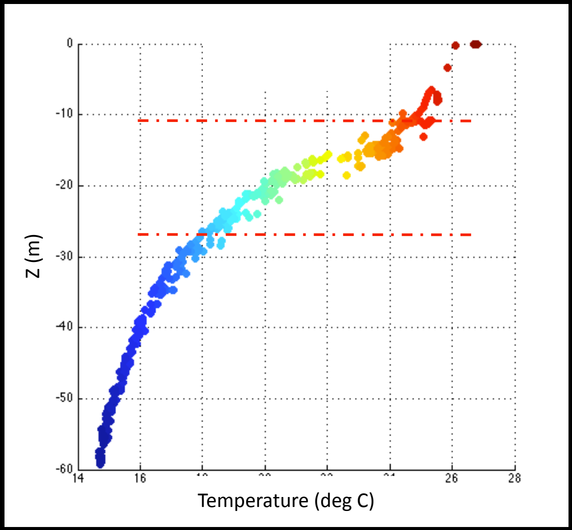
Autonomous Adaptive Environmental Assessment and Feature Tracking via Autonomous Underwater Vehicles

- Tracking the Thermocline -



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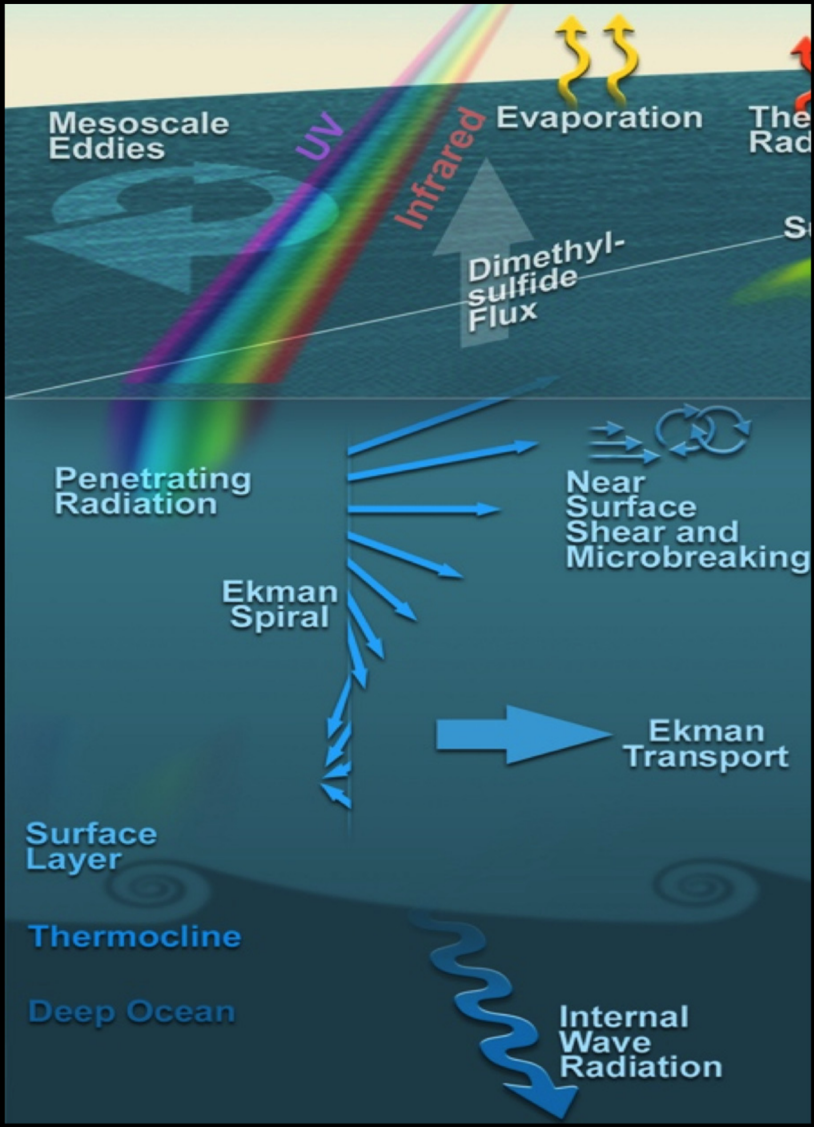
WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Overview

