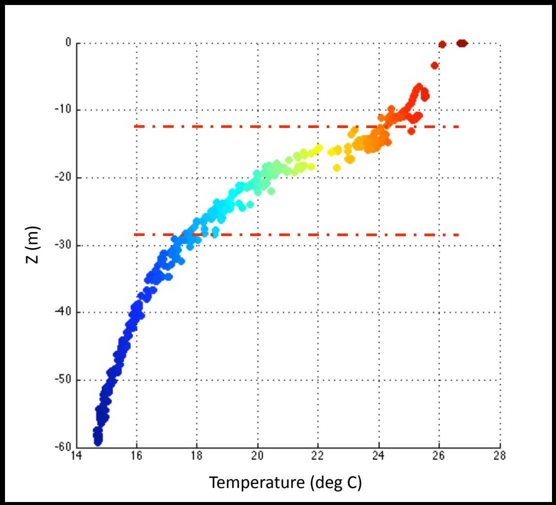
Adaptive Oceanographic Feature Tracking On Board Autonomous Underwater Vehicles

- Tracking the Thermocline -



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Advisor: Henrik Schmidt

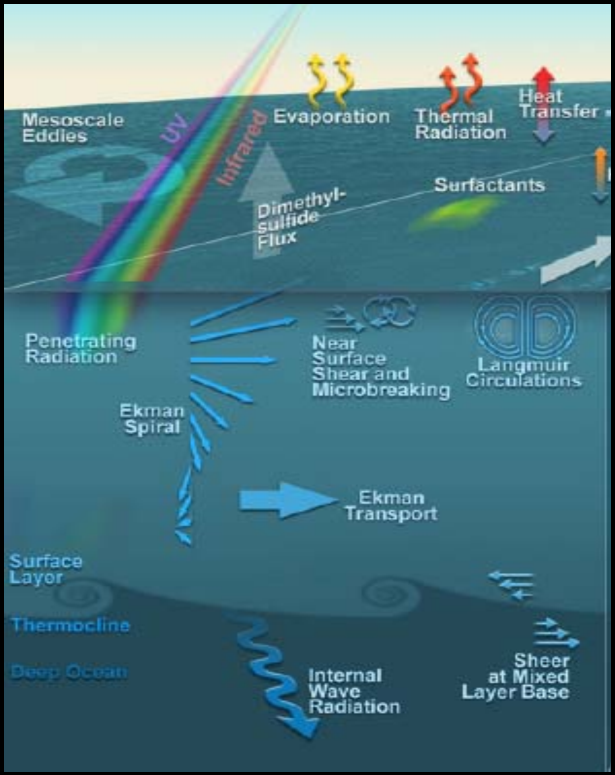
Qualifying Examination Thesis Presentation
27 January, 2010

Overview

- Background & Motivation
- Autonomous Adaptive Sampling
  - Problem Definition
  - Theory & Algorithm
  - Implementation on AUVs
    - pEnvtGrad
- Field Experiments & Results
- Conclusions
- Future Work

Background & Motivation: *The Missing Piece*

- Incorporate real-time instrumental (e.g., CTD) data into adaptive sampling behaviors on board AUVs
  - Track oceanographic features
    - Thermoclines, haloclines, pycnoclines
    - Sound speed
    - O_2 & Cl concentrations, fluorescence
    - Light attenuation
    - Fronts
    - Currents

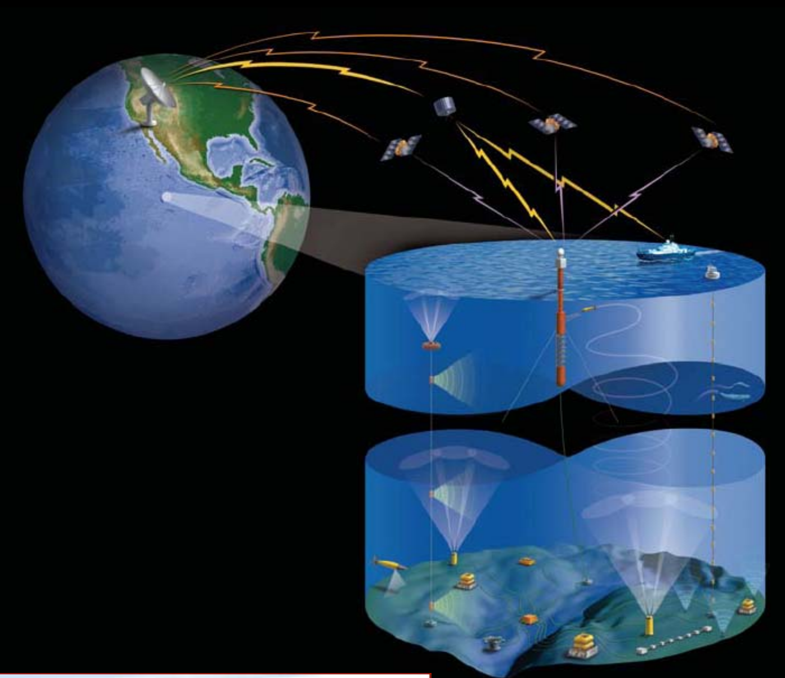


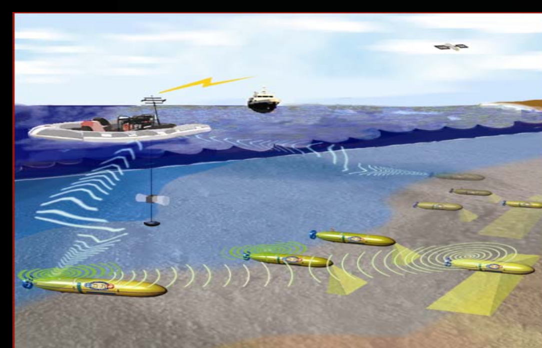
Oceanographic Features[1]

[1]John Delaney (concept) www.ooi.washington.edu/story/Oceans+and+Life

Background & Motivation: *OOI*

- Ocean Observatories Initiative (OOI)
  - Continuous ocean presence
  - Make oceanographic data more readily accessible to scientists
  - Ease of collection
    - Automate data collection in the ocean using a variety of AUVs
  - Minimization of costs





OOI Ocean Network[1]

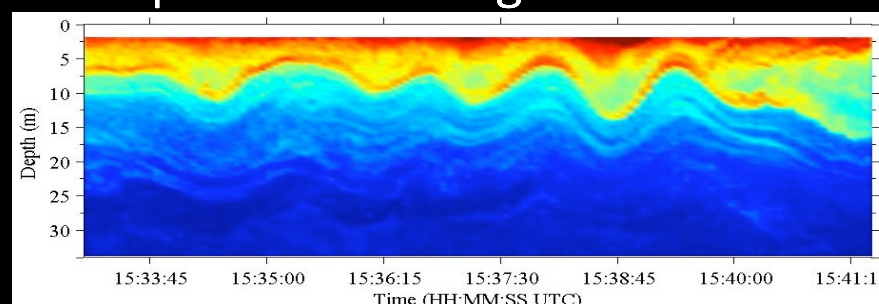
[1]OOICI Development Team

Background & Motivation: *Thermocline Tracking*

- Example and proof-of-concept
- Most AUVs are equipped with a CT or CTD sensor

CTD[1]

- Similar to the underwater sound speed profile
  - Acoustic communications
    - Placement of AUV in water column to optimize acoustic communications
- Biology
  - Phytoplankton, plankton and plankton-eating fish in thermocline
- Physical Oceanography
  - Surface mixing
  - Internal waves

