Nested Autonomy: A Robust Operational Paradigm for Adaptive and Collaborative Ocean Acoustic Sensing

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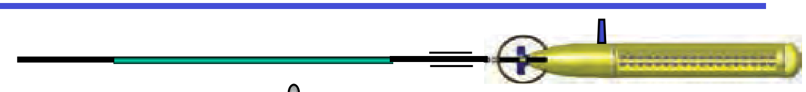
MIT Lab
Autono



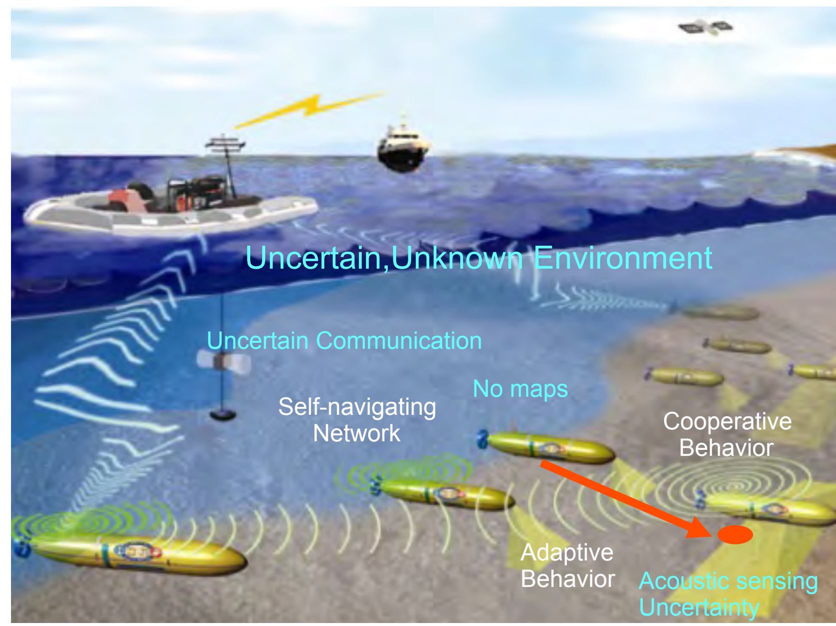
Outline

- Introduction
- Nested Autonomy Paradigm
- Tutorial Example
- Environmental Ocean Acoustics
- Model-based Adaptive Autonomy
- Field Examples
- Summary

Ocean Sensing Systems Paradigm Shift

Platform-centric Sensing Systems

Net-centric, Distributed Autonomous Sensing Systems



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Undersea Network Communication

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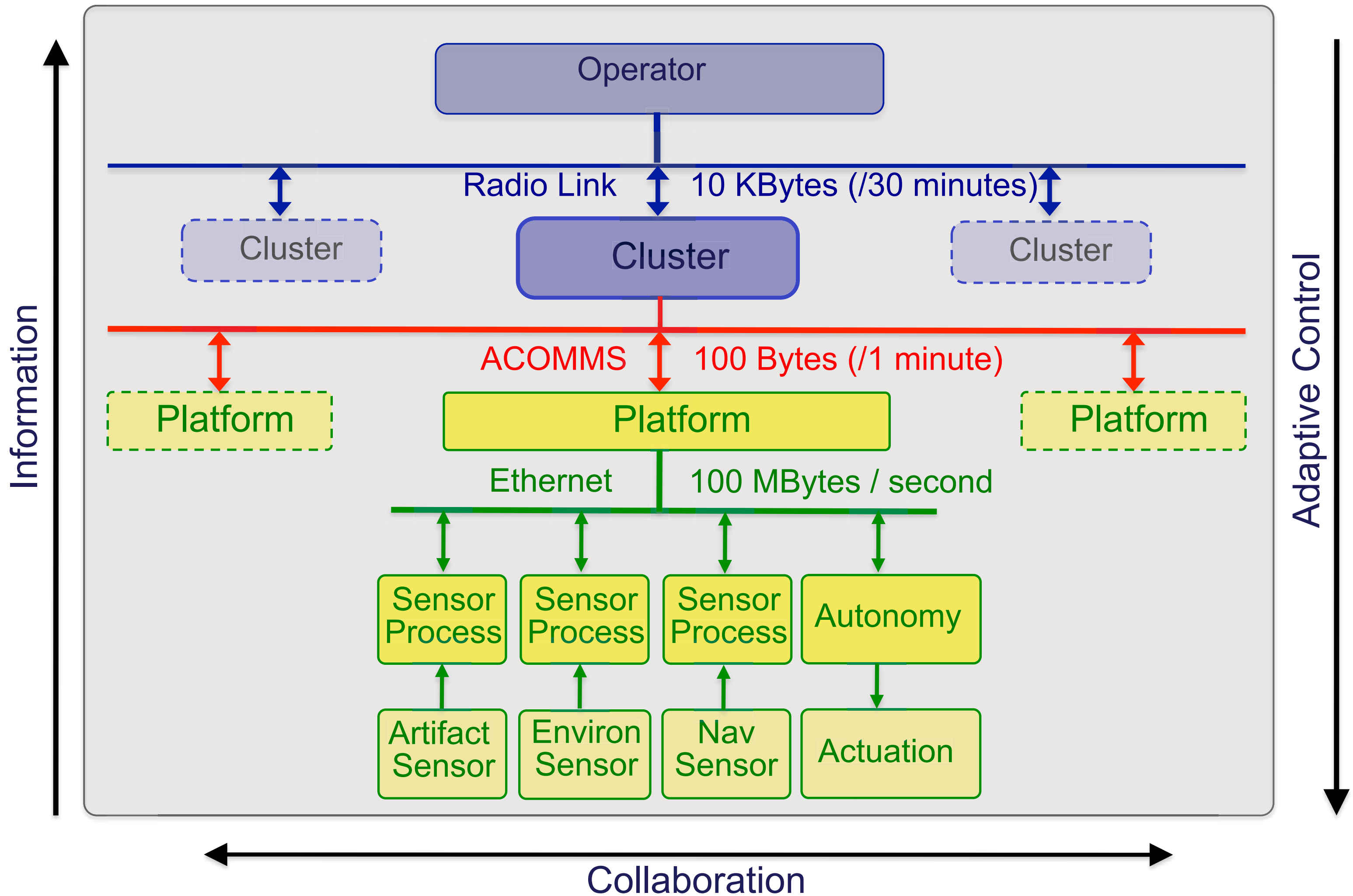
Nested Autonomy

