AUTONOMY IN ROBOTICS FOR OCEANOGRAPHIC SCIENCE: SUCCESSES, CHALLENGES AND OPPORTUNITIES

Michael V. Jakuba, Woods Hole Oceanographic Inst.

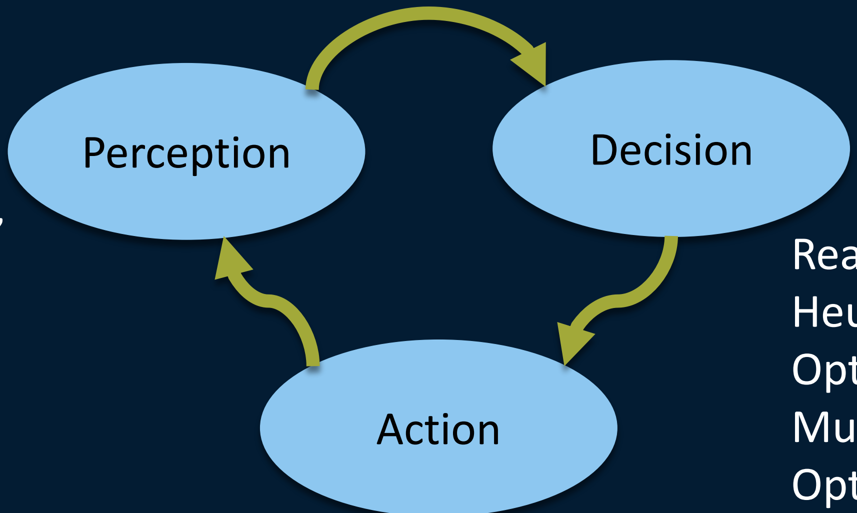
Objectives

- Provide an overview of the state of the art through case studies
- Provide a definition of autonomy and delineate its forms as implemented in practice
- Identify the character of oceanographic science questions that have benefited from autonomy
  - What forms of autonomy are pertinent to illuminating aspects of Carbon Cycle?

Definitions, Biases

- Autonomy

Sense,
Log,
Process,
Cluster,
Classify,
Map,
Predict



Reactive,
Heuristic,
Optimization,
Multi-objective
Optimization

Deployment, Trajectory, Sampling
Parameters, Communicate,
Intervene

- Oceanographic Science: PO, BO, CO, Geology

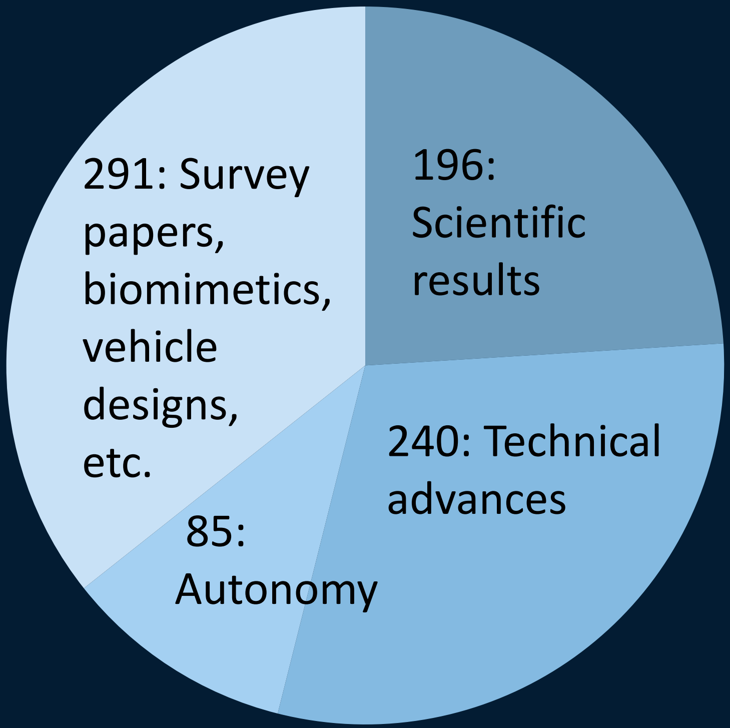
Automatic vs. Autonomous…

- Technical Advances:
  - Vehicle Systems and Reliability
  - Dynamics and Control
  - Behaviors and Mission Primitives
  - Navigation including SLAM
  - Path Planning
  - Fault Detection/Tolerance
  - Multi-Vehicle Formation Control
  - Communication/Compression
  - Instrumentation
- Autonomy:
  - Model-driven adaptive sampling
  - Model-based feature detection/classification
  - On-line learning
  - Semi-supervised learning
  - Deliberative planners

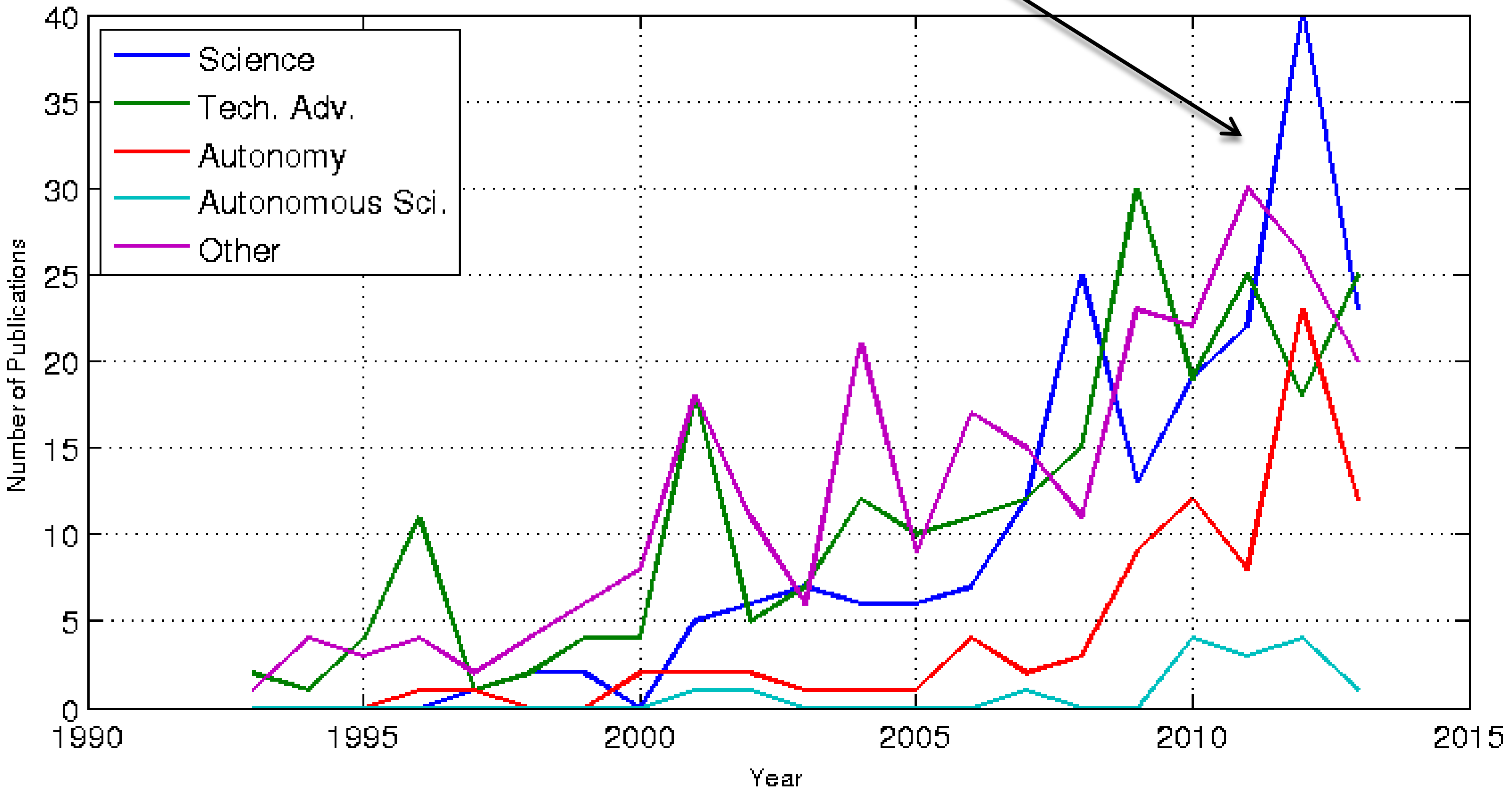
Literature

ISI Web of Knowledge search criteria:
Topic=AUV OR (autonomous AND
    underwater AND vehicle)
Refined by:
Research Domains=(SCIENCE TECHNOLOGY)
AND Research Areas=(OCEANOGRAPHY OR
ROBOTICS OR GEOLOGY…)