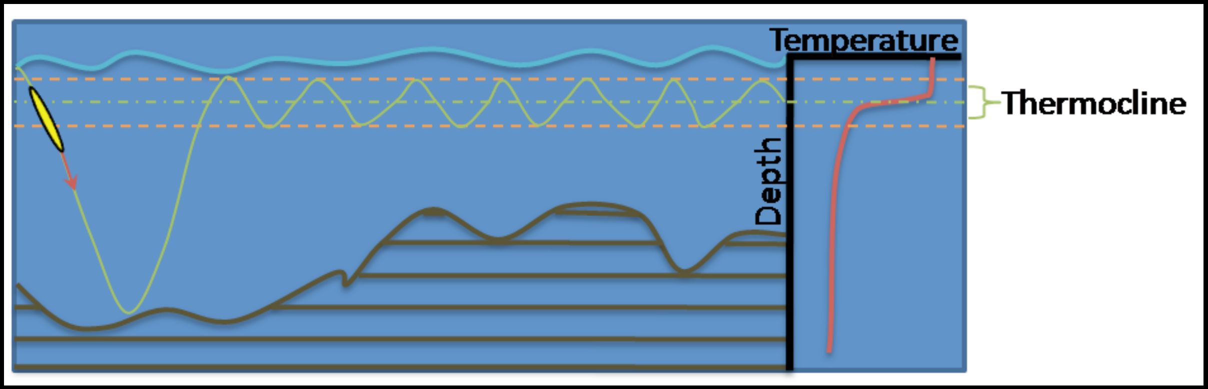


Internal Waves[2]

[1]www.seabird.com
[2]myweb.dal.ca/kelley/SLEIWEX

Autonomous Adaptive Sampling: *Problem Definition*

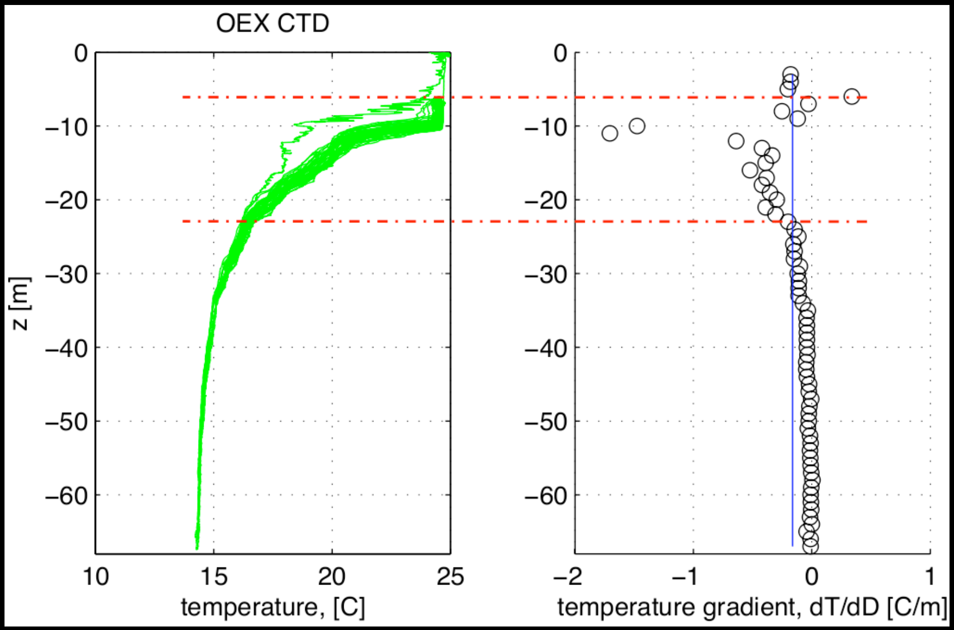
- Vehicle moving through the water column in time and space
- Where is the thermocline?
  - Based on *just* the environmental information the AUV collects and processes *on board*
- Completely autonomous
- Quantitatively define thermocline



Thermocline tracking by adapting yoyo motion.

Autonomous Adaptive Sampling: *Thermocline Definition*

- Qualitative
  - "the region in a thermally stratified body of water which separates warmer surface water from cold deep water and in which temperature decreases rapidly with depth" [www.merriam-webster.com]
- Quantitative
  - The depth range over which the vertical derivative of temperature, dT/dz, exceeds a threshold value



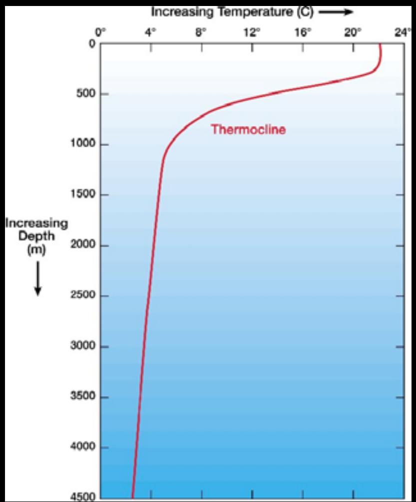
Thermocline region between dotted lines

Autonomous Adaptive Sampling: *Algorithm*

In theory…

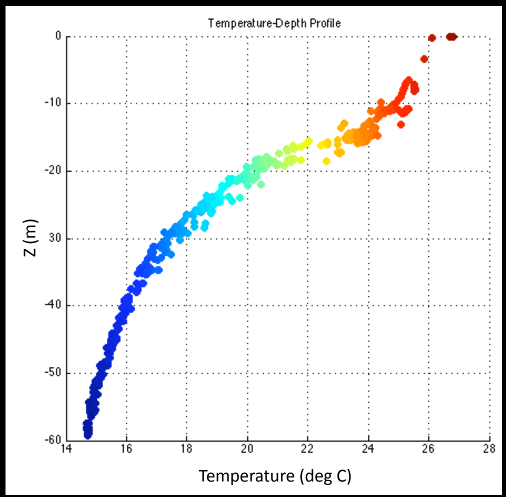
- Ideal temperature profile at some (Lat, Lon)

- T = temperature [°C]
- z = depth [m, +↑]
- H = water depth [m]



Ideal Profile

≈



Data Profile

Autonomous Adaptive Sampling: *Algorithm, cont.*

- Calculate slope of the temperature curve at each point in depth (z')

$$\left.\frac{\partial T}{\partial z}\right|_{z'}$$

- Average the vertical derivatives over the span of the water column
  - Threshold value

$$\left(\frac{\partial T}{\partial z}\right)_{tot\_avg} = \frac{1}{H}\int_{z'=0}^{-H}\left.\frac{\partial T}{\partial z}\right|_{z'} dz'$$

Autonomous Adaptive Sampling: *Algorithm, cont.*

- Determine upper and lower depth limits of the thermocline

$$\text{if : } \left| \left. \frac{\partial T}{\partial z} \right|_{z'} \right| \geq \left| \left(\frac{\partial T}{\partial z} \right)_{tot\_avg} \right|$$

