Sampling the world's Oceans Autonomously

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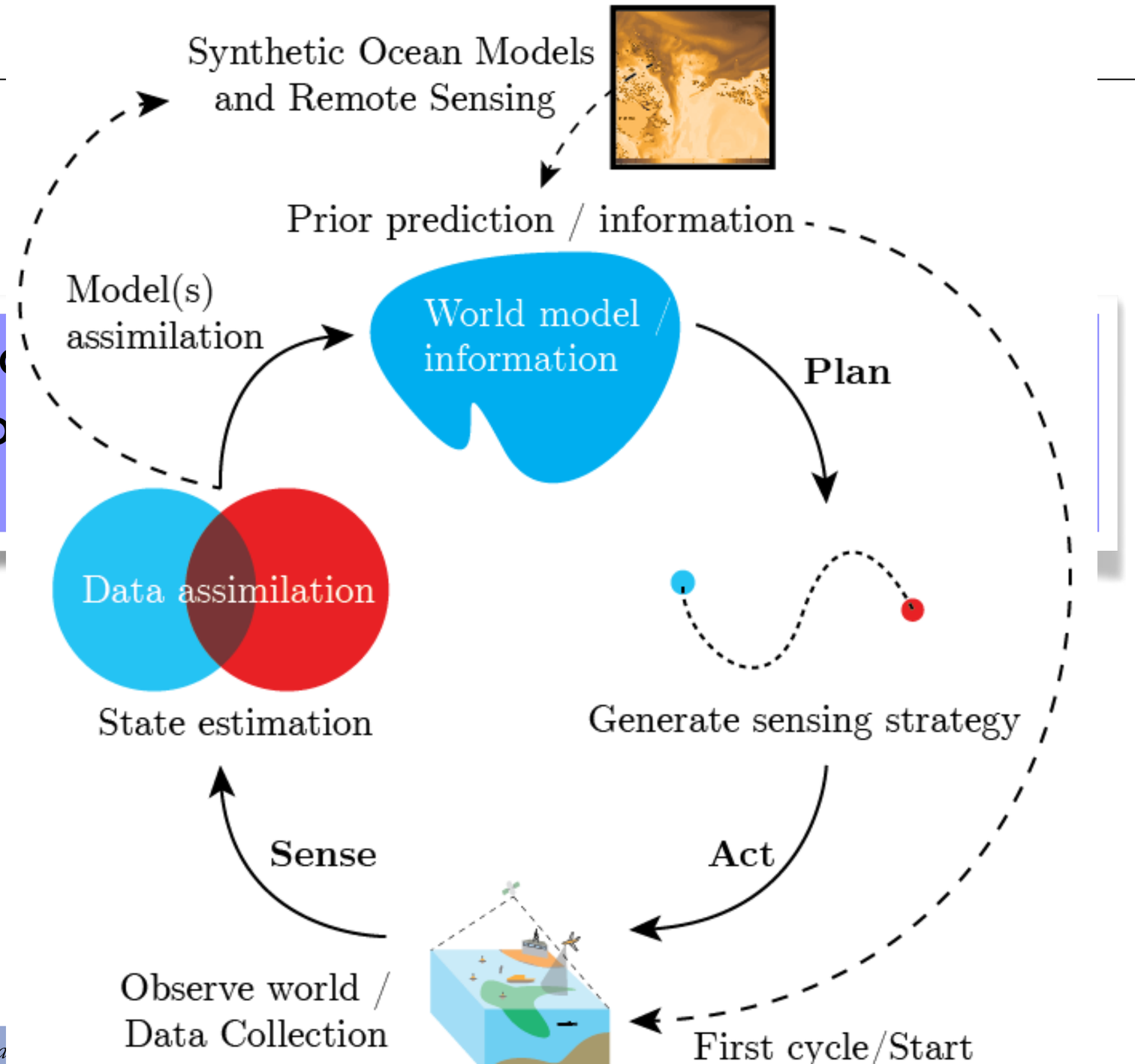
Most of the previous century could be called a "century of undersampling."

Walter Munk
Testimony to The U.S. Commission On Ocean Policy, 18 April 2002

By the end of this decade we need to have a sustained, integrative and inclusive way of observing the ocean through intelligent robotic sampling and intelligent modeling

To pr
for o

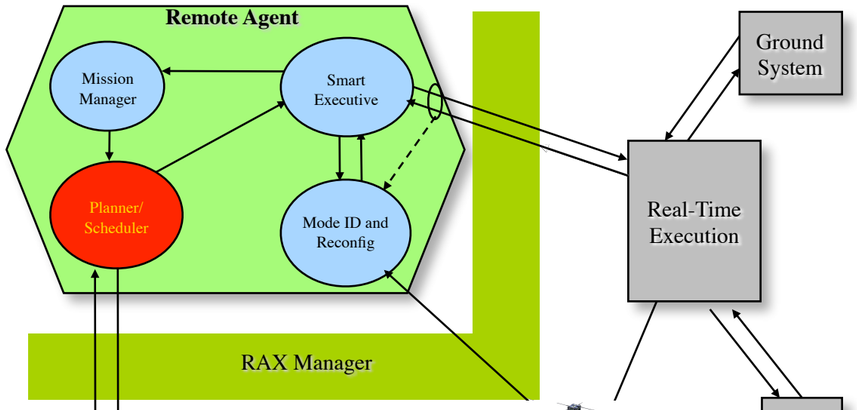

Synthetic Ocean Models
and Remote Sensing
Prior prediction / information
Model(s)
assimilation
World model /
information
Plan
Data assimilation
State estimation
Generate sensing strategy
Sense
Act
Observe world /
Data Collection
First cycle/Start

why (decision-theoretic) AI?

The Sampling Conundrum

1. Finite Time
2. Finite Energy
3. Finite Sampling Resources
4. Uncertainty of occurrence of phenomenon
5. Uncertainty of location, size, shape and strength of feature signal

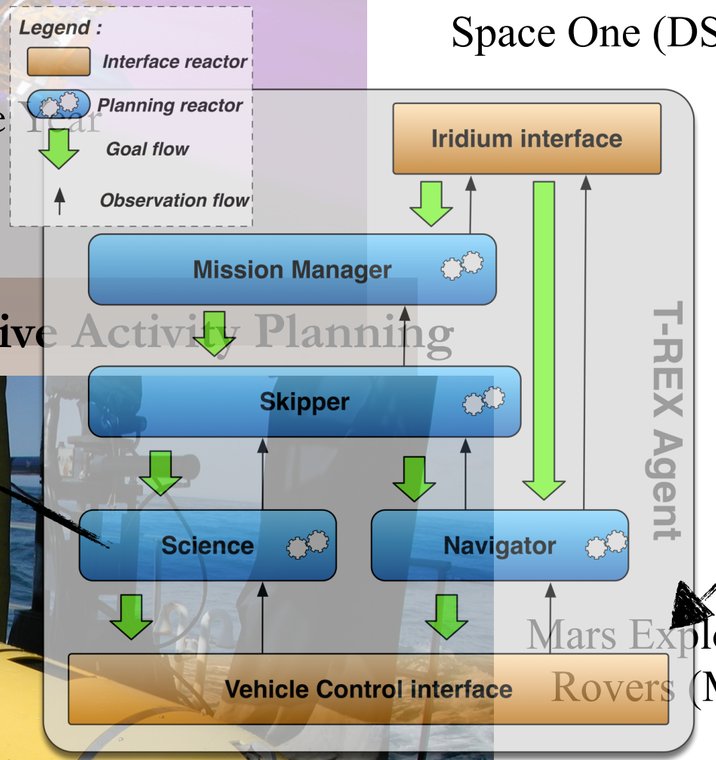
research: understanding the nature of autonomy



