Marine robots in environmental surveys: current developments at ISME

Andrea Caiti – andrea.caiti@unipi.it

Università di Pisa – Dipartimento di Ingegneria dell’informazione & Centro ‘’E. Piaggio’’
ISME – Interuniversity Center of Integrated Systems for the Marine Environment

R. Costanzi, T. Fabbri, F. Fabiani, D. Fenucci, S. Grechi, V. Manzari
Università di Pisa – Dipartimento di Ingegneria dell’informazione & Centro ‘’E. Piaggio’’
ISME – Interuniversity Center of Integrated Systems for the Marine Environment

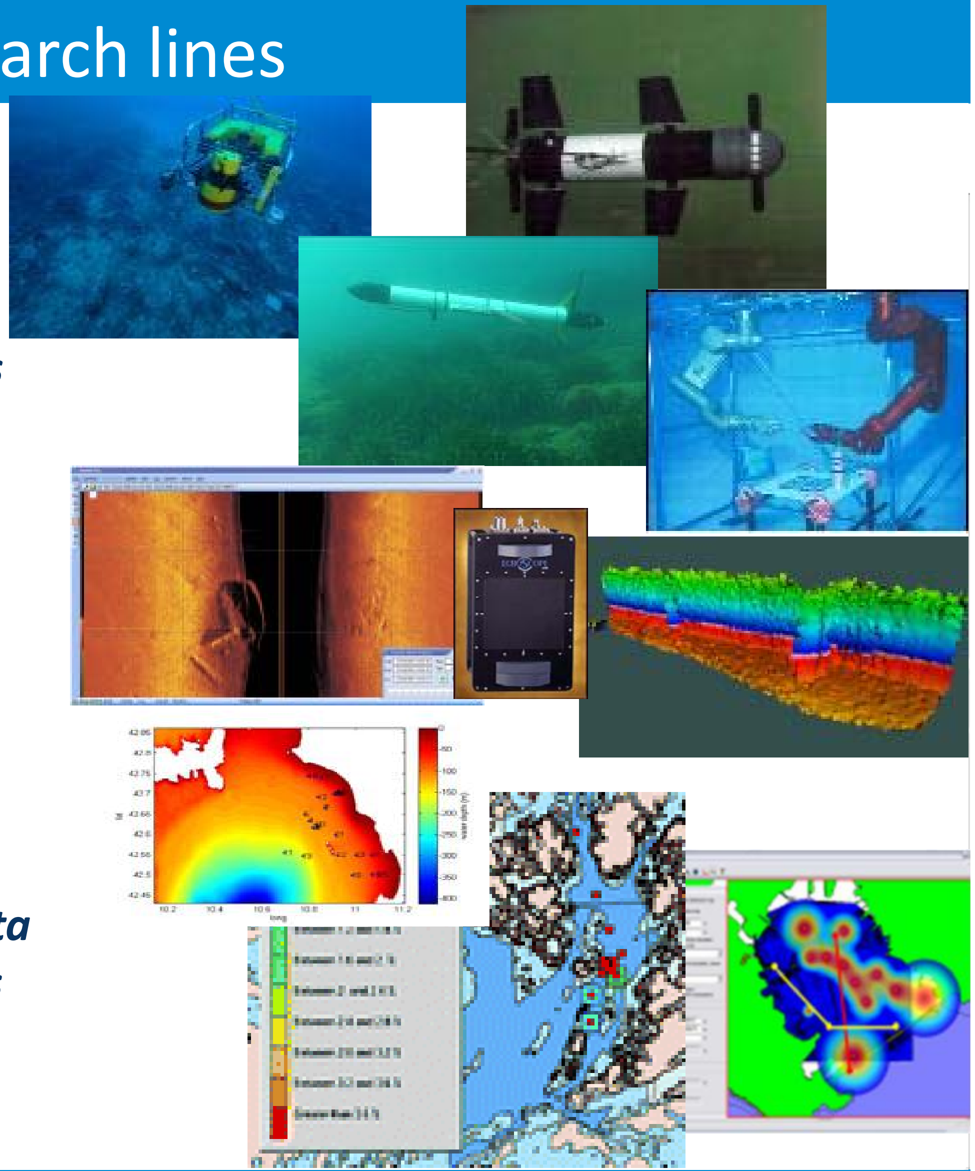
B. Allotta, J. Gelli, E. Meli, N. Monni, L. Pugi, A. Ridolfi
Università di Firenze – Dipartimento di Ingegneria Industriale
ISME – Interuniversity Center of Integrated Systems for the Marine Environment

Oceanic Engineering Research in Italy

Integrated Systems for Marine Environment

Inter-University Research Centre
Established in 1999
Today: 9 Universities, >70 researchers
Shared infrastructures, labs, equipment

ISME: resarch lines



- ***Marine robotics***
  - ***ROV, AUV***
  - ***Underwater manipulation systems***
  - ***Guidance, Navigation & Control***

- ***Underwater acoustics***
  - ***geoacustics, acoustic tomography***
  - ***imaging & sonar systems***
  - ***uw comms & networking***

- ***Signals & data processing***
  - ***Oceanographic/environmental data***
  - ***Geographical Information Systems***
  - ***Decision Support Systems***

ISME: Funding and projects

All ISME research is funded by contracts with agencies, industries, third parties

Resources from any participating lab are available to ISME

ISME-owned resources are available to any participating lab

Strong emphasis to applied research and field activities

ISME: Collaboration with the Italian Navy

SEALab – shared laboratory and infrastructures between
ISME and Italian Navy – Center for Naval Support and Experimentation

SEALab
SISTEMI ETEROGENEI AUTONOMI MARINI

ISME
Integrated Systems for Marine Environment

MARINA MILITARE

CSSN
CENTRO SUPPORTO SPERIMENTAZIONE NAVALE

Underwater Robotics in ISME

- **Autonomous Underwater Vehicles (AUV) Development**
  - **Seabed survey, environmental monitoring, archaeology**
- **Acoustic Navigation**
- **Long-term endurance**
- **Underwater Comms & Cooperation**

Vehicles Development
(our babies)

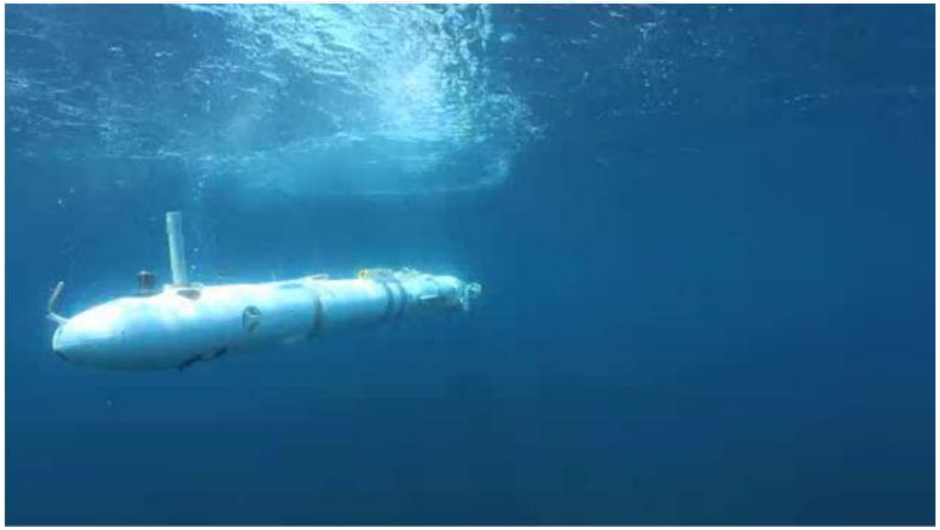
Typhoon class AUVs

Sensor	TifOne	TifTu
Xsens IMU	✓	✓
KVH FOG	✓	×
Teledyne DVL	✓	×
STS DTM	✓	✓
Evologics USBL	Localizable Modem	Localizing Transducer
PC-104 GPS	✓	✓

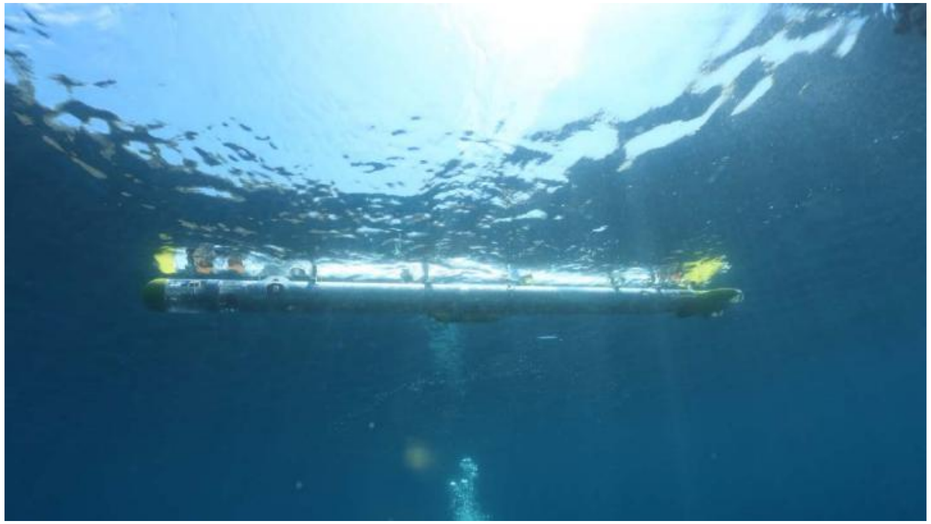
Typhoon class AUVs

Some sea test campaigns

- GEOSUB Experiment with Italian Navy – RV Leonardo, **Palmaria Island (La Spezia, Italy)** – April 11th -15th, **2016**
- ARROWS Project Final Demonstration I – **Aegadian Islands (Sicily, Italy)** – March 23rd - June 5th, **2015**
- ARROWS Project Final Demonstration II – **Baltic Sea (Tallinn, Estonia)** – July 16th-24th, **2015**
- ARROWS Project Demonstration – **Biograd na Moru (Croatia)** – October 5th-24th, **2014**
- IAA Archaeology Mission – **Akko, Caesarea, Atlit, Haifa (Israel)** – June 17th – July 1st, **2014**
- CommsNet13 with NATO-STO CMRE – RV Alliance, **Palmaria Island (Italy)** – Sept. 24th – Oct. 3rd, **2013**
- THESAURUS Project Final Demonstration – **Livorno (Italy)** – end of August **2013**