717 papers total since 1990



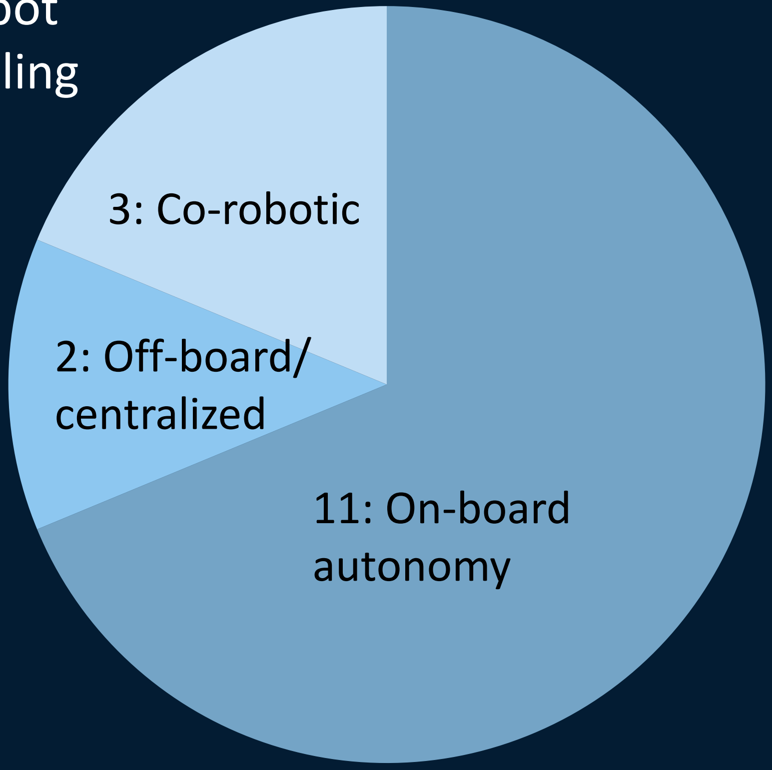
Dull, dirty,
Dangerous



Autonomous Ocean Science

- Deepwater Horizon
- Hotspot sampling

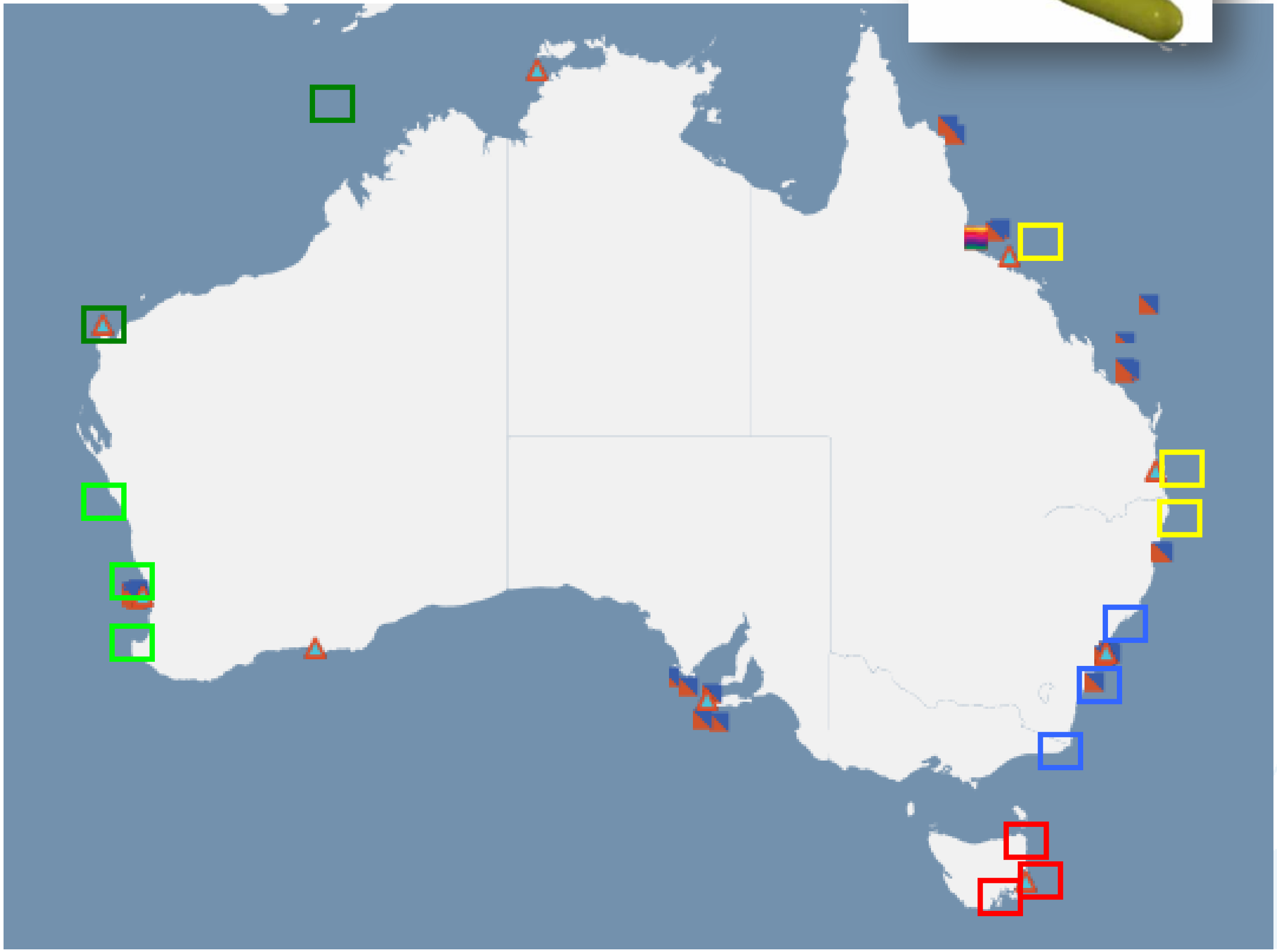
- AOSNs
- Glider fleets



- Plume tracing
- Animal tracking
- Hydrothermal exploration
- DEPTHX
- Triggered sampling (INLs, DWH)
- Thermocline tracking
- Ocean front tracking

Case Study 1: IMOS AUV Facility

IMOS AUV Facility Benthic Reference Sites



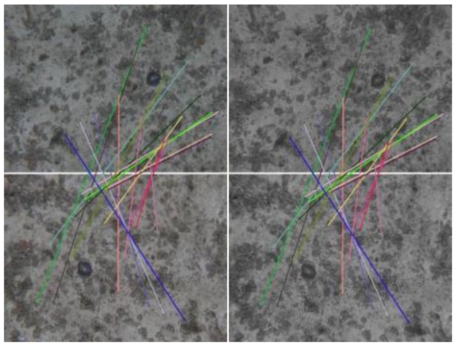
National Reference Stations

Regional Moorings

AUV Benthic Reference Sites

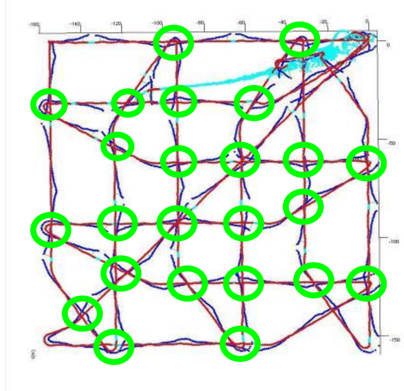
- NSW
- Tasmania
- WA - Temperate
- WA - Tropical
- SE Qld

ACFR Underwater Survey Pipeline

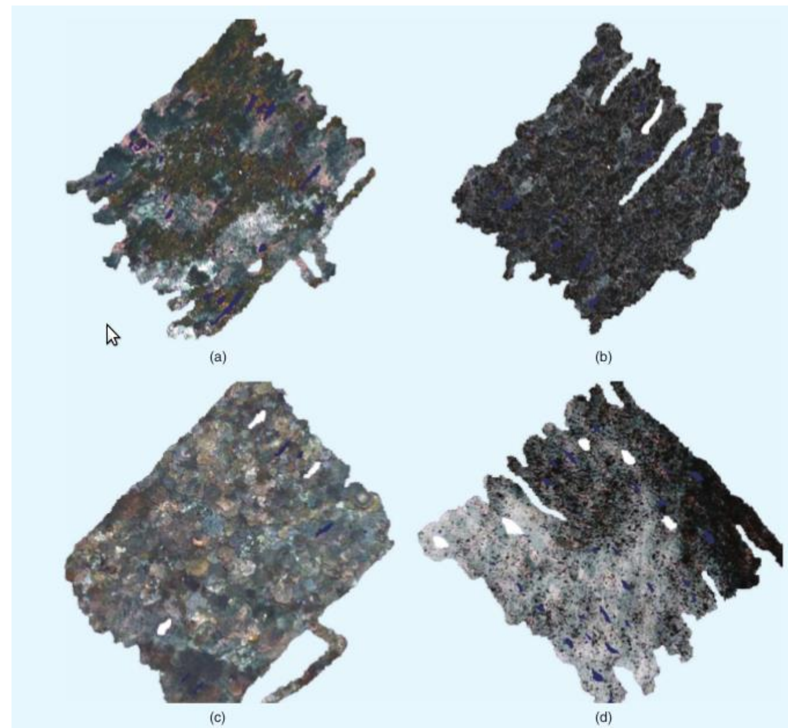


Visual Feature Registration

ACFR
AUSTRALIAN CENTRE
FOR FIELD ROBOTICS



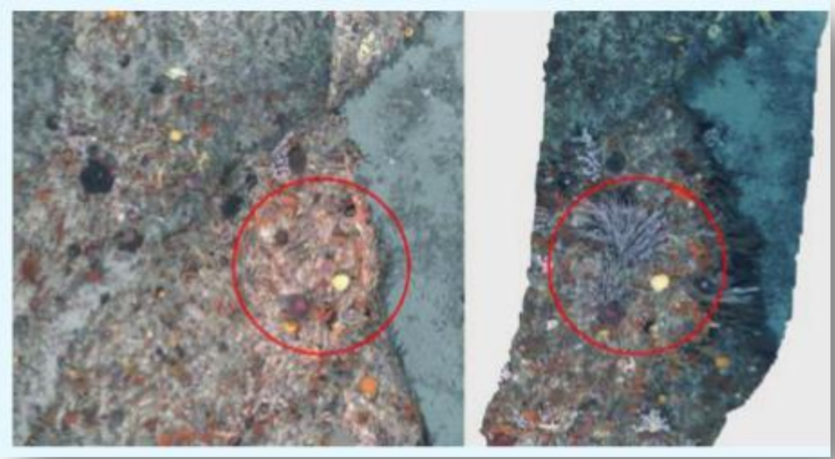
SLAM



Visually consistent 3D reconstruction

S. Williams et al., “Monitoring of benthic reference sites: Using an autonomous underwater vehicle.” IEEE Robotics and Automation Magazine, 19(1):73–84, 2012.

Resolving Benthic Change



S. Williams et al., "Monitoring of benthic reference sites: Using an autonomous underwater vehicle." IEEE Robotics and Automation Magazine, 19(1):73–84, 2012.

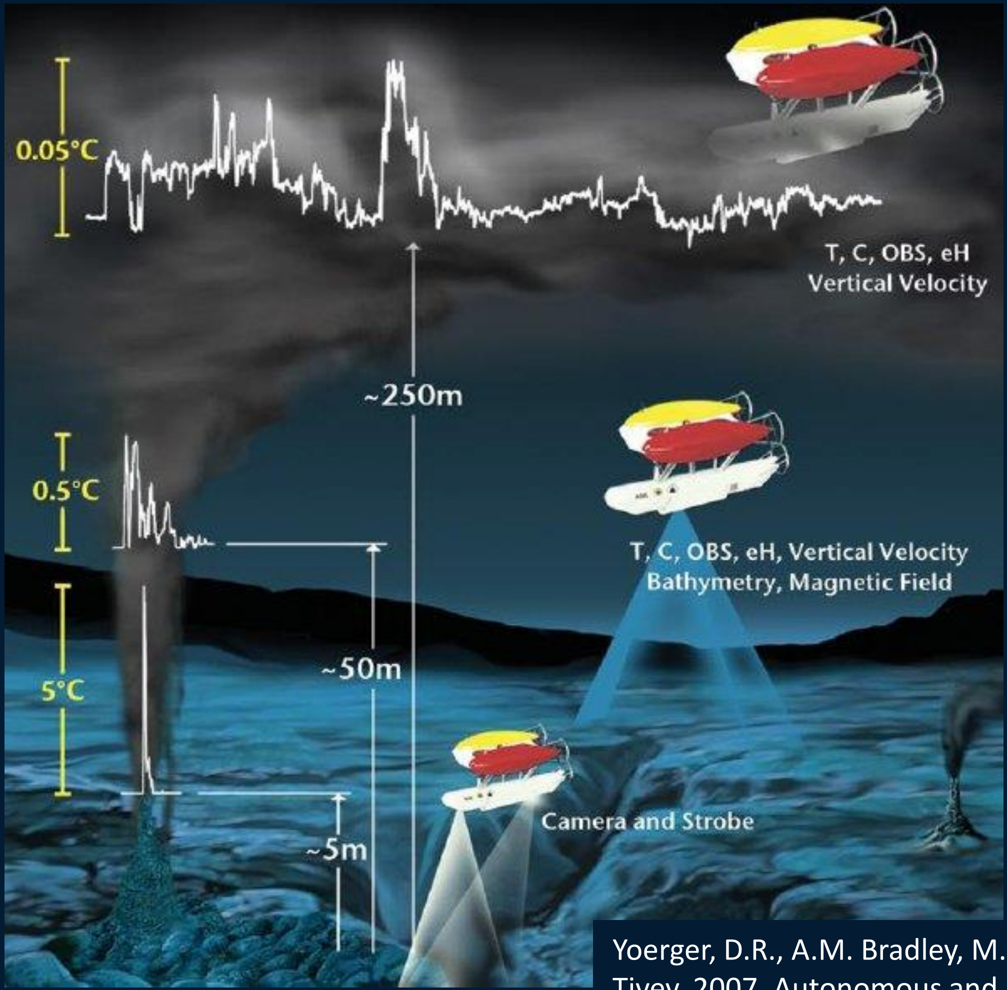
ACFR
AUSTRALIAN CENTRE FOR FIELD ROBOTICS

D. A. Smale et al., "Regional-scale benthic monitoring for Ecosystem-Based Fisheries Management (EBFM) using Autonomous Underwater Vehicle (AUV) technology. ICES Journal of Marine Science, 2012,