$$\text{then : } z' \text{ is within the thermocline } (z_{in\_thermocline})$$

$$upper\_thermocline\_depth \equiv -\max(z_{in\_thermocline})$$

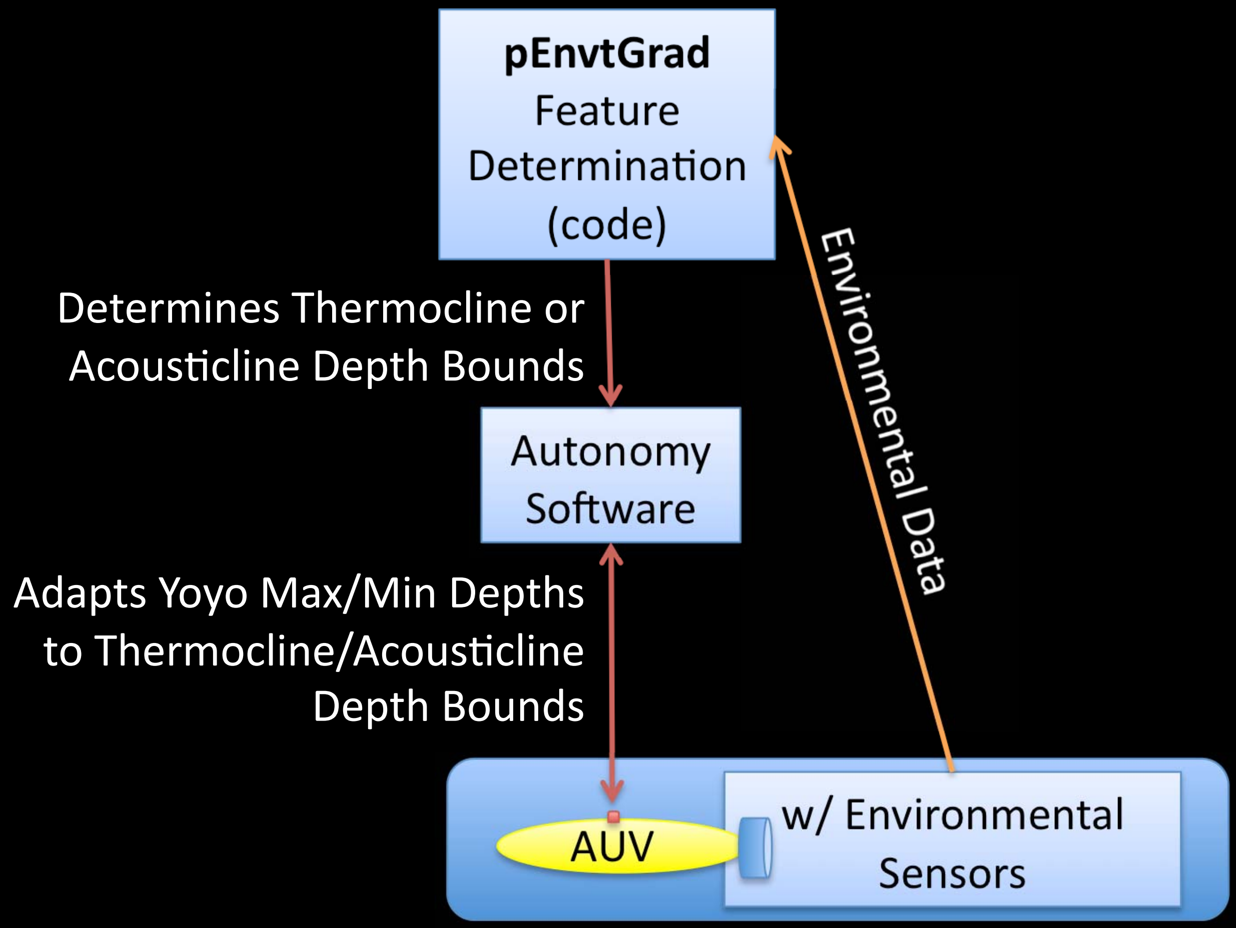
$$lower\_thermocline\_depth \equiv -\min(z_{in\_thermocline})$$

- An analogous determination could be done for the region of maximum sound speed variation over depth, ‘acousticline’ (or halocline or pycnocline)

Autonomous Adaptive Sampling: *Implementation*

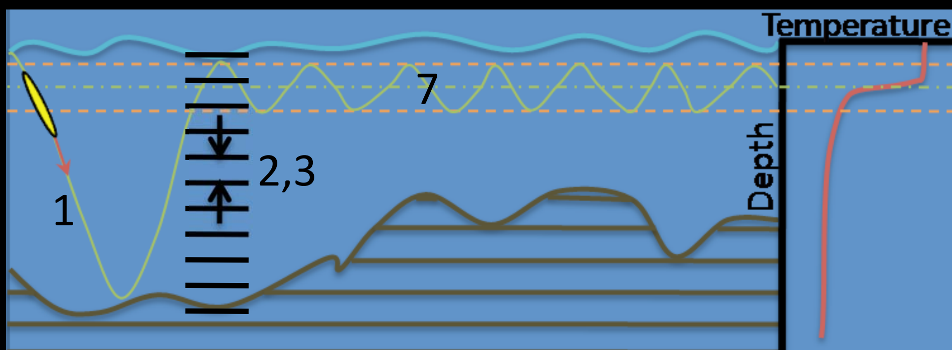
- Restrictions on board AUV lead to imperfect data coverage
  - Safe dive range
  - Surface obstacles (ships)
  - Daytime ops (mostly, due to battery life)
  - Actual depth (pressure) readings accurate to ~1 m
    - changes in depth much more accurate
- pEnvtGrad
  - Environmental gradient determination process
    - used with adaptive yoyo behavior
  - Quantitatively defines and detects
    - Thermocline
    - Acousticline

Autonomous Adaptive Sampling: *Implementation, cont.*

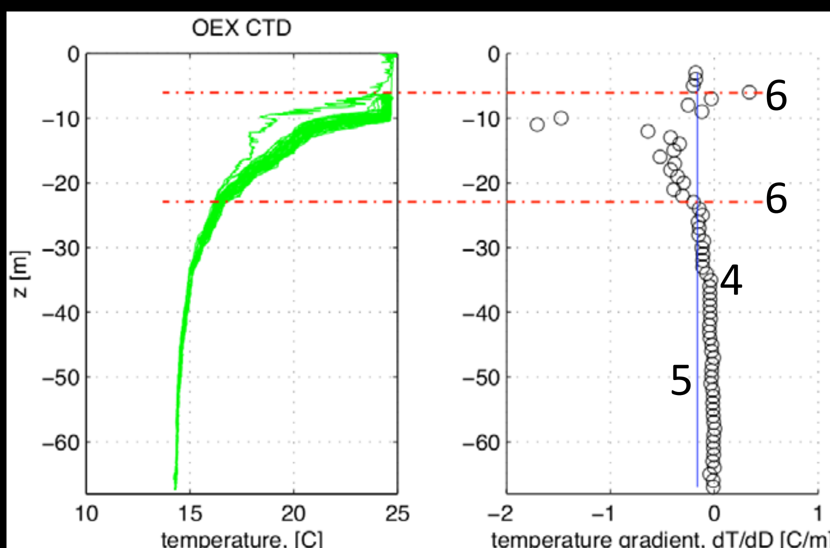


Autonomous Adaptive Sampling:
pEnvtGrad – Process

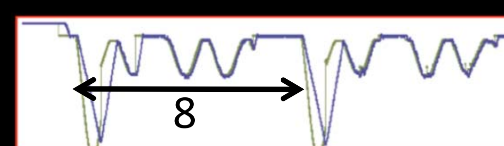
- Track Gradients: Temperature, Sound Speed -



1) Initial yoyo
2) Create depth "bins"
3) Average T in bin
4) Vertical derivative ($\Delta T/\Delta z$) over adjacent bins 'o'



5) Threshold – Average $\Delta T/\Delta z$ over water column
6) Determine thermocline range (max|$\Delta T/\Delta z$|) '- - - - - -'
7) Track! – adjust yoyo limits continuously
8) Periodic reset



Depth vs. Time

Autonomous Adaptive Sampling: *Scales*

- Concept of scales in the ocean
- How large should depth bins be to detect a thermocline?
  - Eliminate sub-scale variations in measurements
  - Only need rough estimate of thermocline bounds

	Bathymetry	Thermocline Range	Depth Bin Range
Shallow Water / Coastal System	O(100m)	O(10m)	~1m
Open Ocean	O(1km)	O(100m)	~10m