MARTA: MArine Robotic Tool for Archaeology

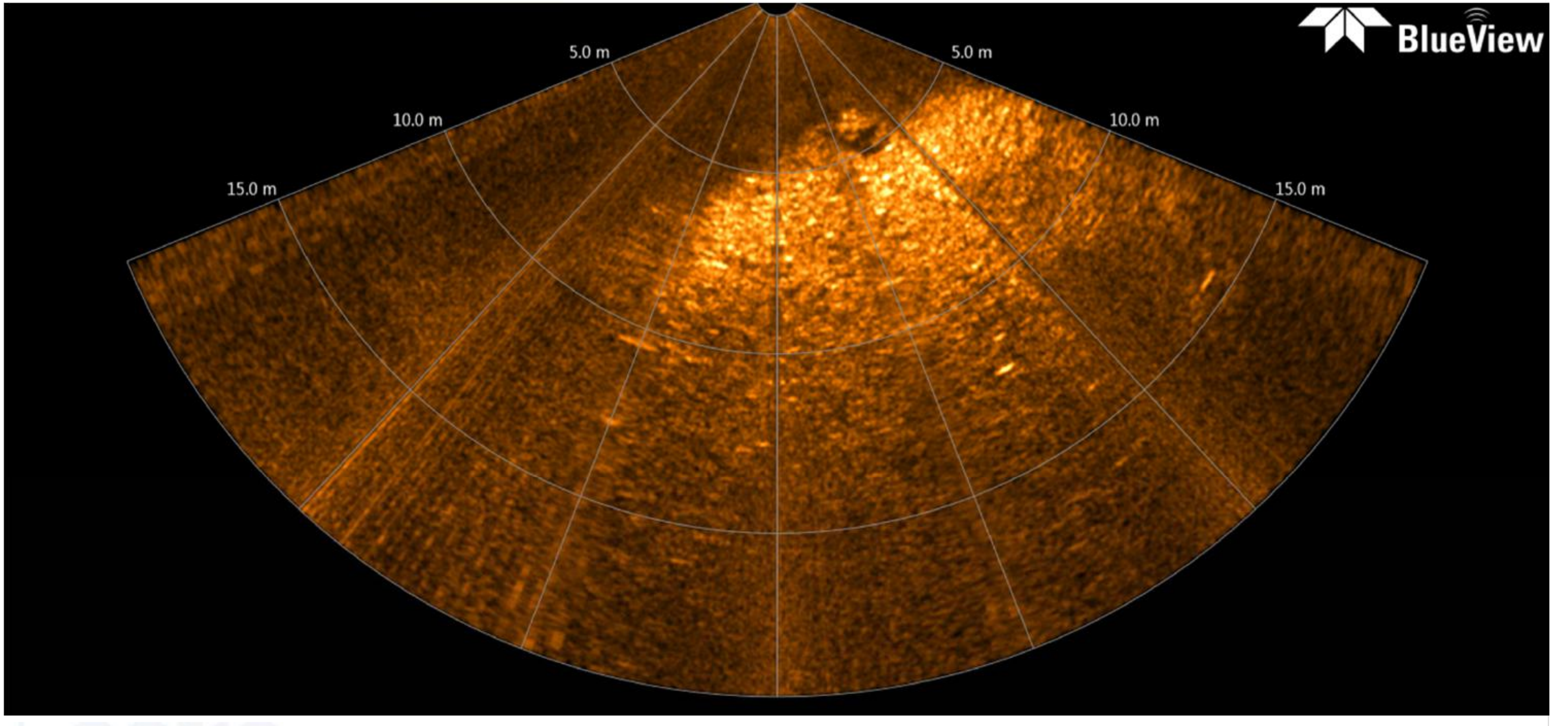


ARROWS
ARCHAEOLOGICAL ROBOT SYSTEMS FOR THE WORLD'S SEAS

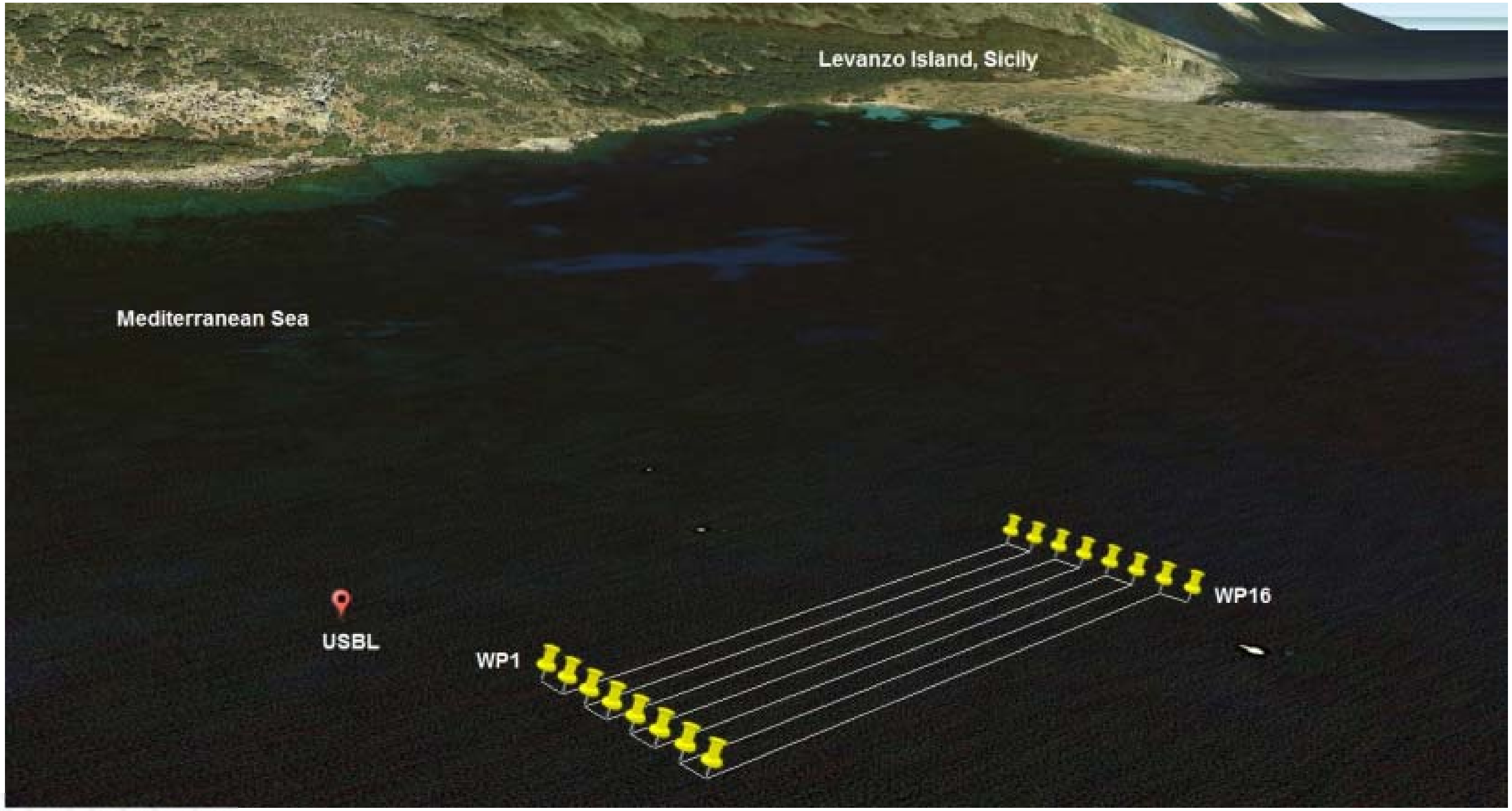
MARTA – official missions

- Sicily (Levanzo, June 2015)
- Baltic sea (Tallinn, July 2015)
- Arno river (Florence, June 2016)

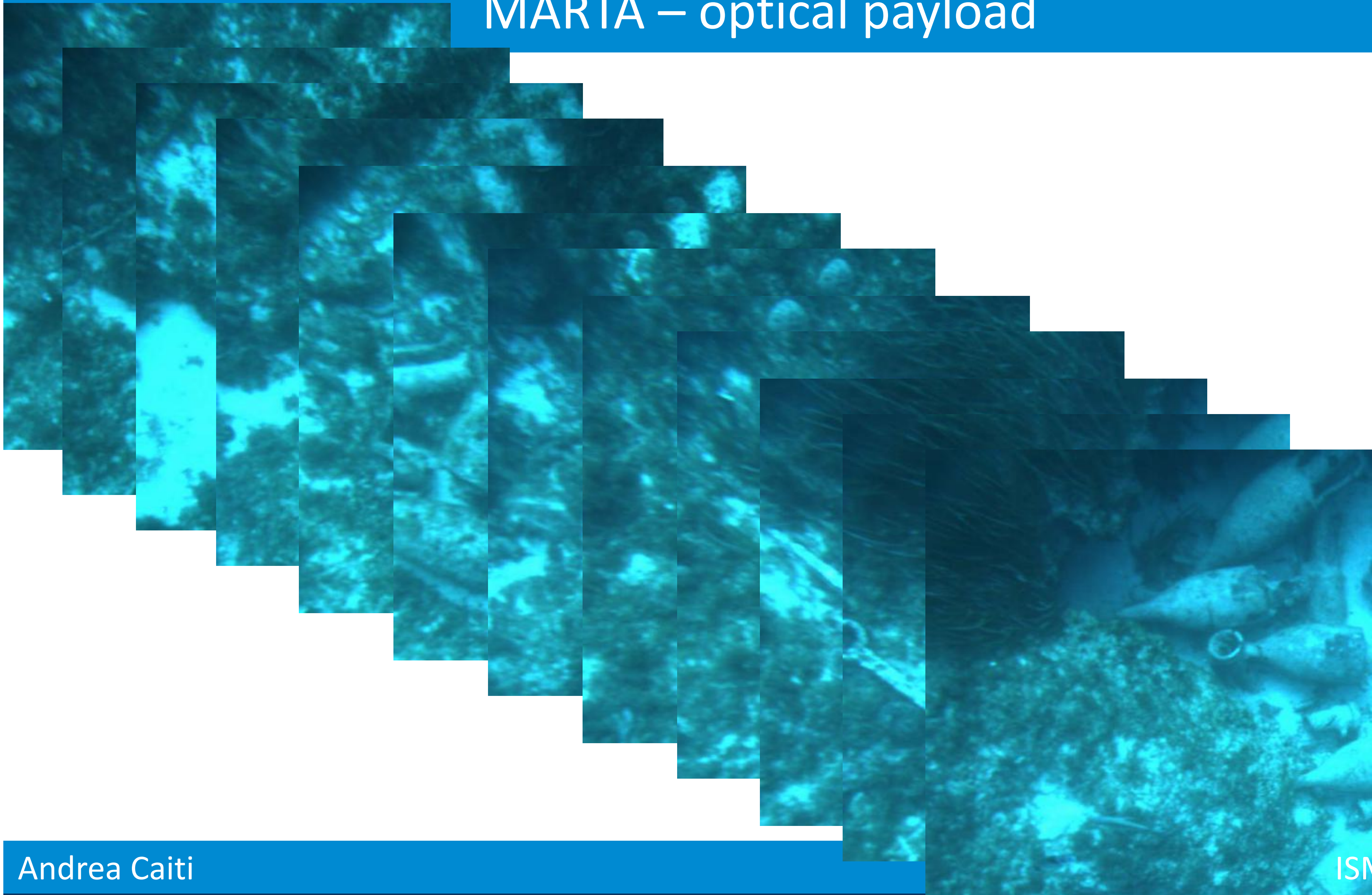
MBES in Arno river



ARROWS Project – Final Demonstration (Sicily, 2015)



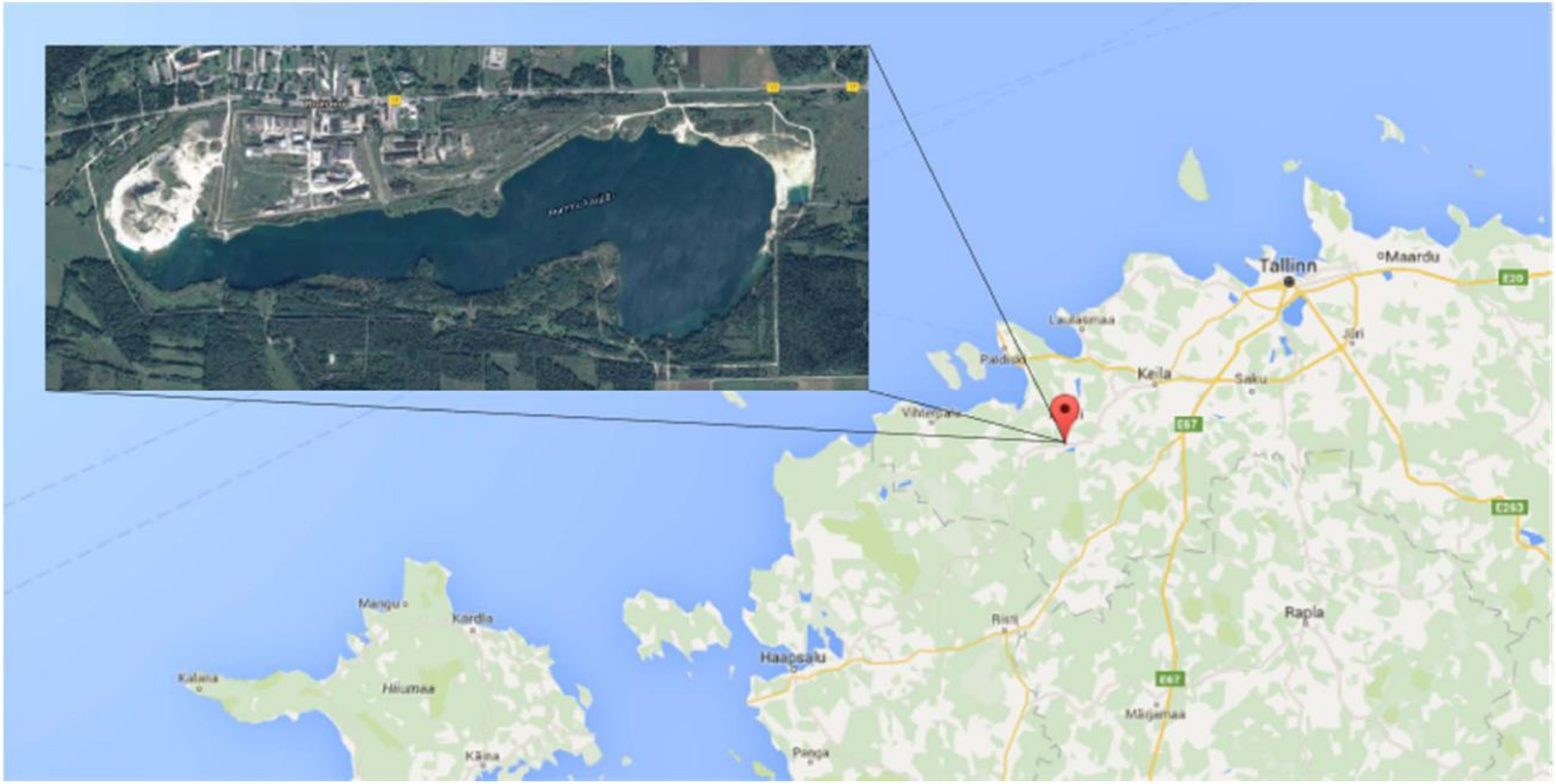
MARTA – optical payload



MARTA in Sicily 2015

MARTA in Sicily 2015

ARROWS Project – Final Demonstration (Estonia, 2015)