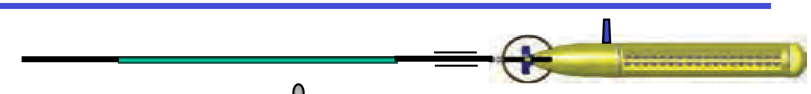
Field C2
Modeling
Mission Control
Planning/Sched

Mission Autonomy
Collaboration
Planning
Network Control

Platform Autonomy
Modeling
Sensor Processing
Navigation
Autonomy
Actuation/Control

Platform Navigation & Control
Sensors
Actuators





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Nested Autonomy Paradigm

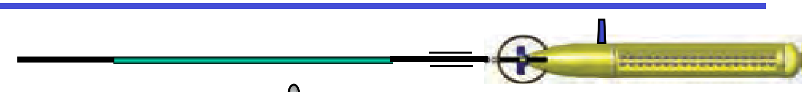
Objective

- Autonomy system capable of adapting to the environmental and tactical situation to achieve mission objectives, without being dependent on continuous connectivity with operators.
- Autonomy system which takes advantage of communication windows to exploit collaboration with other network nodes for enhanced mission performance

Platform Autonomy

Integrated Sensing, Modeling and Control

- Automated processing of sensor data for detection, classification, localization and tracking of tactical or environmental event
- Data-driven modeling for forecasting of tactical and environmental situation
- Intelligent decision-making based on situational awareness, adaptive and collaborative strategies (behaviors), and learning, to adapt to forecast for enhanced performance



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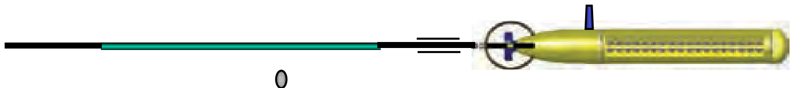
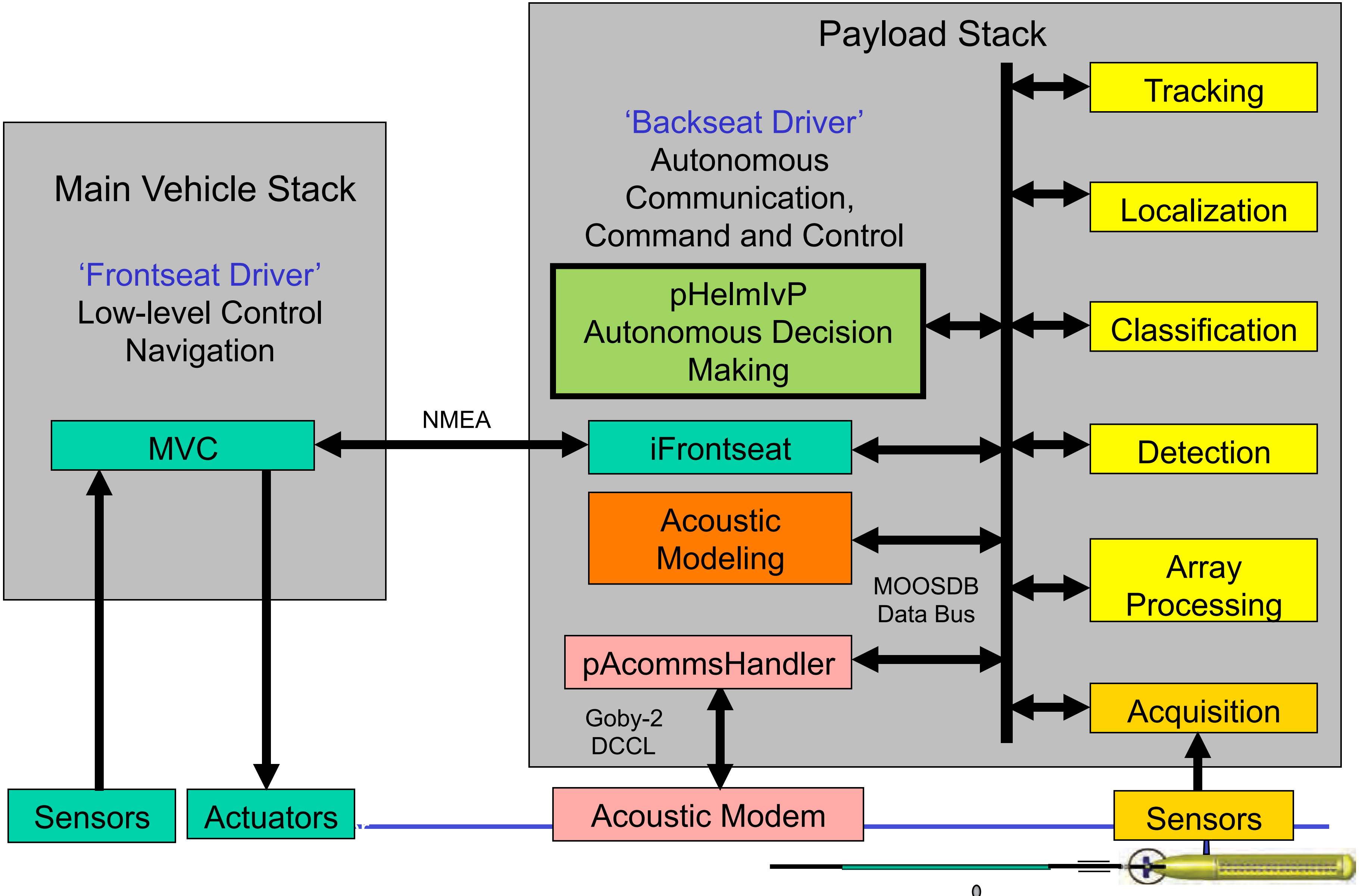
Platform Autonomy Components

- Platform Helm ("Captain of the Ship")
  - Command and control platform maneuvers for optimally achieving mission objectives as devised by Mission Autonomy and C2 ("Chief Scientist"), while maintaining platform safety and preparedness.
- Sensor Data Management ("Sonar Officer")
  - Configure sensor systems in accordance with mission directives from Mission Autonomy and C2.
  - Coordinate sensor operation with other platform systems (communication, propulsion, actuators).
  - Process and interpret sensor data for real-time support of decision making by the Helm
  - Prepare sensor system reports for decision for communication to the Helm and MA
- Communication ("Radio Officer")
  - Package and prioritize outgoing communication for available communication channels
  - Handle and distribute incoming communication to Helm and Sensor system.
- Platform Mobility ("Helmsman – Engine Room")
  - Converts speed, heading and depth commands to rudder and propulsion commands
  - Performs basic platform navigation
  - Manufacturer dependent