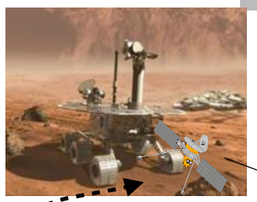
Remote Agent Experiment (DS1)

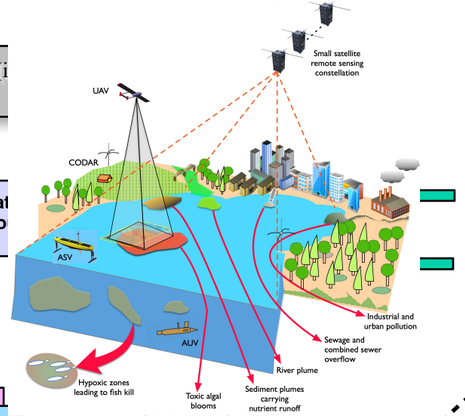
- Flew onboard Deep Space 1, May 17-21, 1999
- 65 Million miles from Earth, during *Ballistic Cruise*
- One of six principals
- NASA's 1999 Software of the Year

New Millennium Deep Space One (DS1)

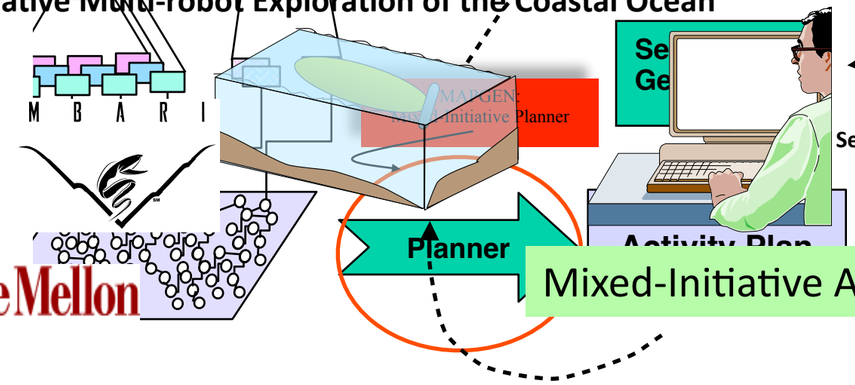


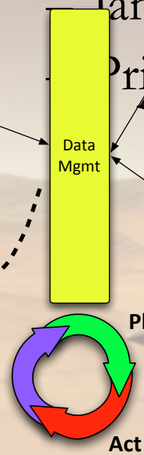
MAPGEN: Mixed-Initiative Activity Planning

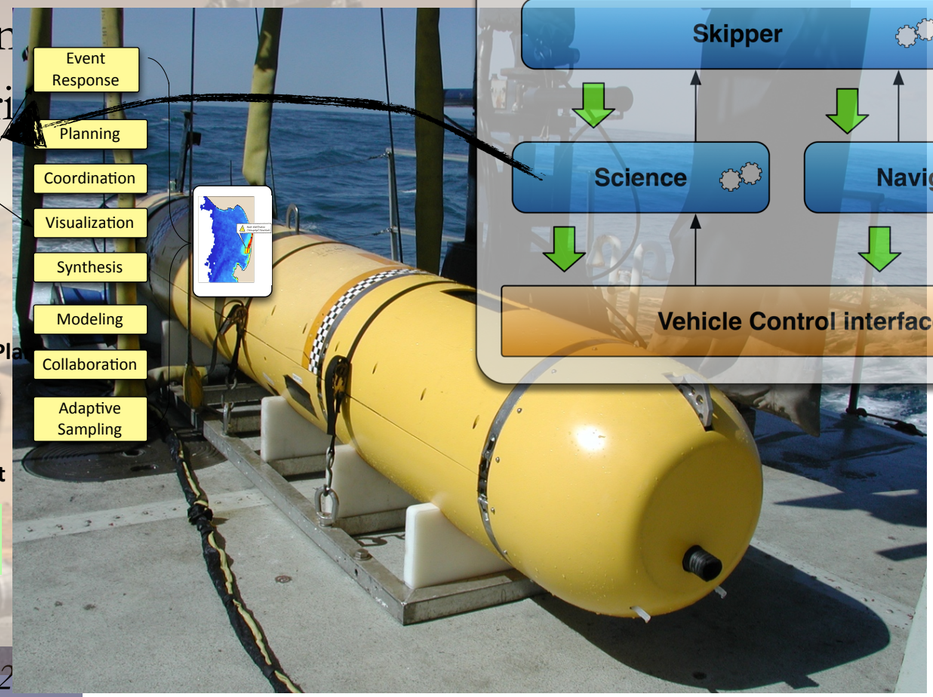




NSF: Collaborative Multi-robot Exploration of the Coastal Ocean





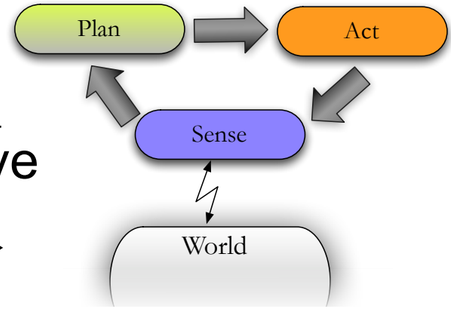


Mixed-Initiative Autonomy

Mars Exploration Rovers (MER)