Case Study 1: Conclusions

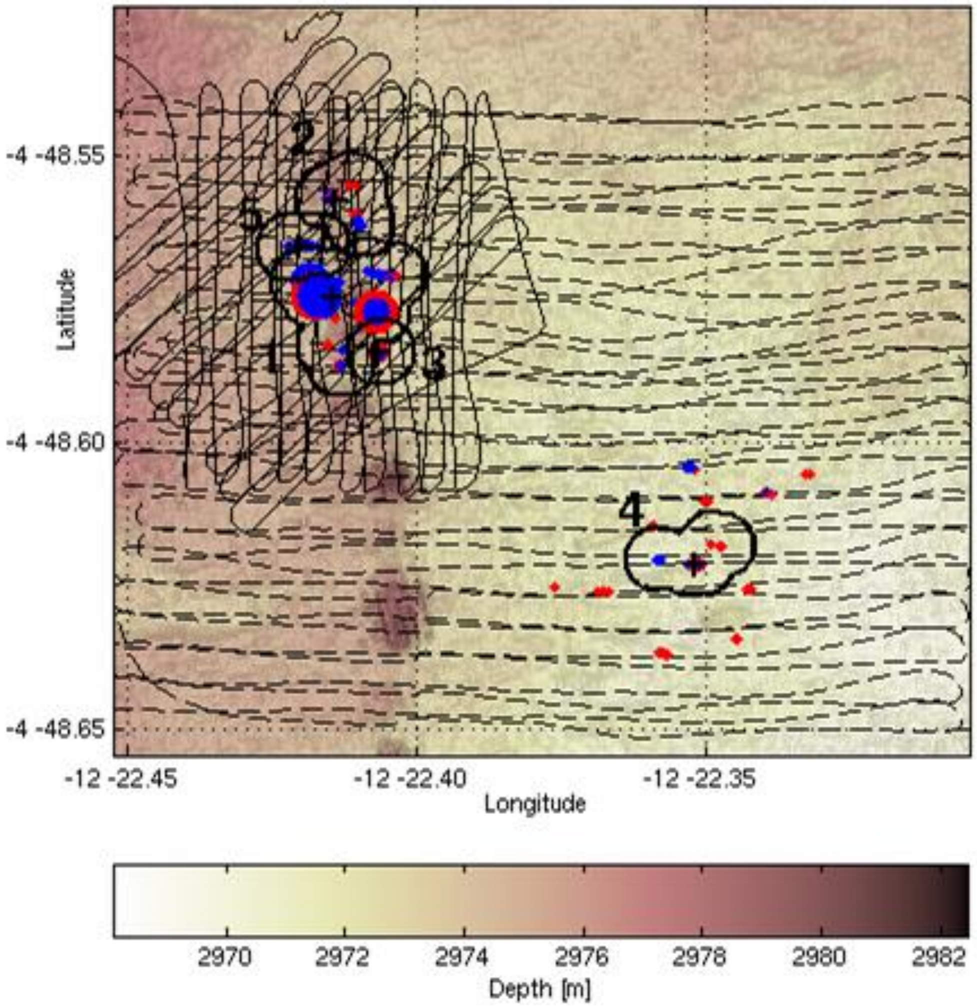
- Statistical power of data comes from precise re-visitation and/or high-resolution.   Little need for real-time perceptual autonomy
- Challenges:
  - Data volume demands automated processing into semantic meaning
- Opportunities:
  - Knowledge discovery

Case Study 2: Geophysical Plume Studies with AUVs ABE and Sentry



- Opportunity
  - Synopticity, lower cost, reduced operating constraints
  - Increased scientific yield from data-driven surveys
- Challenges:
  - Identifying feature of interest in sensor data
  - Responding appropriately to contact with feature
  - Data integrity and sensor failure
  - Risk-aversion in expeditionary science

Yoerger, D.R., A.M. Bradley, M. Jakuba, C.R. German, T. Shank, and M. Tivey. 2007. Autonomous and remotely operated vehicle technology for hydrothermal vent discovery, exploration, and sampling. *Oceanography* 20(1):152–161

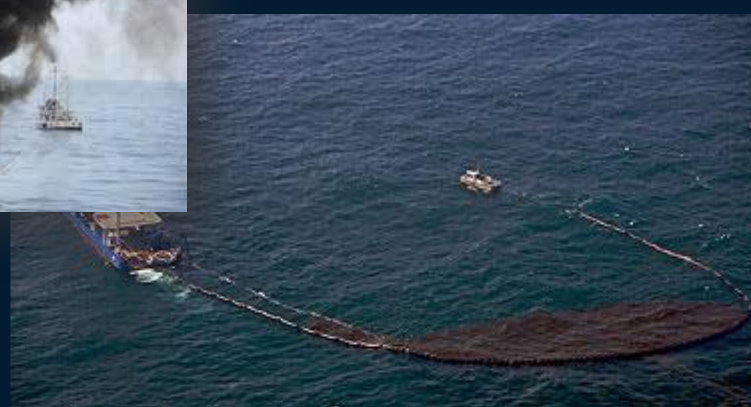


- A modest early success:
  - On-board autonomy revisits “best” sites
  - Guaranteed minimum data set
  - Appropriate when feature signature is qualitatively known

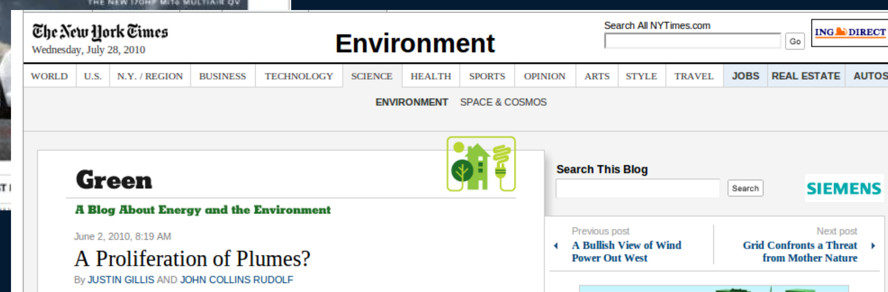
Yoerger, Dana R., et al. "Techniques for deep sea near bottom survey using an autonomous underwater vehicle." *The International Journal of Robotics Research* 26:1 (2007): 41-54.

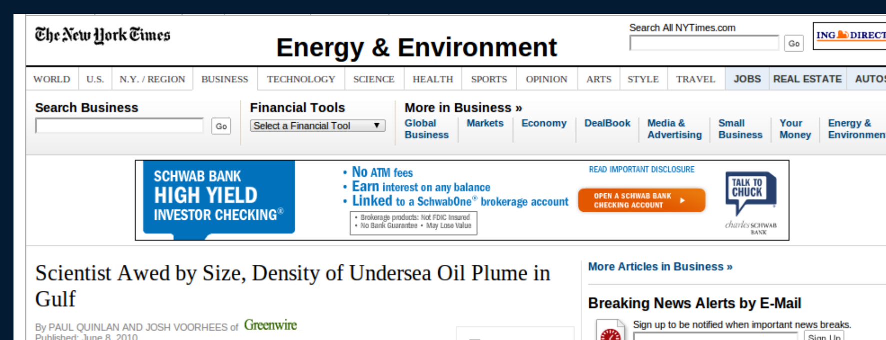
Rapid Event Response: DWH

- Additional challenges:
  - Unknown signature
  - Limited development time
- Modern acoustic communication permits a co-robotic approach



Subsurface Hydrocarbon Plumes?





