METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Fernando Aguado, Univ. of Vigo

Pierre Lermusiaux, MIT

Kanna Rajan, Univ. of Porto*

Joao Sousa, Univ. of Porto

Ajit Subramaniam, Columbia Univ.

Joaquin Tintore, SOCIB, Balearic Islands

https://kanna.rajan.systems

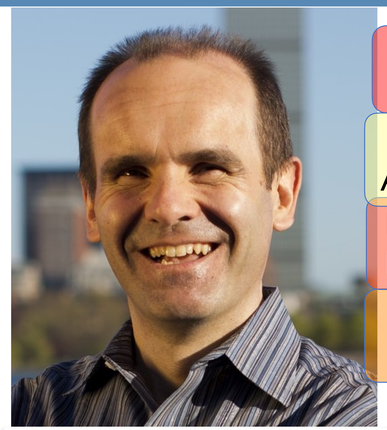
METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Team

SmallSats

Satellite Comms

Fernando Aguado



Adaptive Sampling

Bayesian Assimilation

Machine Learning

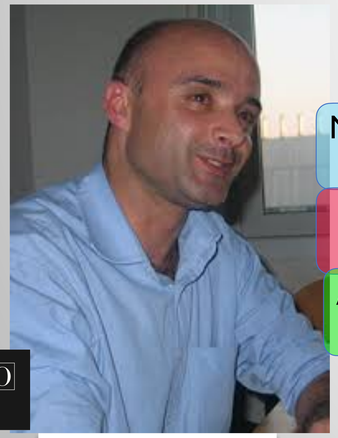
Probabilitic Modeling

Pierre Lermusiaux

Operational Oceanography

Physical Oceanography

Joaquin Tintore



Networked robotics

Control Theory

Autonomous Systems

Joao Sousa

Artificial Intelligence

Machine Learning

Autonomous Systems

Adaptive Sampling

Kanna Rajan

Biological Oceanography

Ocean optics

Adaptive Sampling

Ajit Subramaniam

METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Most of the previous century could be called a "century of undersampling."

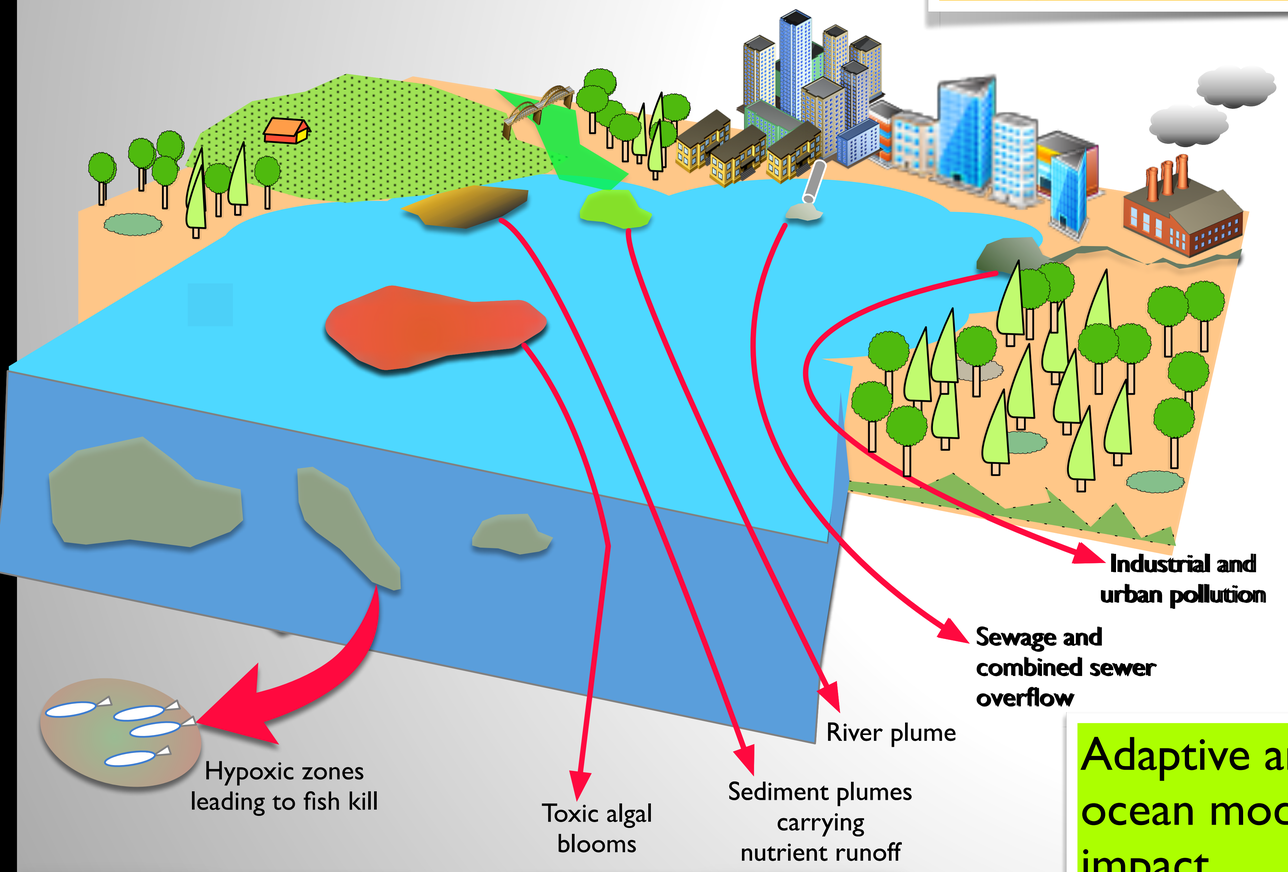
Late *Walter Munk*
Secretary of the Navy/Chief of Naval Operations Oceanography Chair
Scripps Inst. of Oceanography
Testimony to The U.S. Commission On Ocean Policy,
18 April 2002

By the end of this decade METEOR envisions a sustained, integrative and inclusive way of observing the ocean through intelligent robotic sampling, AI and intelligent modeling

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Why?