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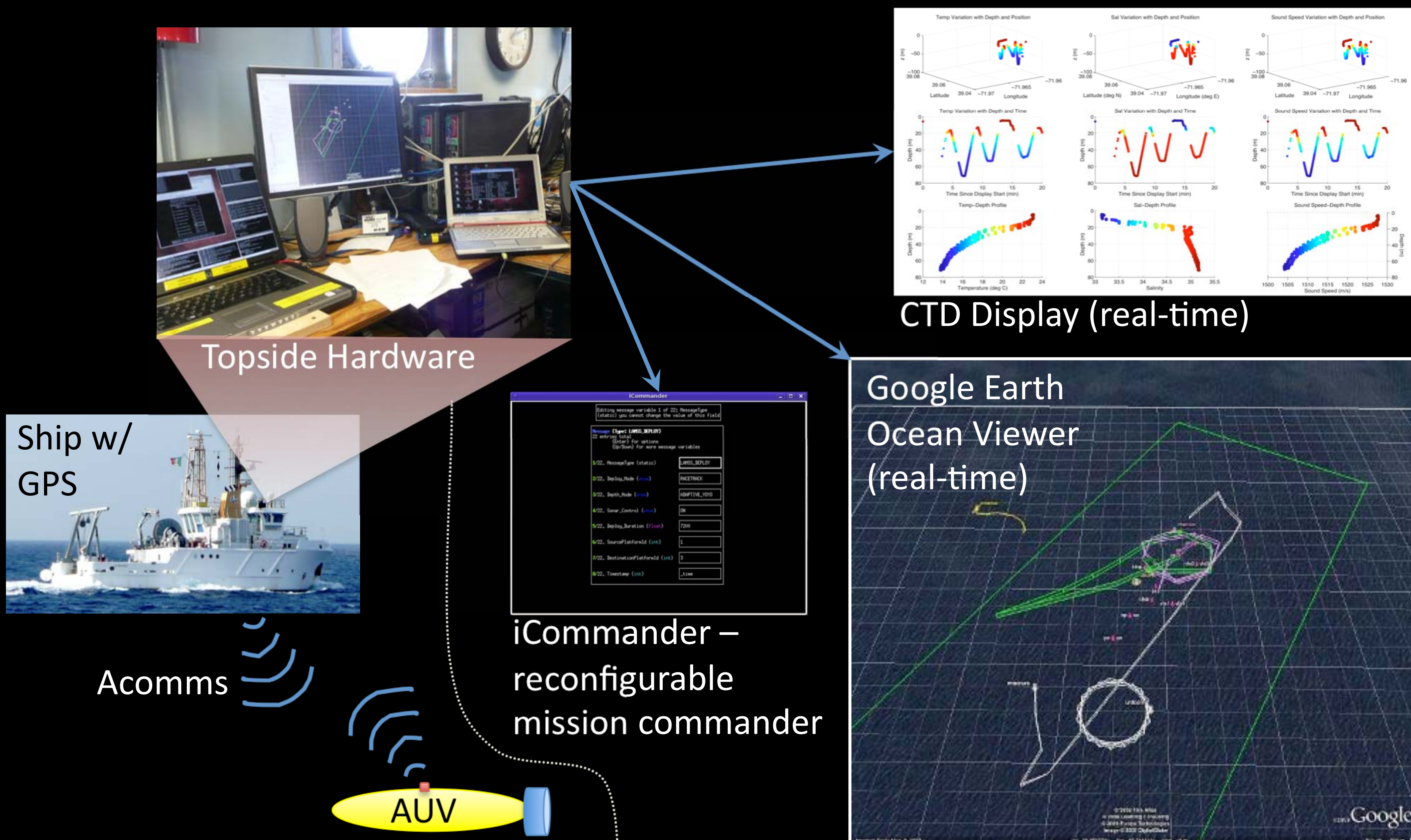
LAMSS[1] Topside

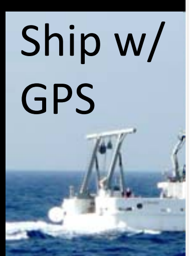
Command & Control Station, Situation Display

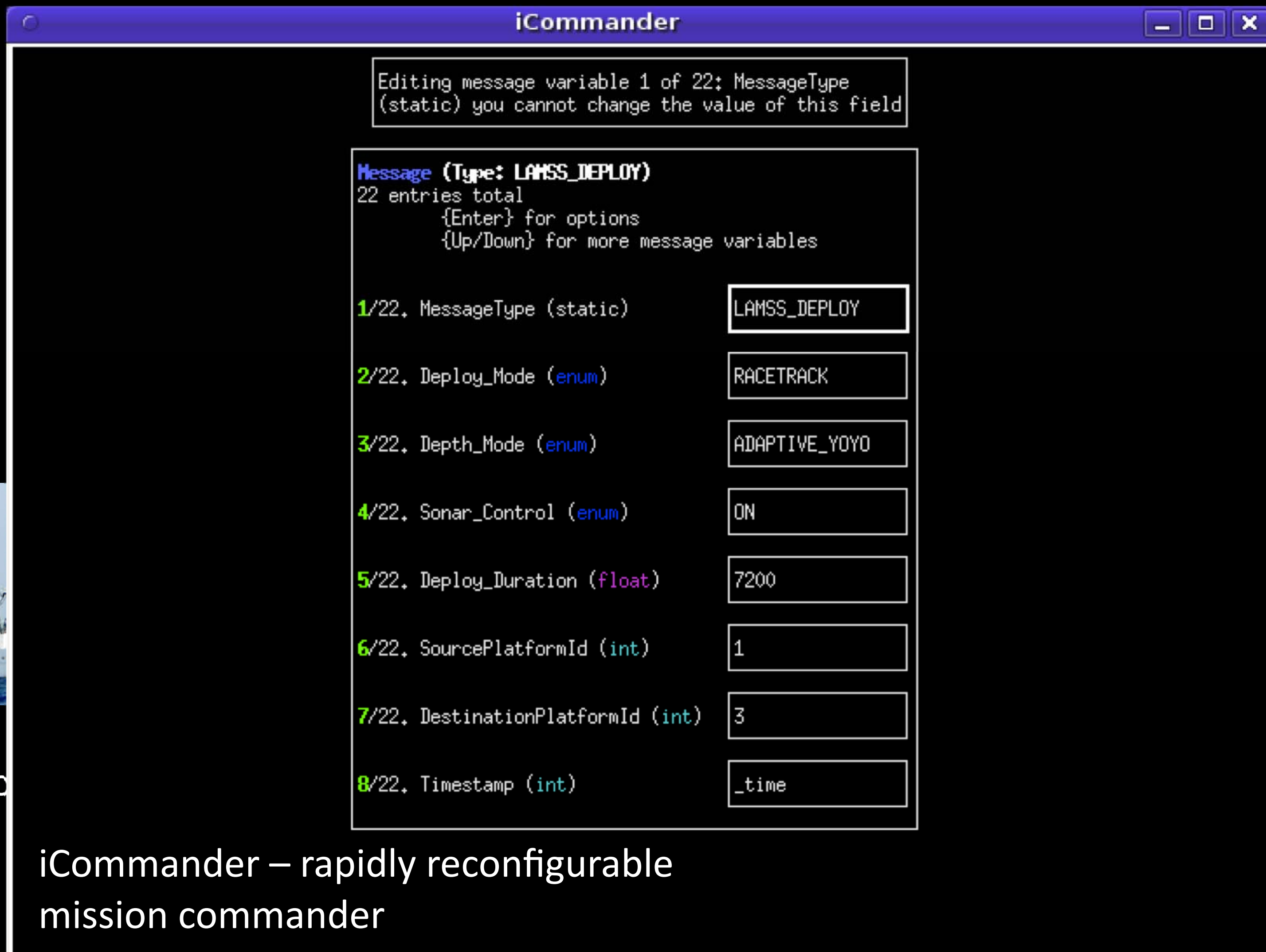


[1]Laboratory for Autonomous Marine Sensing Systems (MIT)

LAMSS Topside

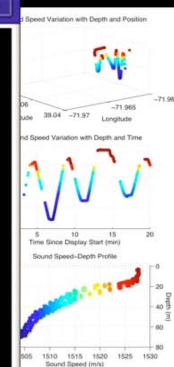
Command & Control Station, Situation Display