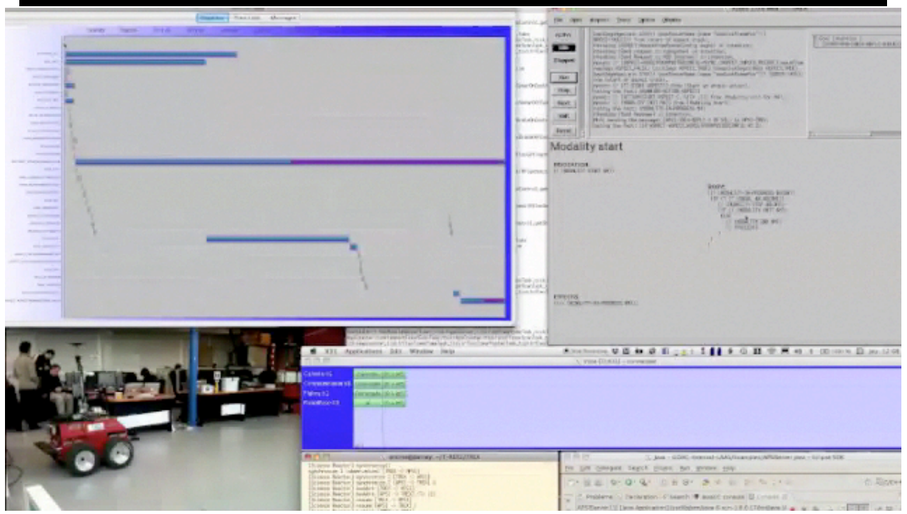
Teleo-Reactive EXecutive (T-REX)

onboard plan synthesis and execution



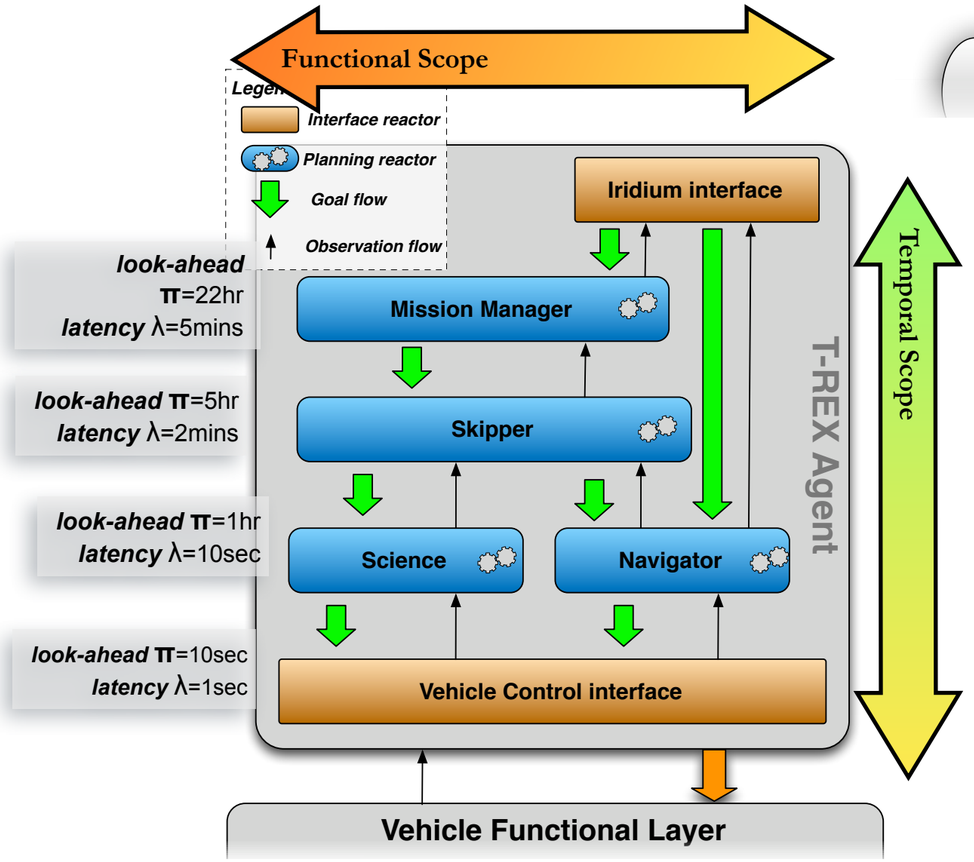
- Functional scope along the lines of *what*
- Temporal scope along the lines of *when*

Terrestrial robot planning



European Space Agency Mars rover Testbed

T-REX: Teleo-Reactive EXecutive



A Systematic Agent Framework for Situated Autonomous Systems

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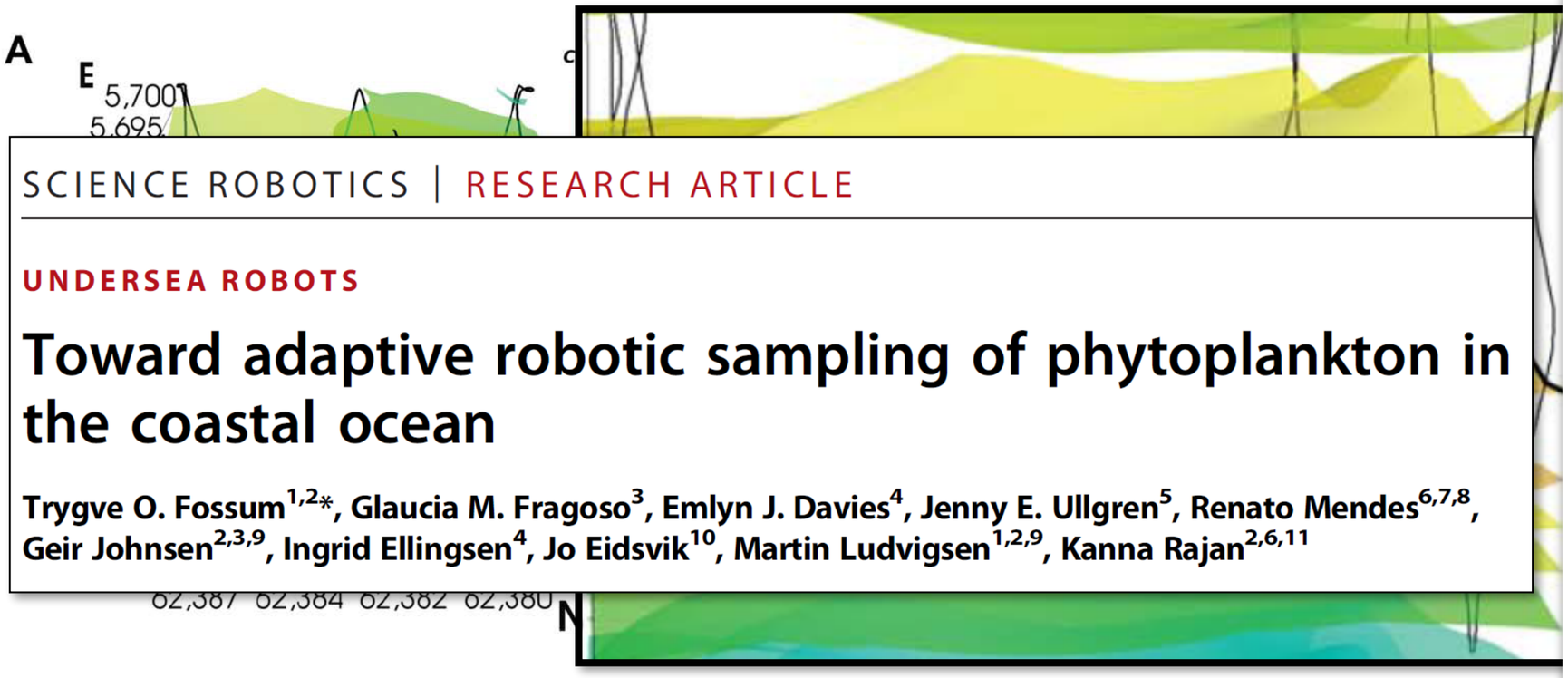
applications: surveys & field reconstruction