- Background & Motivation
- AAEA & Feature Tracking
  - Problem Definition
  - Theory & Algorithm
  - Implementation on AUVs
    - pEnvtGrad
- Field Experiments & Results
- Summary

Background & Motivation: *The Missing Piece*

- Bridge Science and Engineering
- 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



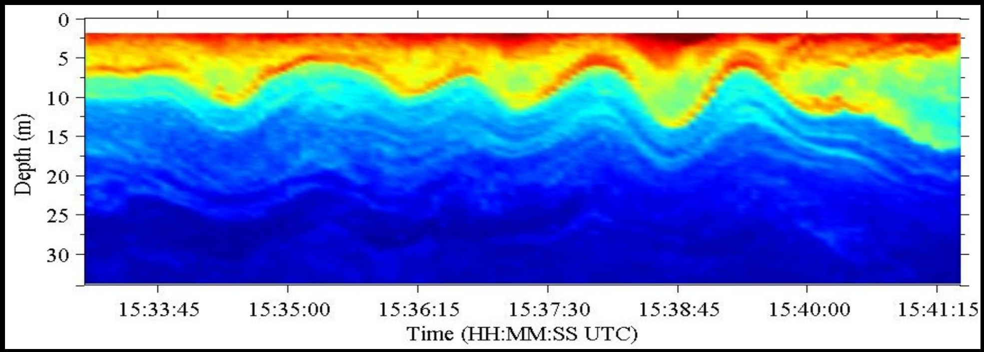
Oceanographic Features[1]

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

Background & Motivation: *Thermocline Tracking*

- Example and proof-of-concept of AAEA & feature tracking
- Present in most large bodies of water
- Most AUVs are equipped with a CT or CTD sensor

- Widely studied in the oceanographic community
  - Acoustic communications
  - Biology - phytoplankton, plankton and plankton-eating fish
  - Physical oceanography - surface mixing, internal waves



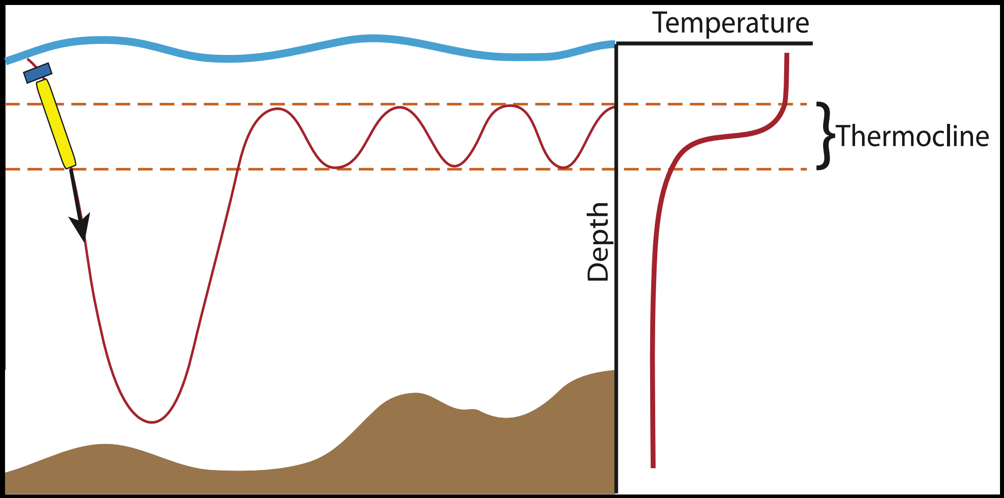
Internal Waves[2]

CTD[1]

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

Autonomous Adaptive Environmental Assessment (AAEA) & Feature Tracking: *Problem Definition*

