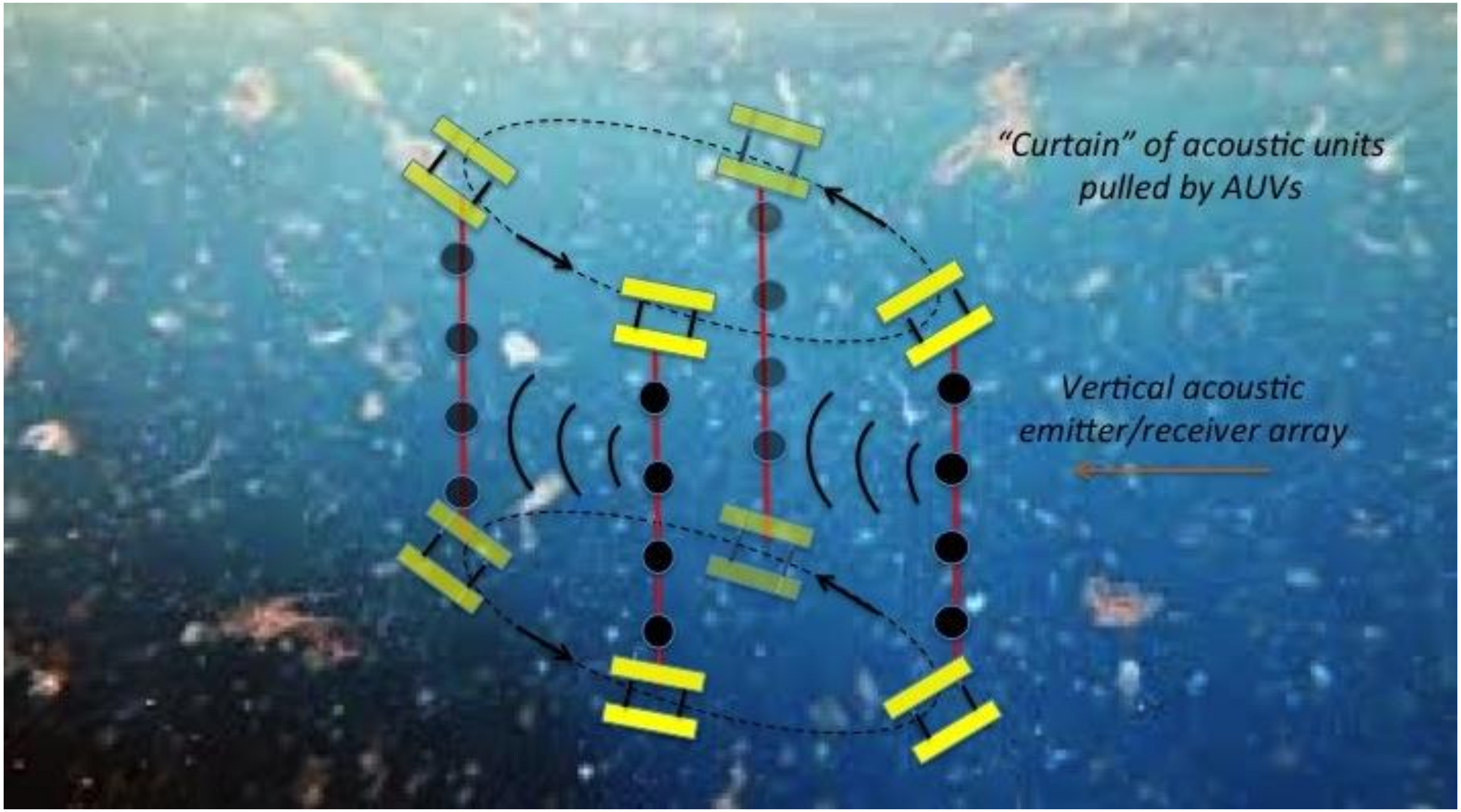
ies l'institut d'électronique

ViCOROB Computer Vision and Robotics
IMAG

EDF
Montpellier Méditerranée Métropole
Hydrokarst Groupe
CENOTE
SyERA
REEDS
IQUA Robotics