LAMSS
Payload Autonomy Architecture

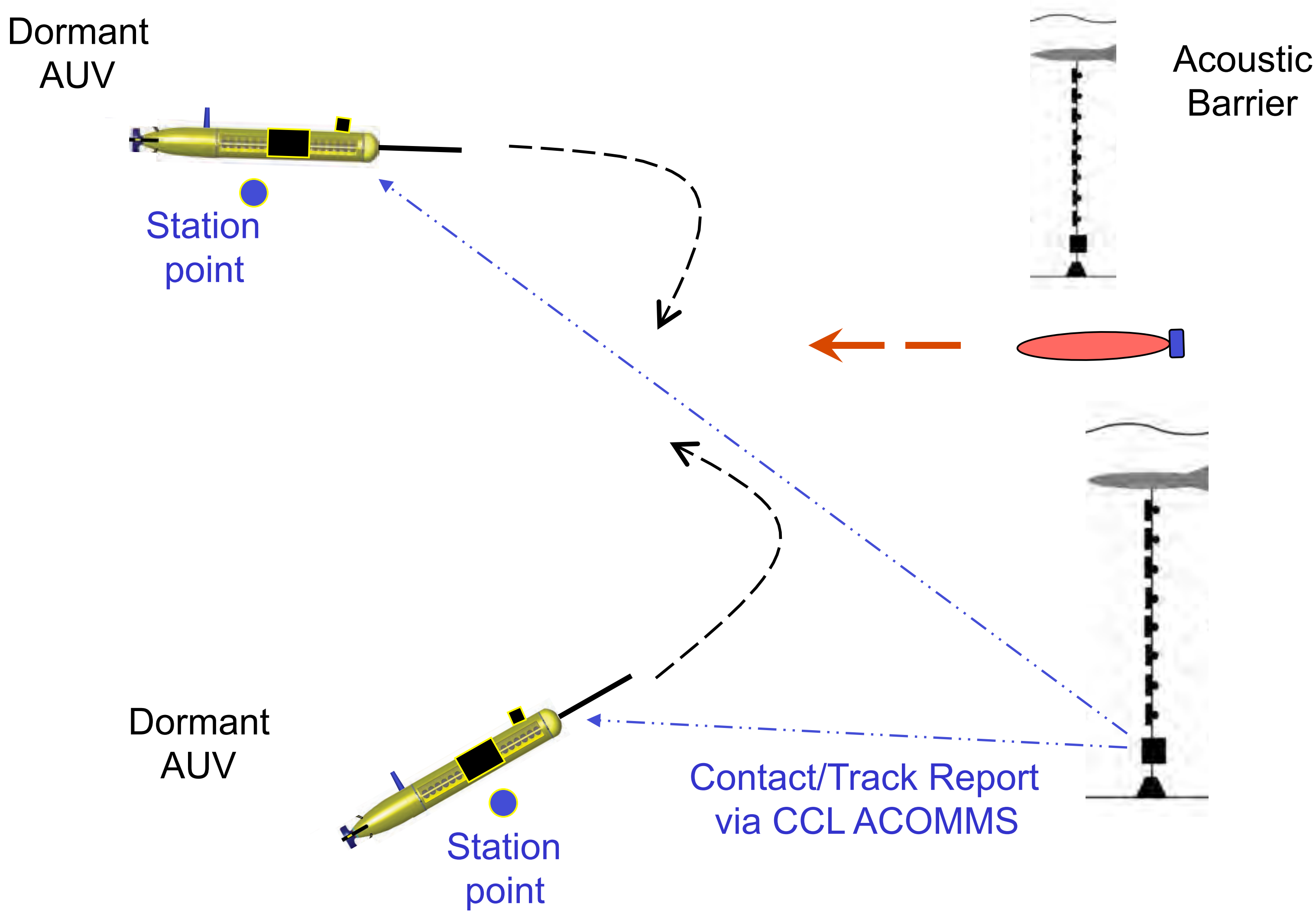


Nested Autonomy Tutorial Example

Port Entry Surveillance

Port Surveillance CONOPS

Collaborative, Adaptive DCLT



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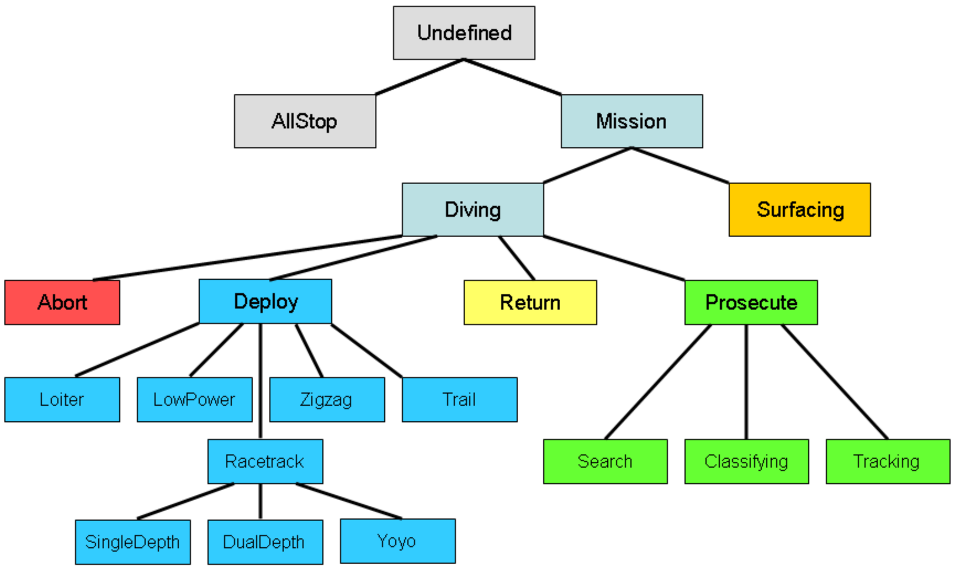
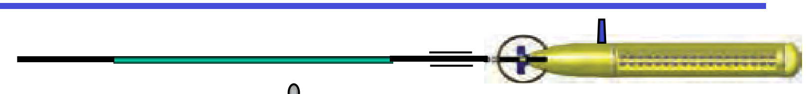
Nested Autonomy with MOOS-IvP