ARROWS
ARCHAEOLOGICAL ROBOT SYSTEMS FOR THE WORLD'S SEAS

MARTA in Estonia 2015

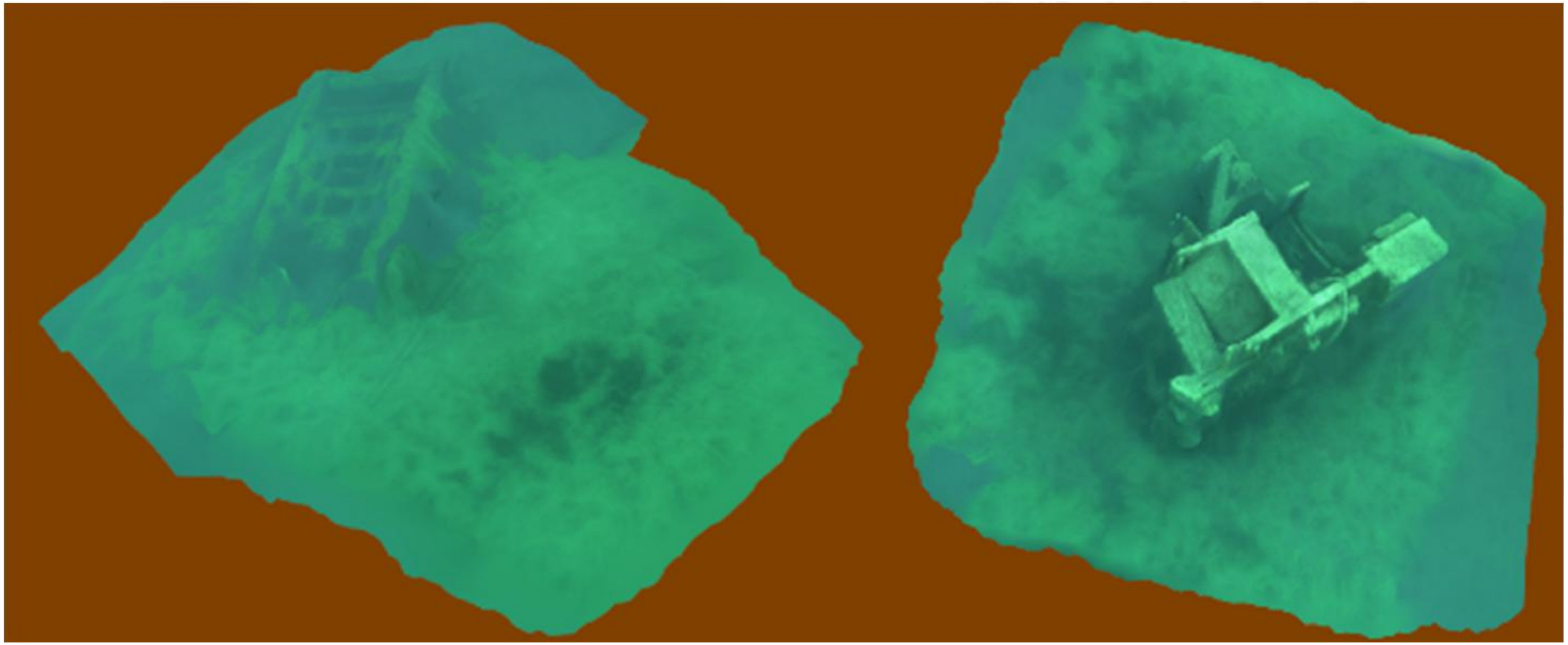
Search and Inspection Mission

Iver3 (S-AUV) – Heriot-Watt University

MARTA (I-AUV)

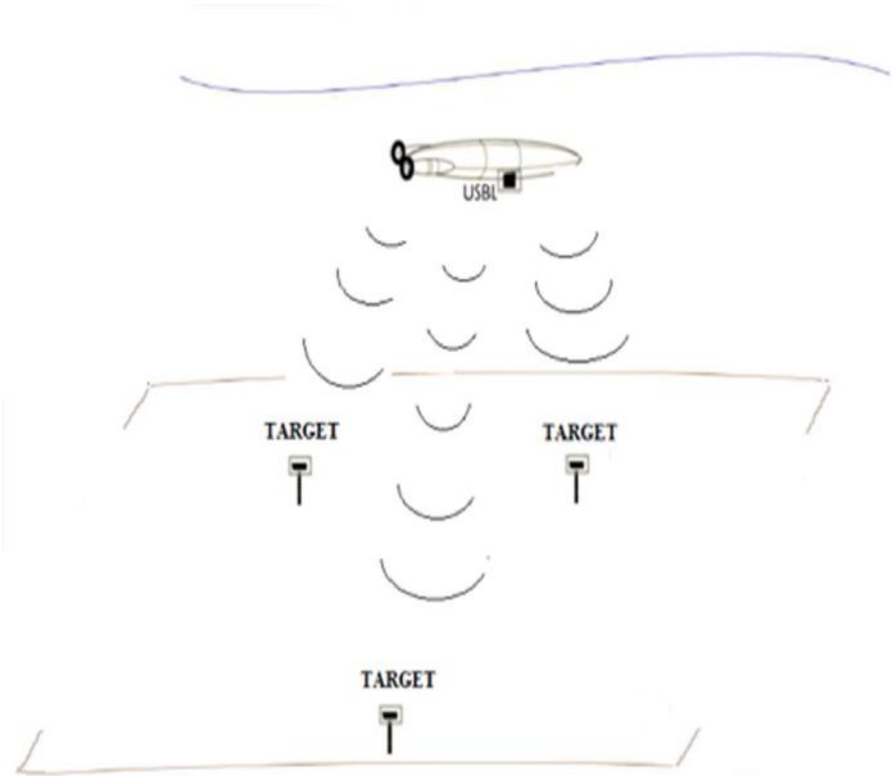
MARTA in Estonia 2015

3D model of the two targets



Acoustic navigation

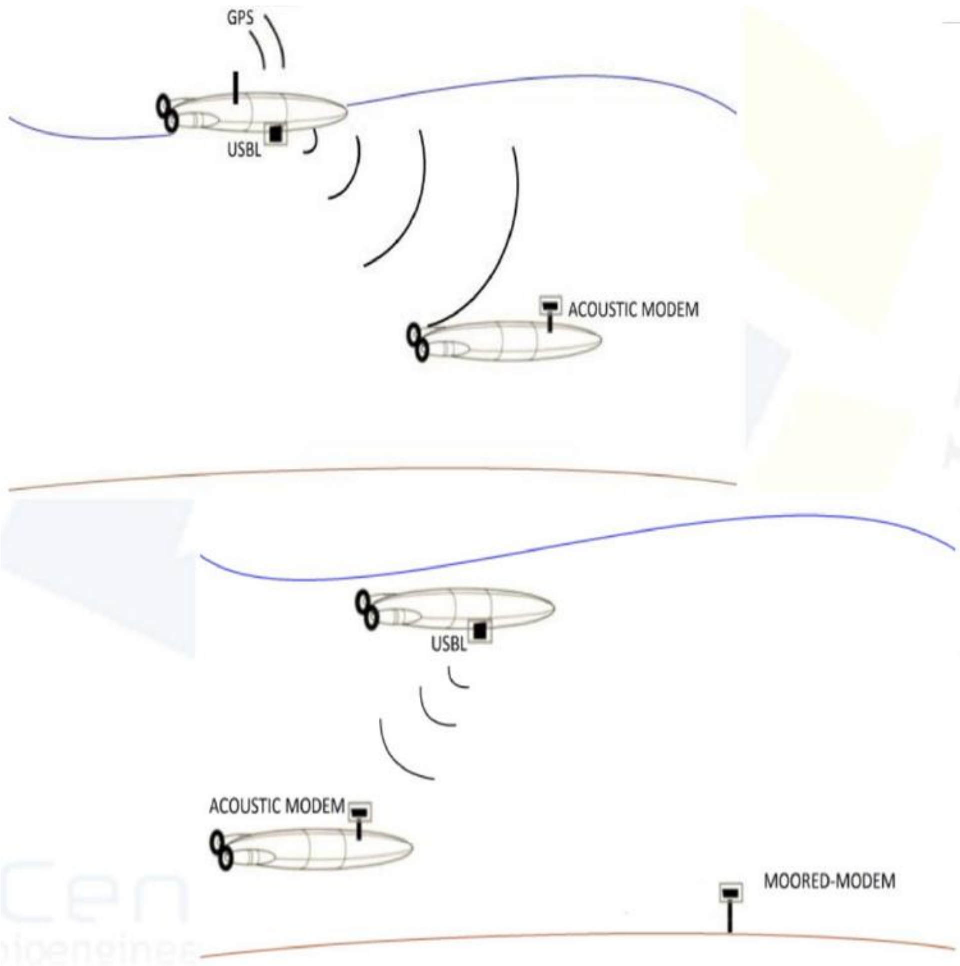
Mixed LBL/USBL



- Network of fixed beacons
- AUV
  - IMU
  - USBL
  - Other navigation aids (if available – e.g., DVL)

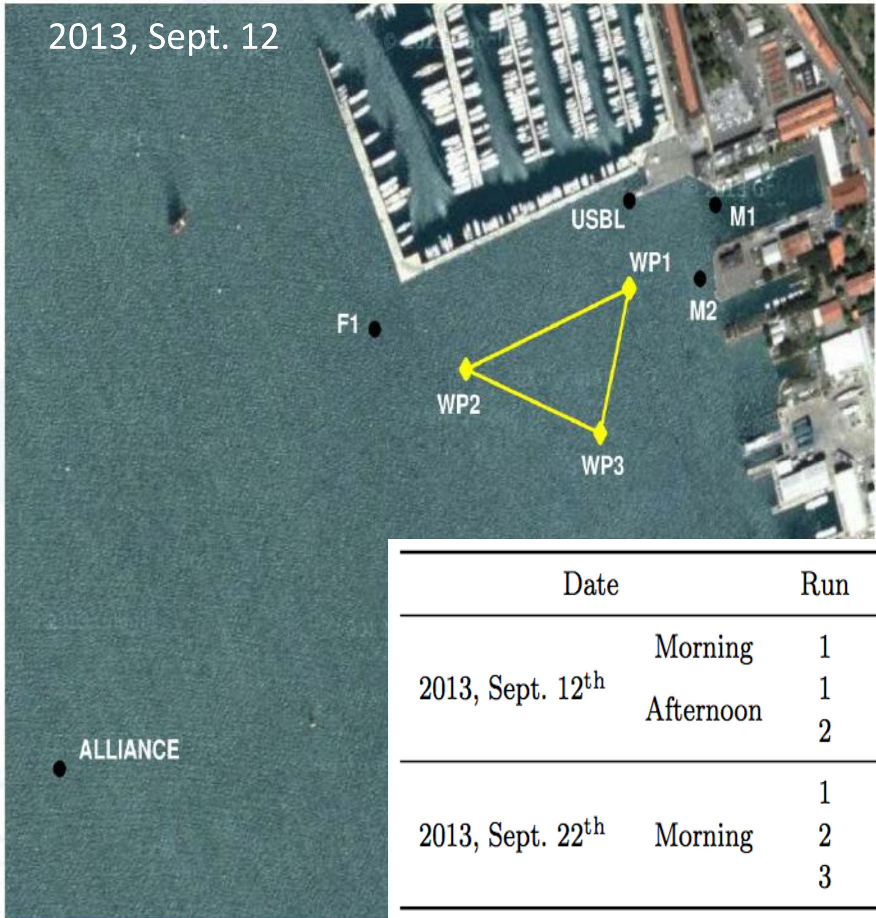
Node Position Estimation and Vehicle Navigation