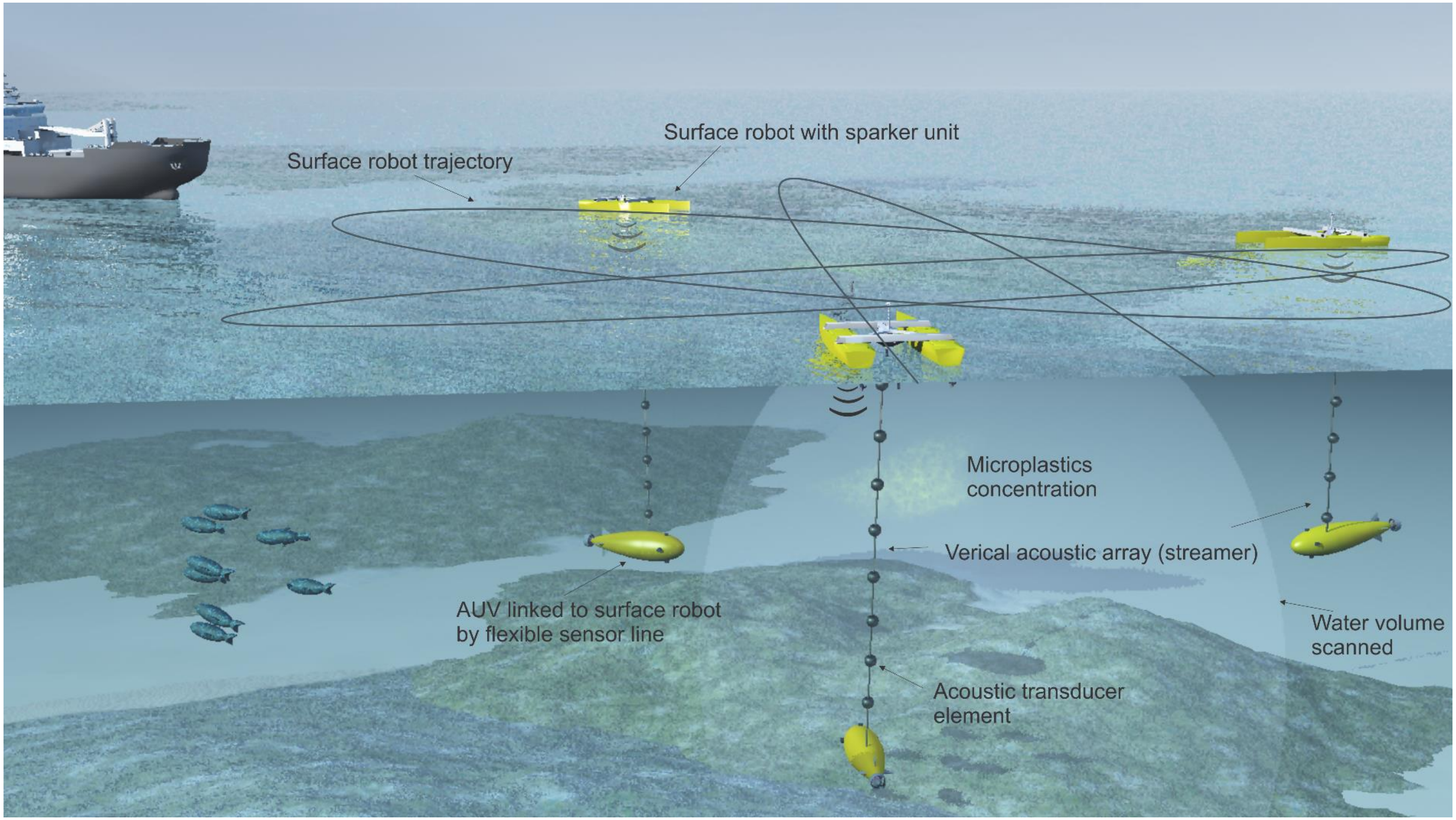
EU - SARDINES

Detection, Tracing, and Mapping of Microplastics in the Ocean

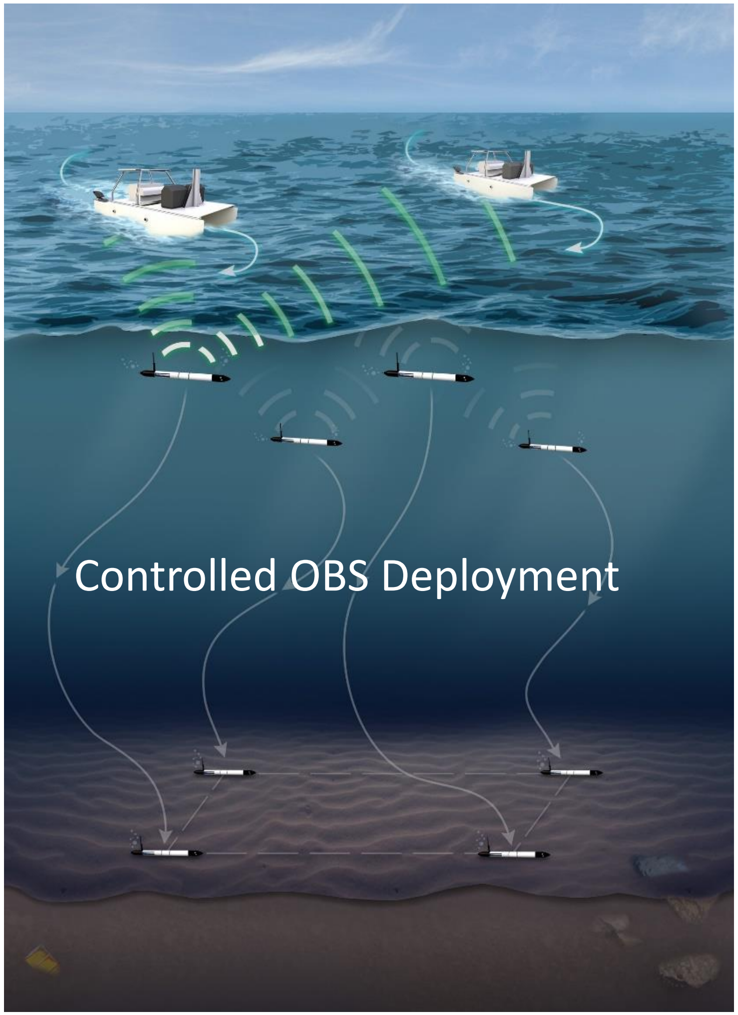


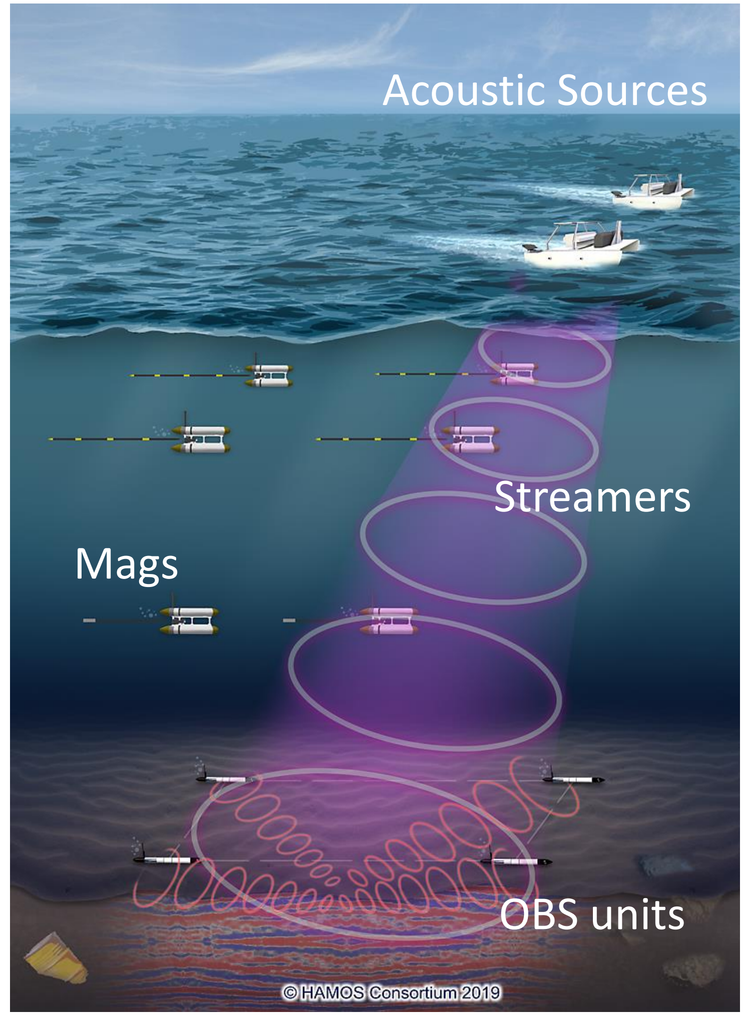
EU - SARDINES

Detection, Tracing, and Mapping of Microplastics in the Ocean



The Future: Advanced Geotechnical Suveys
EC-WiMUST Consortium, 2019

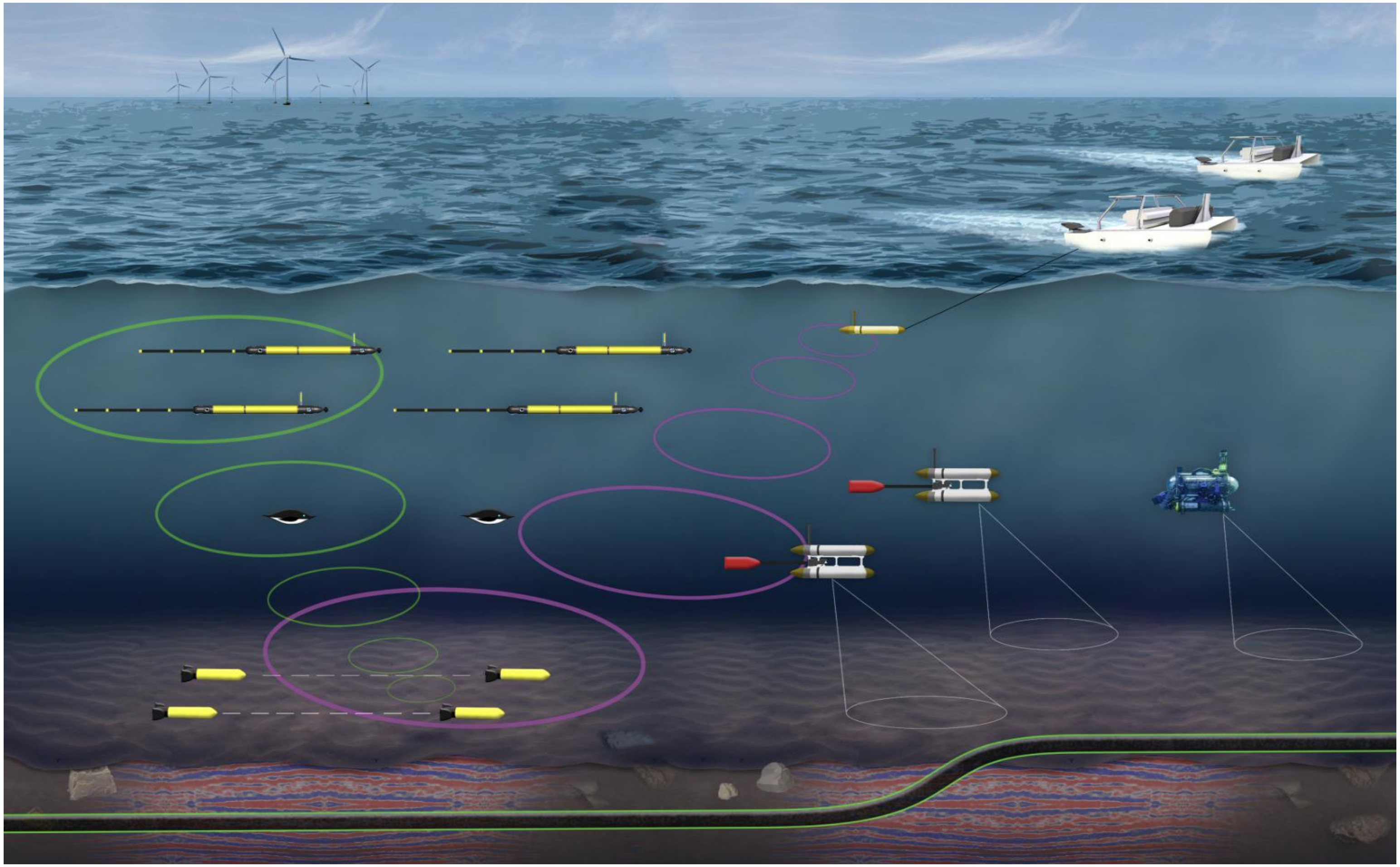