Concept of Operations

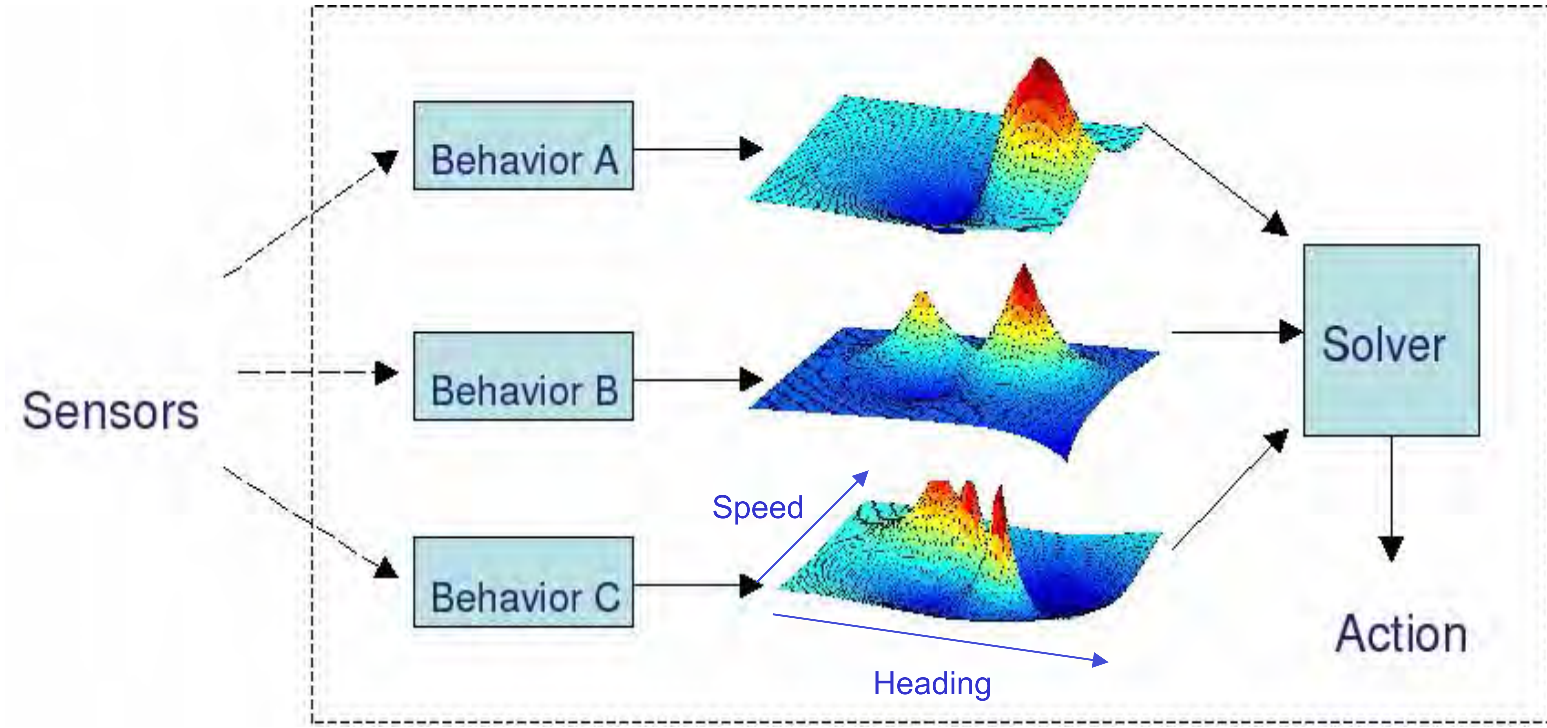
Hierarchical Mode Structure



- Mission-defined Autonomy System
  - Hierarchical Mode Structure
  - No programmed sequencing
  - Modes and behaviors perpetual until actively changed by mission planning and control infrastructure
- Autonomy Modes
  - Contains behavior set for Speed, Heading and Depth
  - ‘Perpetual’ until transitioned
  - Mode transitions
    - Onboard Mission Planning and Control
    - C2 through ACOMMS
- Behaviors
  - Mode defined
    - Mission objectives
    - Safety
  - Dynamic Configuration
    - Parameter updates
    - Spawned behaviors
      - Collision avoidance
      - Collaborative sensing



IvP-Helm
Multi-Objective Optimization

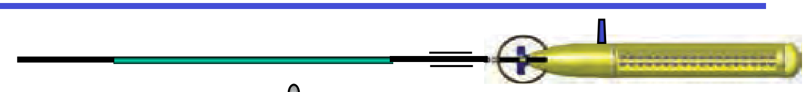


Behavior Examples – Search

TowHeading – Minimize noise interference
CloseRange – Approach predicted target track
TurnMemory – Protect towed array
GotoDepth – Optimal detection depth

Behavior Examples – Tracking

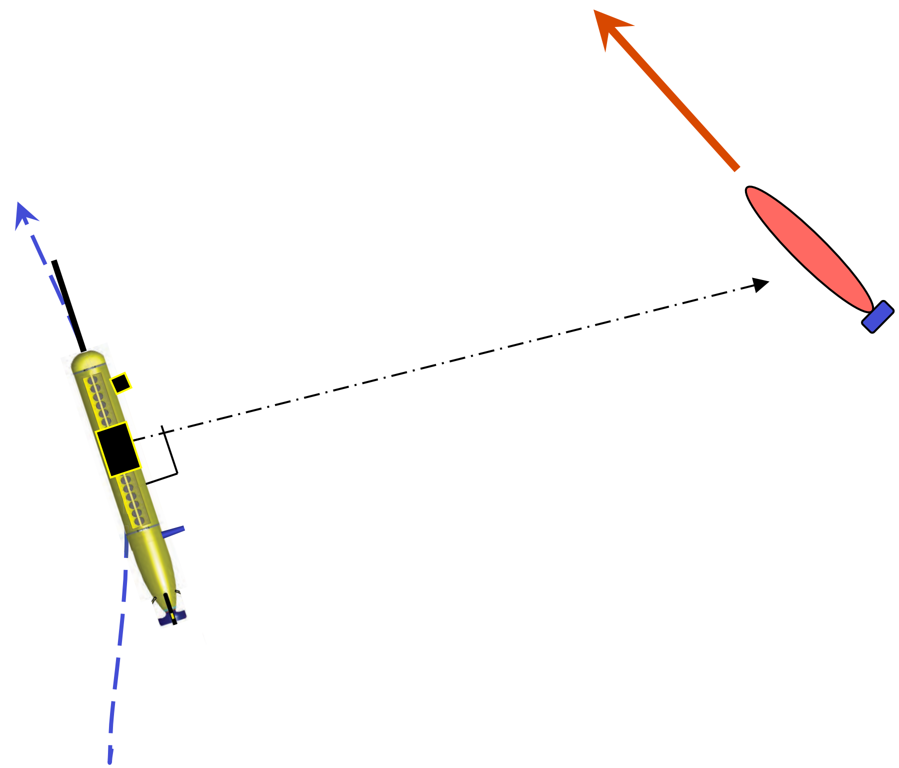
ArrayTurn – Break L/R ambiguity
ArrayAngle – Optimize target tracking
TurnMemory – Protect towed array