- The Coastal Ocean has a range of natural and anthropomorphic stressors
- Insufficient spatial, temporal, and spectral resolution of remote sensing products
- Complex dynamics evolving in fine spatial/temporal scales
- Model skill affected by lack of synoptic insitu measurements
- Lags in spatio-temporal measurements



- Rapid advances in Technology in:
  - Command and control software for intelligent sampling
  - AI and Machine Learning
  - Electronics, power sources and communications
  - Interoperability for heterogeneous systems and coordination frameworks
  - Visualization and data science
  - Small satellites

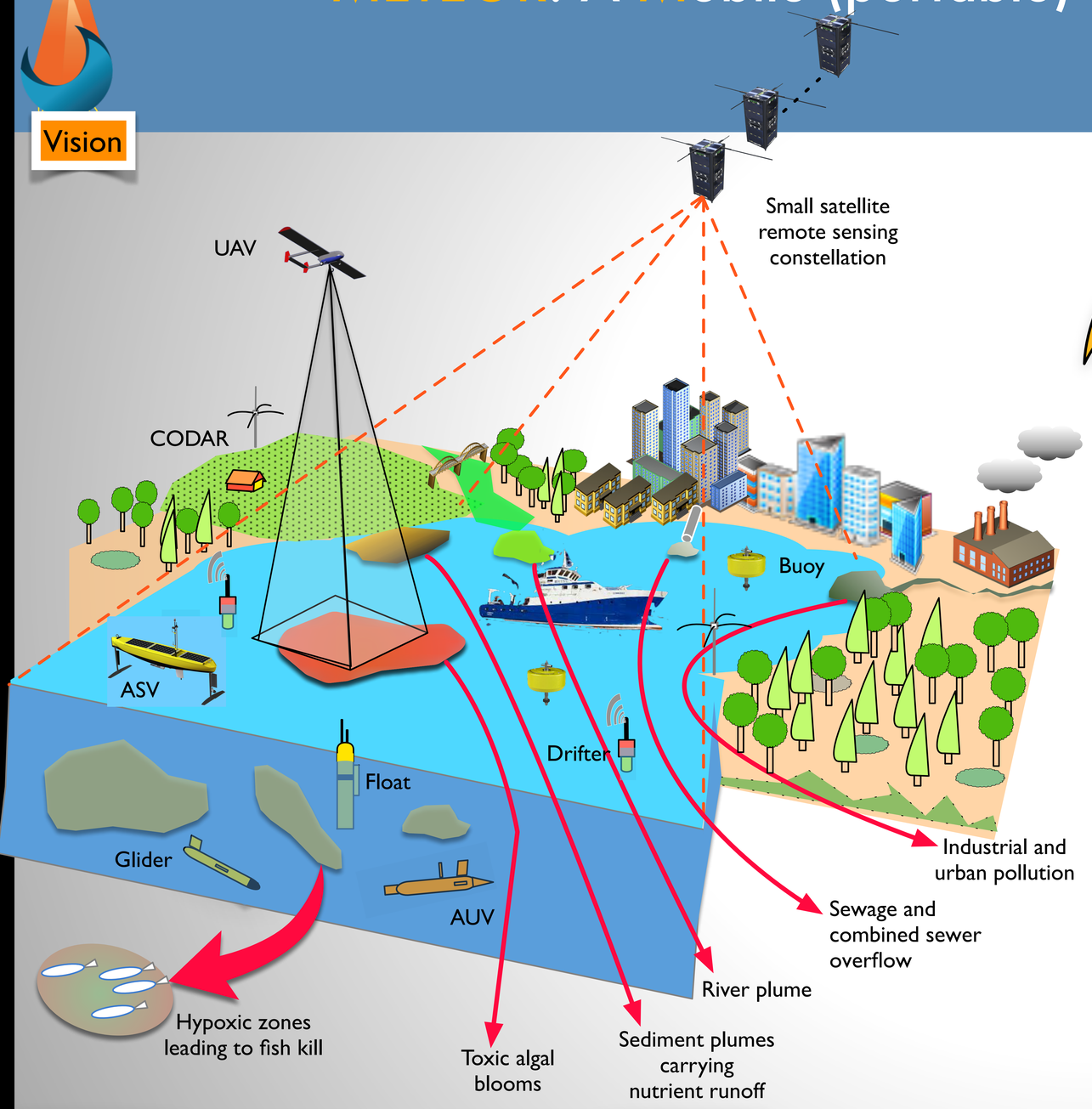
What is needed

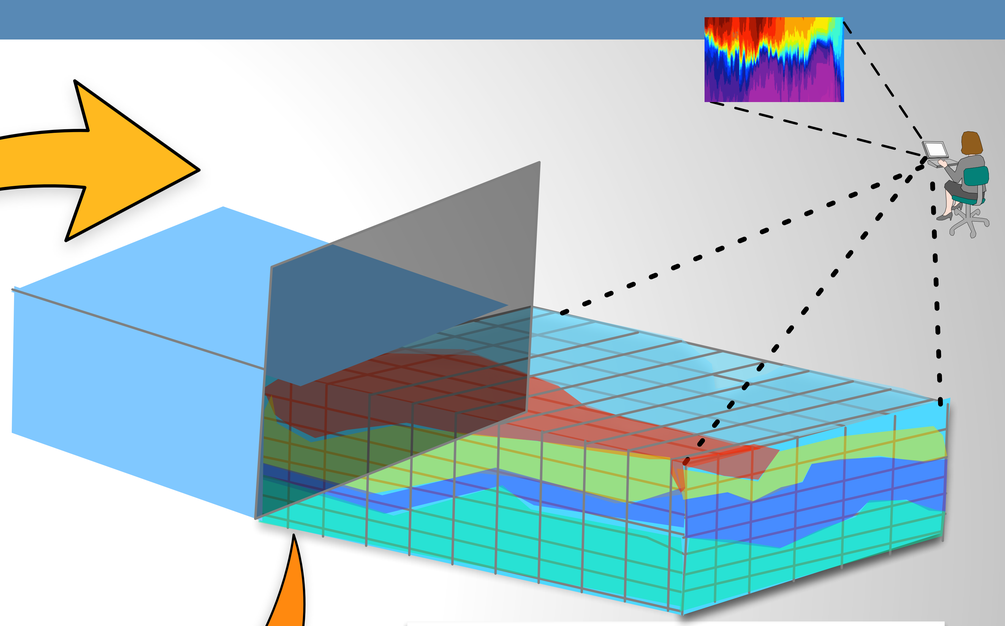
Adaptive and relocatable coastal observation systems integrated with ocean models, for transformative local-to-global science and societal impact.

METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Vision





Closing the loop

Modeling

AI

Principled methods