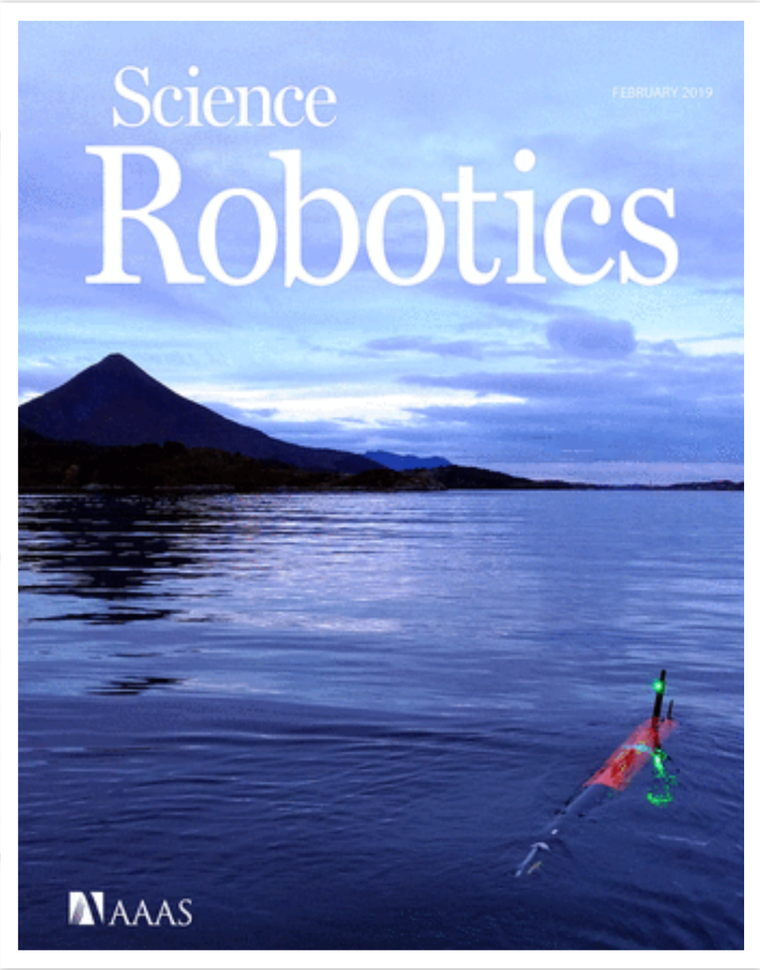


SCIENCE ROBOTICS | RESEARCH ARTICLE

UNDERSEA ROBOTS

Toward adaptive robotic sampling of phytoplankton in the coastal ocean

Trygve O. Fossum[1,2]*, Glaucia M. Fragoso[3], Emlyn J. Davies[4], Jenny E. Ullgren[5], Renato Mendes[6,7,8], Geir Johnsen[2,3,9], Ingrid Ellingsen[4], Jo Eidsvik[10], Martin Ludvigsen[1,2,9], Kanna Rajan[2,6,11]



Estimated distribution after MODE 1

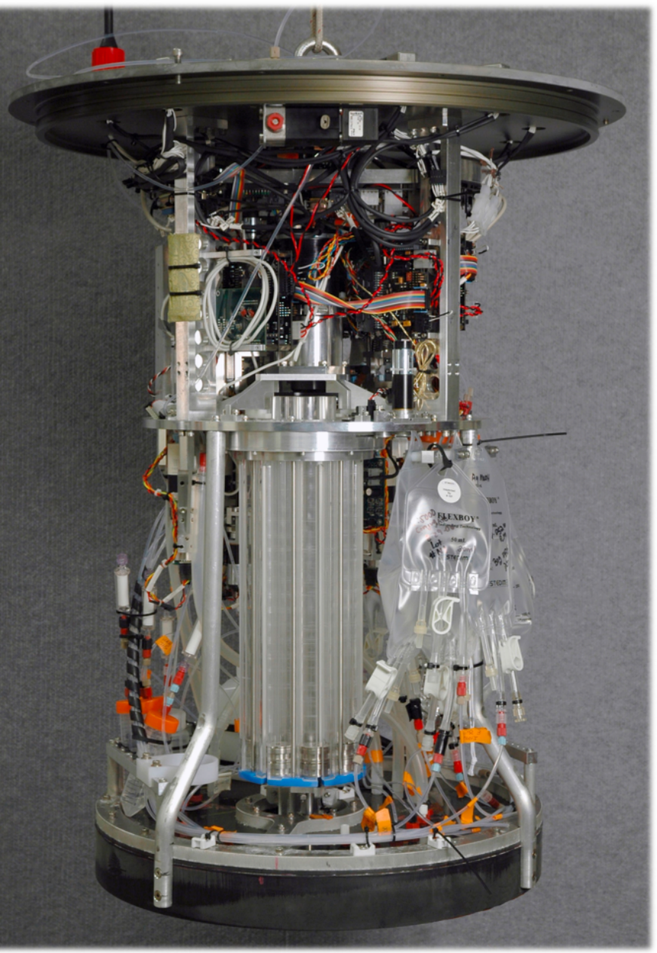
Estimated distribution after MODE 2

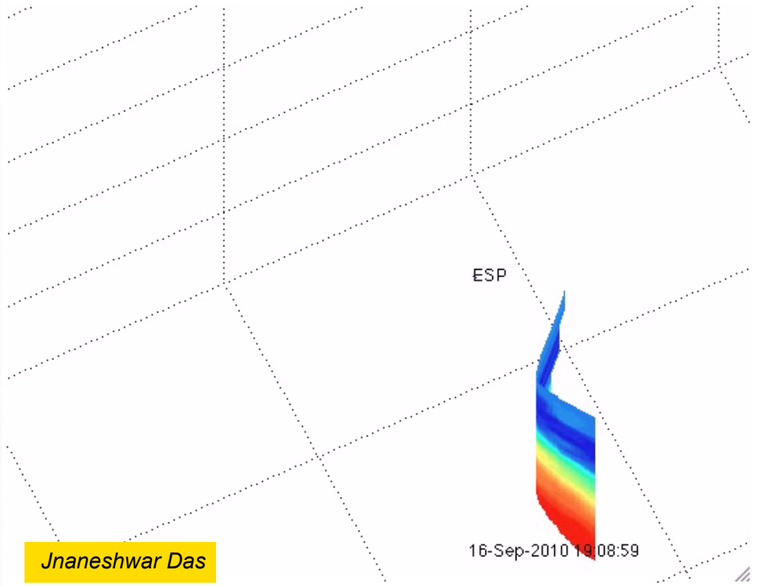
after MODE 2 (side view)