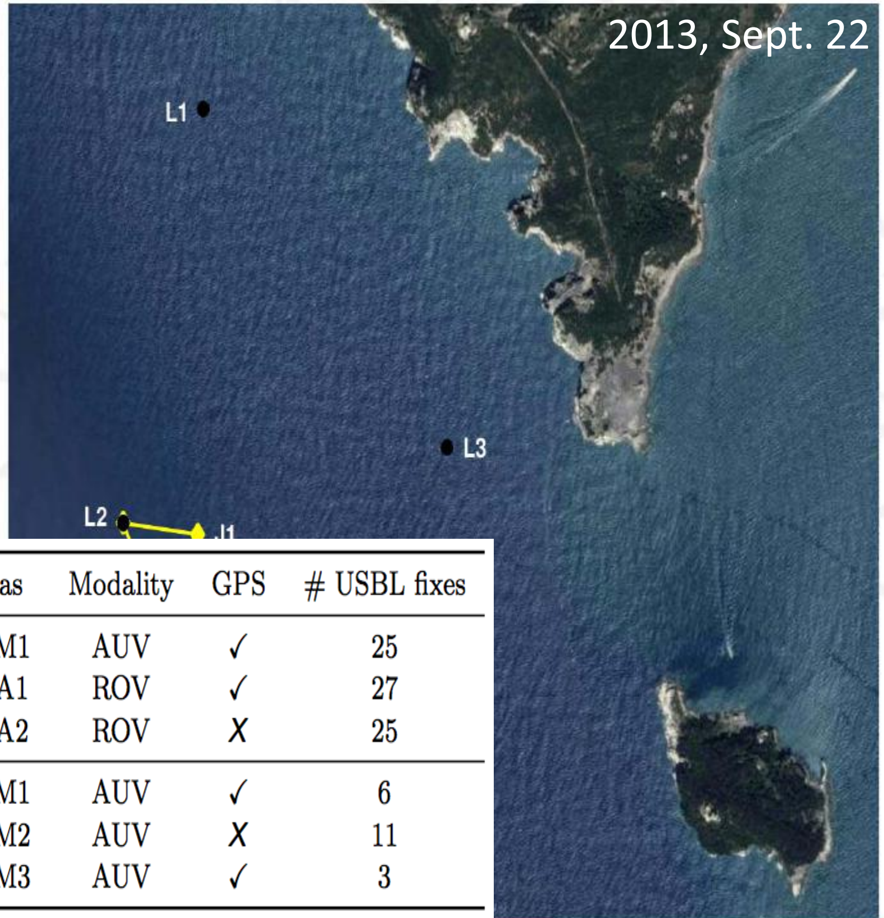
Cooperative Navigation



- ➢ Network of fixed beacons
- ➢ Team of multiple mobile agents
  - 1 *master (USBL)*
- ➢ Communication infrastructure

CommsNet13 – a NATO S&TO CMRE led cruise

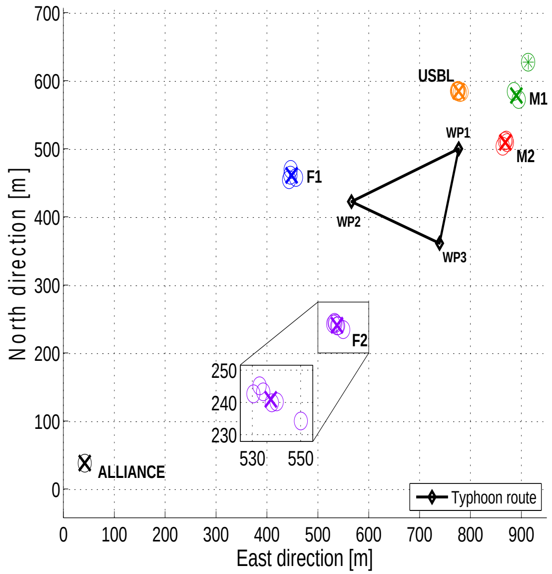


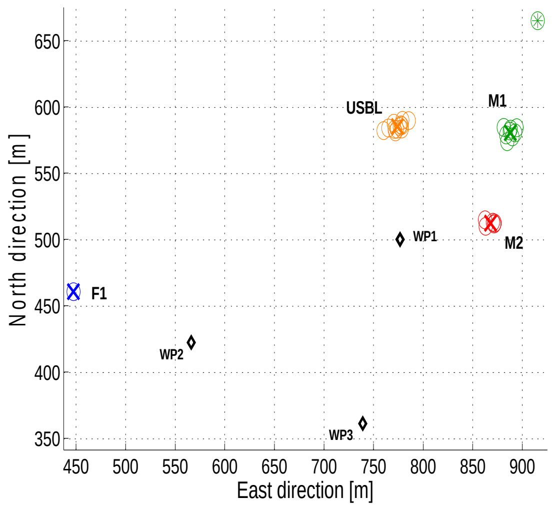


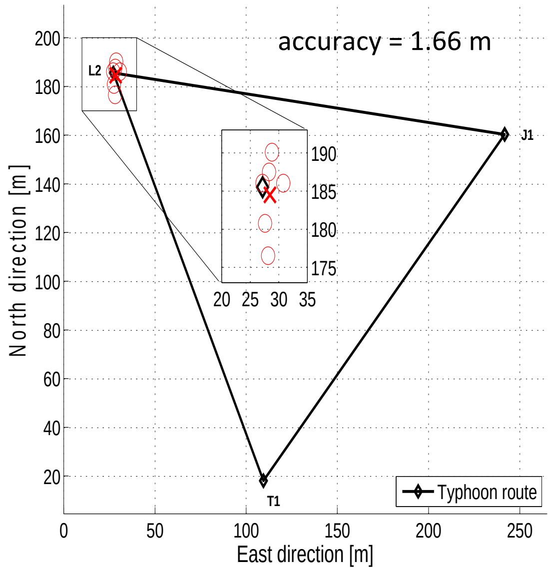
Date		Run	Alias	Modality	GPS	# USBL fixes
2013, Sept. 12^{th}	Morning	1	12_M1	AUV	✓	25
	Afternoon	1	12_A1	ROV	✓	27
		2	12_A2	ROV	X	25
2013, Sept. 22^{th}	Morning	1	22_M1	AUV	✓	6
		2	22_M2	AUV	X	11
		3	22_M3	AUV	✓	3