SmallSats

Assimilate

Predict

Sample

Sense

Intelligent robotics

METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

System-of-Systems Integration (software, data sources, hardware)

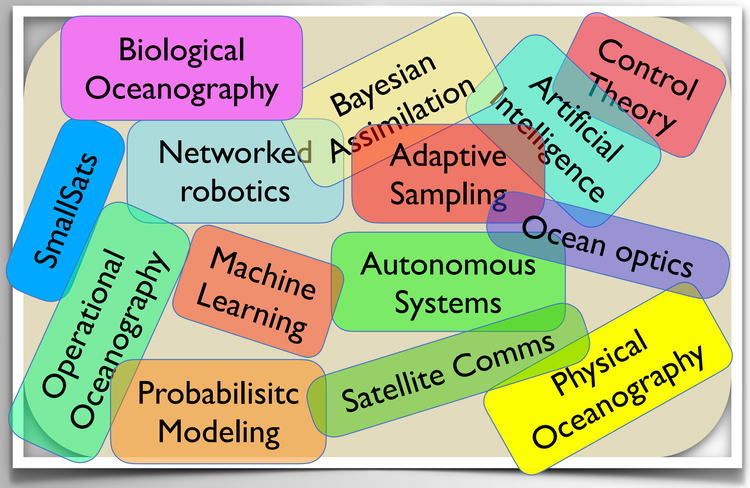
Nonproprietary with open connectivity

High SmallSat revisit time

Rapid deployment of novel space-based sensors

Open Source

Democratizes information access



Mobile and portable

Strong educational/outreach component

Agile multi-platform system-of-systems

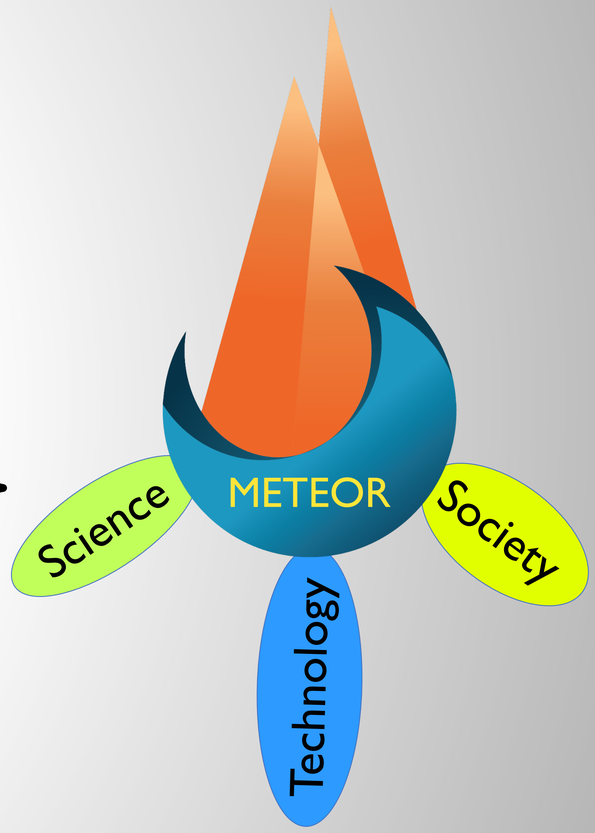
High resolution data

Locally built apps

Science, Societal, Security applications

Scalable software

Complementary to existing observational methods (incl. satellites)



METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

Vision

Small Satellites (**SmallSats**))
remote sensing, ocean surface observations
10,000's km^2
15000 knots

Unmanned Aerial Vehicle (**UAV**)
atmospheric measurements, ocean surface optical measurements
1000's km^2
40-60 knots