Tracking Mode

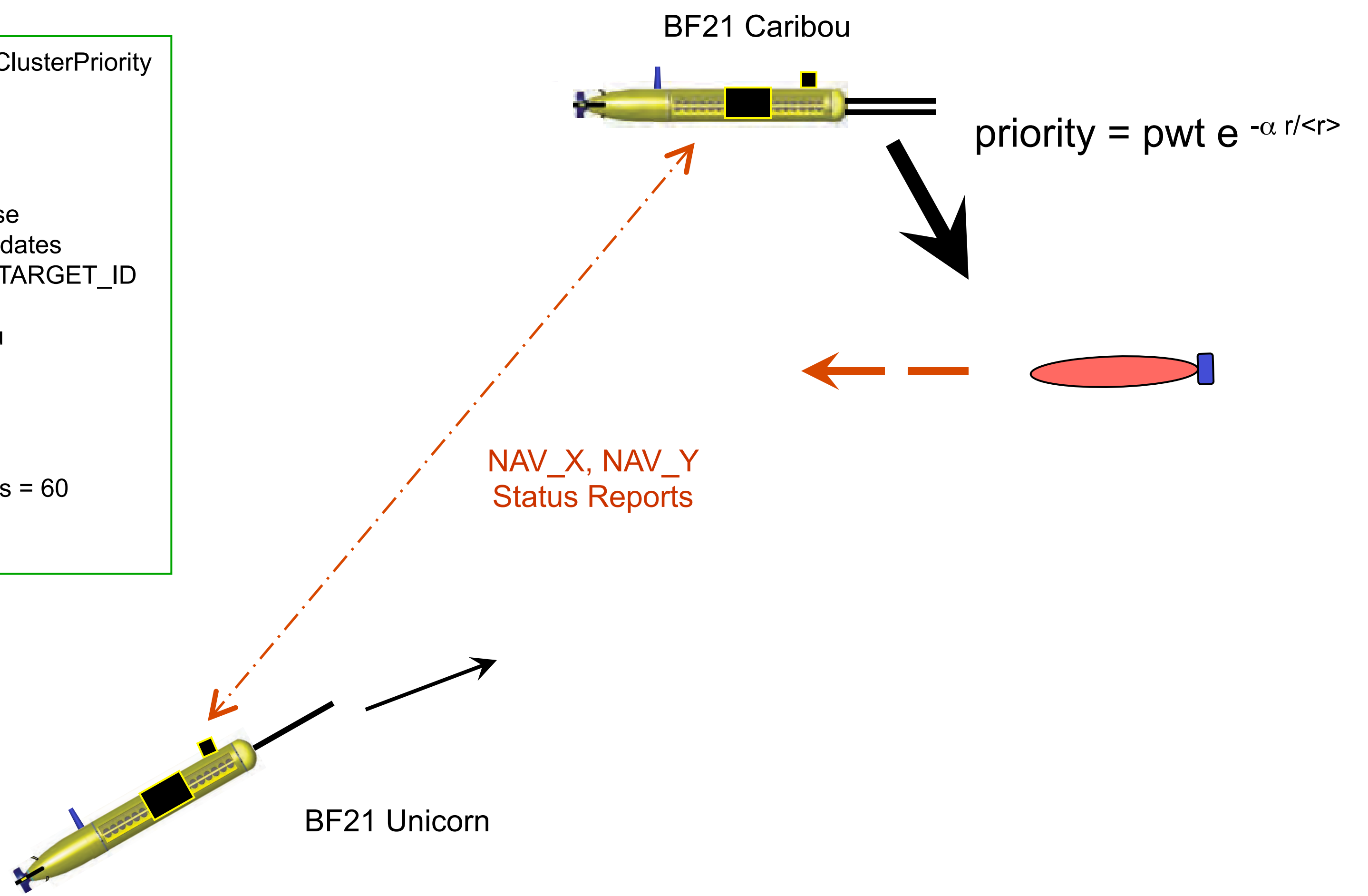
BHV_ArrayAngle

```
 Behavior = BHV_HArrayAngle
{
  name = track_array_angle
  pwt  = 100
  width = 60
  desired_angle = 90
  condition = MODE == TRACKING
}
```