First of two steps: fixed nodes localization

Sept. 12th, morning | **Sept. 12th, afternoon** | **Sept. 22nd, morning**



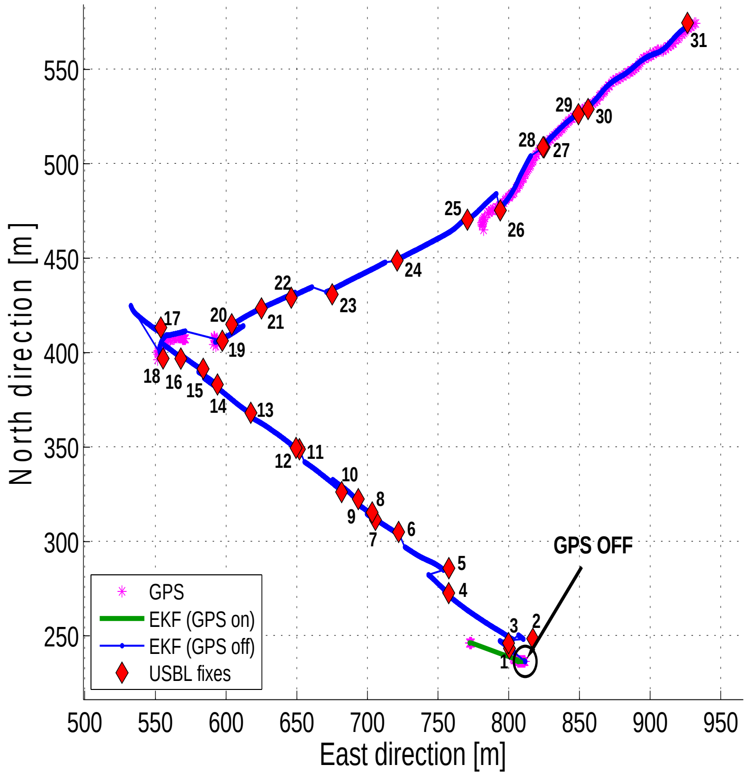




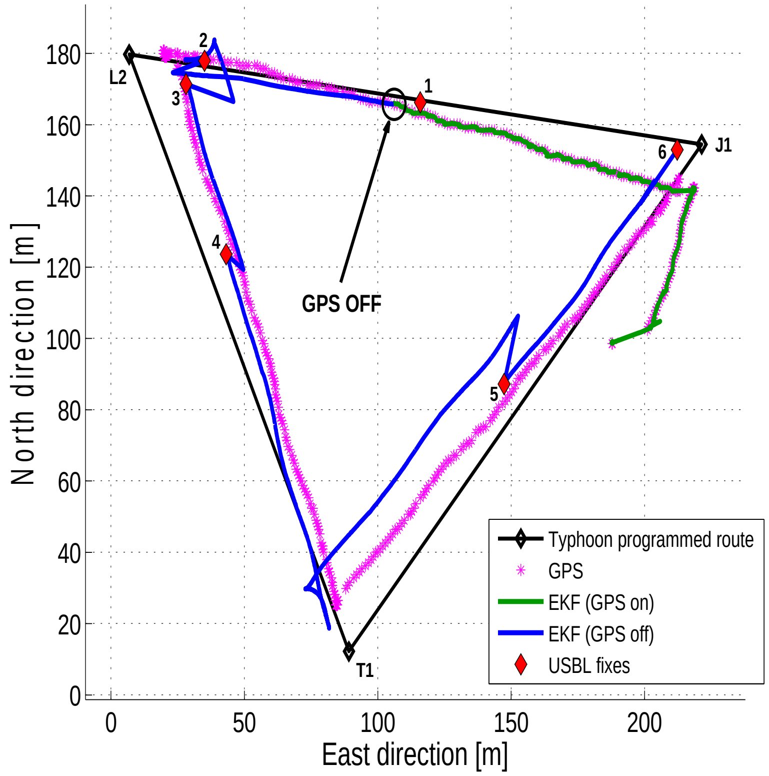
std. dev. = 4 m

Second step: navigation

Sept. 12th, afternoon

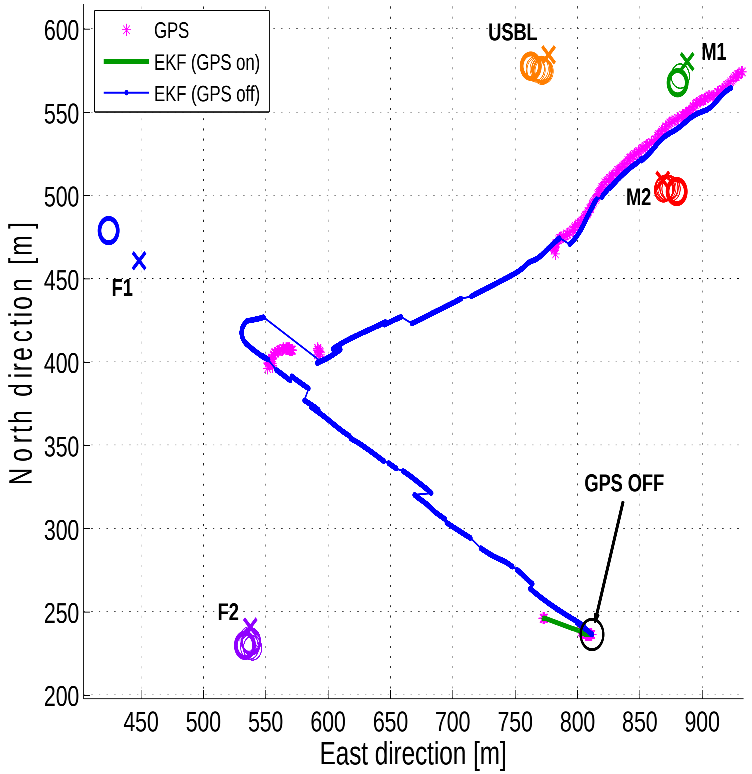


Sept. 22nd, morning

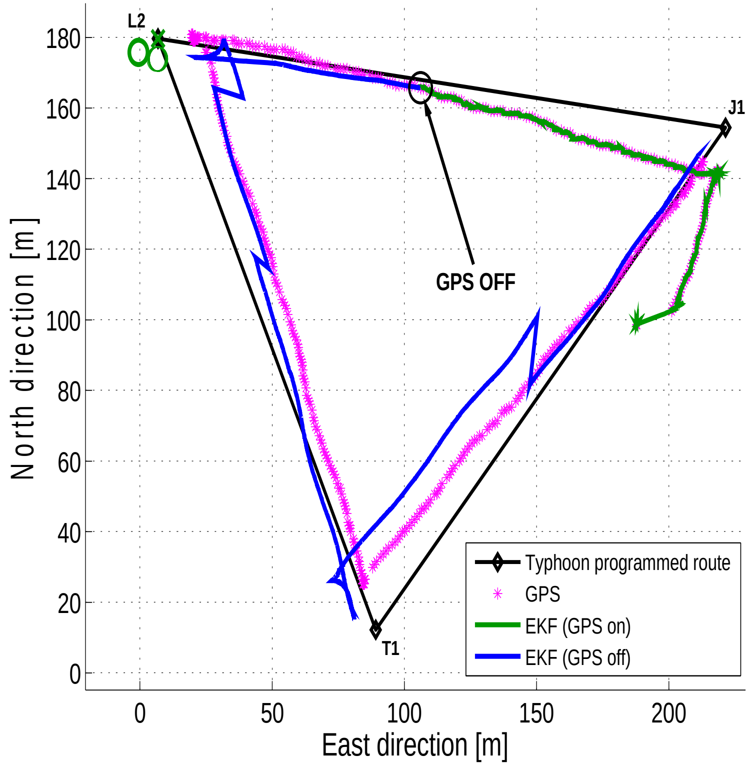


A-SLAM: estimated path

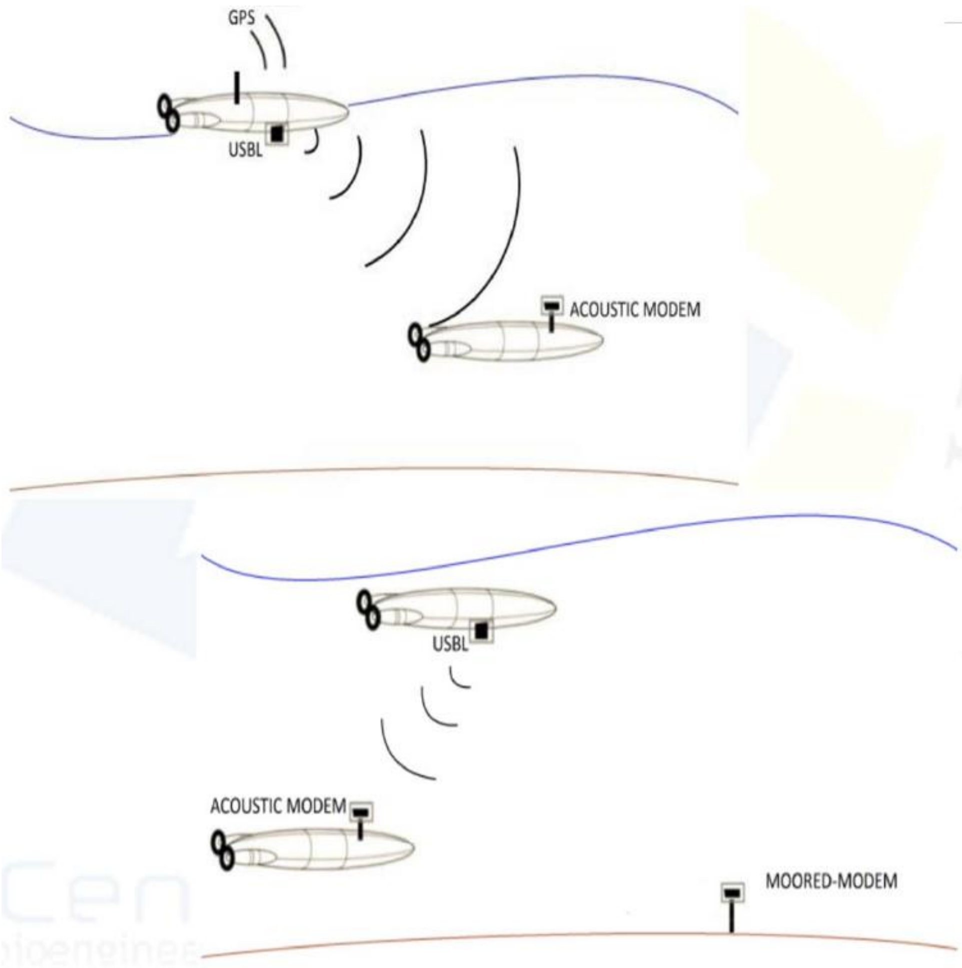
Sept. 12th, afternoon



Sept. 22nd, morning

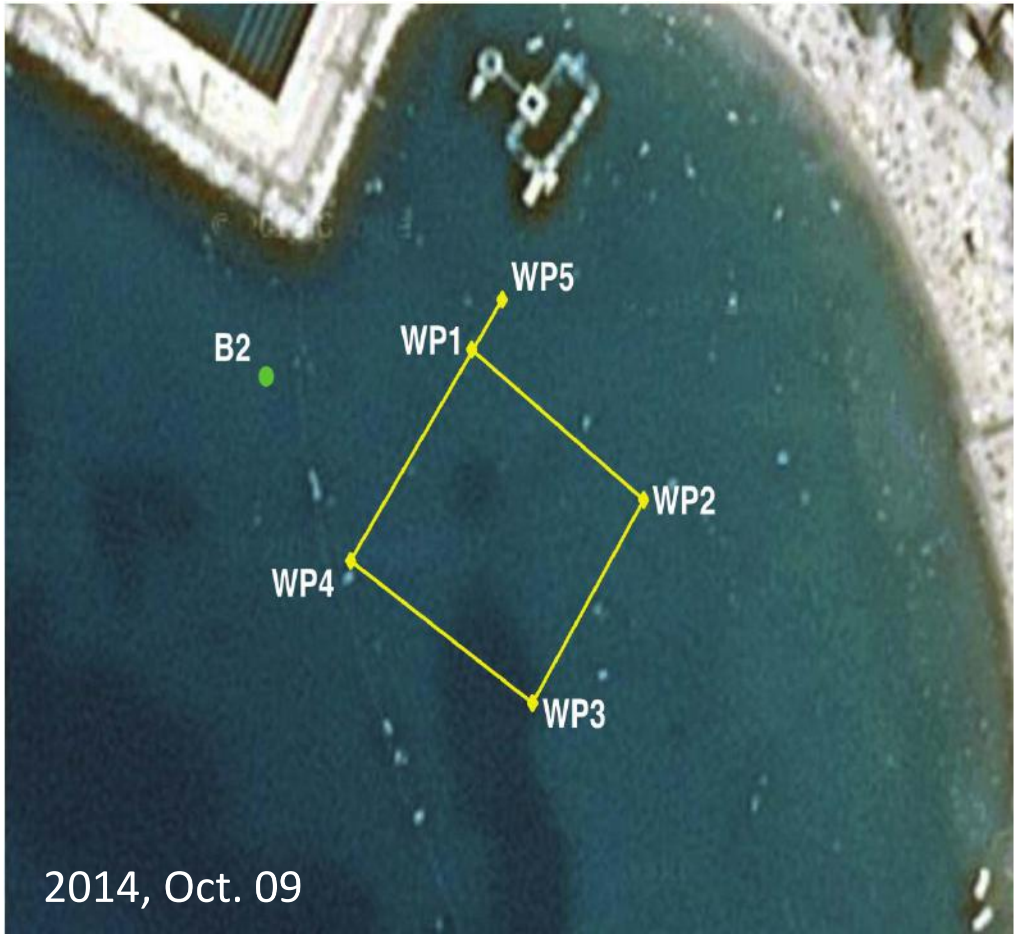


Cooperative Navigation

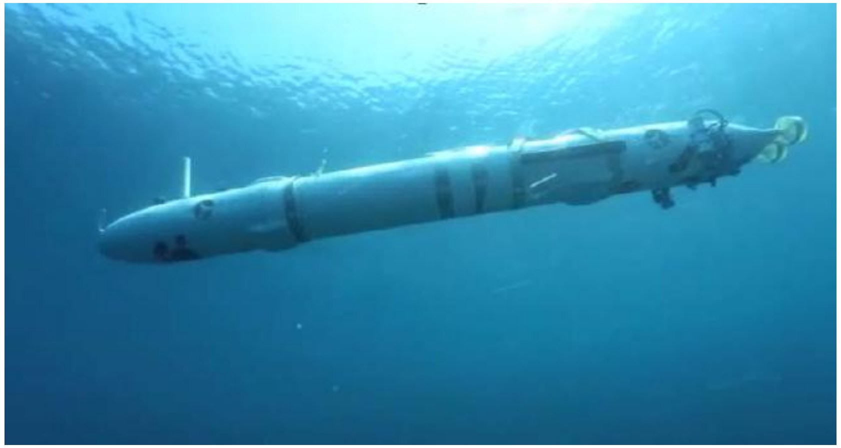


- Network of fixed beacons
- Team of multiple mobile agents
    - 1 *master (USBL)*

Breaking the Surface 2014



- Master moored in B2
- Slave equipped with DVL



Cooperative A-SLAM

System Model

$$\dot{\boldsymbol{p}}_n = \boldsymbol{v}_n$$
$$\dot{\boldsymbol{v}}_n = {}^n\mathrm{R}_b(\boldsymbol{\Theta})\left(\mathrm{a}_b - \boldsymbol{\epsilon}_b + \boldsymbol{\nu}_a\right) + \boldsymbol{g}_n$$
$$\dot{\boldsymbol{\epsilon}}_b = \boldsymbol{\nu}_\epsilon$$
$$\dot{K}_{\mathrm{thr}} = \nu_K$$
$$\dot{\boldsymbol{p}}_{m_i,n} = \boldsymbol{v}_{m_i,n}$$
$$\dot{\boldsymbol{v}}_{m_i,n} = \boldsymbol{\nu}_{m_i}$$
$$i \in \mathcal{V}(t) \subseteq \{1, \ldots, N_f + N_m - 1\}$$

Output Model

$$\boldsymbol{y}_{\mathrm{gps}} = \left[\mathrm{I}_2 \quad 0_{2\times 1}\right] \boldsymbol{p}_n + \boldsymbol{\eta}_{\mathrm{gps}}$$
$$\boldsymbol{y}_{\mathrm{usbl}_i} = \tilde{\boldsymbol{y}}_{\mathrm{usbl}_i}$$
$$\tilde{\boldsymbol{y}}_{\mathrm{usbl}_i} = \boldsymbol{p}_{\mathrm{u\text{-}m}_i,u} + \boldsymbol{\eta}_{\mathrm{usbl}}$$
$$y_{\mathrm{depth}} = \left[0 \quad 0 \quad 1\right] \boldsymbol{p}_n + \eta_{\mathrm{depth}}$$
$$\boldsymbol{y}_{\mathrm{surge}} = K_{\mathrm{the}} \boldsymbol{v}_n + {}^n\mathrm{R}_b(\boldsymbol{\Theta}) \boldsymbol{\eta}_{\mathrm{surge}}$$
$$\boldsymbol{y}_{\mathrm{m_i}} = \begin{bmatrix} \boldsymbol{p}_{m_i,n} \\ \boldsymbol{v}_{m_i,n} \end{bmatrix} + \boldsymbol{\eta}_{\mathrm{m_i}}$$

Measure Model

$$\boldsymbol{y}_{\mathrm{gps}} = \boldsymbol{p}_{\mathrm{gps},n} + \boldsymbol{\eta}_{\mathrm{gps}}$$
$$\boldsymbol{y}_{\mathrm{usbl}_i} = {}^u\mathrm{R}_b {}^b\mathrm{R}_n(\boldsymbol{\Theta})\left(\boldsymbol{p}_{m_i,n} - \boldsymbol{p}_n\right) + \boldsymbol{\eta}_{\mathrm{usbl}}$$
$$y_{\mathrm{depth}} = p_{\mathrm{depth},n} + \eta_{\mathrm{depth}}$$
$$\boldsymbol{y}_{\mathrm{surge}} = {}^n\mathrm{R}_b(\boldsymbol{\Theta})\left(\left[\tau_{\mathrm{surge},b} \quad 0 \quad 0\right]^T + \boldsymbol{\eta}_\tau\right)$$
$$\boldsymbol{y}_{\mathrm{m_i}} = \begin{bmatrix} \hat{\boldsymbol{p}}_n^{[\mathrm{m_i}]} \\ \hat{\boldsymbol{v}}_n^{[\mathrm{m_i}]} \end{bmatrix} + \boldsymbol{\eta}_{\mathrm{m_i}}$$

System Model

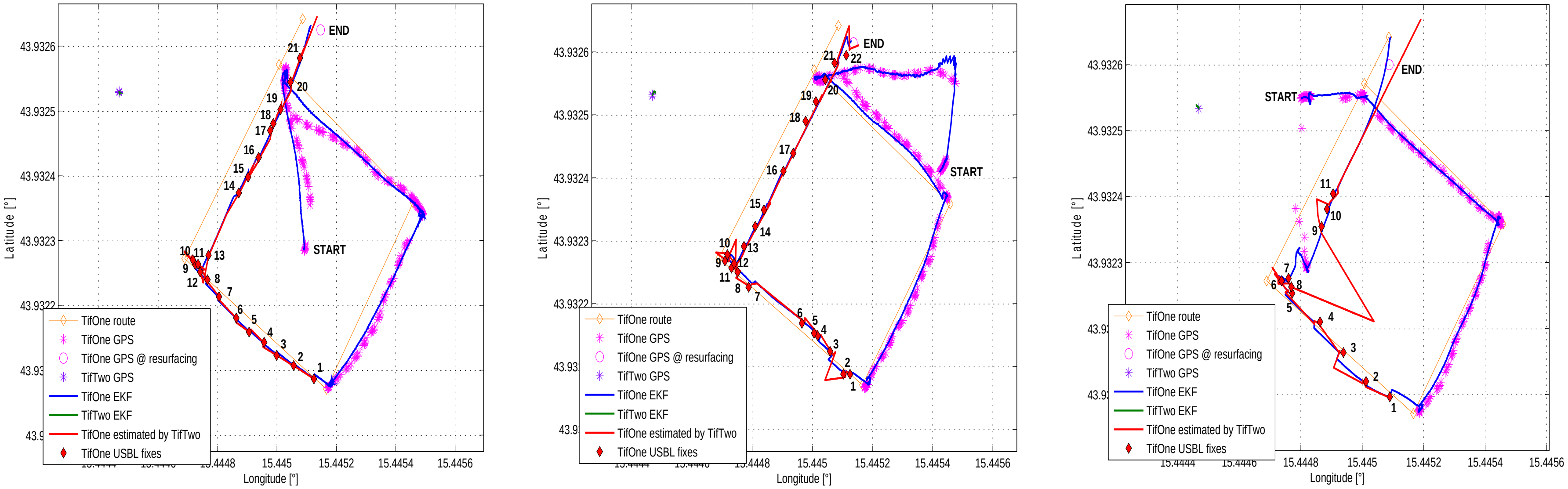
$$\dot{\boldsymbol{p}}_n = \boldsymbol{v}_n$$
$$\dot{\boldsymbol{v}}_n = {}^n\mathrm{R}_b(\boldsymbol{\Theta})\left(\mathrm{a}_b - \boldsymbol{\epsilon}_b + \boldsymbol{\nu}_a\right) + \boldsymbol{g}_n$$
$$\dot{\boldsymbol{\epsilon}}_b = \boldsymbol{\nu}_\epsilon$$