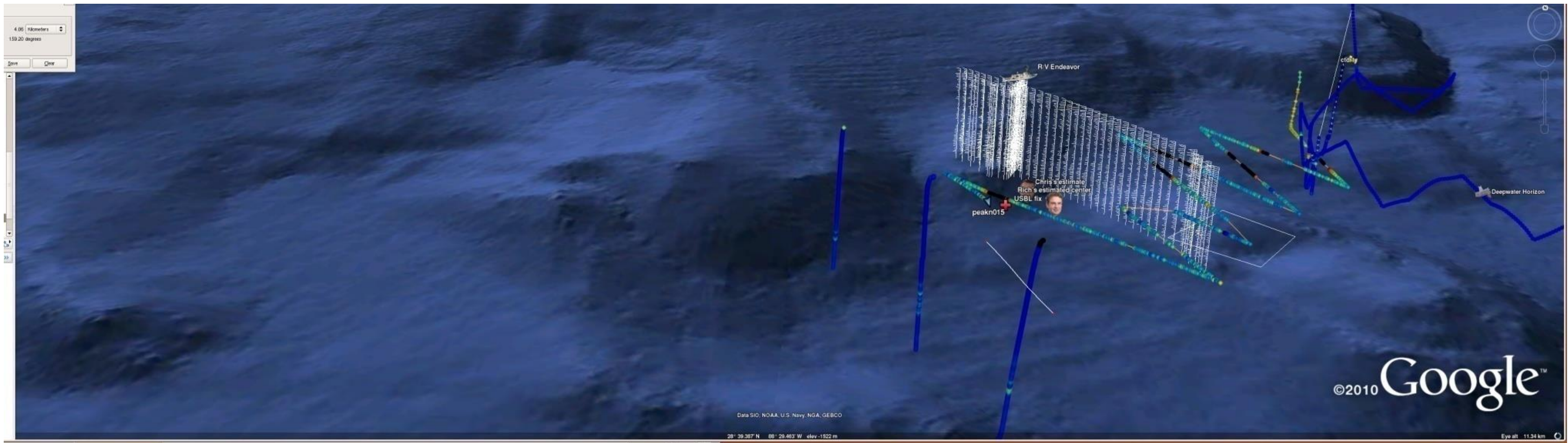
Subsea Assets

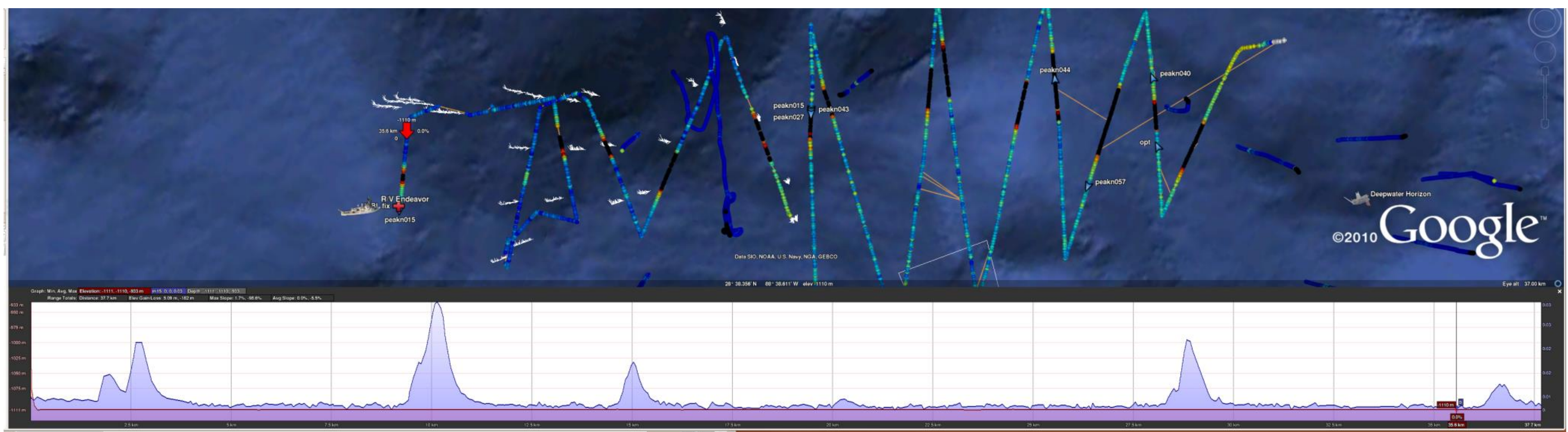
AUV Sentry

Cabled CTD and
Water Sampler

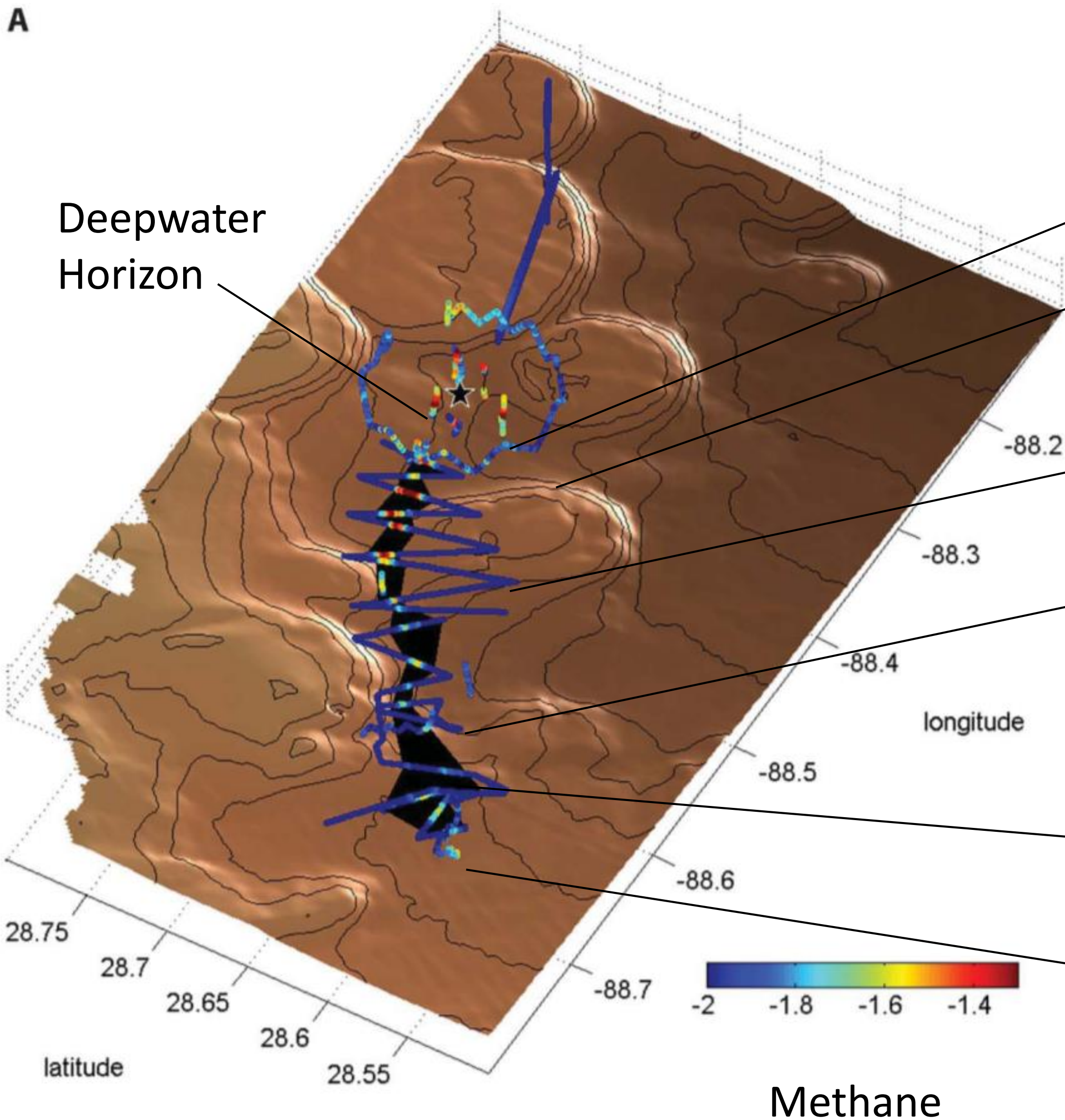
TETHYS Mass Spectrometer

Real-time Visualization





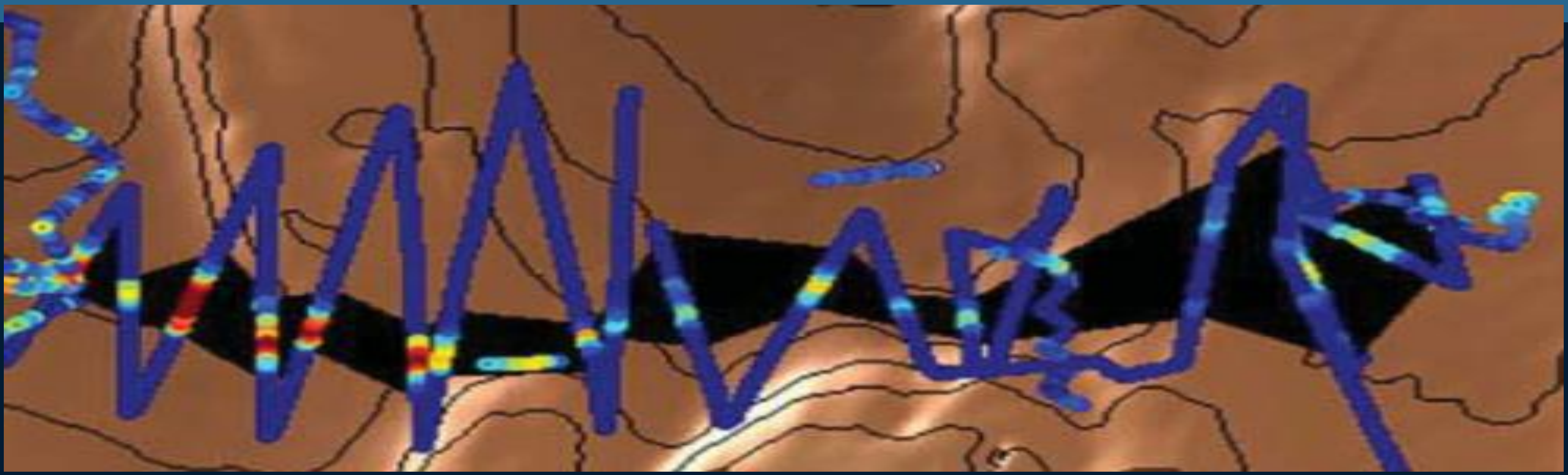
Plume mapped to 35 km From Site

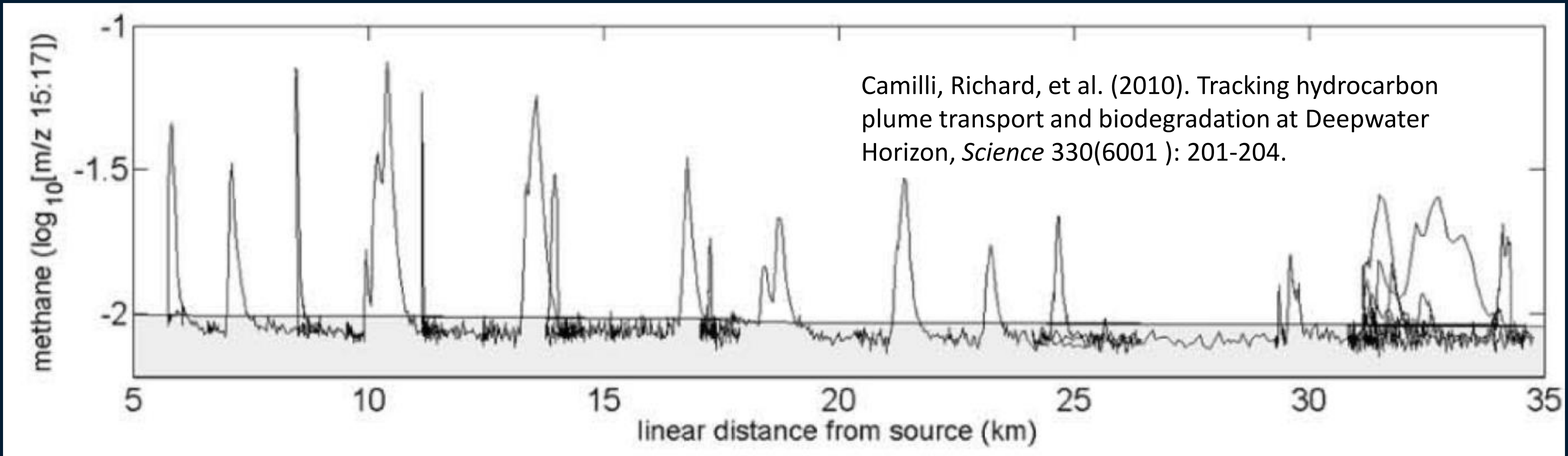


- Vertical casts confirm existence of deep plume
- Circular CTD "Tow-yo" around site perimeter finds strongest methane anomalies to southwest
- Sentry AUV dive 064 maps plume 15 km downstream using preplanned mission
- Sentry AUV dive 065 maps plume further 5 km downstream before losing contact on the basis of acoustically telemetered methane readings
- Operators acoustically retask vehicle until contact is reestablished
- Sentry AUV tracks plume 8 km further downstream

Camilli, Richard, et al. (2010). Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon, *Science* 330(6001): 201-204.