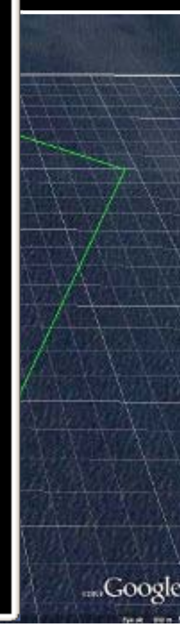




iCommander – rapidly reconfigurable mission commander

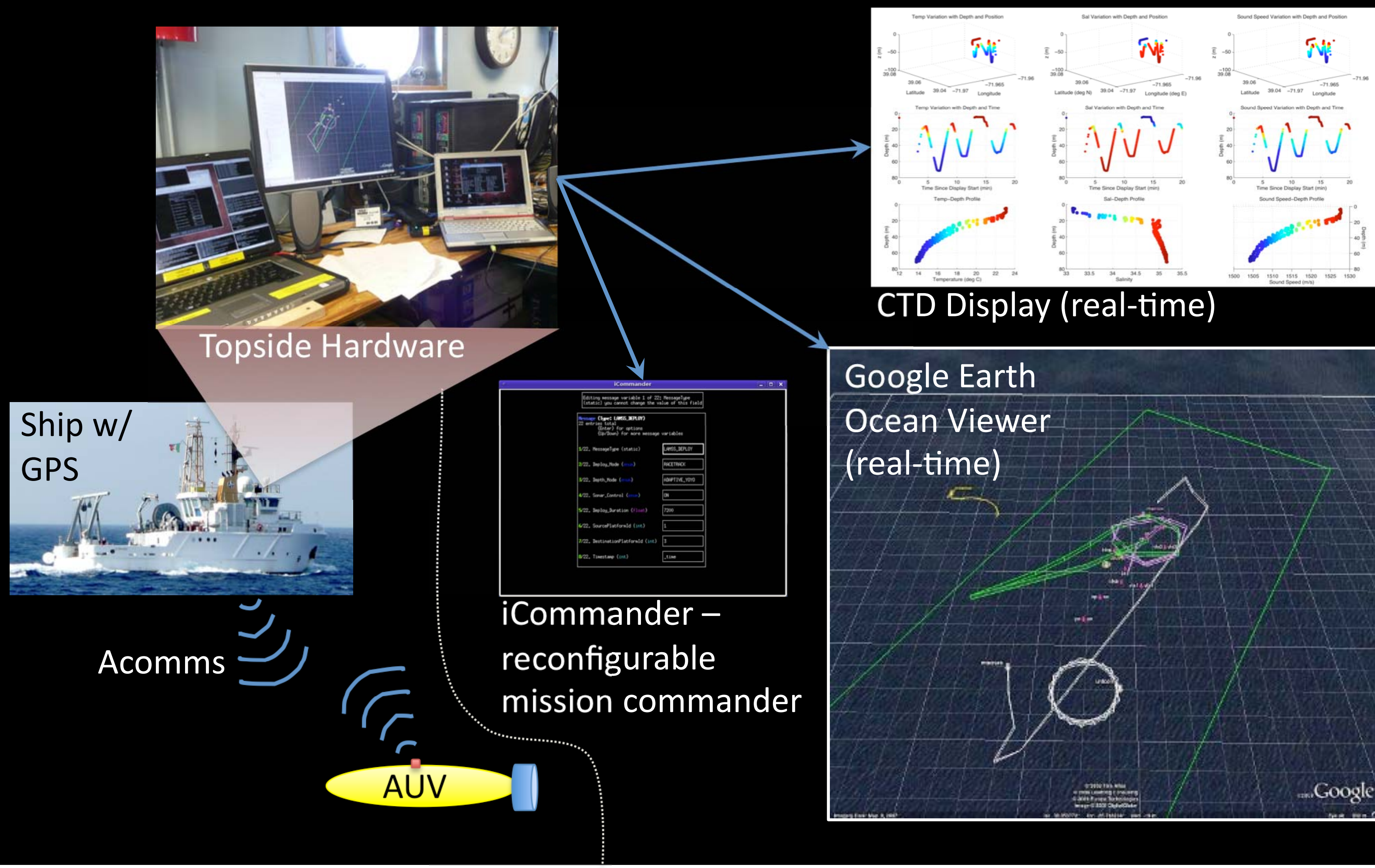
Aco





LAMSS Topside

Command & Control Station, Situation Display



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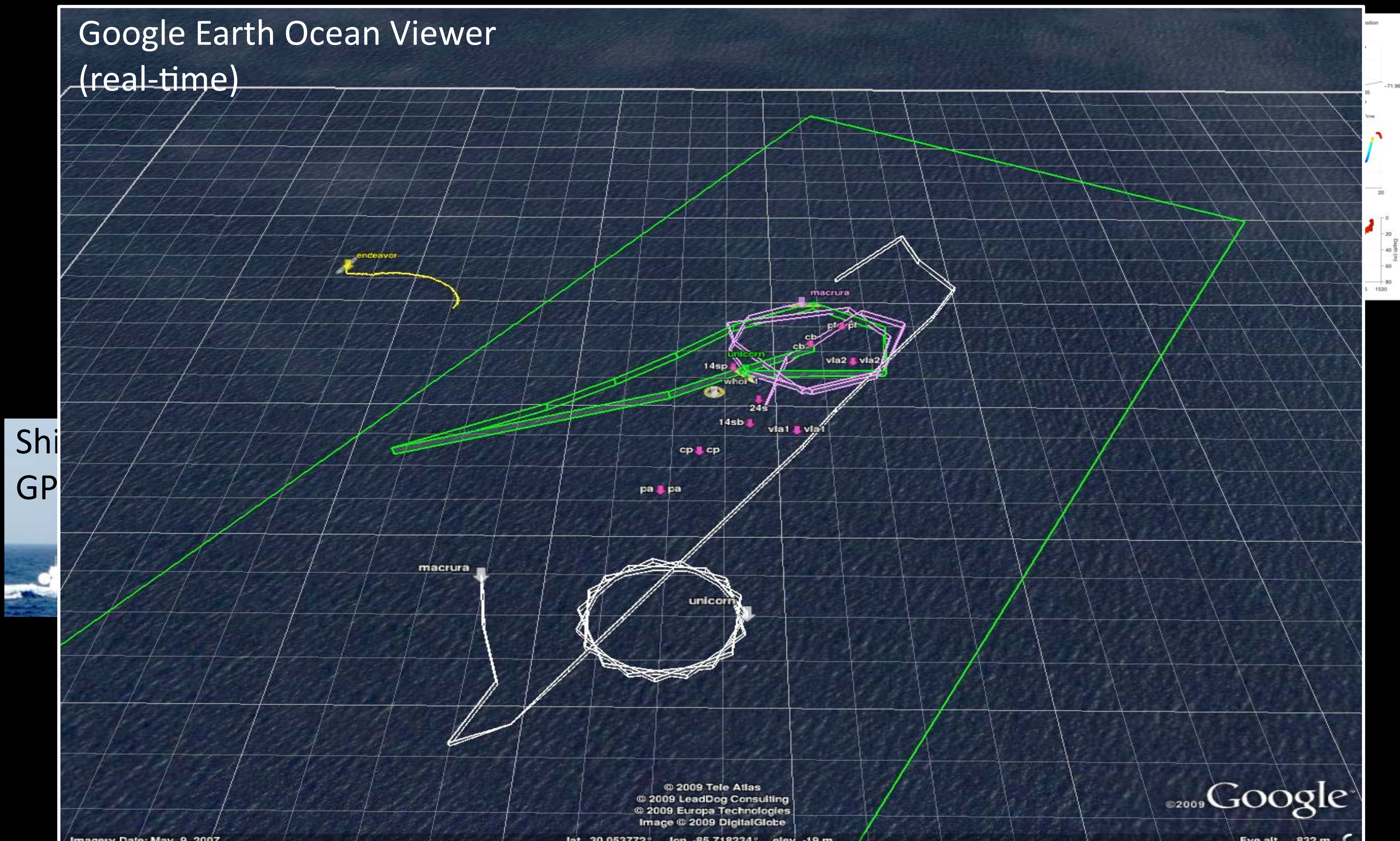