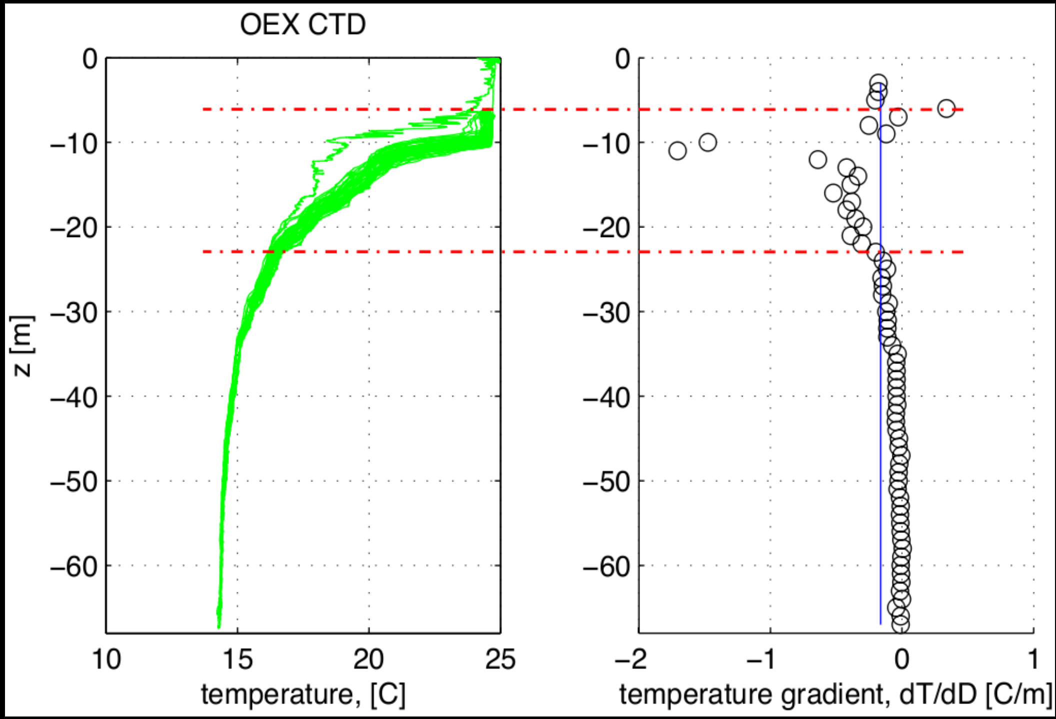
- Vehicle moving through the water column in time and space
- Where is the thermocline (or any feature)?
  - Based on *just* the environmental information the AUV collects and processes *on board*
- Completely autonomous (MOOS-IvP autonomy architecture)
- Quantitatively define thermocline



Thermocline tracking by adapting yoyo motion.

AAEA & Feature Tracking: *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



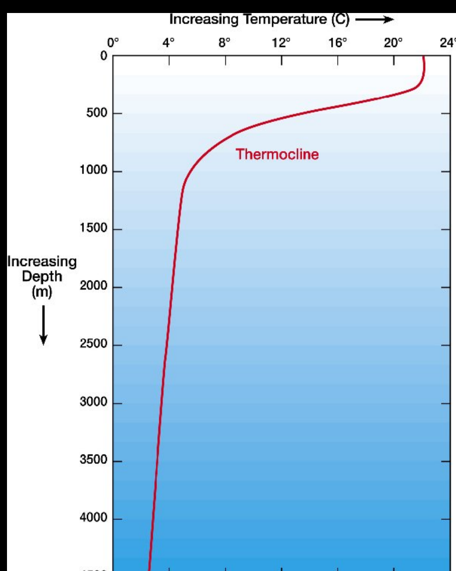
Thermocline region between dotted lines

AAEA & Feature Tracking: *Algorithm*

In theory…

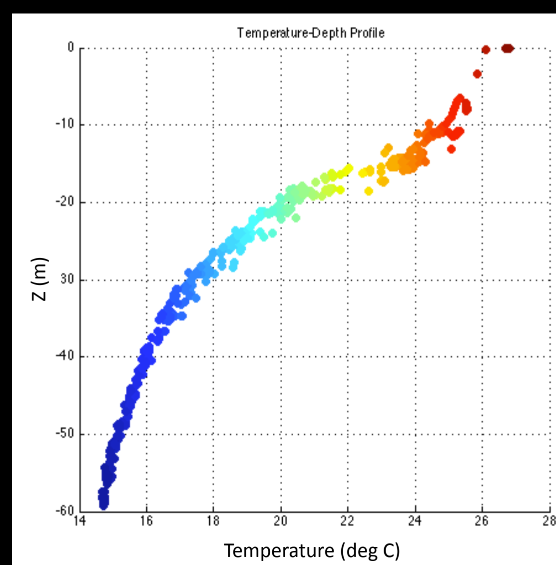
- Ideal temperature profile at some (Lat, Lon)