Output Model / Measure Model

GPS, depth, …

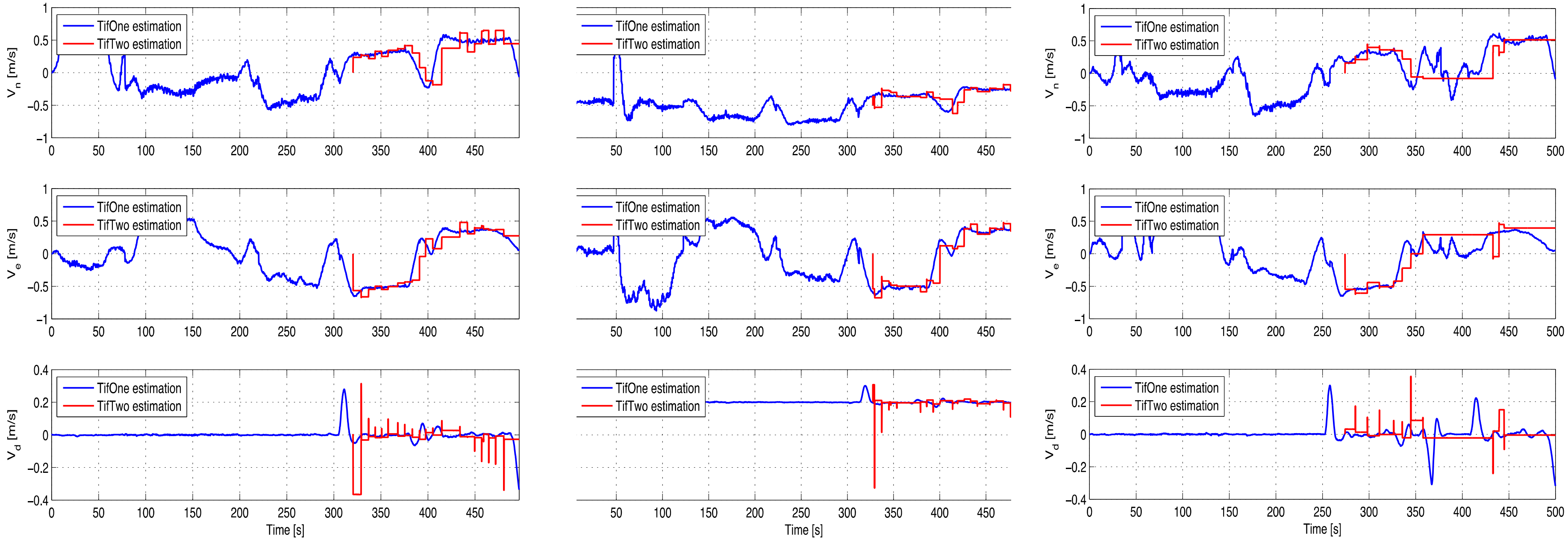
$$\boldsymbol{y}_{\mathrm{dvl}} = {}^b\mathrm{R}_n(\boldsymbol{\Theta}) \boldsymbol{v}_n + \boldsymbol{\eta}_{\mathrm{dvl}} \qquad \boldsymbol{y}_{\mathrm{dvl}} = \boldsymbol{v}_{\mathrm{dvl},b} + \boldsymbol{\eta}_{\mathrm{dvl}}$$
$$\boldsymbol{y}_{\mathrm{master}} = \boldsymbol{p}_n + \boldsymbol{\eta}_{\mathrm{master}} \qquad \boldsymbol{y}_{\mathrm{master}} = \hat{\boldsymbol{p}}_{m_i,n}^{[\mathrm{master}]} + \boldsymbol{\eta}_{\mathrm{master}}$$

Cooperative A-SLAM: results



Mission run	Estimated travelled distance (m)	# USBL pings	USBL error Mean (m)	Std. dev. (m)	Error at the resurfacing (m)
1	337	21	0.32	0.05	2.7
2	403	22	0.35	0.05	0.6
3	333	11	0.32	0.02	4.6

Cooperative A-SLAM: estimated speed



Long-term endurance

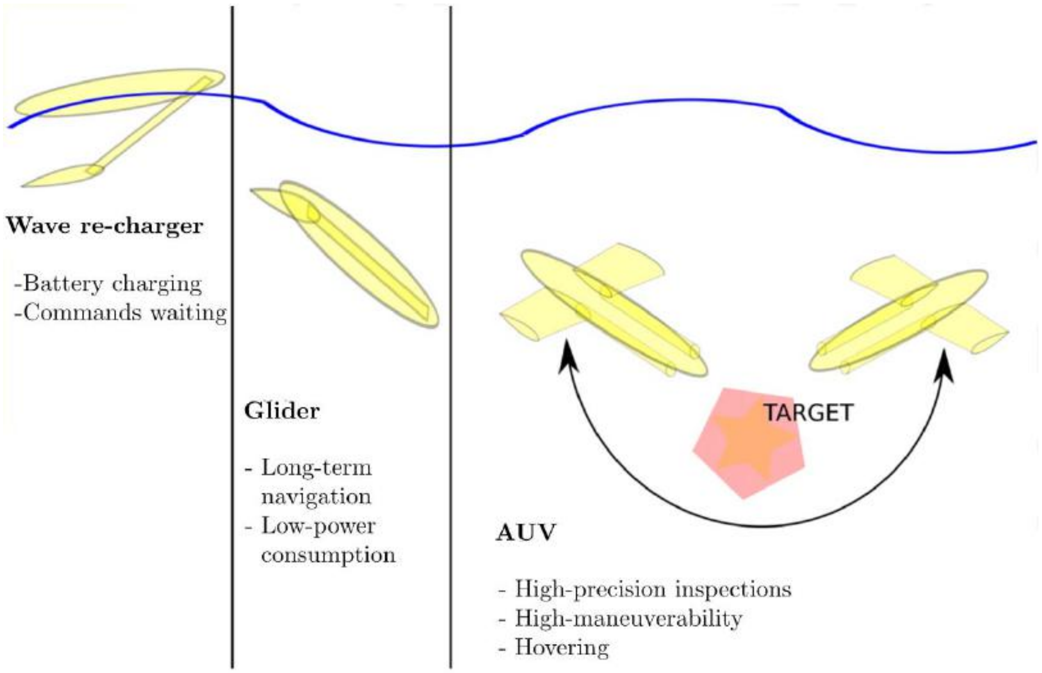
WAVE: the idea

WAVE: Wave-powered Autonomous Vehicle for marine Exploration

GOAL: development of a hybrid glider/AUV with battery charging capacity exploiting renewable energy

- Solar
- **Wave motion**

(Pilot study CSSN/ISME - 2012)



WAVE: the prototype

- Modular design
- Carrier vehicle
  modular glider/AUV eFolaga+ (GraalTech)

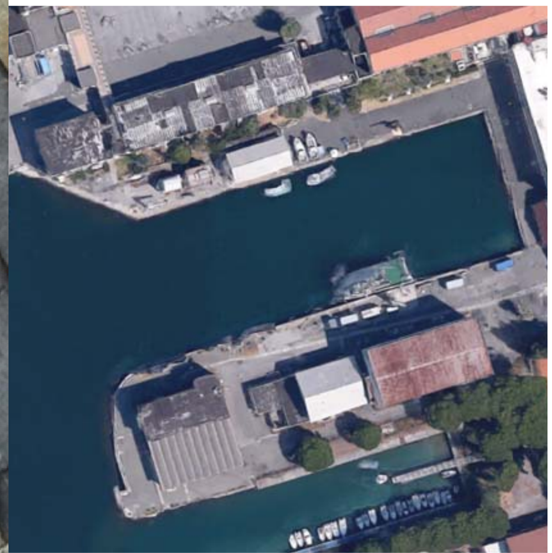
Preliminary sea-trial (April 2016)

First run - La Spezia harbour, SEALab, CSSN

* Payload test

* Mission configuration and control via acoustic communication

Preliminary sea-trial (April 2016)



Preliminary sea-trial (April 2016)

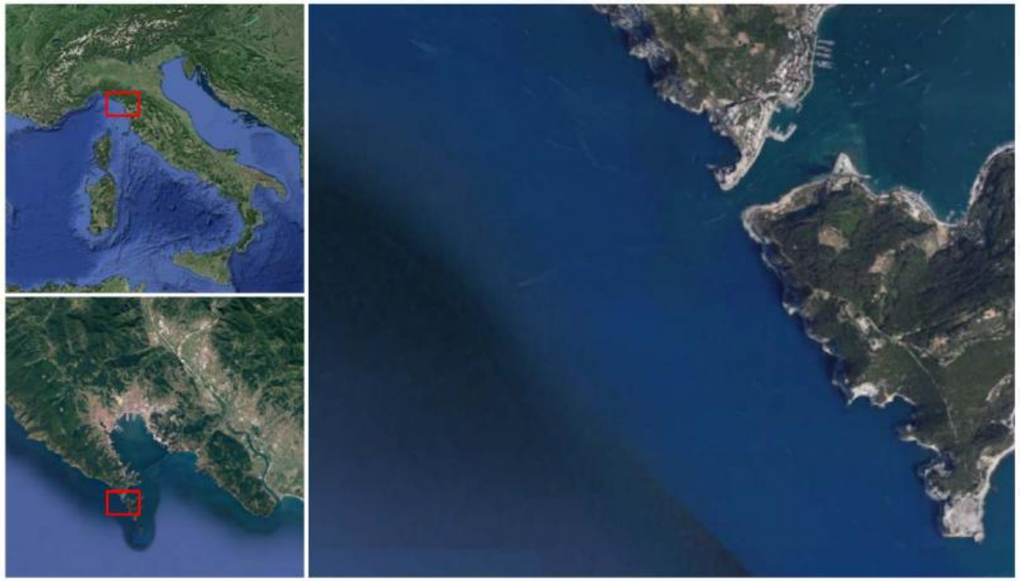
Preliminary sea-trial (April 2016)

Second run - Palmaria Island, R/V Leonardo support

* WAVE module test

* Two-day test
  - Day 1: sea state 1
  - Day 2: sea state 2

* No direct connection with batteries



Preliminary sea-trial (April 2016)

Second run - Palmaria Island,

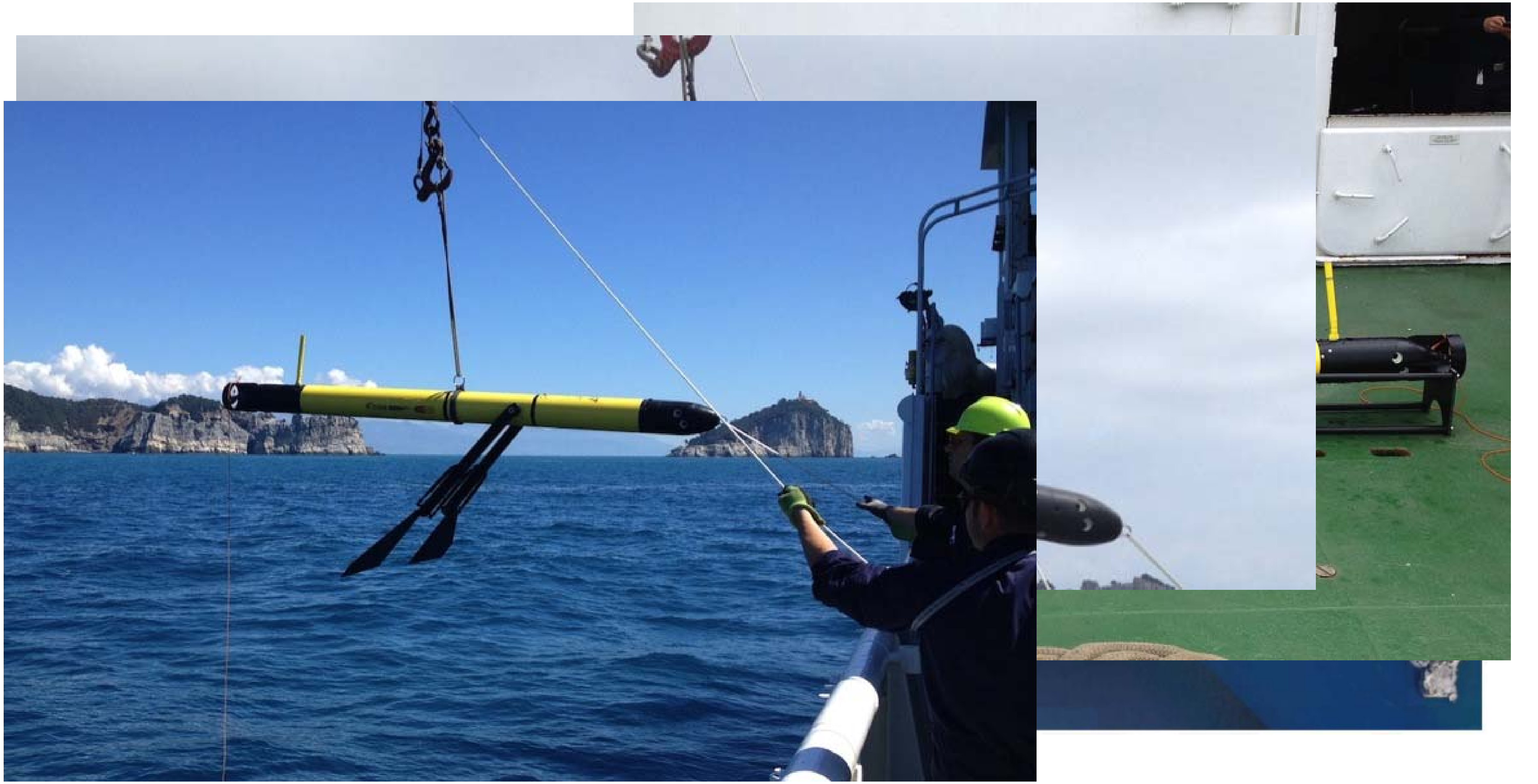
* WAVE module test

* Two-day test
  - Day 1: sea state 1
  - Day 2: sea state 2

* No direct connection with batteries

Preliminary sea-trial (April 2016)