*SCM= sub-surface Chl. max

Trygve Olav Fossum

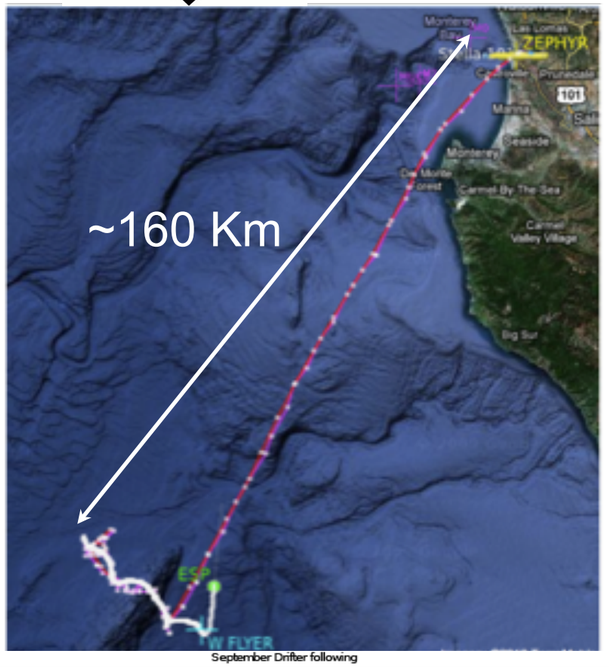
applications: patch following

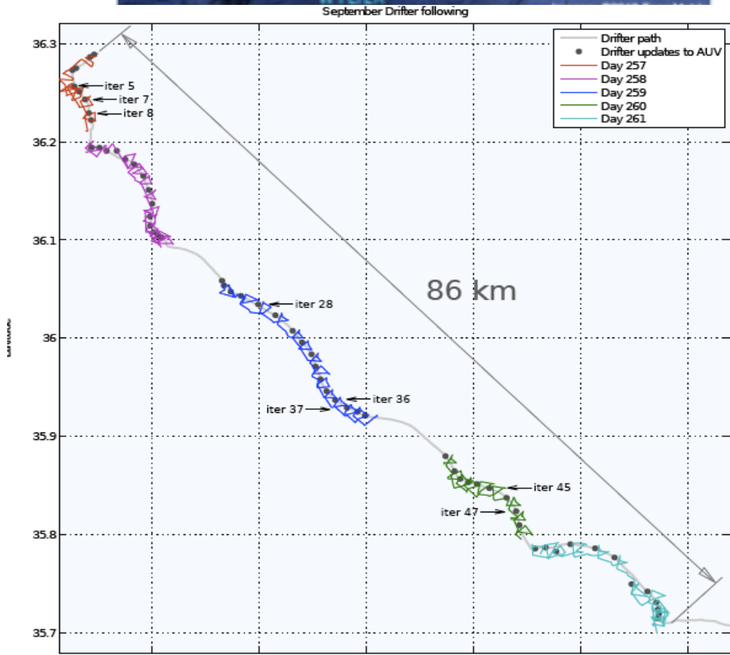




Jnaneshwar Das

Salinity Sept 2010

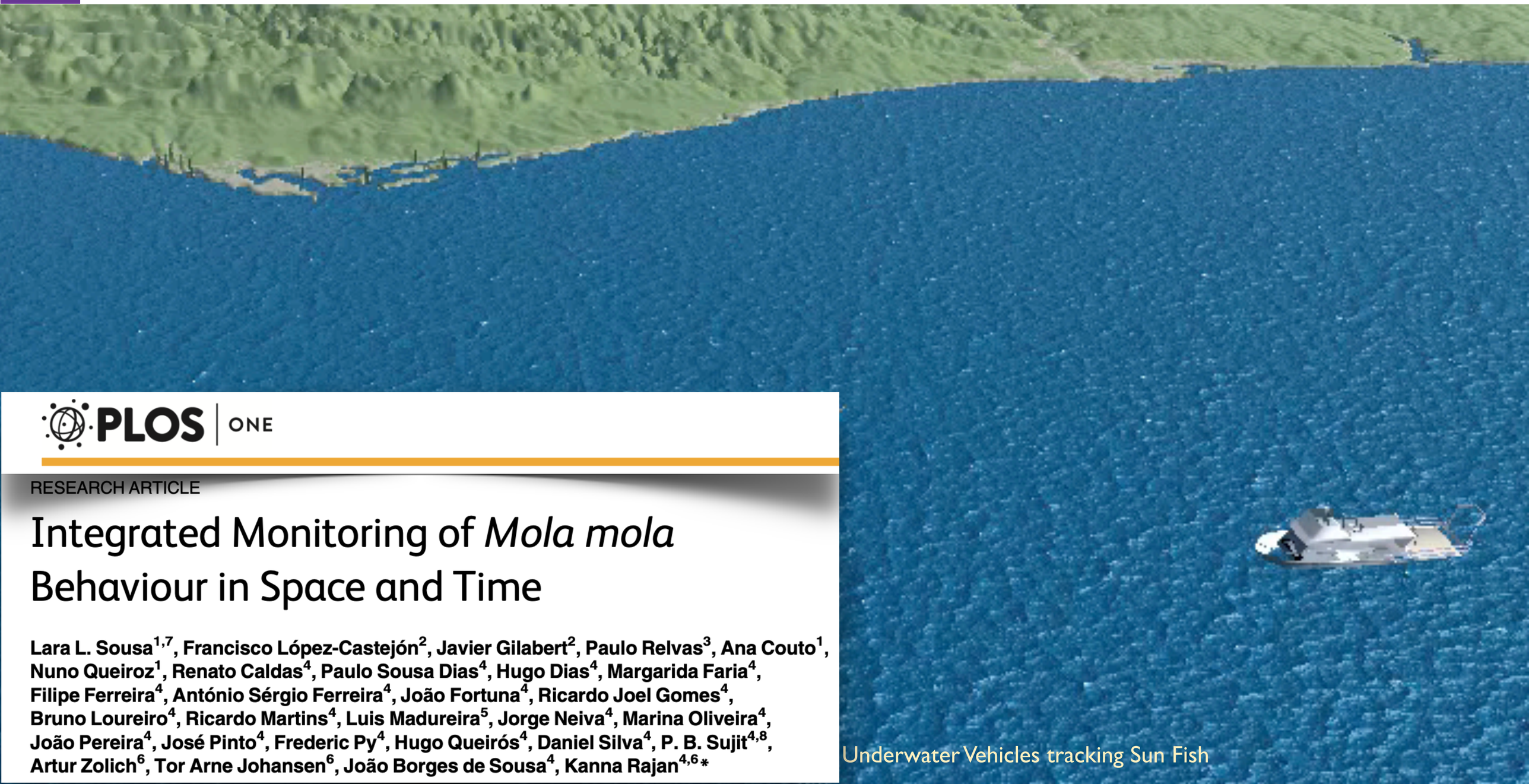




→ Repeated static-plan surveys not suitable for range of drifter speeds

Coordinated sampling of dynamic oceanographic features with underwater vehicles and drifters
Jnaneshwar Das, Frederic Py, Thom Maughan, Tom O'Reilly, Monique Messi´e, John Ryan, G. S. Sukhatme, K. Rajan, April **IJRR**, 2012