Threshold-Based Detection





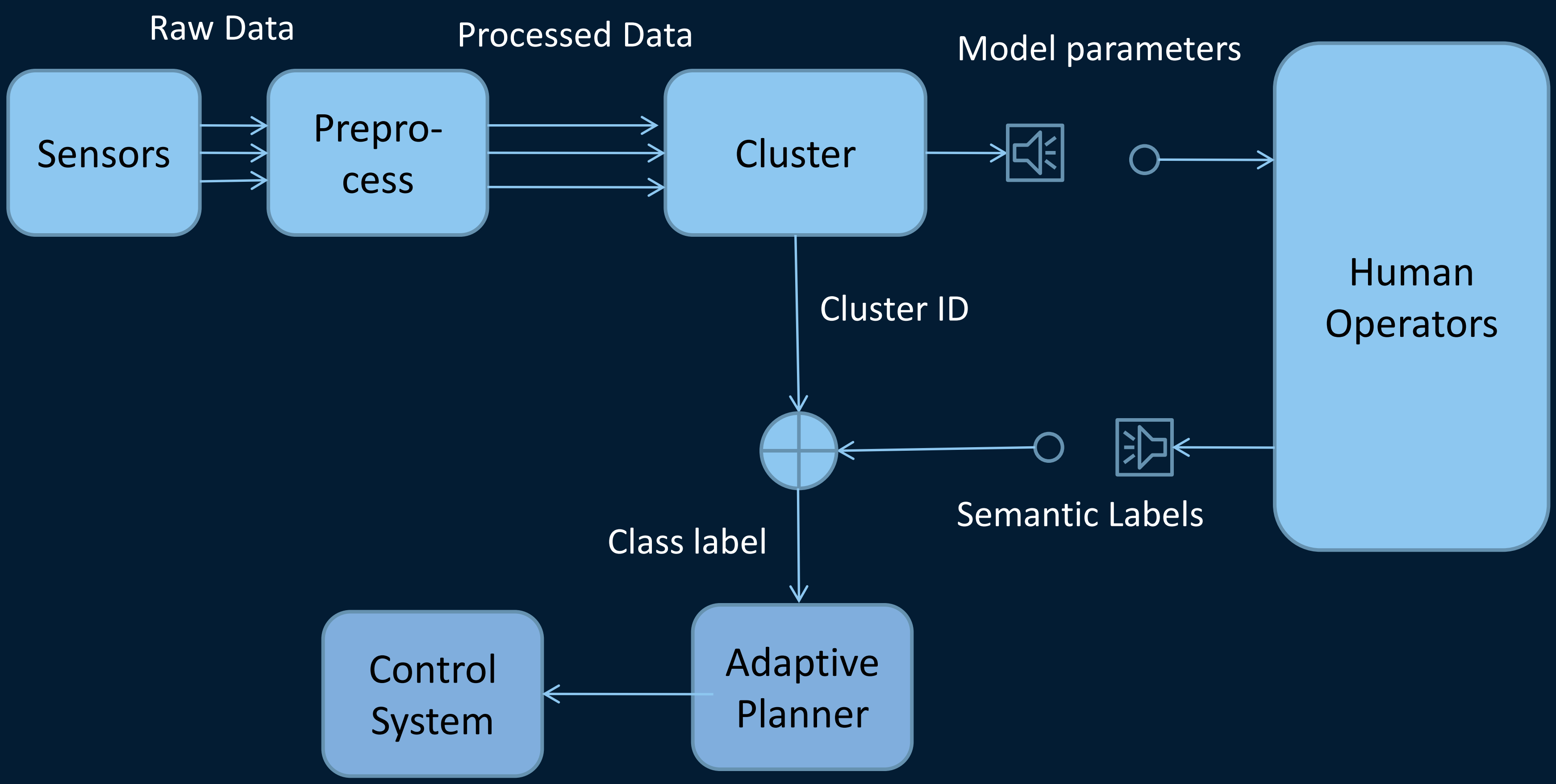
Camilli, Richard, et al. (2010). Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon, *Science* 330(6001): 201-204.

Chemical Sensors Aboard *Sentry*

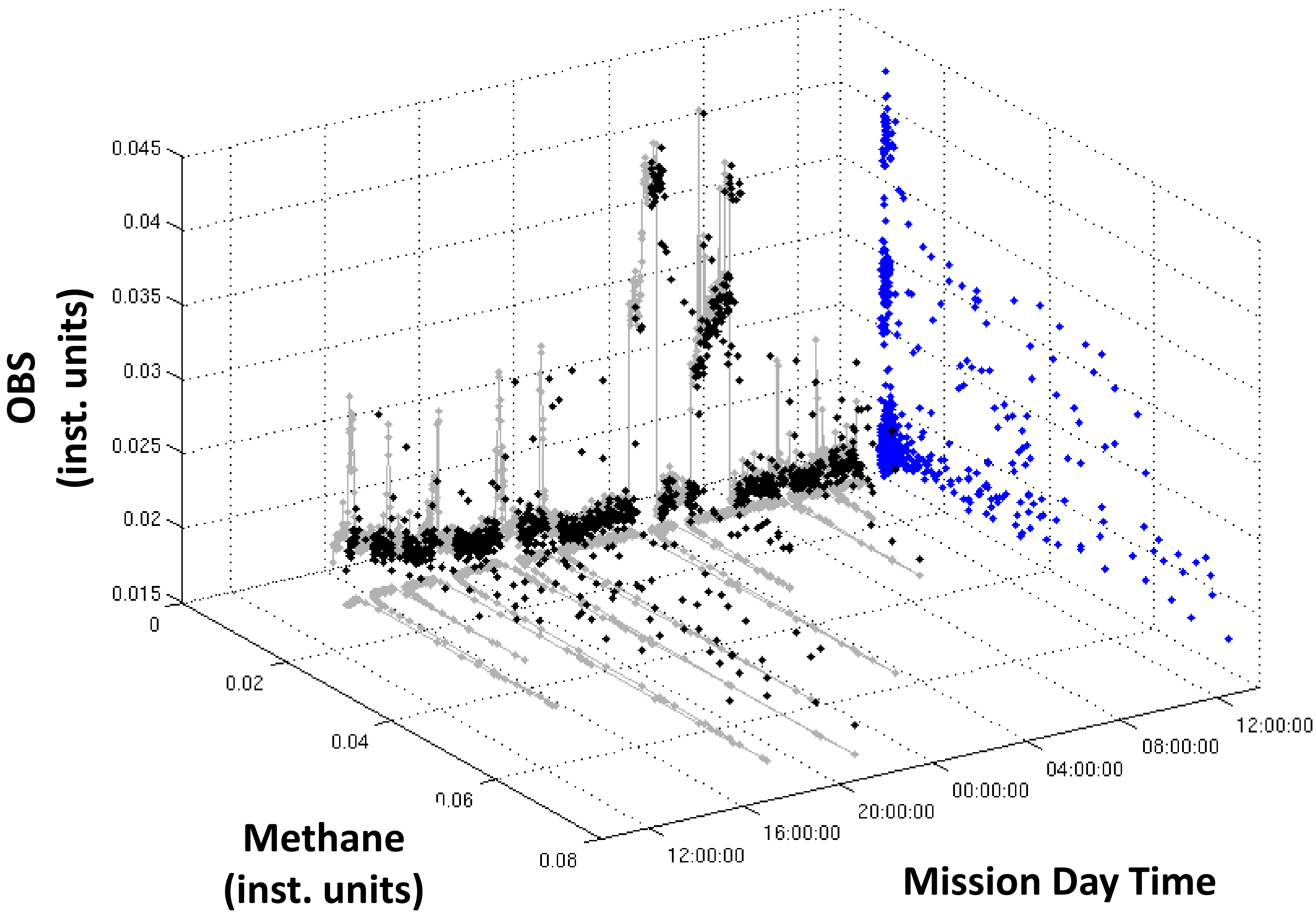
Measurement	Sensor	Normalization
Methane (Methyl ion, m/z 15)	TETHYS	water vapour
Water vapour ion (m/z 17)	TETHYS	Argon
C_{2+} (m/z 27)	TETHYS	water vapour
Oxygen (m/z 32)	TETHYS	Carbon Dioxide
Argon (m/z 40)	TETHYS	water vapour
C_{3+} (m/z 43)	TETHYS	water vapour
Carbon Dioxide (m/z 44)	TETHYS	water vapour
C_{4+} (m/z 57)	TETHYS	water vapour
benzene (m/z 78)	TETHYS	water vapour
naphthalene (m/z 128)	TETHYS	water vapour
Potential Temp. (1)	SeaBird Electronics SBE49 CTD	background profile (CTD)
Salinity (1)	SeaBird Electronics SBE49 CTD	background profile (CTD)
Oxygen Concentration	AAnderaa Optode	None
Optical Backscatter (OBS)	Seapoint Turbidity	None
Potential Temp. (2)	Neil Brown Ocean Sensors, Inc. GCTD	background profile (CTD)
Salinity (2)	Neil Brown Ocean Sensors, Inc. GCTD	background profile (CTD)