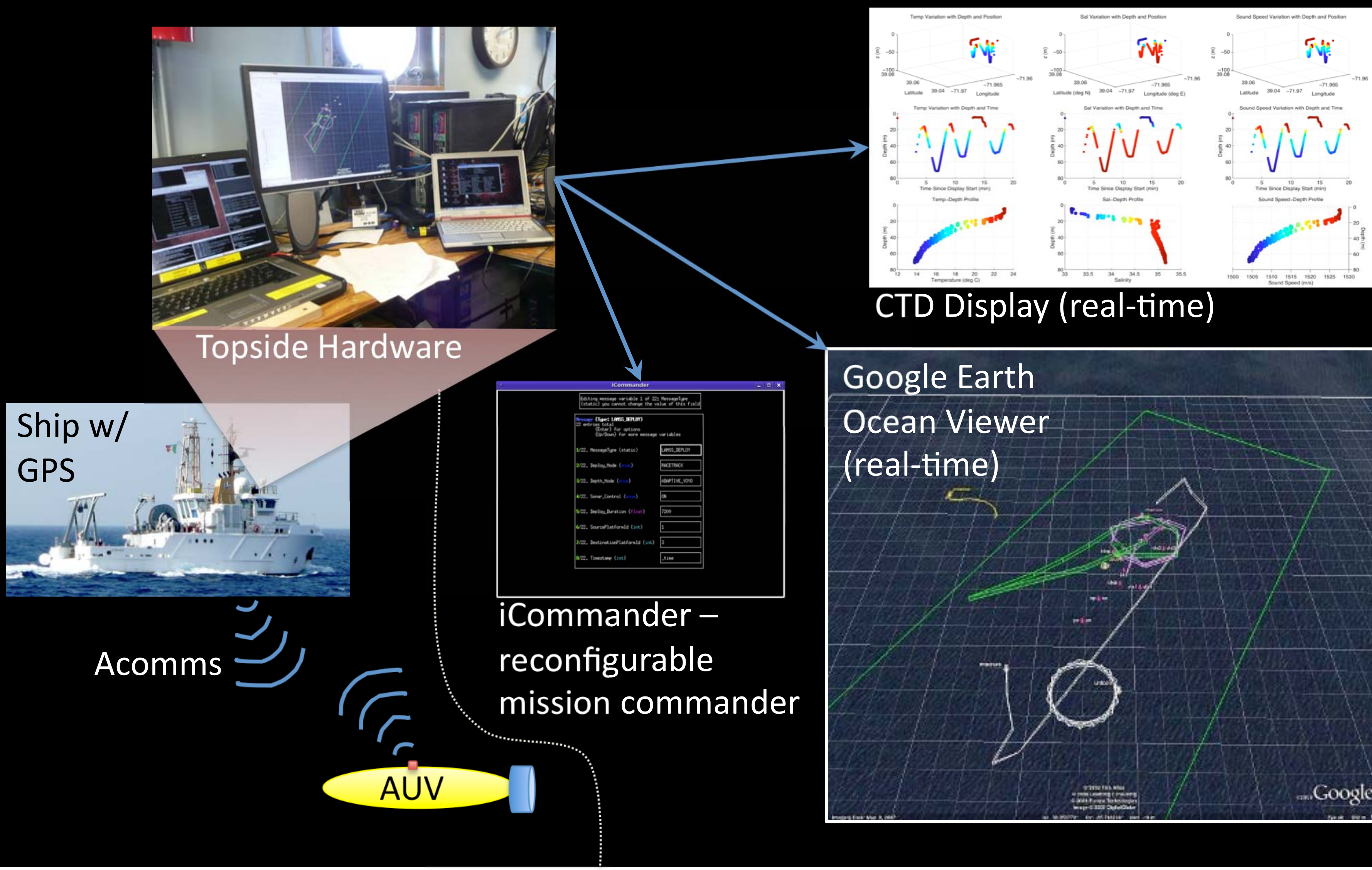


LAMSS Topside

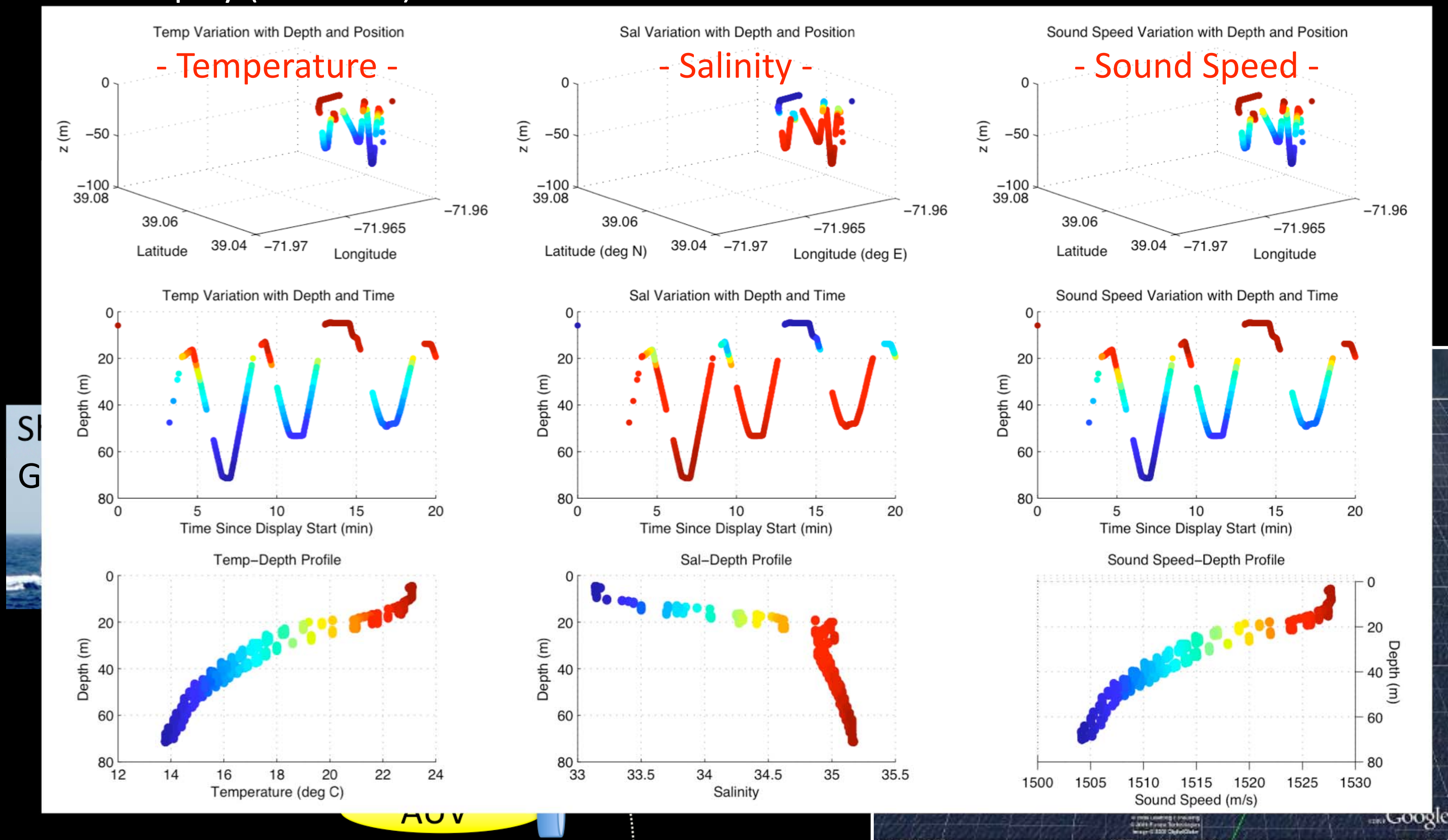
Command & Control Station, Situation Display



LAMSS Topside

Command & Control Station, Situation Display

CTD Display (real-time)