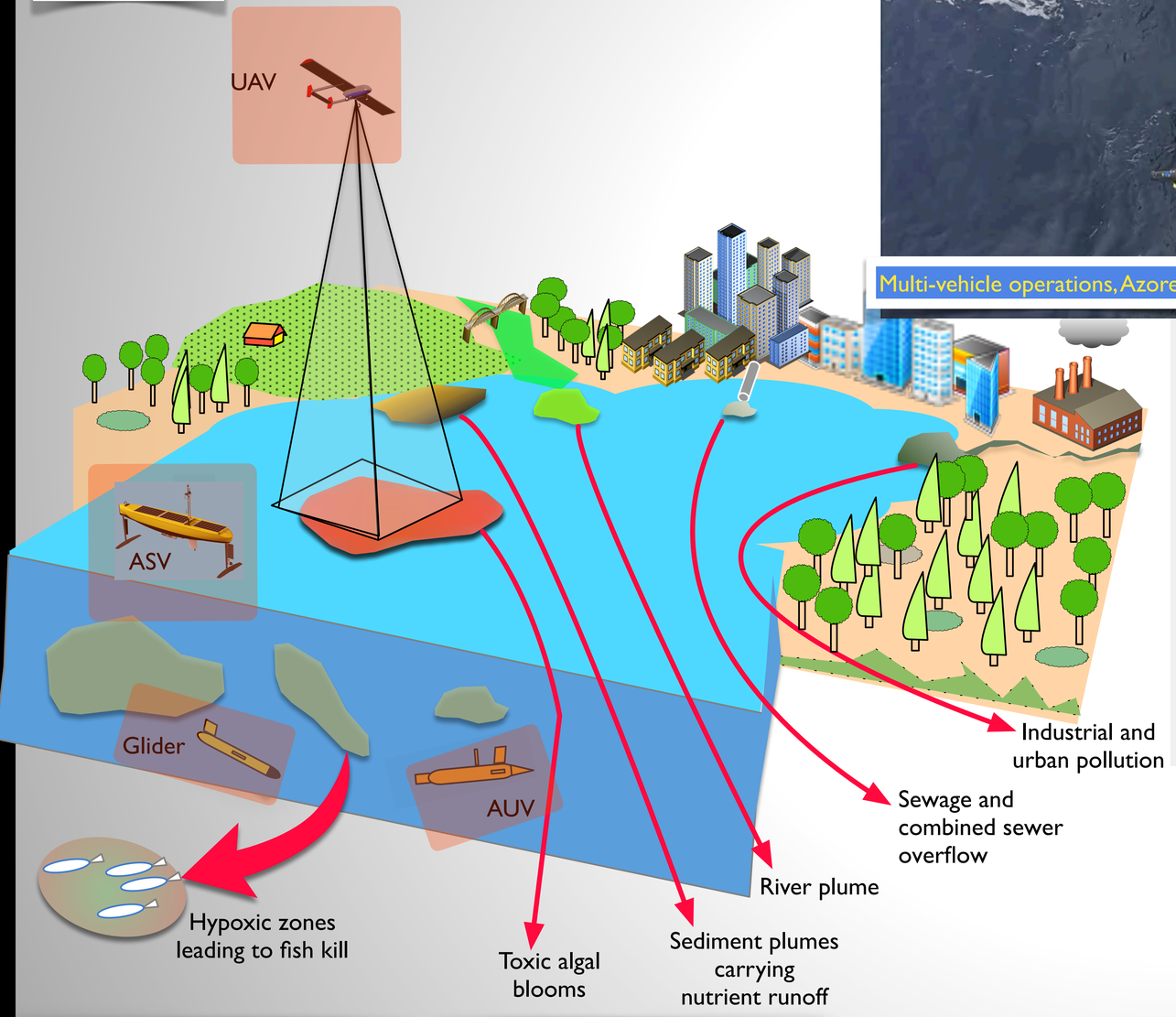
Autonomous Surface Vehicle (**ASV**)
air/sea flux measurements
100's km^2
2-4 knots

Autonomous Underwater Vehicle (**AUV**)
in-situ observations, water sampling, imaging
10's km^2
1-4 knots

METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Robotics/AI



Multi-vehicle operations, Azores, 2015

Tracking Mola-mola Portugal, 2014

Multi-vehicle operations, Azores, 2015

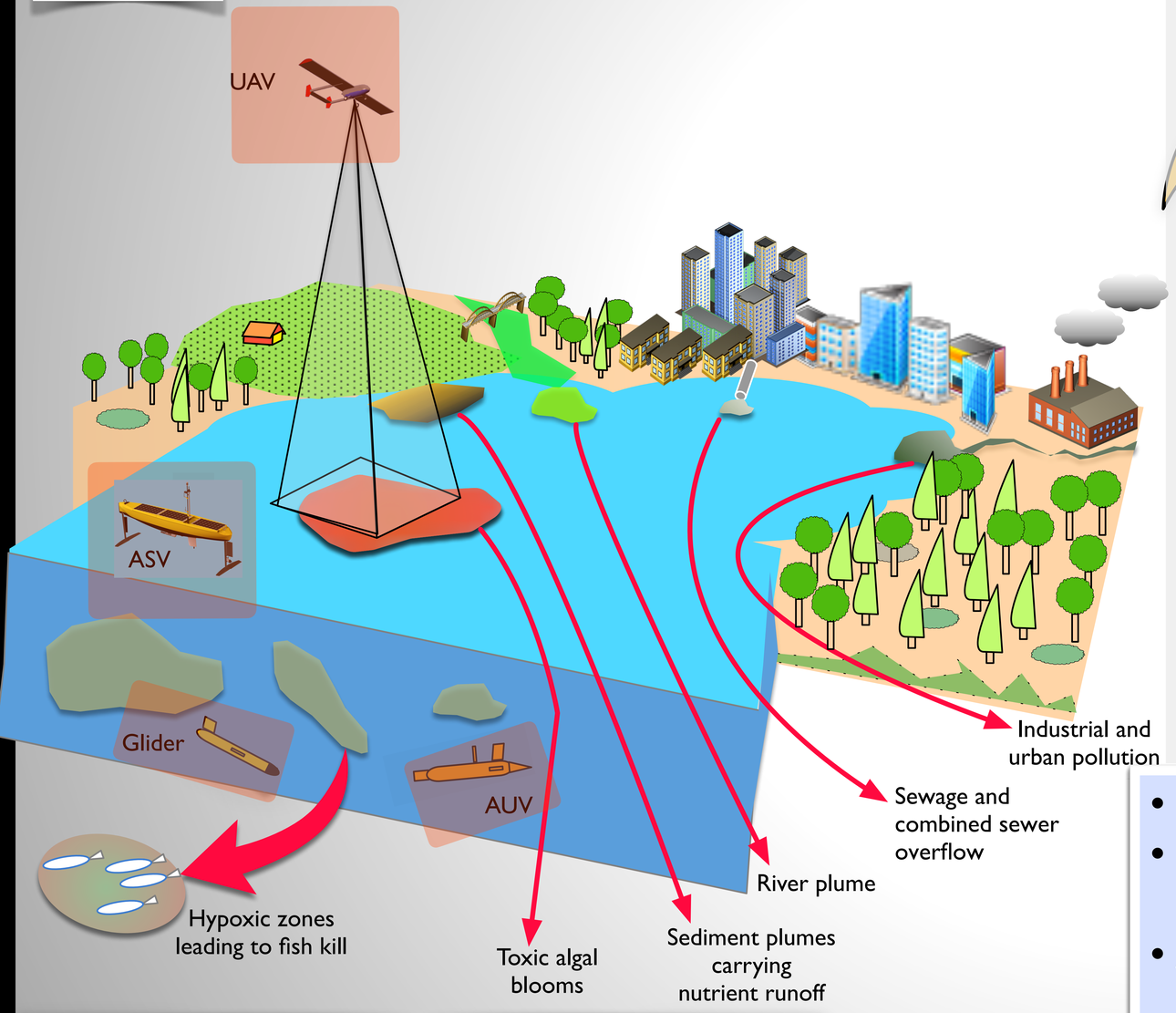
digital twin

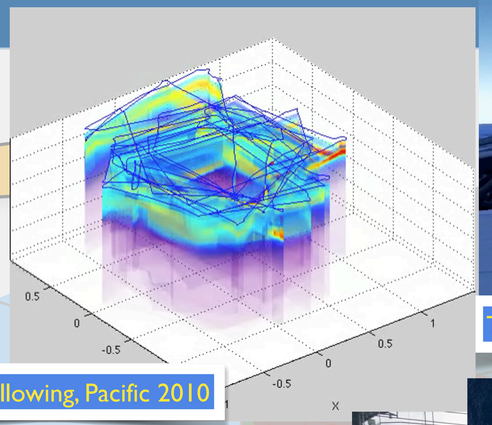
- Robust low-cost hardware
  - designed for endurance and interactions
  - driven by decision-theoretic AI control
  - heterogenous multi-domain robotic swarms extend observational capacity
- Sub-synoptic to super-synoptic observations

METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

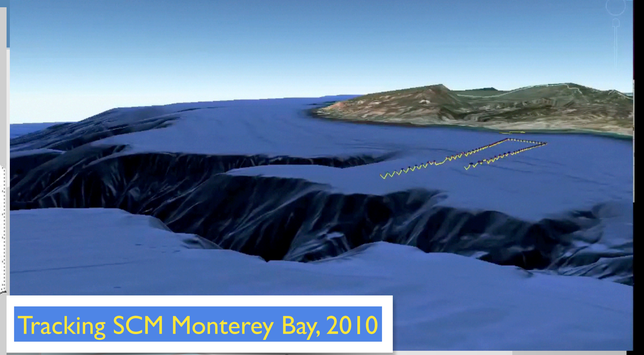
METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Robotics/AI