- Opportunity: Co-robotic feature detection

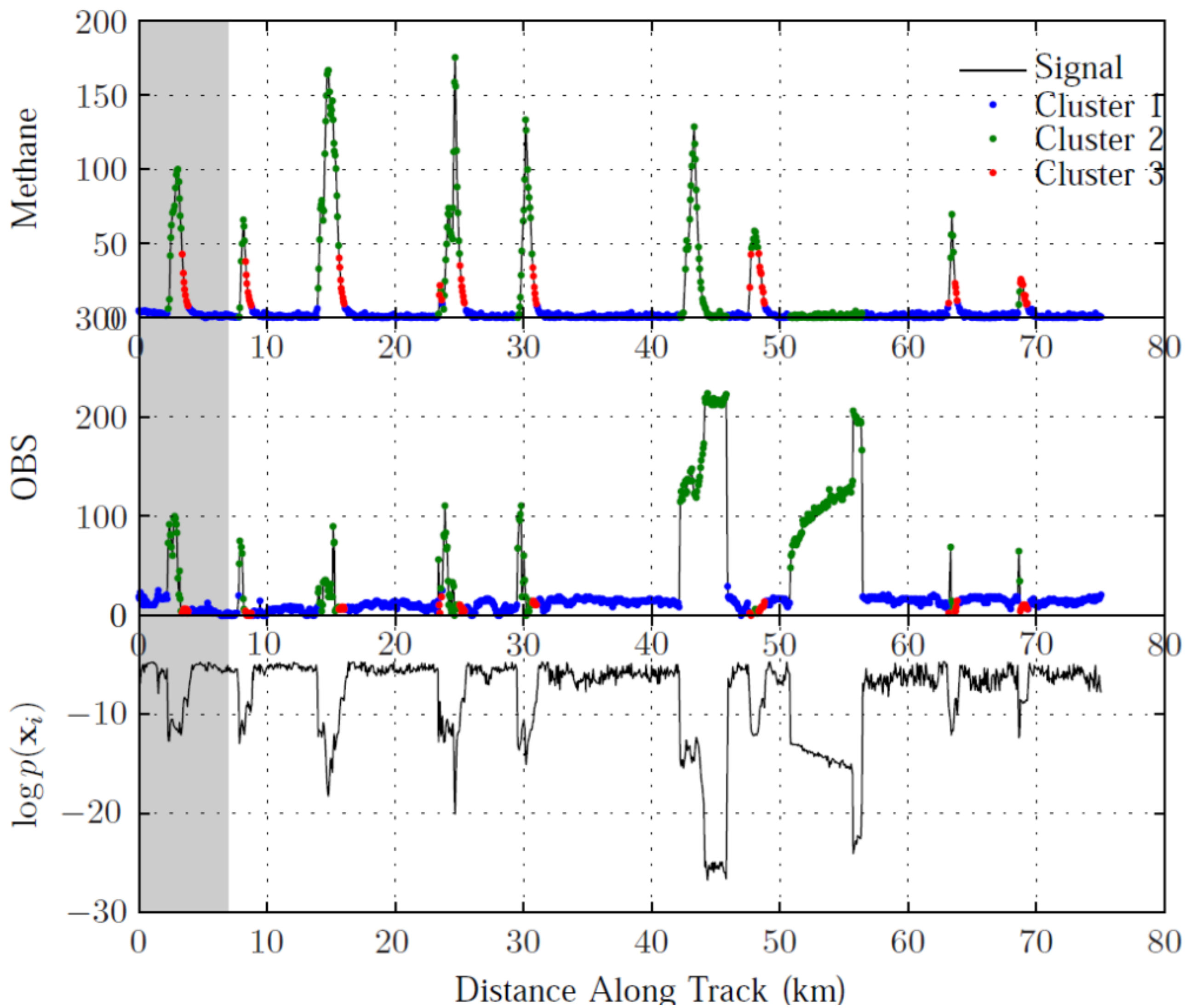
Co-Robotic Adaptive Plume Survey



Methane and OBS, Sentry 064

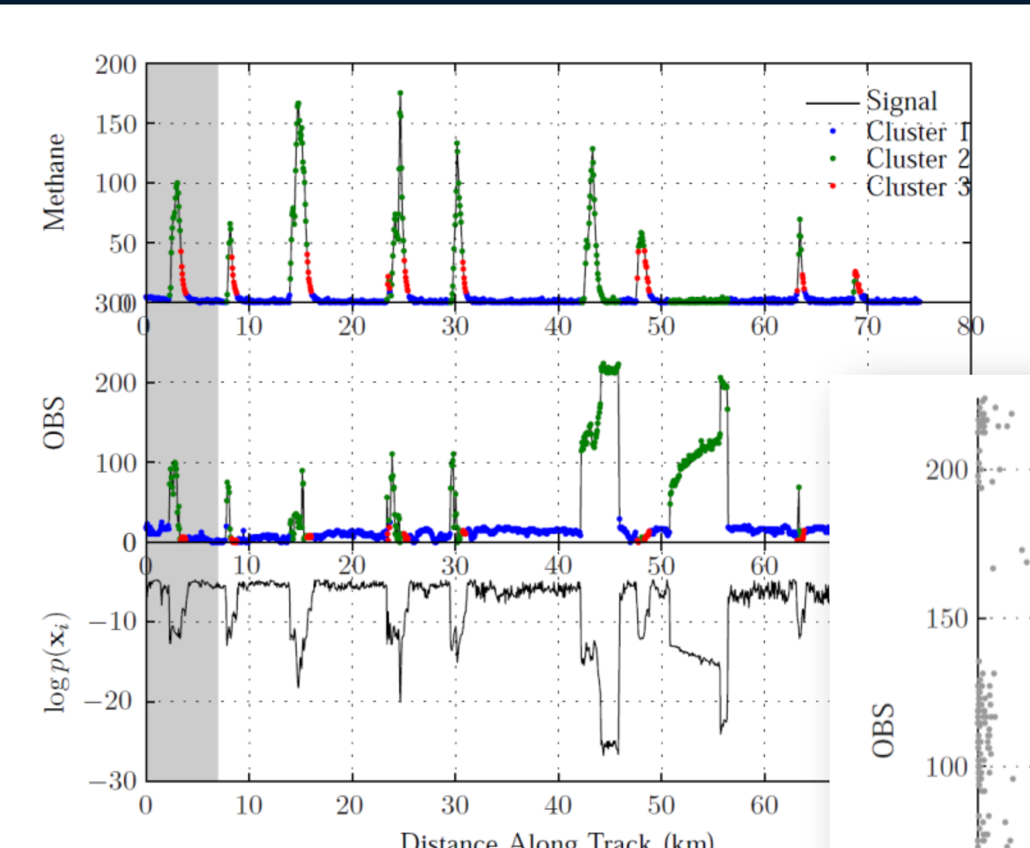


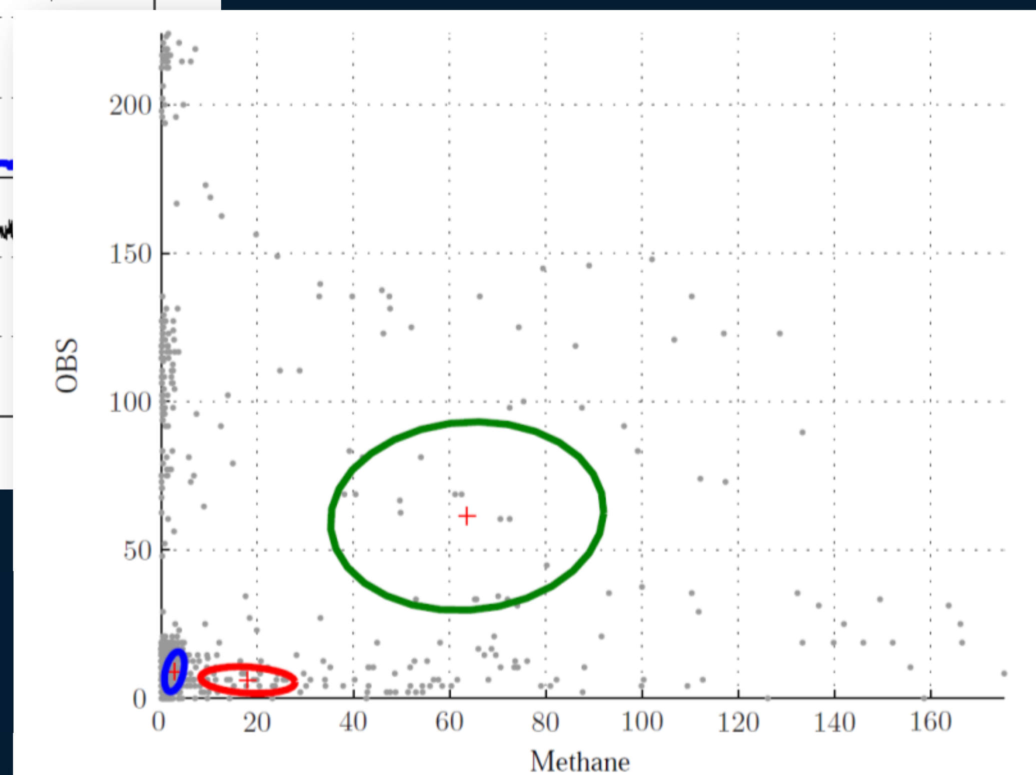
VDP Learned from 8 km of Dive



Jakuba, Michael V., et al. "Toward automatic classification of chemical sensor data from autonomous underwater vehicles." Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. IEEE, 2011.

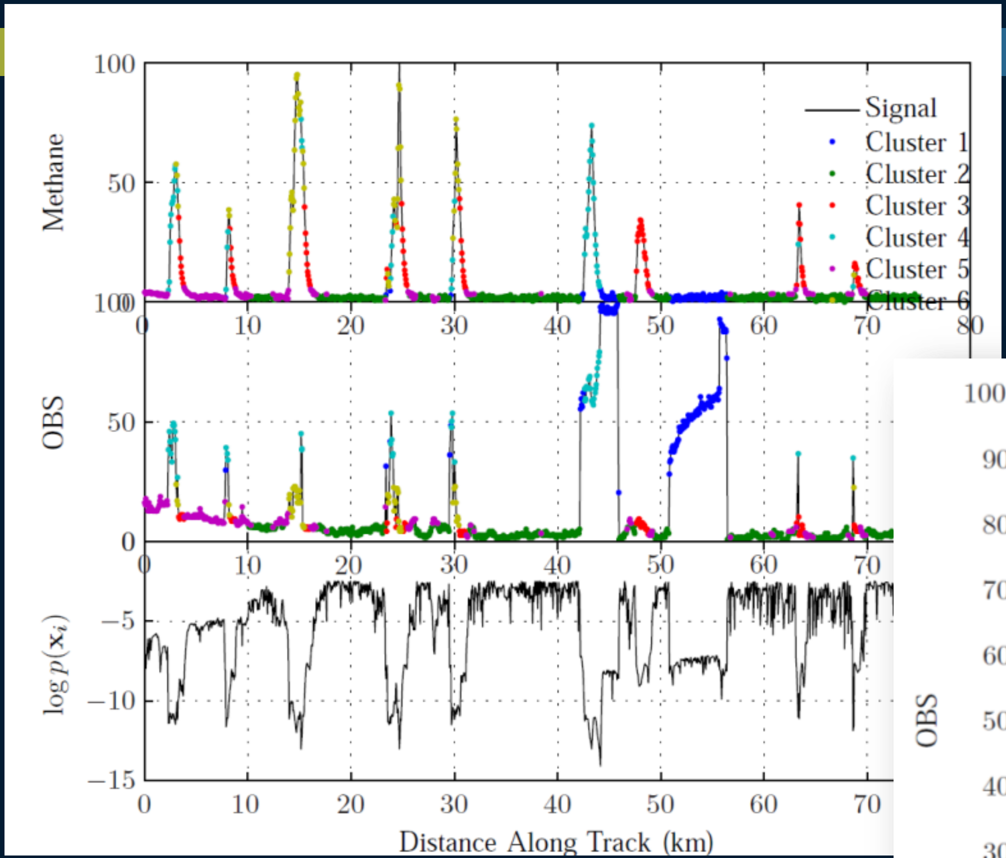
VDP Learned from 8 km of Dive

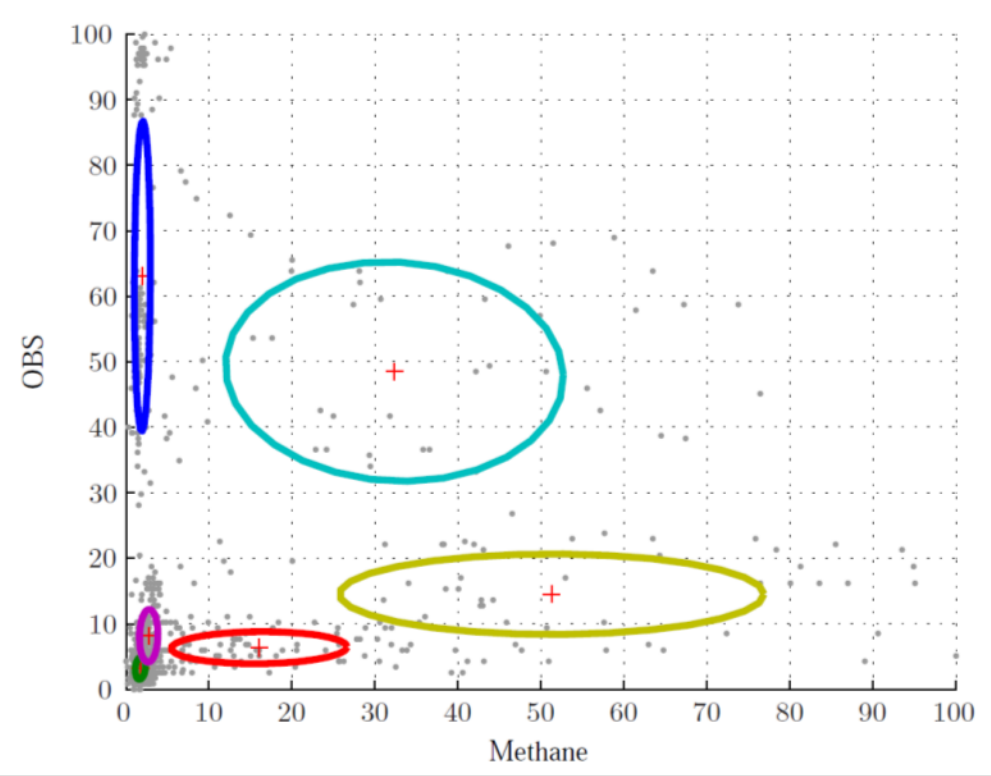




Jakuba, Michael V., et al. "Toward automatic classification of chemical sensor data from autonomous underwater vehicles." Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. IEEE, 2011.