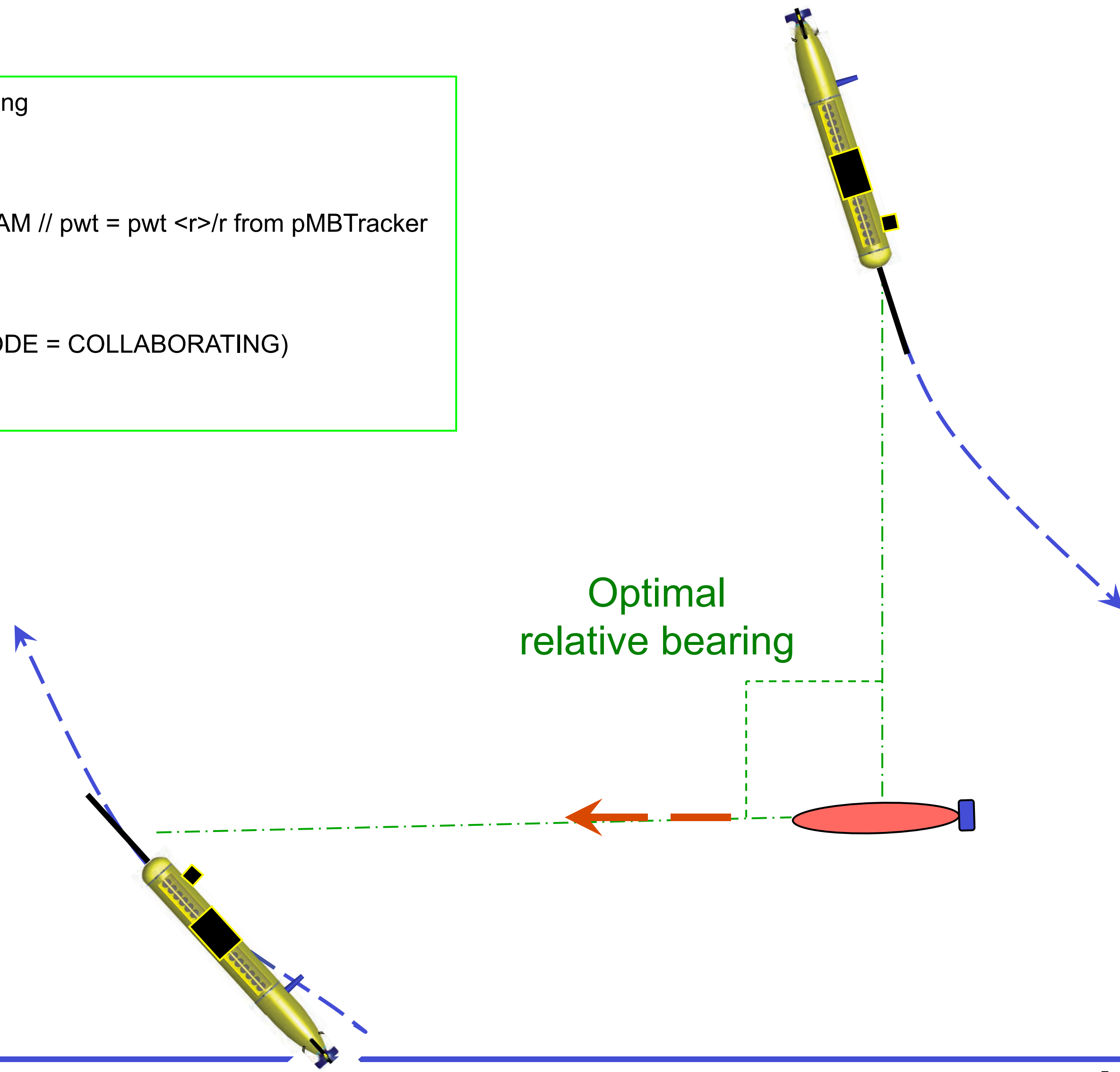
Collaborative Autonomy
pClusterPriority

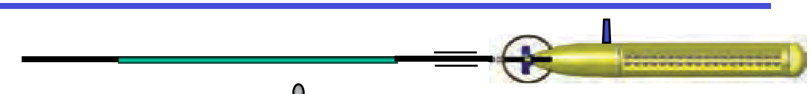
```
ProcessConfig = pClusterPriority
{
  AppTick    = 4
  CommsTick  = 4

  verbosity = verbose
  target = target_updates
  target_updates = TARGET_ID

  ownship = caribou
  friend = unicorn

  pwt =  100

  max_delay_friends = 60
}
```



Collaborative Autonomy
BHV_CollaborativeTracking

```
Behavior = BHV_CollaborativeTracking
{
  name = 2v_tracking
  pwt = 140
  updates = COLLABORATION_PARAM // pwt = pwt <r>/r from pMBTracker
  position_uncertainty = 1
  measurement_uncertainty = .017
  condition = MODE == TRACKING
  condition = (COLLABORATION_MODE = COLLABORATING)
}
```





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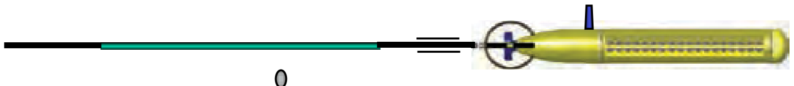
Nested Autonomy

Ocean Acoustic Sensing
Environmental Ocean Acoustics



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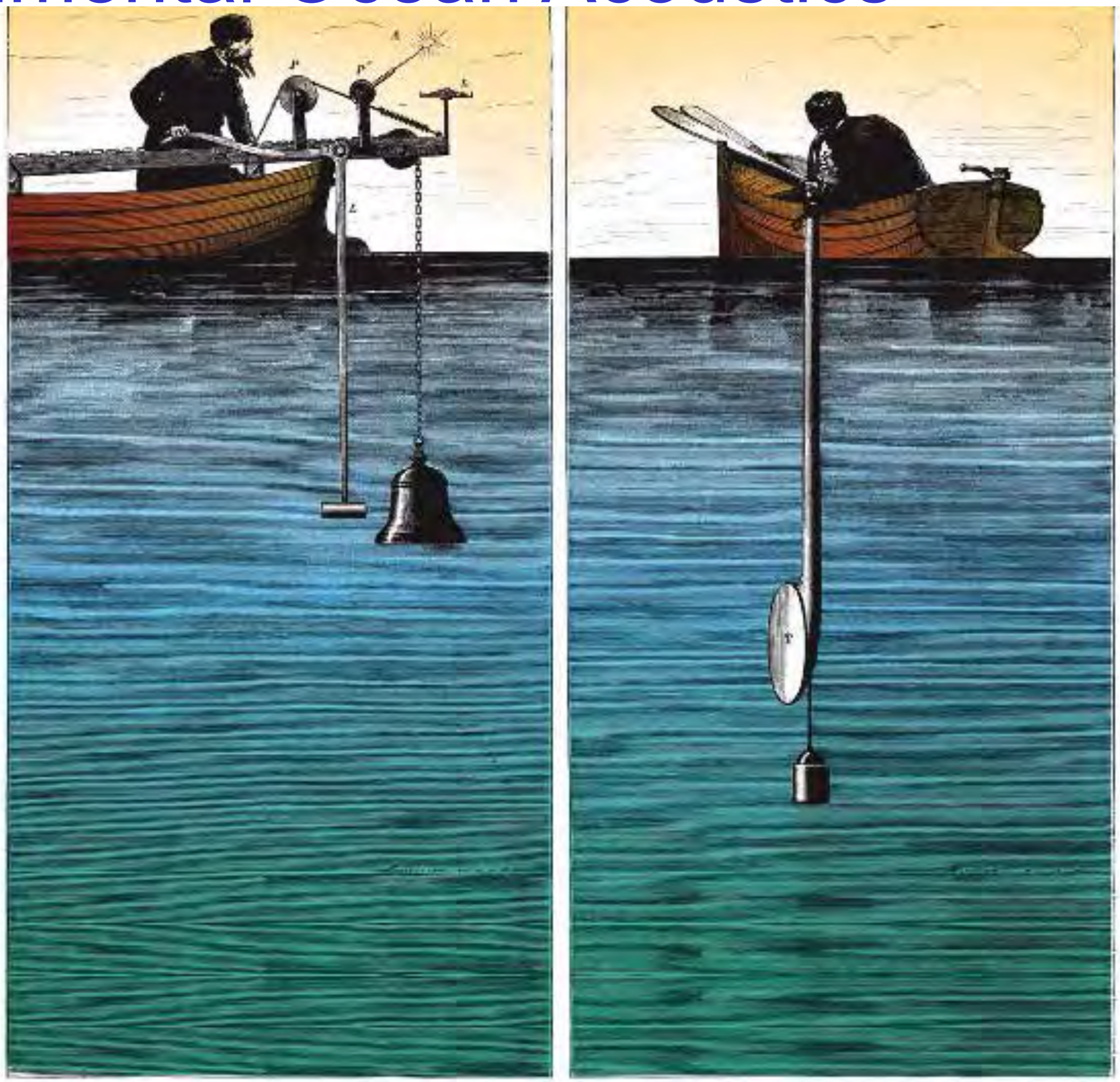
What is “Environmental Ocean Acoustics”