applications: chasing fish



PLOS ONE

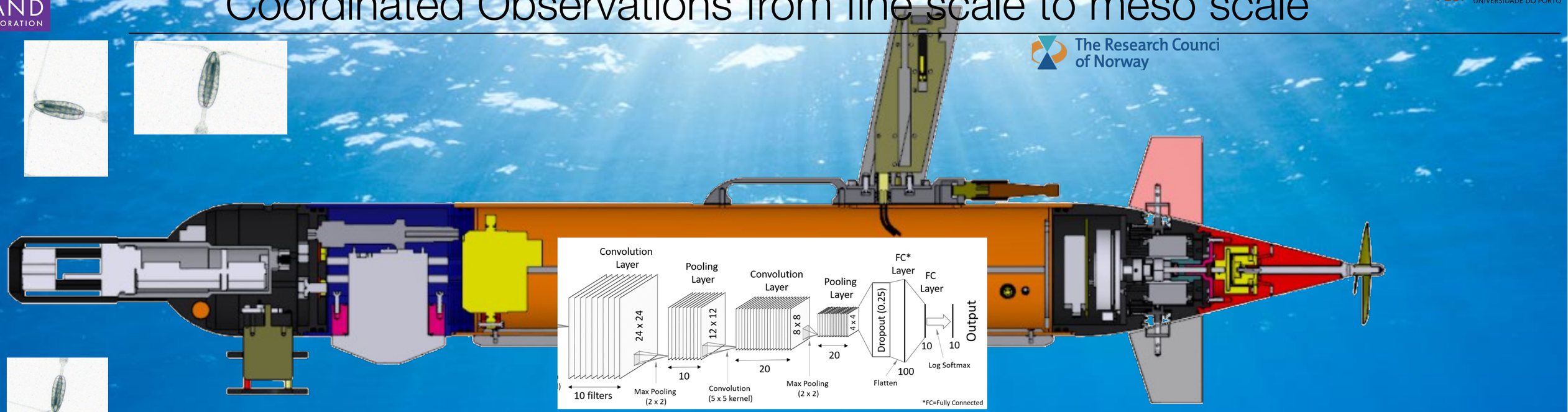
RESEARCH ARTICLE

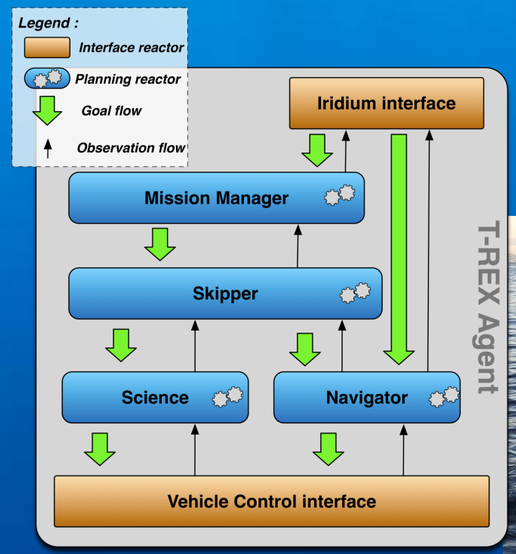
Integrated Monitoring of *Mola mola* Behaviour in Space and Time

Lara L. Sousa[1,7], Francisco López-Castejón[2], Javier Gilabert[2], Paulo Relvas[3], Ana Couto[1], Nuno Queiroz[1], Renato Caldas[4], Paulo Sousa Dias[4], Hugo Dias[4], Margarida Faria[4], Filipe Ferreira[4], António Sérgio Ferreira[4], João Fortuna[4], Ricardo Joel Gomes[4], Bruno Loureiro[4], Ricardo Martins[4], Luis Madureira[5], Jorge Neiva[4], Marina Oliveira[4], João Pereira[4], José Pinto[4], Frederic Py[4], Hugo Queirós[4], Daniel Silva[4], P. B. Sujit[4,8], Artur Zolich[6], Tor Arne Johansen[6], João Borges de Sousa[4], Kanna Rajan[4,6]*

Underwater Vehicles tracking Sun Fish

Coordinated Observations from fine scale to meso scale



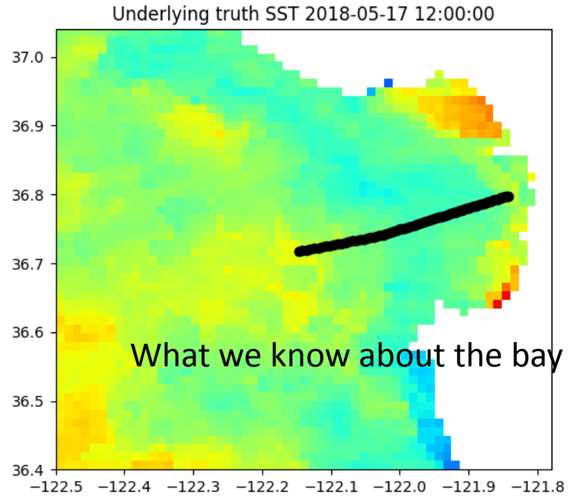


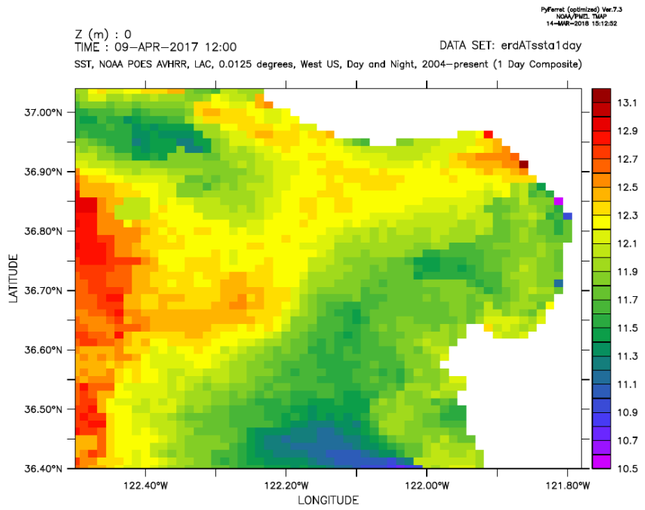
Oceanography 2020

Advancing Ocean Observation with an AI-Driven Mobile Robotic Explorer

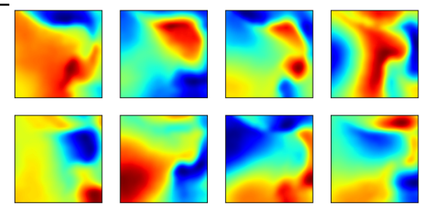
Kanna Rajan

machine learning driven exploration

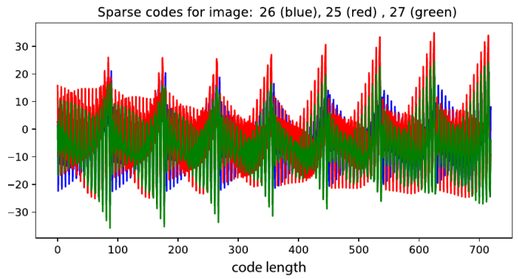




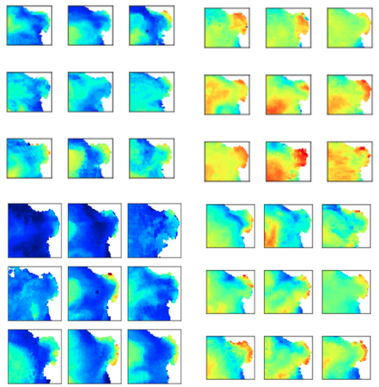
dictionary "D"