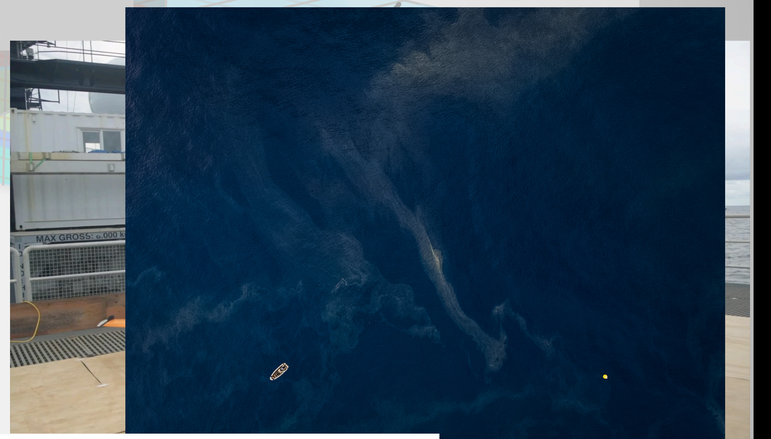




Drifter following, Pacific 2010



Tracking SCM Monterey Bay, 2010



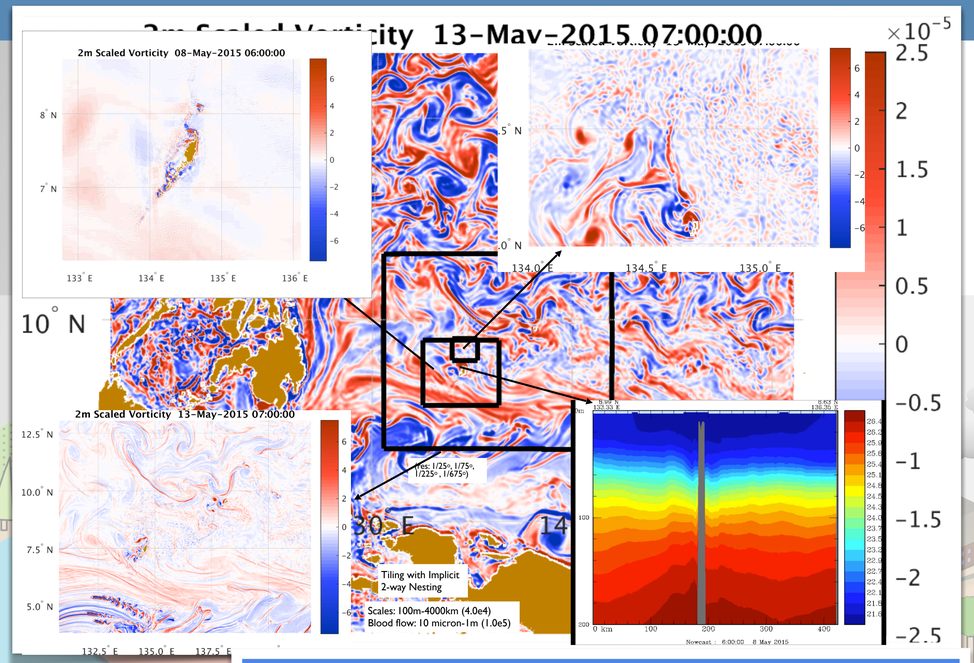
Hyperspectral/IR/visible imaging from a UAV , 2019

- Decision-theoretic AI adapts robot to track features of interest
- Machine-learned compact models allow environmental prediction for smart sampling
- Automated Planning & Execution coordinates multi-vehicle deployment and operation

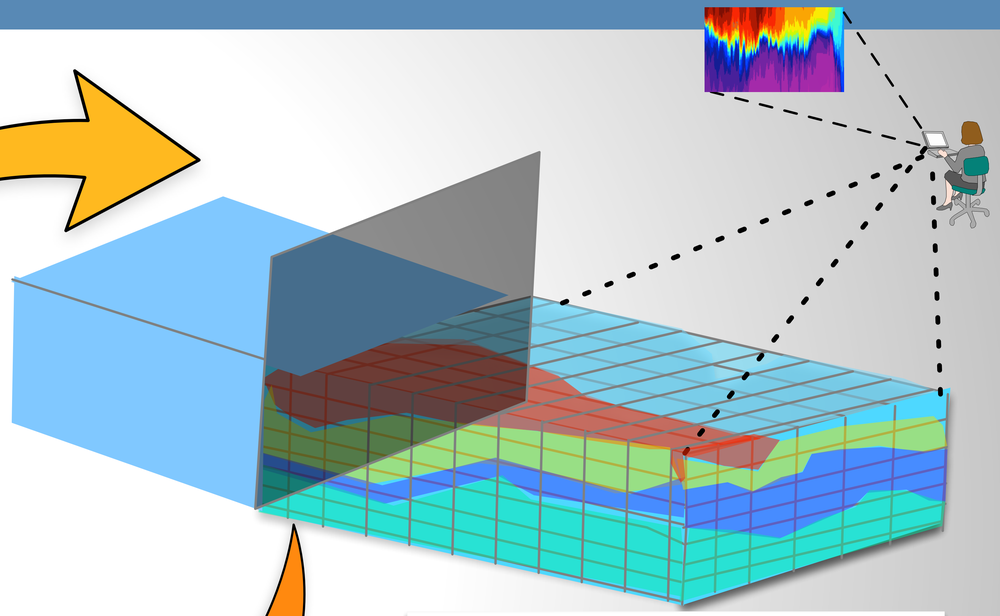
METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Modeling



MIT-MSEAS multi-resolution multi-dynamics modeling, Palau Islands



Data assimilative Ocean model/digital twin

Industrial and urban pollution

Sewage and combined sewer overflow

River plume

Hypoxic zones leading to fish kill

Toxic algal blooms

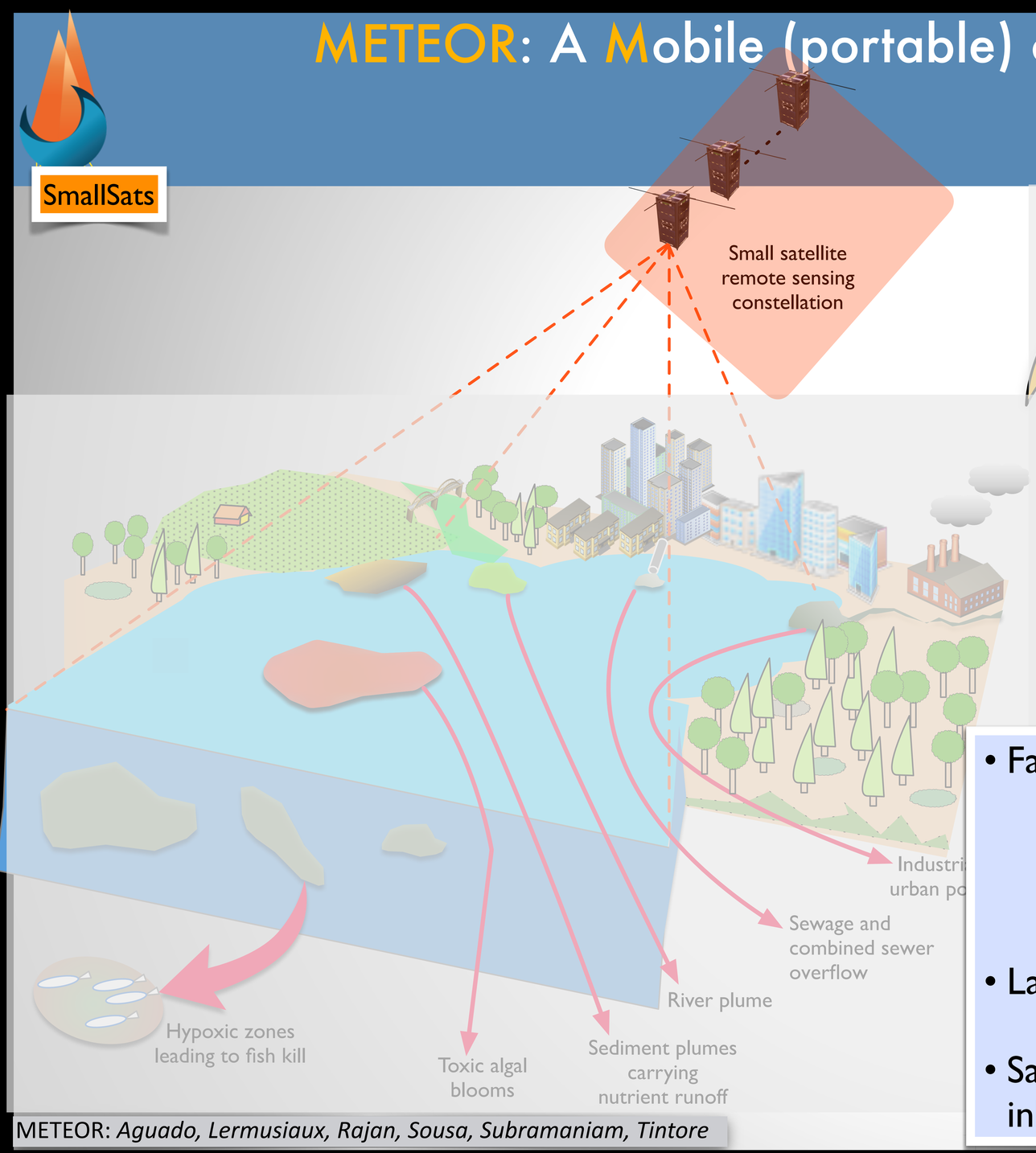
Sediment plumes carrying nutrient runoff