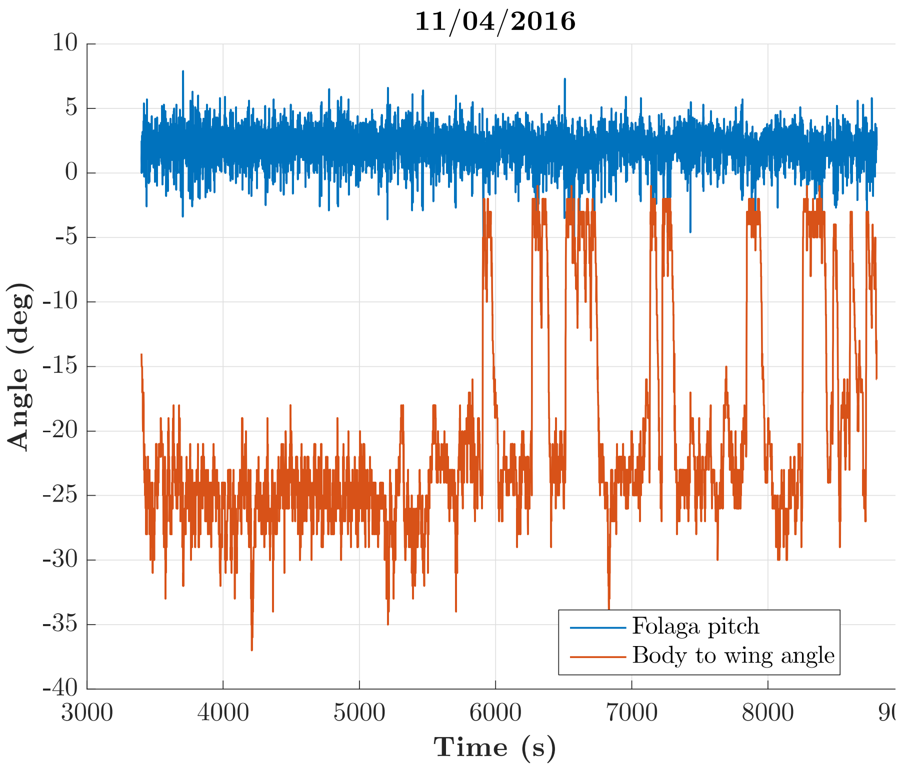
Preliminary sea-trial (April 2016)



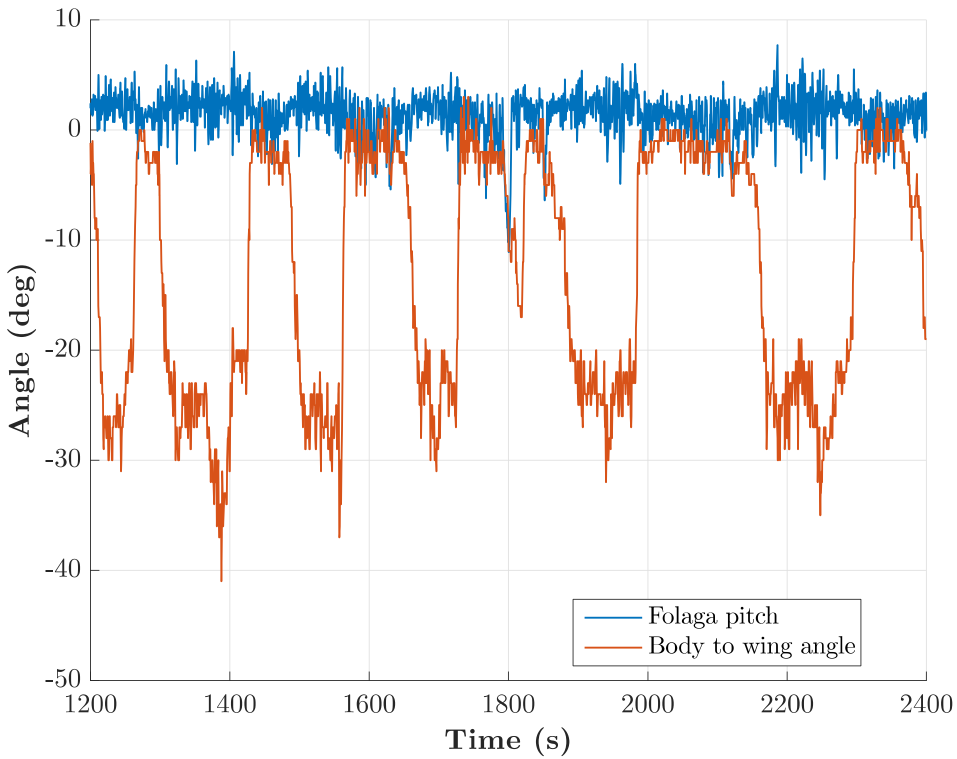
Preliminary sea-trial (April 2016)