- Understanding and Modeling the generation and propagation of sound in the ocean
  - The ocean is a “thin” sheet with horizontal extend ~ 100 times the vertical, creating a waveguide.
  - Sound speed variability
    - ~ 10% in vertical
    - ~ 1% in horizontal for typical propagation ranges
  - Boundary Interaction
    - Bottom an “infinite” acoustic and elastic medium
    - Ice cover in polar regions
    - Surface waves and bubbles
  - Signals and noise
  - Scattering and Reverberation

The Birth of Environmental Ocean Acoustics



Colladen and Sturm
Lake Geneva 1826

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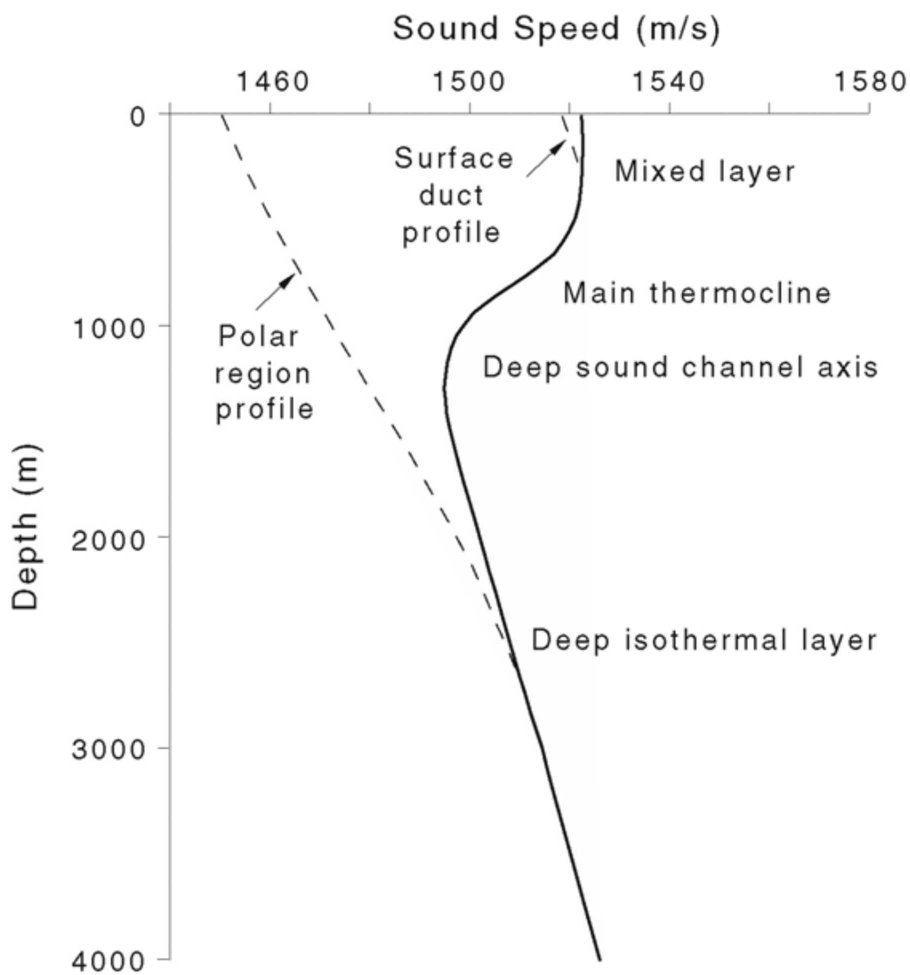
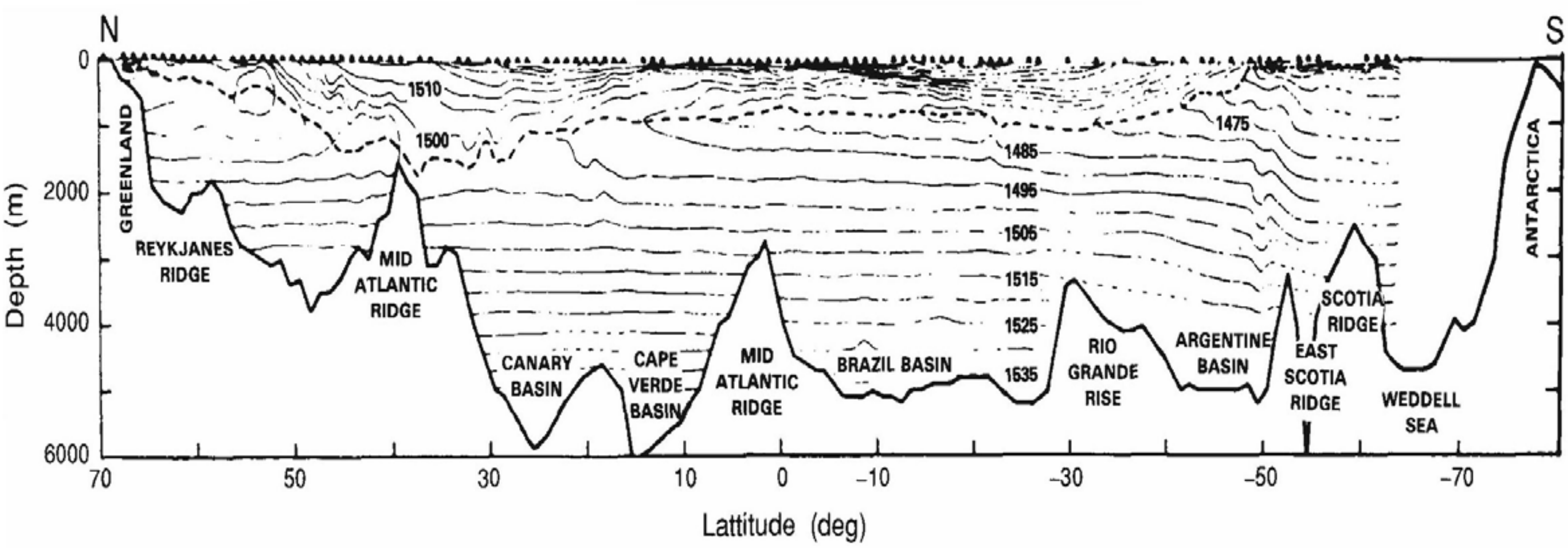
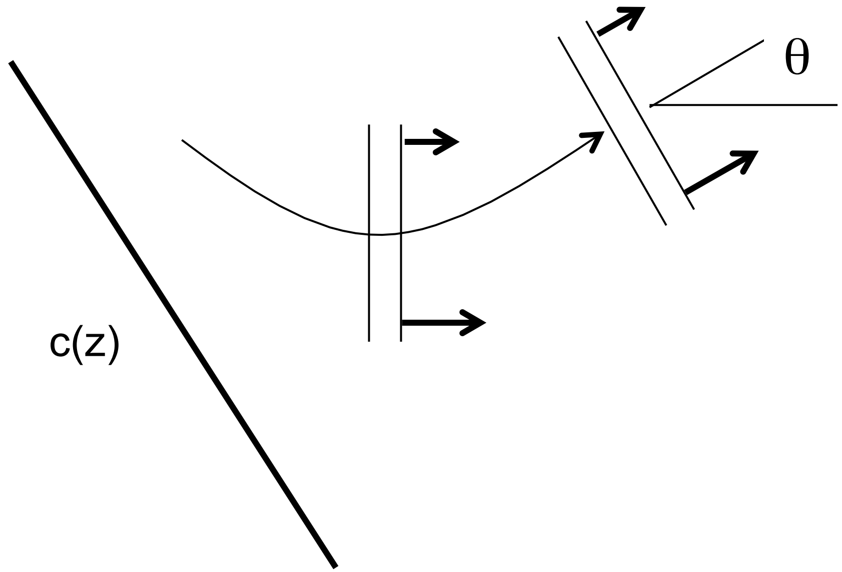
Generic Sound Speed Profile