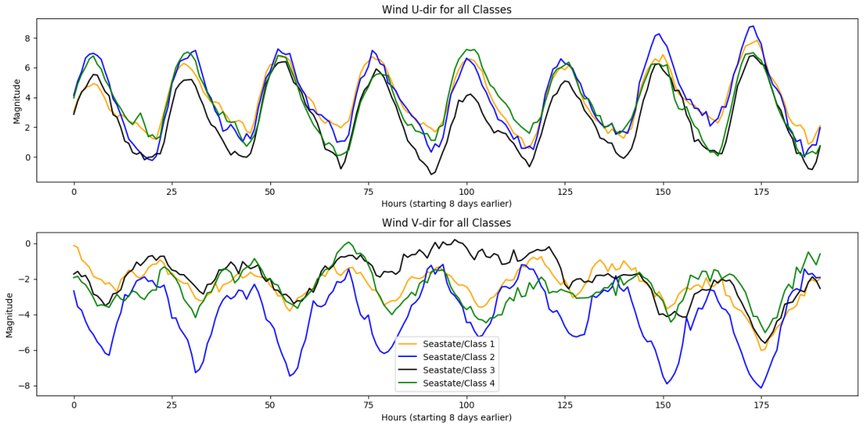
sparse code "α"



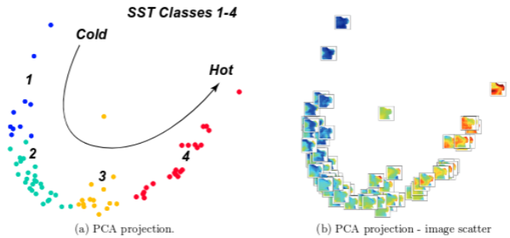
Classify each image



Dictionary Learning, Sparse Coding, Classification, and Verification.



Verify results with supporting data



Intnl. J of Robotics Res.

Compact Ocean Models for Adaptive Sampling in the Coastal Ocean

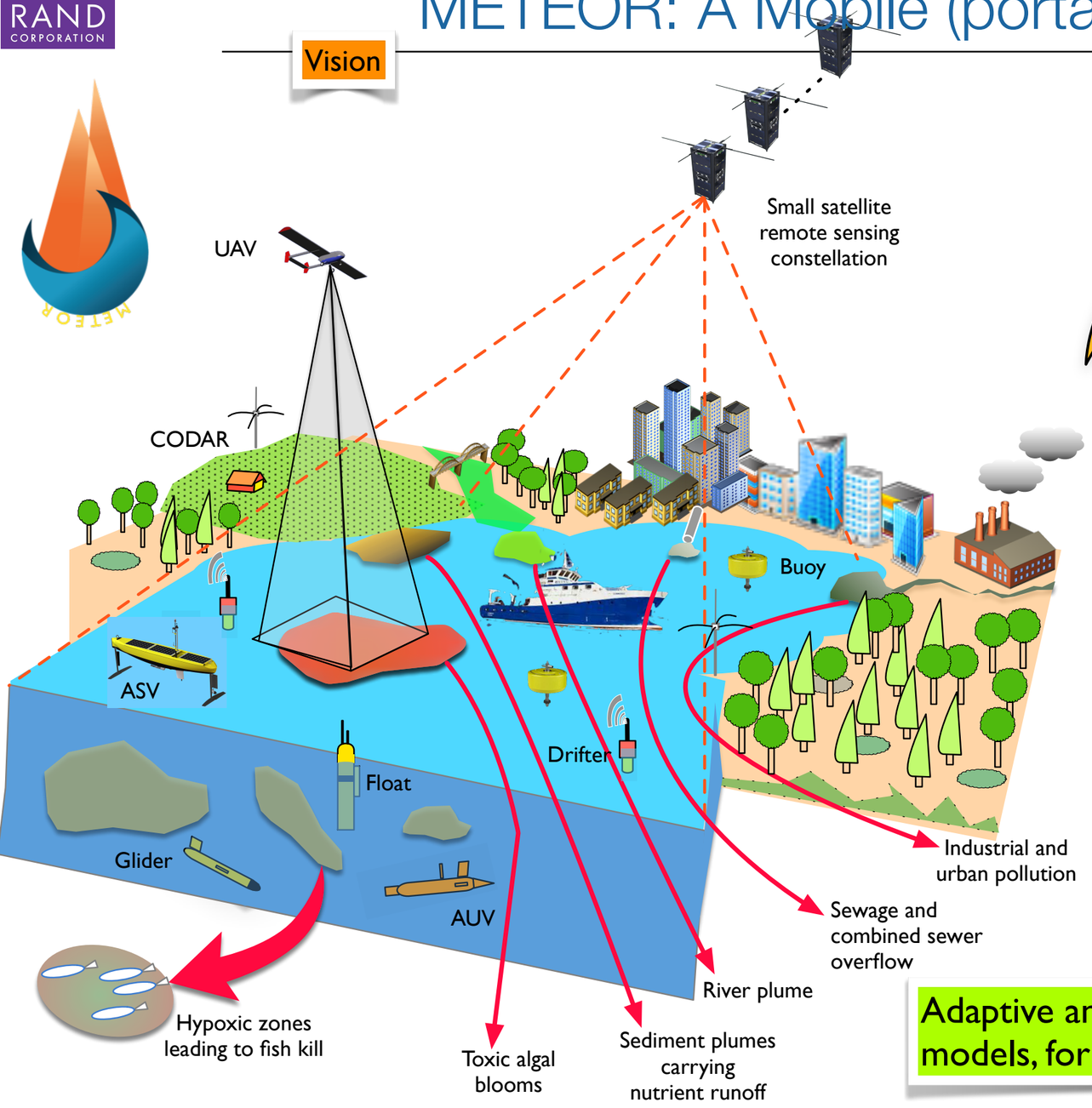
Trygve Olav Fossum[1,7], John Ryan[2], Tapan Mukerji[3],
Jo Eidsvik[4], Thom Maughan[2], Martin Ludvigsen[1,5], and Kanna Rajan[6,7,8].