Body to wing angle

Sea state 1



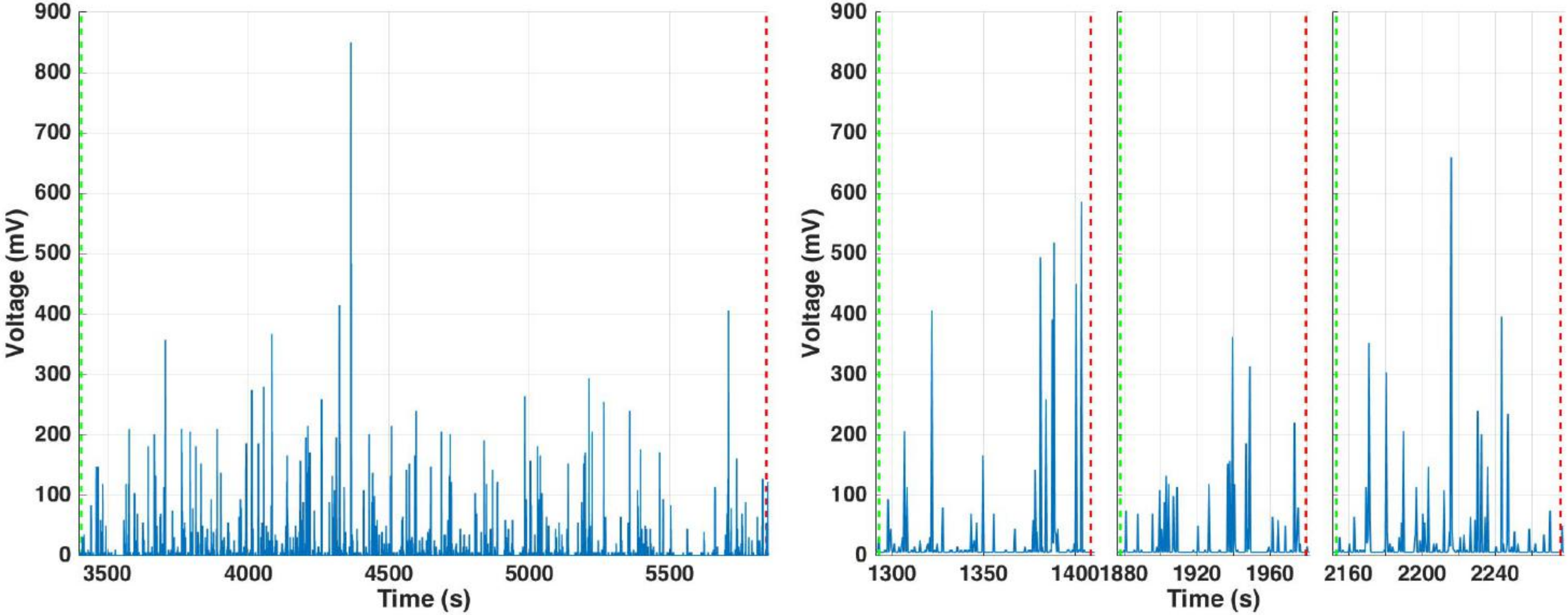
Sea state 2



Generated voltage

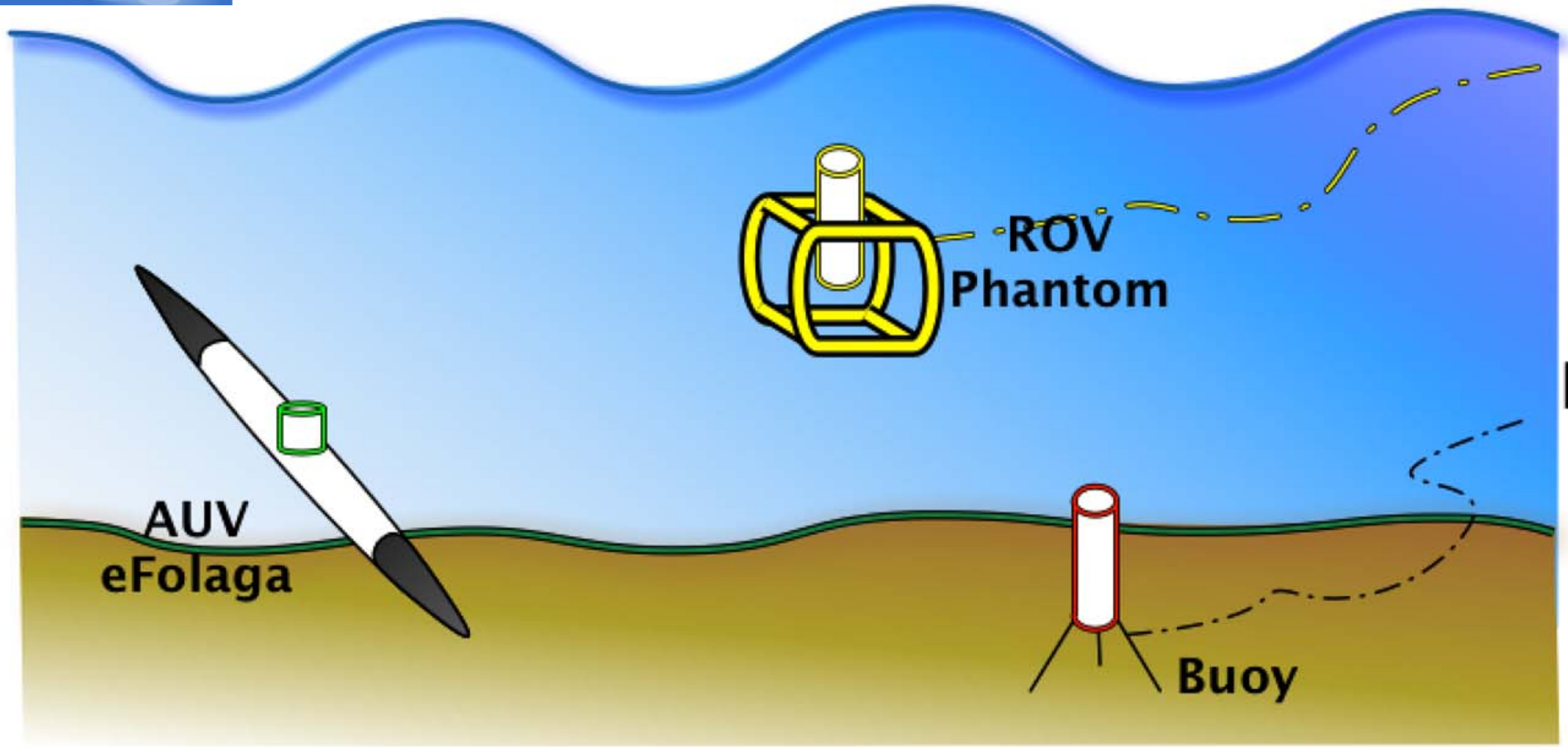
Sea state 1

Sea state 2

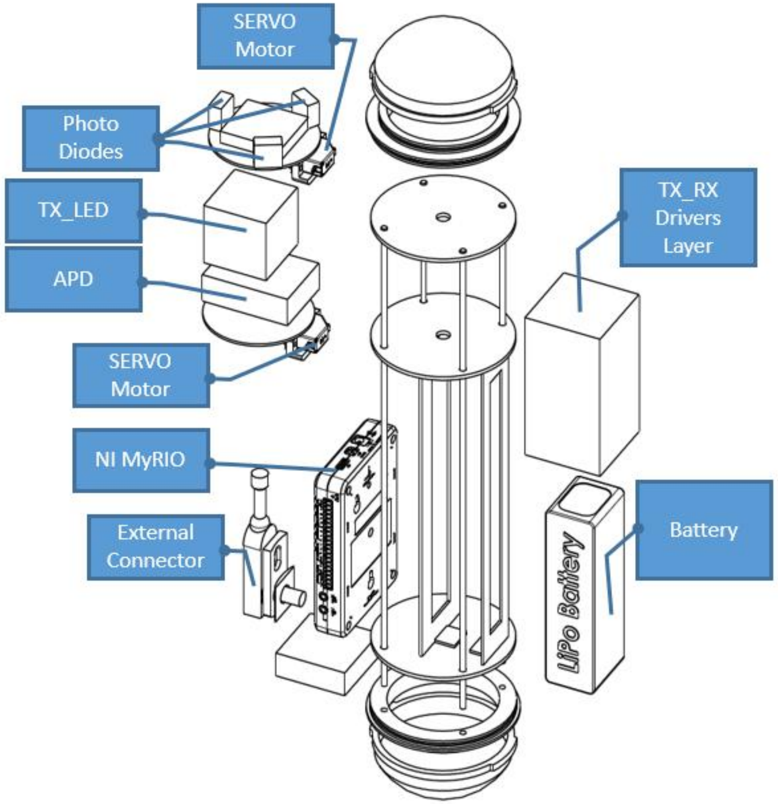


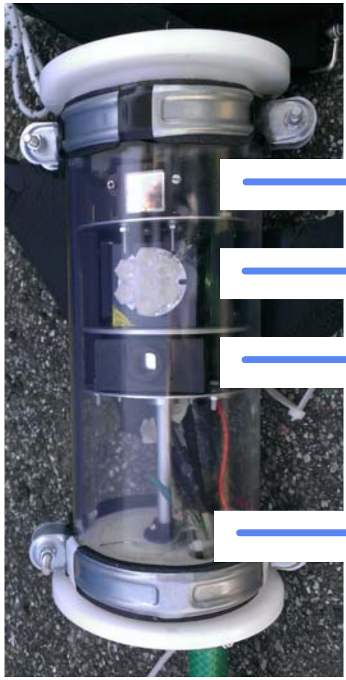
Optical communication

OptoCOMM project: scenario



The Optical Modem





PhotoDiode (PD)

Blue LEDs

AvalanchePhotoDiode (APD)

Humidity Sensor

Sea Tests

Results in very shallow harbour water & daylight

- File transferred at a distance of 2.5 m

File Dim. (Mbyte)	Rx Ampl. (dB)	Packet Dimension (byte)	Sent Packets	Packet Loss (%)
4.5	10	1024	4200	0 (0)
14.6	10	1024	14376	0 (0)

- File transferred at a distance of 5 m

File Dim. (Mbyte)	Rx Ampl. (dB)	Packet Dimension (byte)	Sent Packets	Packet Loss (%)
4.5	20	1024	4200	0 (0)
14.6	20	1024	14376	0 (0)

- File transferred at a distance of 7.5 m

File Dim. (Mbyte)	Rx Ampl. (dB)	Packet Dimension (byte)	Sent Packets	Packet Loss (%)
4.5	30	1024	4287	87 (2.03)
4.5	24	1024	4212	12 (0.28)
14.6	24	1024	14447	71 (0.49)
4.5	24	512	8491	8 (0.09)
14.6	24	512	29070	33 (0.11)
4.5	30	512	8531	47.5 (0.56)

AUV Team Cooperation

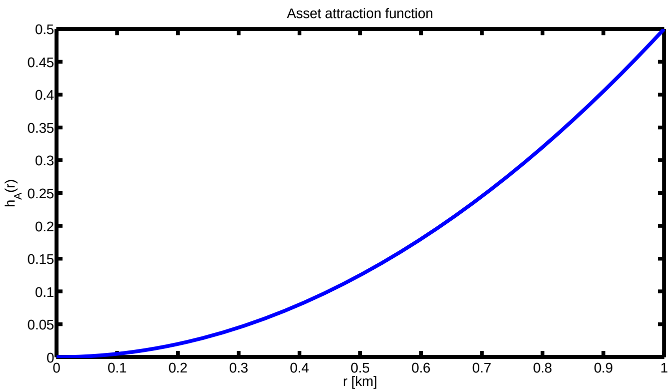
Introduction and motivations

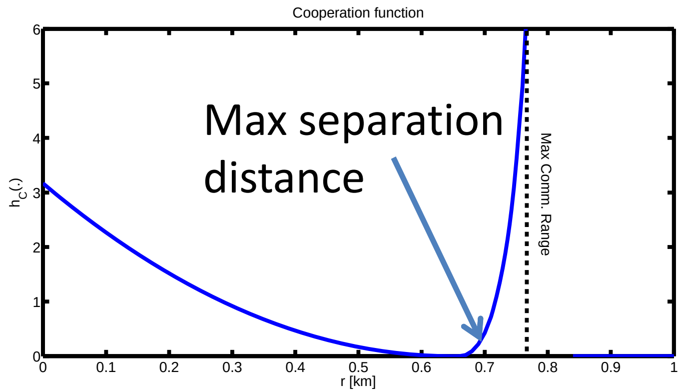
- **Past research** [Caiti et al., 2013]

Rule-based vehicle behaviour to cover the greatest area around an asset:

* Rule 1: Move towards the asset
* Rule 2: Move away from your closest neighbor – but keep in touch

Implemented through gradients of *artificial potential* functions, modeled in a **potential game** framework.

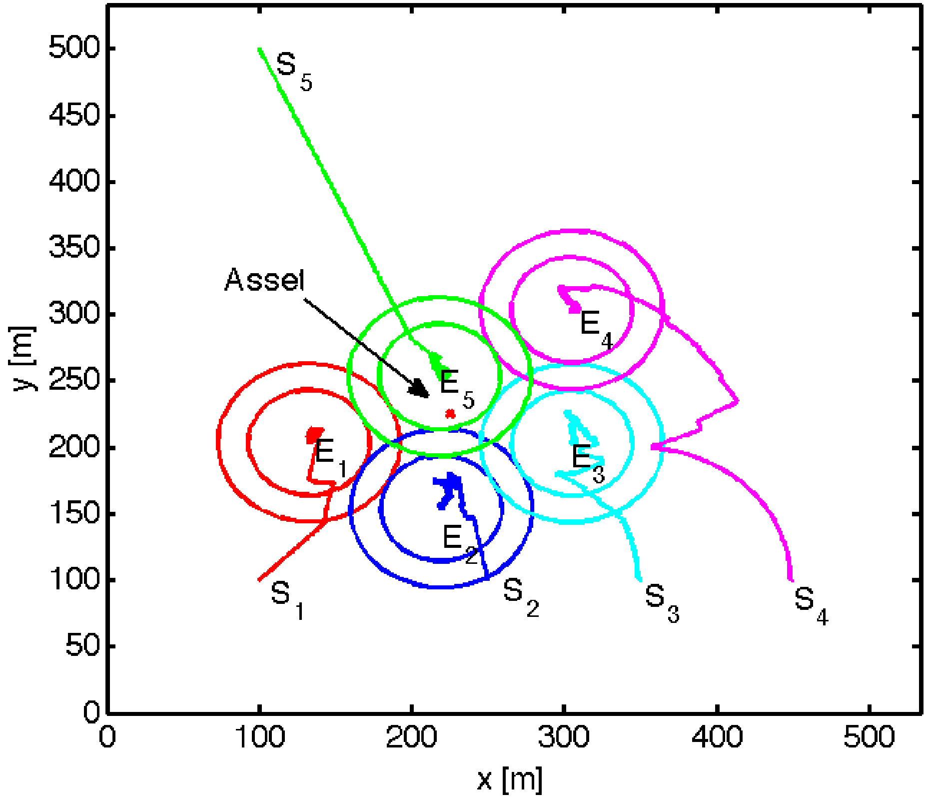




Distributed potential game for asset coverage

- Control algorithm:

$$u(t) = u_A(t) + u_C(t) = \nabla h_A + \nabla h_C$$



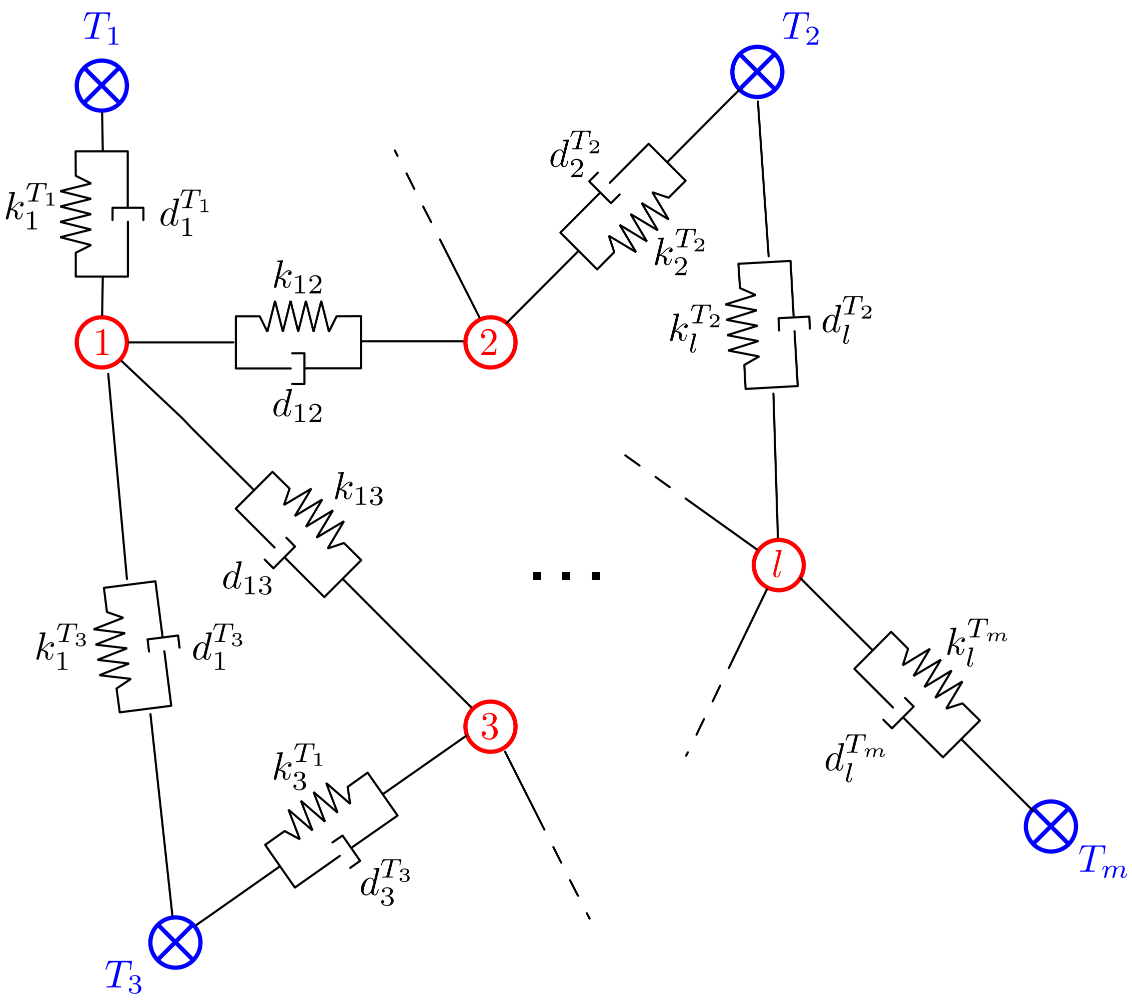
✓ Inherently robust to communication loss

✓ Distributed

✓ Equilibria established and stable

✧ **Stability in the large? Will the AUV get to the equilibria?**

A stability proof through a passivity-based approach



Virtual spring-damper connections:

1. Can be tuned to replicate the potential fields
2. *The passivity of the system can be exploited to proof convergence*

[Fabiani et al., CAMS'16 , Ocean'16 Monterey]

Marine robots in environmental surveys: current developments at ISME

THANK YOU!