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



Ideal Profile

≈



Data Profile

AAEA & Feature Tracking: *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

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

AAEA & Feature Tracking: *Algorithm, cont.*

- Determine upper and lower depth limits of the thermocline

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

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

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

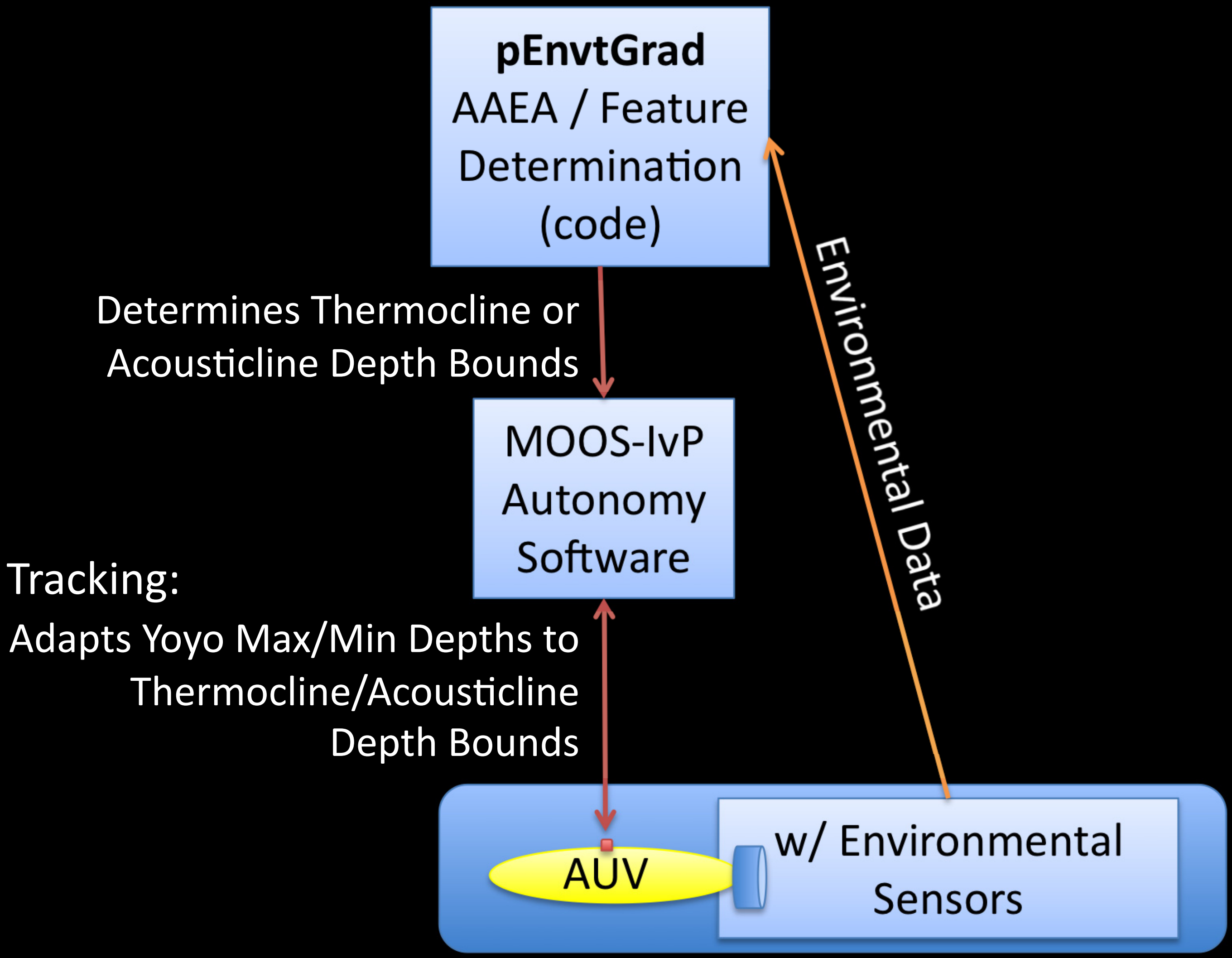
$$lower\_thermocline\_depth \equiv -\min(z_{in\_thermocline})$$