Streamers, Mags, and OBS (Ocean Bottom Surveying units)

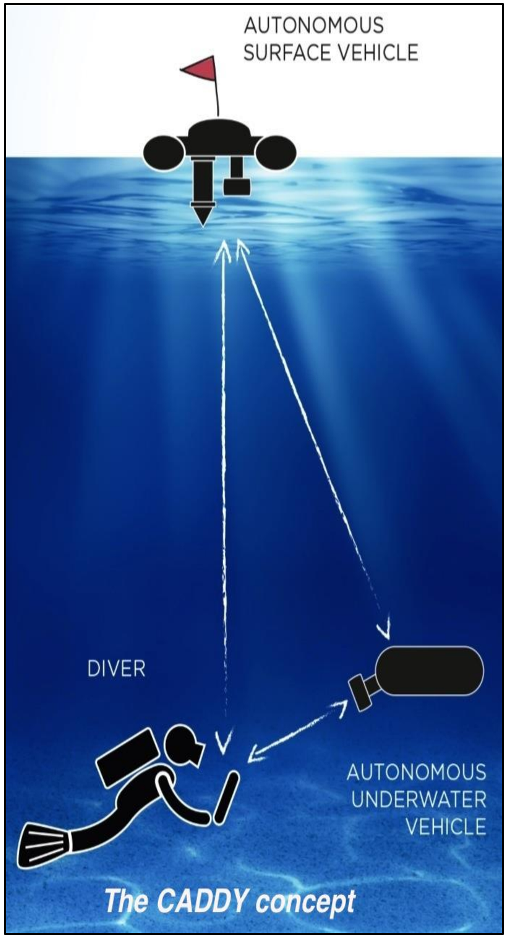
EU - DRIIM

A Distributed Robotic-Based System for Underwater Infrastructures Inspection



The future: Cooperative Robots and Humans in the Loop

CADDY
Cognitive Autonomous Diving Buddy



Ocean Literacy
Cultural Heritage (underwater archaeology)

National and International Cooperation

- Woods Hole Oceanographic Institute (WHOI, USA)
- L´Institut Français de Recherche pour l´Exploitation de La Mer (FR)
- Zentrum fur Marine Umweltvissenschaften at Bremen (MARUM, DE)
- Norwegian University of Science and Technology (NTNU / AMOS, NO)
- National Institute of Oceanography (NIO, Goa, INDIA)
- National Institute of Ocean Technology (NIOT, Chennai, INDIA)
- Center for Maritime Research and Experimentation (CMRE, La Spezia, IT)
- Korean Advanced Institute of Science and Technology (KAIST, Korea)
- Carnegie Mellon University, Pittsburgh (USA)
- Naval Postgraduate School, Monterey, CA (USA)
- École Polytechnique Fédérale de Lausanne (EPFL, Lausanne, CH)
- Universidade de S. Paulo (BR)
- IMAR/DOP/Uaçores (PT)
- Faculdade de Engenharia da Univ. Porto (FEUP, PT)
- EMEPC, PT

Questions ?