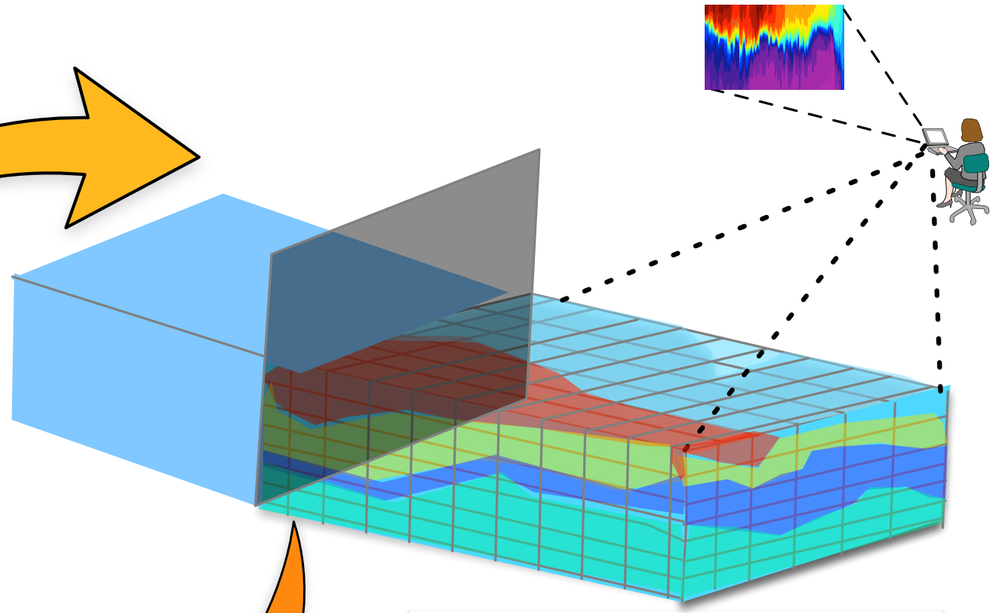
Stanford University

MBARI

METEOR: A Mobile (portable) ocEan roboTic ObsErvatORy

Vision





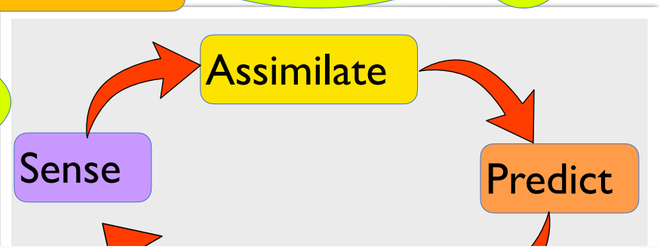
Data assimilative Ocean model/digital twin

Closing the loop

Modeling

AI

Principled methods

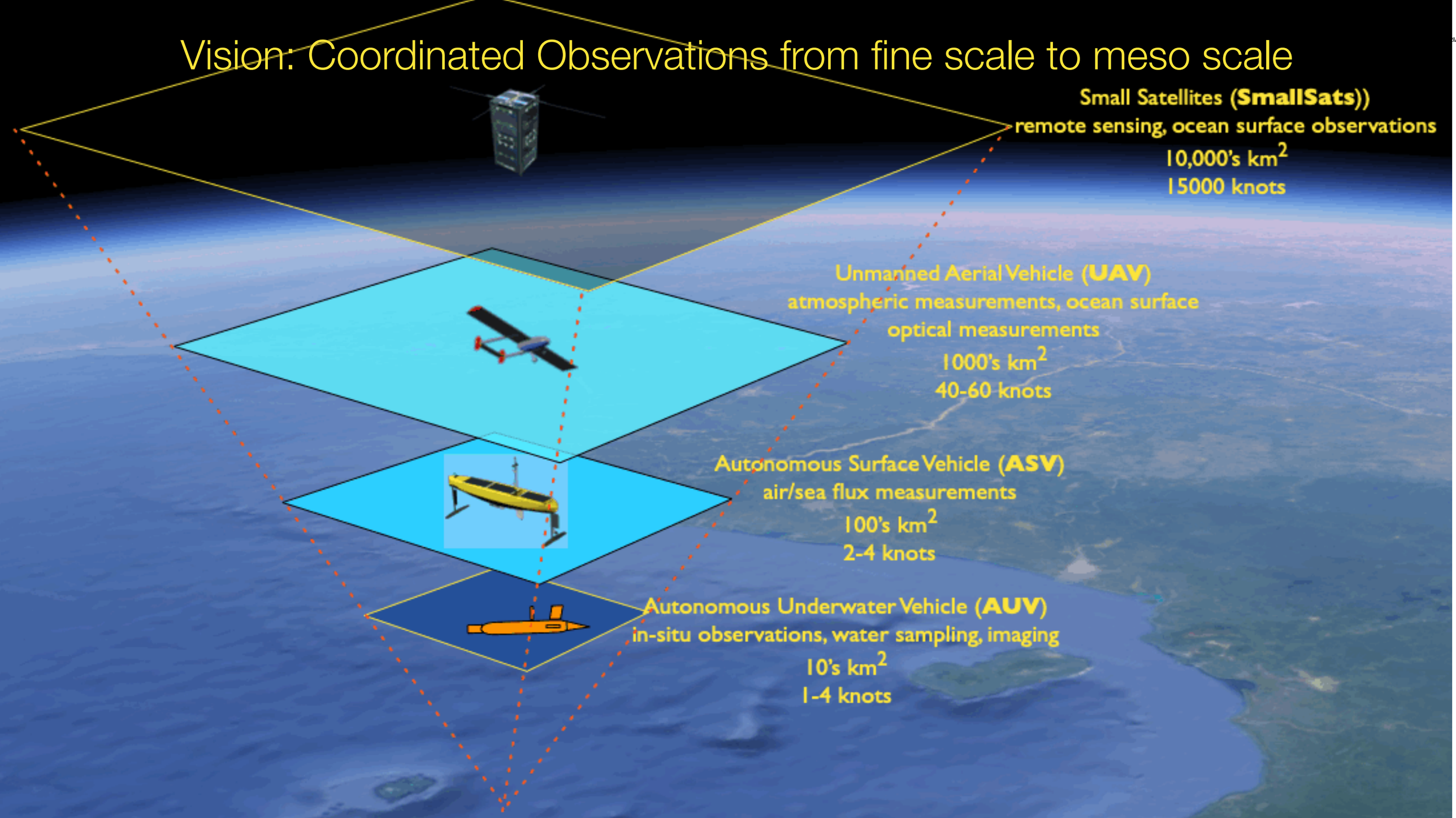


What is needed

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

Intelligent robotics

Vision: Coordinated Observations from fine scale to meso scale



take home message

- The ocean doesn't have straight lines; so why are we sampling along those?
    - Robotic adaptation and statistical methods with control is critical
    - Robotic (and sensing) methods have improved — yet we're still in the 'Charles Darwin' approach to sampling
- Exploration across space and time is more effective with robotics coupled with decision-making (embedded or not)
- Increasing investment in marine robotics to provide new tools and methods to observe should occur at less sclerotic pace
- NSF should/can provide added incentives for Computer Scientists to go "smell" the ocean
- More isn't necessarily better; smarter is — decision-theoretic methods can help
- AI is not ML — there's more to AI than just "data" and "analytics"