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

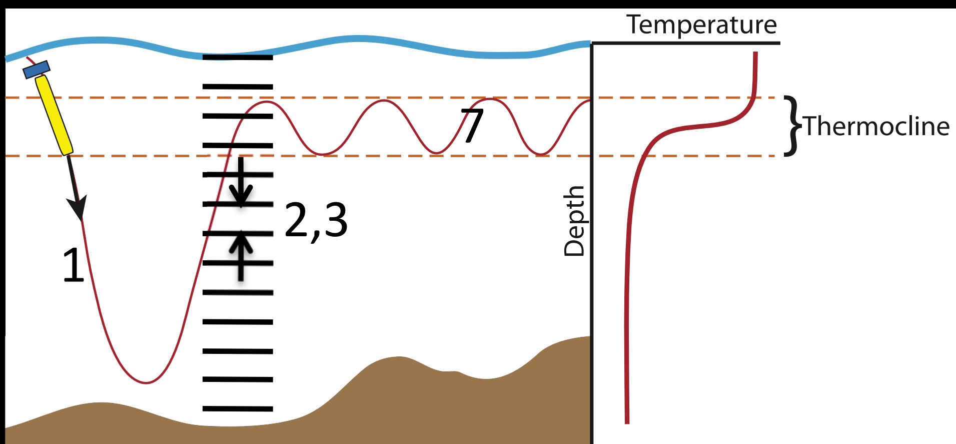
AAEA & Feature Tracking: *Implementation*

- pEnvtGrad (process: Environmental Gradient)
  - Environmental gradient determination process
    - used with adaptive yoyo behavior
  - Quantitatively defines and detects
    - Thermocline
    - Acousticline

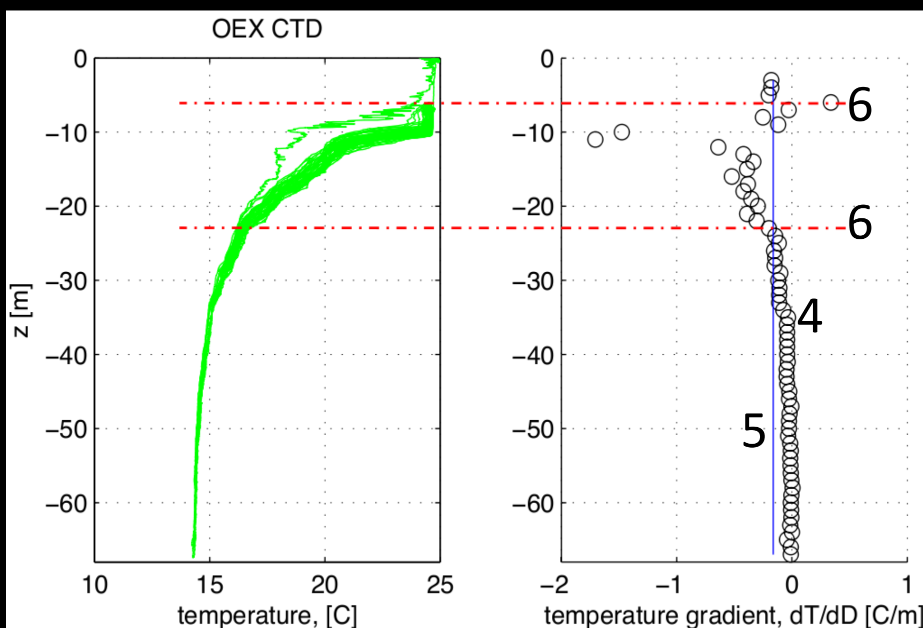
AAEA & Feature Tracking: *Implementation, cont.*



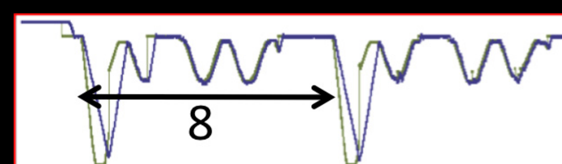
AAEA & Feature Tracking:
pEnvtGrad – Process
- Track Gradients: Temperature, Sound Speed -



1) Initial yoyo
2) Create depth “bins”
3) Average T in bin
4) Vertical derivative (ΔT/Δz) over adjacent bins ‘o’