GLINT '09
Field Experiment

- 13-14 July, 2009
  Adaptive Env't. missions
  - MIT
  - NATO Undersea Research Centre (NURC), La Spezia, Italy
- NURC OEX AUV running autonomy software

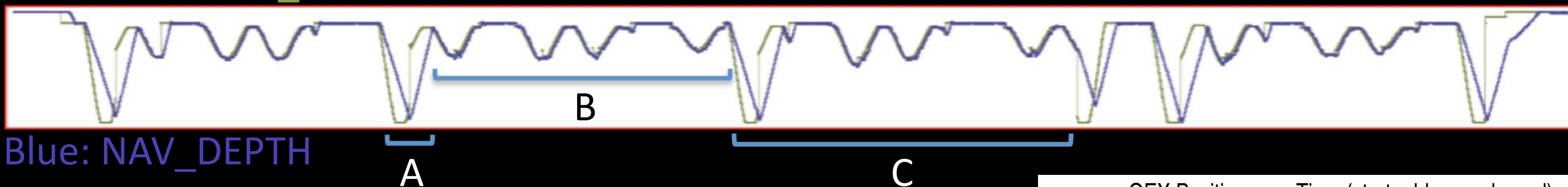
- Development, testing & simulation of pEnvtGrad
- Track acousticline

Tyrrhenian Sea, Italy

GLINT '09

Results (07/14/09)

Green: DESIRED_DEPTH



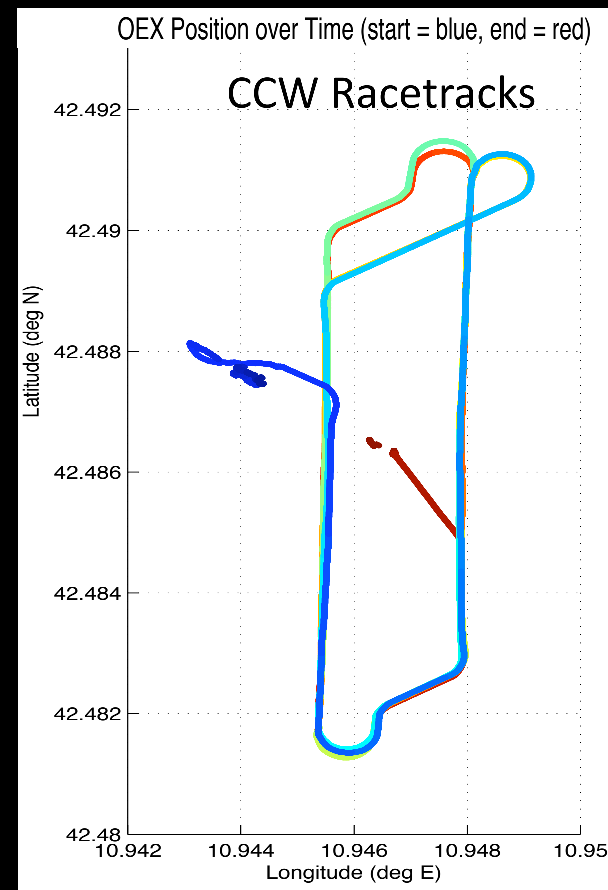
Blue: NAV_DEPTH

Autonomy Behaviors:
Adaptive Yoyo (above) & Racetrack (right)

Mission:
Track the acousticline.

A: Initial yoyo, 7-70m
B: Tracking acousticline, 9-28m
C: Periodic timeout resets yoyo depth limits

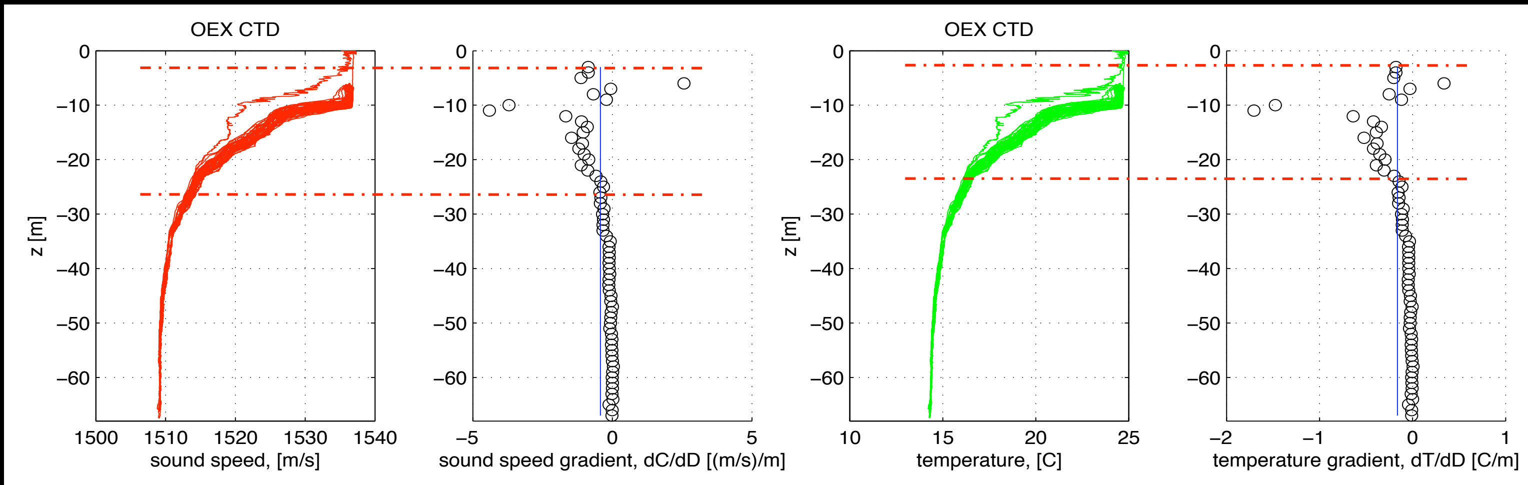
Water Depth: ~100m



GLINT '09

Validation of pEnvtGrad Performance

- OEX CTD Gradient Determination -



Sound Speed (m/s)

$\left(\frac{\Delta c}{\Delta z}\right)_{avg}$ = -0.4269

Acousticline: [3 28]m

Temperature (°C)

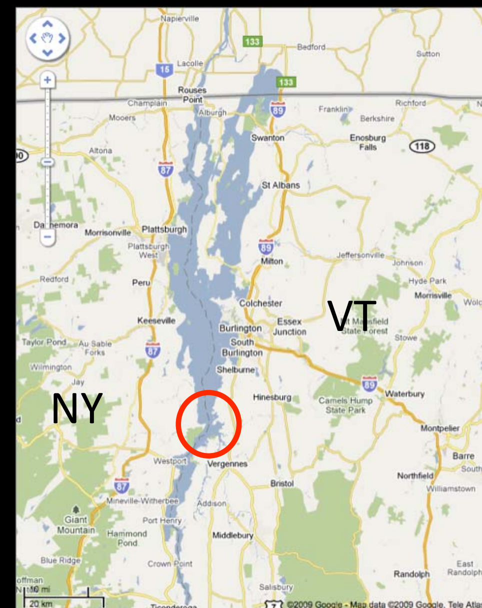
$\left(\frac{\Delta T}{\Delta z}\right)_{avg}$ = -0.1621

Thermocline: [3 23]m

Tyrrhenian Sea – 14 July, 2009

Champlain '09
Field Experiment

- 03-05 October, 2009
  - MIT
  - Naval Undersea Warfare Center (NUWC), Newport, RI
- Iver AUV running autonomy software