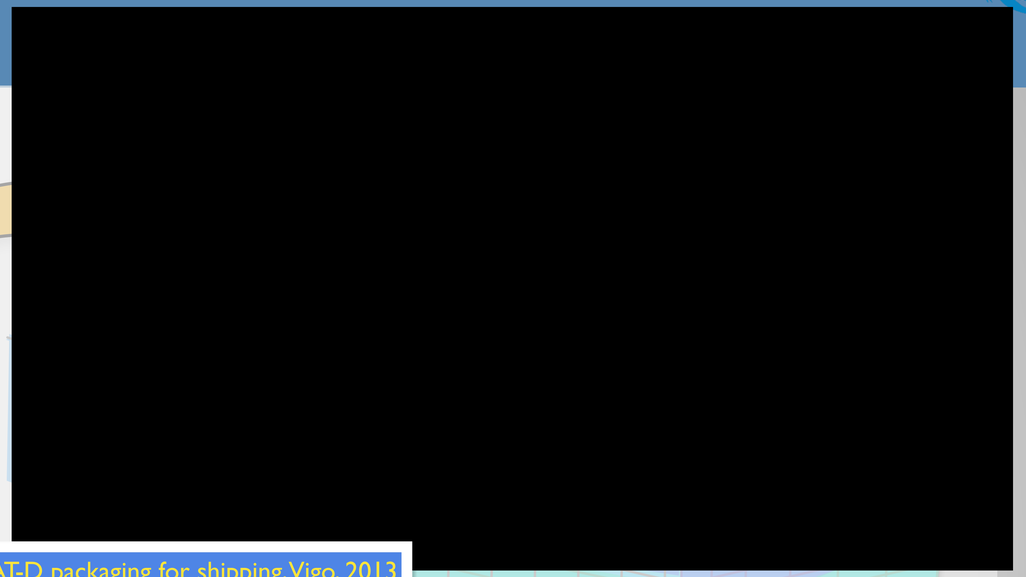
- Probabilistic real-time multi-resolution model predictions
- Bayesian predictions from short to long time-scales, leading to science-informed management
- Rapid multi-platform assimilation
- Near real-time "what-if analysis" with quantitative risk management

METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

SmallSats





HUMSAT-D packaging for shipping, Vigo, 2013

Assimilated Ocean model/digital twin

- Faster to build and affordable (even for univ. environments)
  - Building constellations is extremely viable
  - Increased revisit time (< 3 hours) with high resolution data
  - Complementary to existing space assets
  - Democratizes space remote sensing
- Latest technology can be rapidly integrated/launched/operated
  - Ocean color, SST, SSH, Altimetry, Wind
- Satellite data can be used the world over including for monitoring inland lakes

METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Applications

Oil Spills

looms

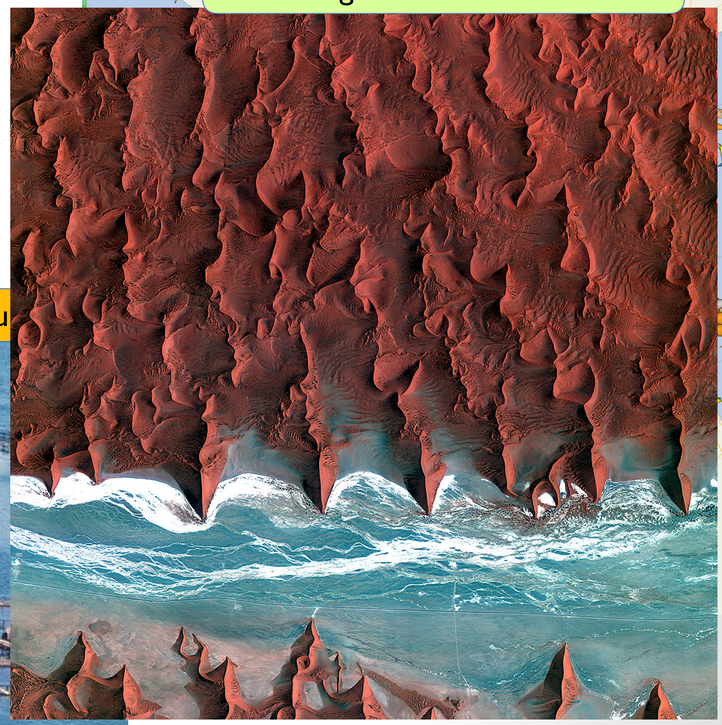
mes/runoff

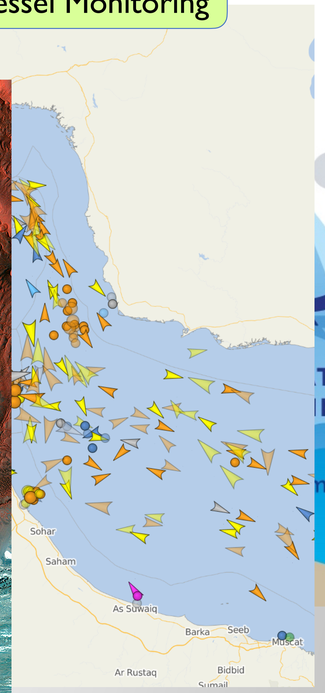
quacultu

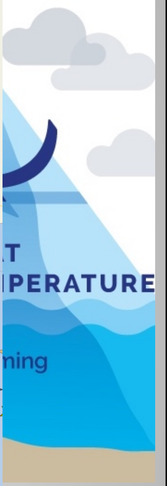
Coastal Monitoring

Vessel Monitoring

Monitoring Remote Coastal Zones

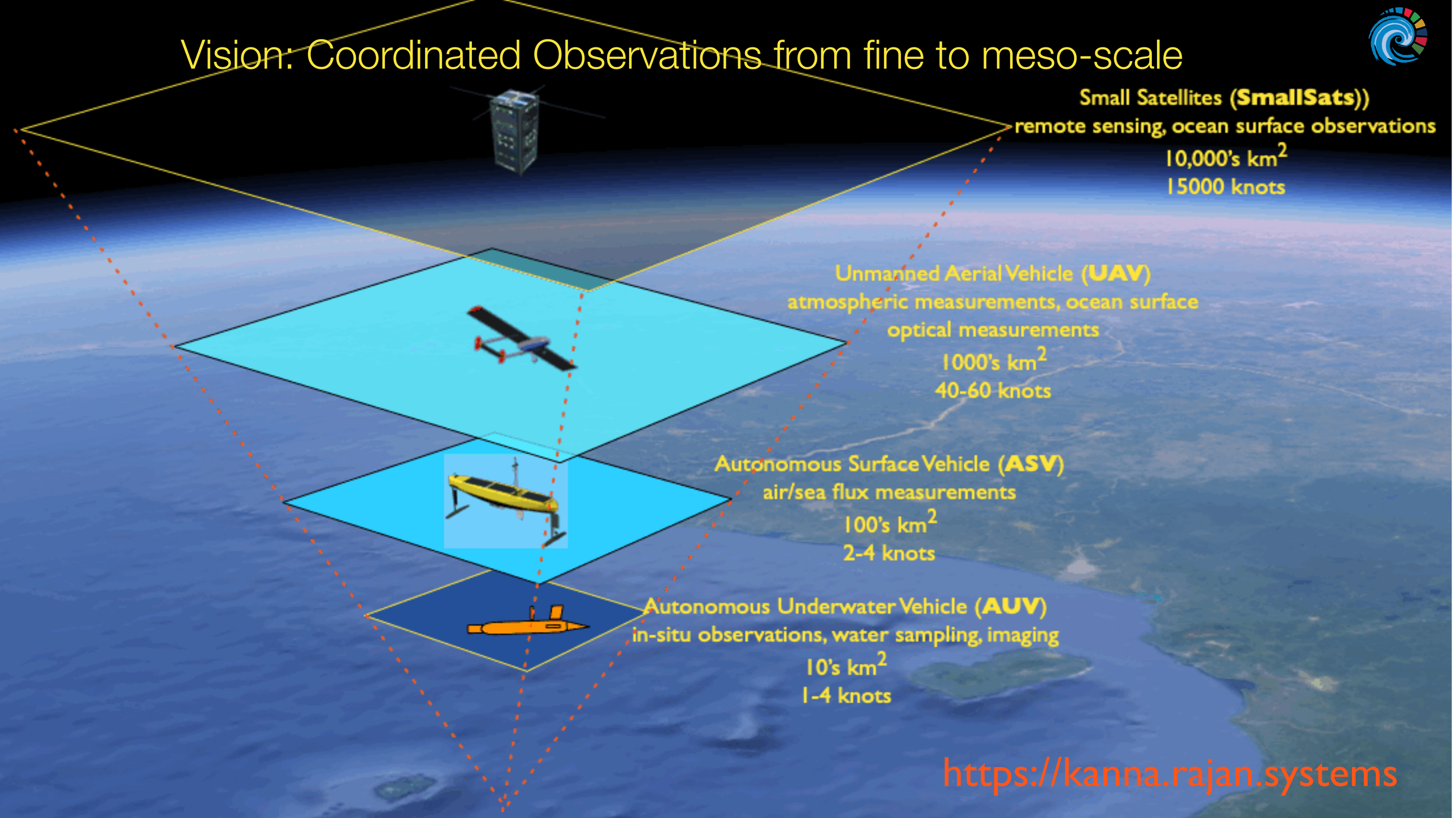






METEOR: *Aguado, Lermusiaux, Rajan, Sousa, Subramaniam, Tintore*

Vision: Coordinated Observations from fine to meso-scale



https://kanna.rajan.systems