5) Threshold – Average ΔT/Δz over water column
6) Determine thermocline range (max|ΔT/Δz|) ‘- - - - - -’
7) Track! – adjust yoyo limits continuously
8) Periodic reset



Depth vs. Time

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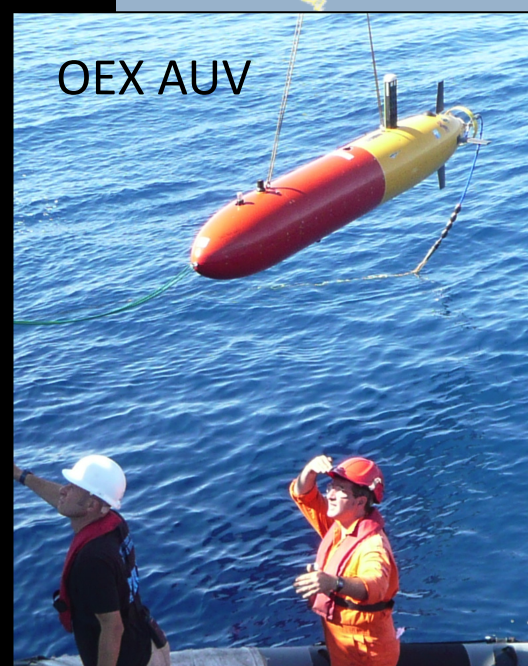
GLINT '09
Field Experiment

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

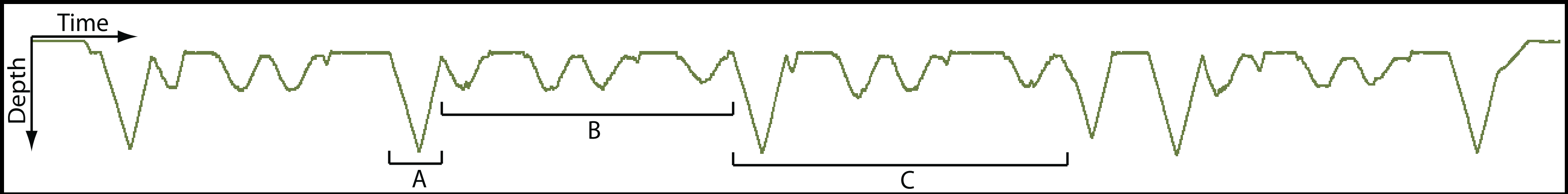
- Development, testing & simulation of pEnvtGrad
- Track acousticline

Tyrrhenian Sea, Italy



GLINT '09

Results (07/14/09)



Autonomy Behaviors:
Adaptive Yoyo (above) & Racetrack (1km x 200m oval)

Mission:
Track the acousticline.

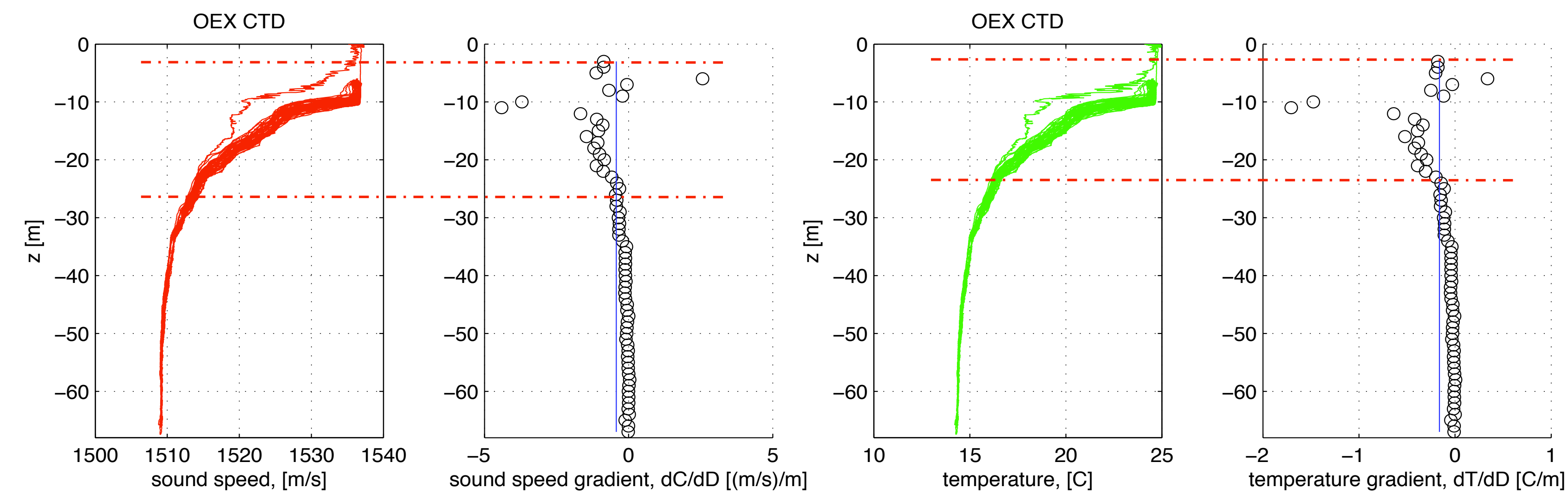
A: Initial yoyo, 7-70m
B: Tracking acousticline, 9-28m
C: Periodic timeout resets yoyo depth limits