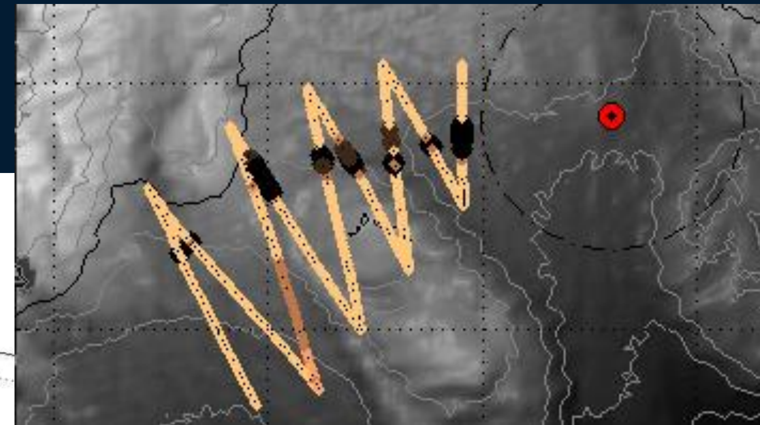
VDP Learned from Complete Dive

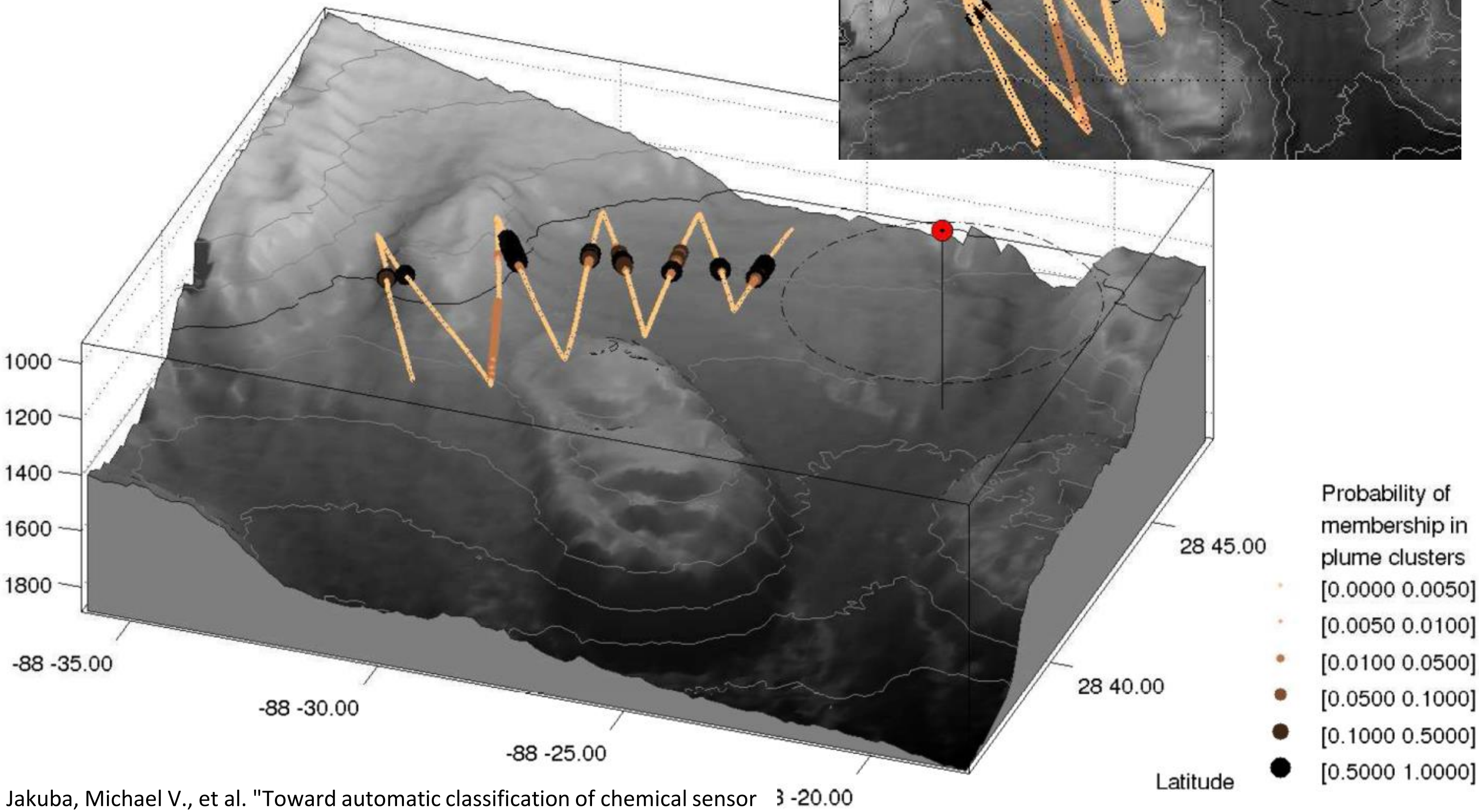




Jakuba, Michael V., et al. "Toward automatic classification of chemical sensor data from autonomous underwater vehicles." Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. IEEE, 2011.

Plume Map





Jakuba, Michael V., et al. "Toward automatic classification of chemical sensor data from autonomous underwater vehicles." Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. IEEE, 2011.

Case Study 2: Conclusions

- Autonomy introduces risk into expeditionary science
- Co-robotics reduces the need for precise descriptions of features or training data
  - Communication and visualization are critical enablers
  - Machine learning methods can yield the dimensionality reduction necessary to use limited communications channels effectively

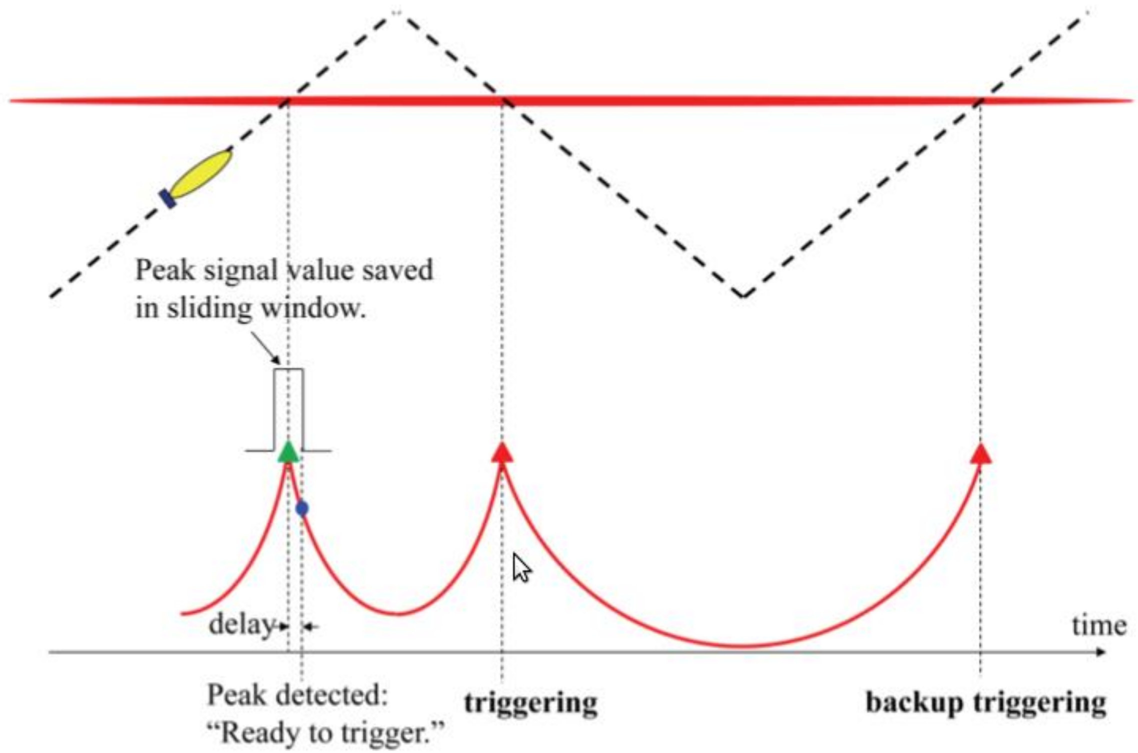
Case Study 3: Ephemeral/Localized Oceanographic Features

- Notable Successes using Autonomy:
  - Ocean Fronts
  - Intermediate Nepheloid Layers/biological hot-spots (patchy phenomena)
- Challenges:
  - Feature description and detection
  - Acquiring the “best” samples
  - High-level goal specification and flexible mission planning