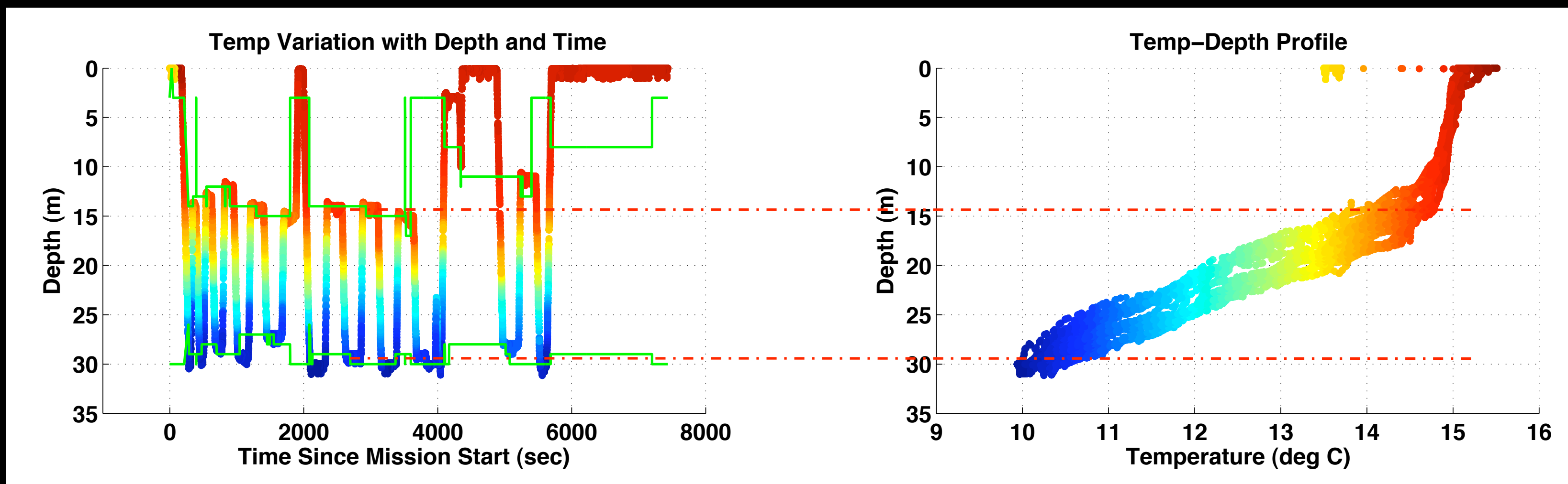


Lake Champlain, VT

- Testing of pEnvtGrad
  - Track thermocline
- Fresh water!


Hammerhead (Iver AUV)

Champlain '09
Thermocline Tracking



05 Oct., 2009 – 1600 UTC

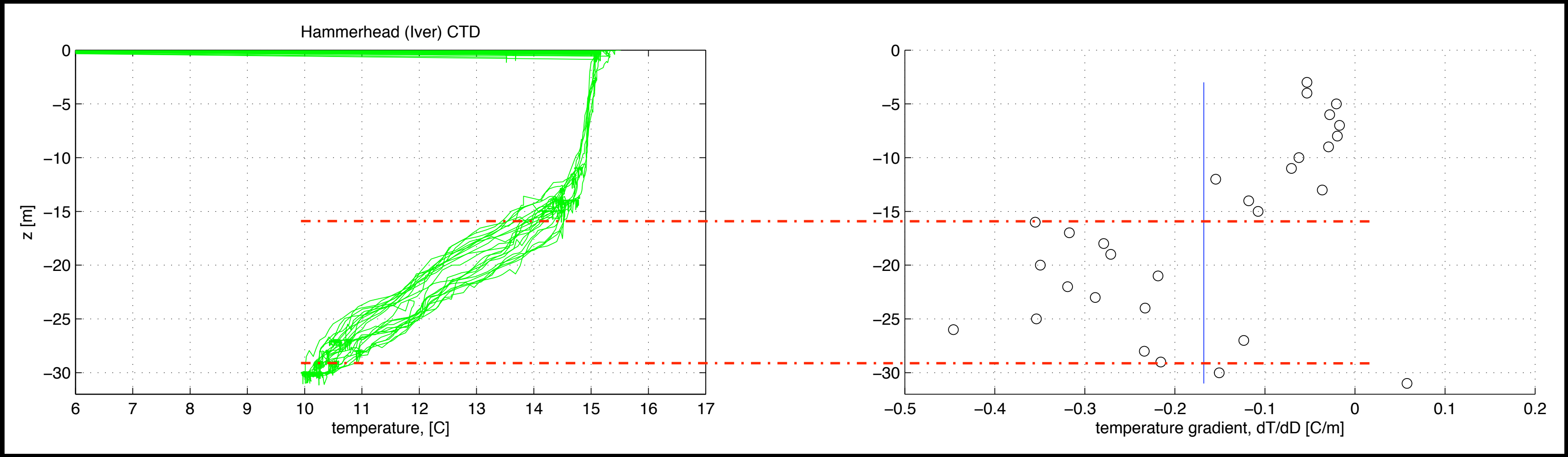
hammerhead_2009-10-05_155954

= thermocline range actively determined by pEnvtGrad on board AUV (~15-30m)

Data coloring corresponds to temperatures in the right-hand plot.

Champlain '09

Thermocline Tracking, cont.



avg(dT/dz) = -0.1679 °C/m

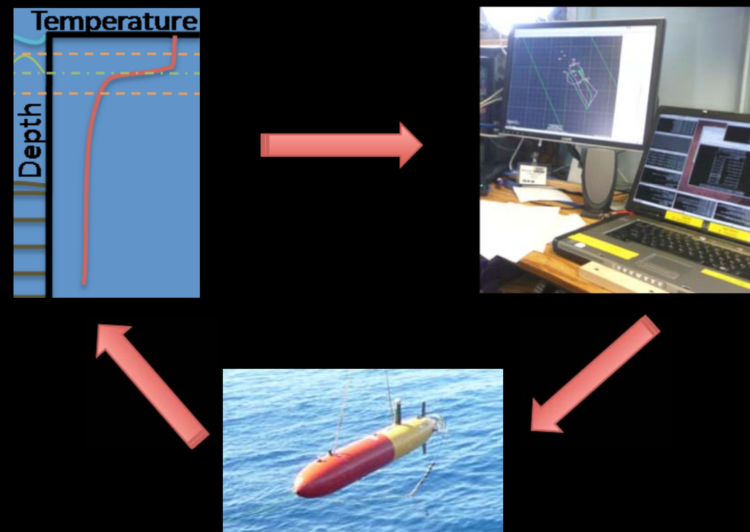
Thermocline = [16   29] m

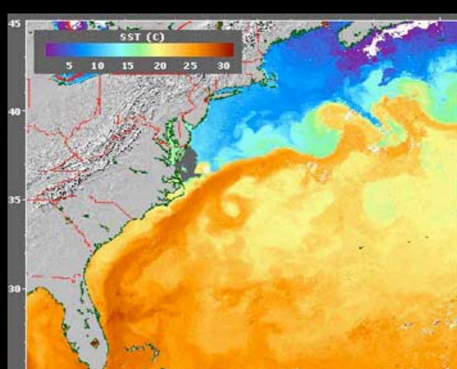
Conclusions

- Successful proof-of-concept for autonomous detection and tracking of hydrographic gradients
  - Most hydrographic features are characterized/ delineated by gradients
- From theory to testing in field experiments
  - pEnvtGrad
  - Successful thermocline & acousticline tracking
  - Fresh and saline environments
  - Different types of AUVs

Future Work

- Fit N^{th} order polynomial to thermocline/acousticline
  - AUV positioning for better acomms
  - Useful when bandwidth is limited
- Track more complex oceanographic features





Gulf Stream[1]

- Multi-vehicle collaboration
  - Better feature coverage in time and space

Underwater Glider

Iver AUV Fleet[2]

[1]oceanmotion.org
[2]NUWC

Acknowledgements

- MIT
  - H. Schmidt, P. Lermusiaux, A. Balasuriya, T. Schneider, K. Cockrell
- NUWC
  - D. Eickstedt, S. Sideleau, M. Incze
- NURC
  - D. Hughes, F. Baralli, M. Mazzi & OEX team