Water Depth: ~105m

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 – 28m

Temperature (°C)

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

Thermocline: 3 – 23m

Tyrrhenian Sea – 14 July, 2009

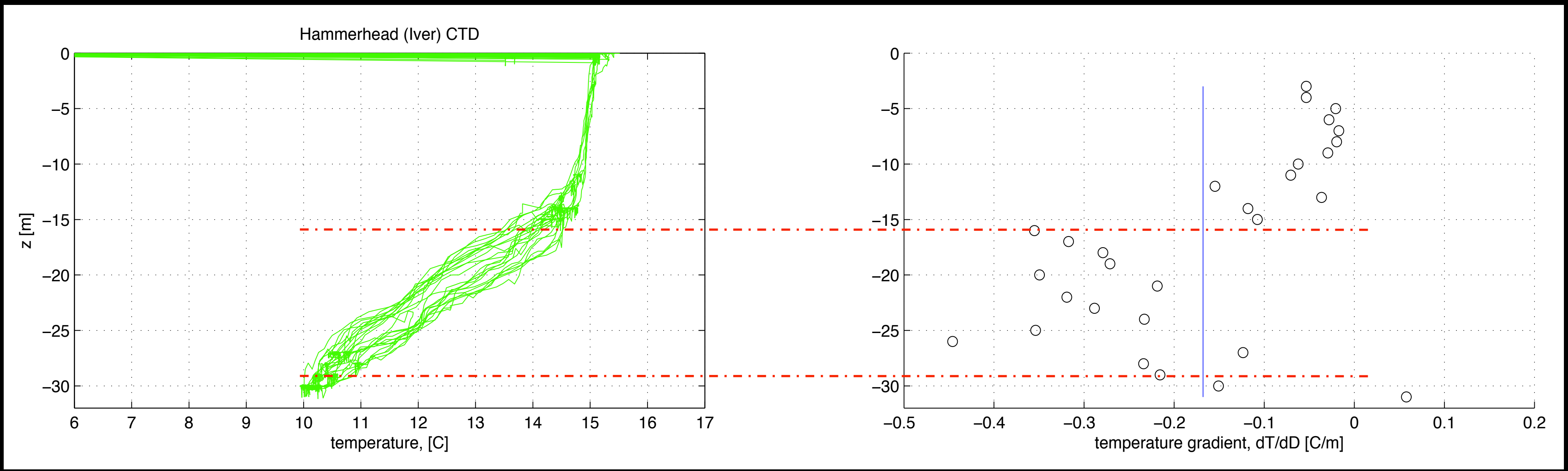
Champlain '09
Field Experiment

- 03-05 October, 2009
  - MIT
  - Naval Undersea Warfare Center (NUWC), Newport, RI
- Iver AUV running autonomy software
- Testing of pEnvtGrad
  - Track thermocline
- Fresh water!

Lake Champlain, VT

Hammerhead (Iver AUV)

Champlain '09
Thermocline Tracking, cont.



avg(dT/dz) = -0.1679 °C/m
Thermocline = [16   29] m

Summary

- Ongoing advances in AUV autonomy for autonomous & adaptive tracking of environmental features on board AUVs
- Successful proof-of-concept for AAEA & tracking of hydrographic gradients (temperature, sound speed)
- Widely applicable in the field

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