MBARI Gulpers

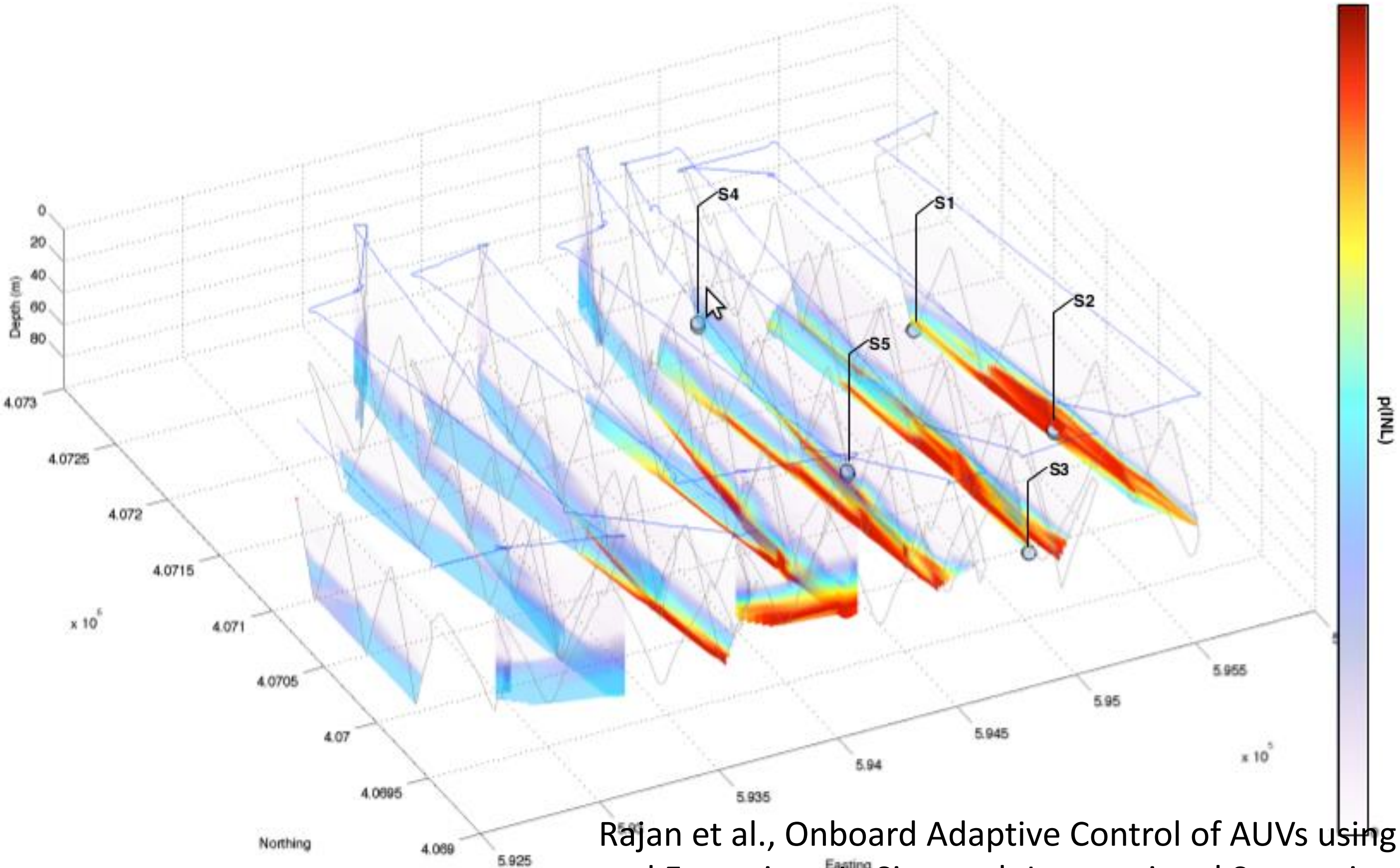
mbari.org

Local Threshold Determination



Zhang, Yanwu, et al. "Autonomous detection and sampling of water types and fronts in a coastal upwelling system by an autonomous underwater vehicle." Limnology and Oceanography: Methods 10 (2012): 934-951.

Flexible Mission Execution

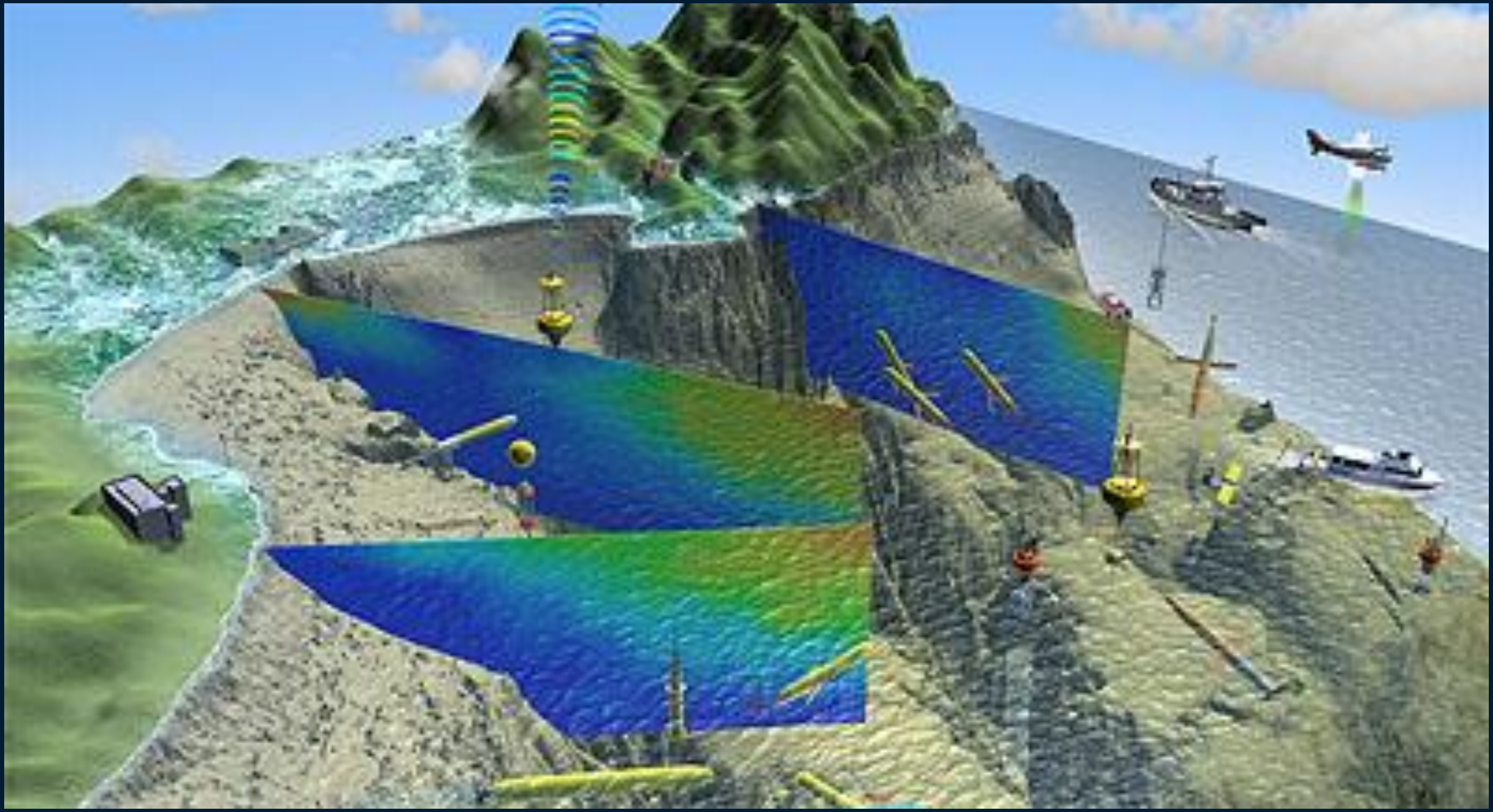


Rajan et al., Onboard Adaptive Control of AUVs using Automated Planning and Execution. In Sixteenth International Symposium on Unmanned Untethered Submersible Technology (UUST09), Durham, NH, Aug. 2009.

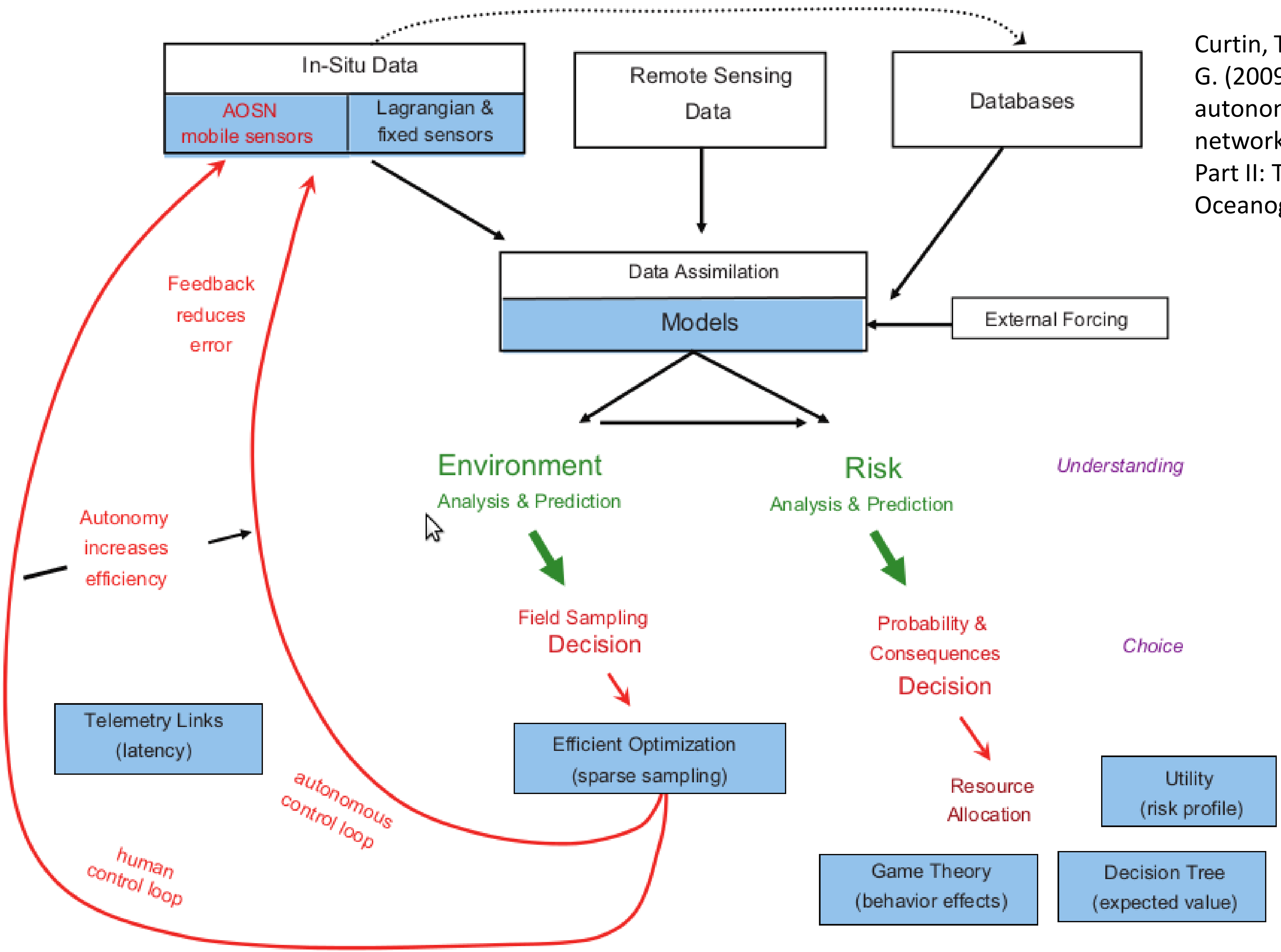
Case Study 3: Conclusions

- Ephemeral or localized features require on-board autonomy
- Good results require good feature descriptors
  - Intuition
  - Detailed knowledge
  - Training from classified data
- Triggering/adaptation implies tradeoffs – frameworks are nascent in the AUV community

Briefly: AOSN



mbari.org



Curtin, T. B., & Bellingham, J. G. (2009). Progress toward autonomous ocean sampling networks. Deep Sea Research Part II: Topical Studies in Oceanography, 56(3), 62-67.

AOSN: Conclusions

- Off-board/Centralized autonomy
  - Computationally intensive GCM-driven sampling
  - Greatest benefits derived from placing slow -moving assets advantageously relative to features of interest
- On-board and co-robotic autonomy increasingly valuable and viable
  - To allow for higher-level goal specification, reduced decision-making burden
  - To incorporate studies of sub-resolution phenomena in context
- Extension to global scales?

Application Space

- On-board Autonomy:
  - Triggered sampling of ephemeral features
  - Extremely small spatial scales or fast temporal scales
- Off-board/Centralized Autonomy:
  - Computational limitations of mobile platforms
  - Multiple scales, many mobile assets, integration with remote sensing
  - Multiple objectives, large, distributed research teams
- Co-robotics:
  - Exploration; evolving mission objectives
  - Poorly characterized features of interest
  - Rapid response

Conclusions (and a Question)

- AUVs are routinely delivering new oceanographic science. The technology is mature.
- Autonomy is beginning to deliver new oceanographic science results in certain applications
- Do the big uncertainties concerning the Carbon Cycle share the characteristics of these applications?