Global Sound Speed Structure

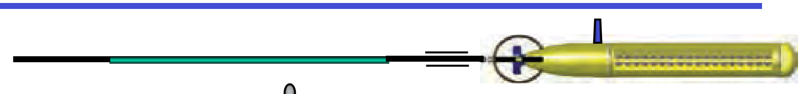


Sound is Attracted to Low Speed of Sound!!

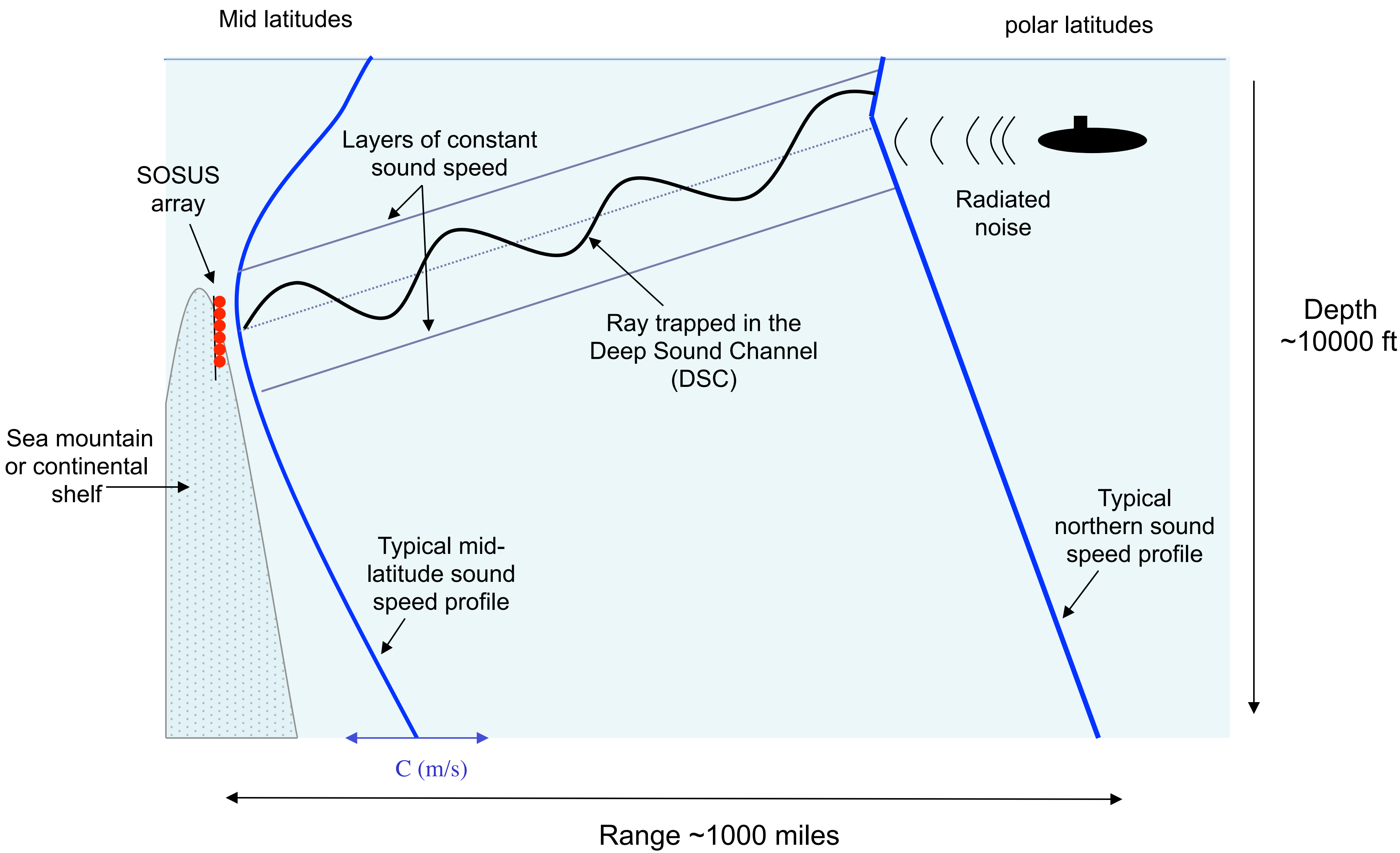


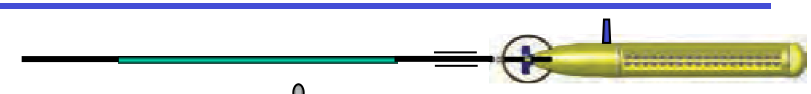
Snell's Law

$$\frac{\cos\ \theta(z)}{c(z)} = \text{const}$$



Adapting Sensor Systems to Environment





Ocean Acoustic Material Properties

Sound Speed

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z.$$

Snell's Law

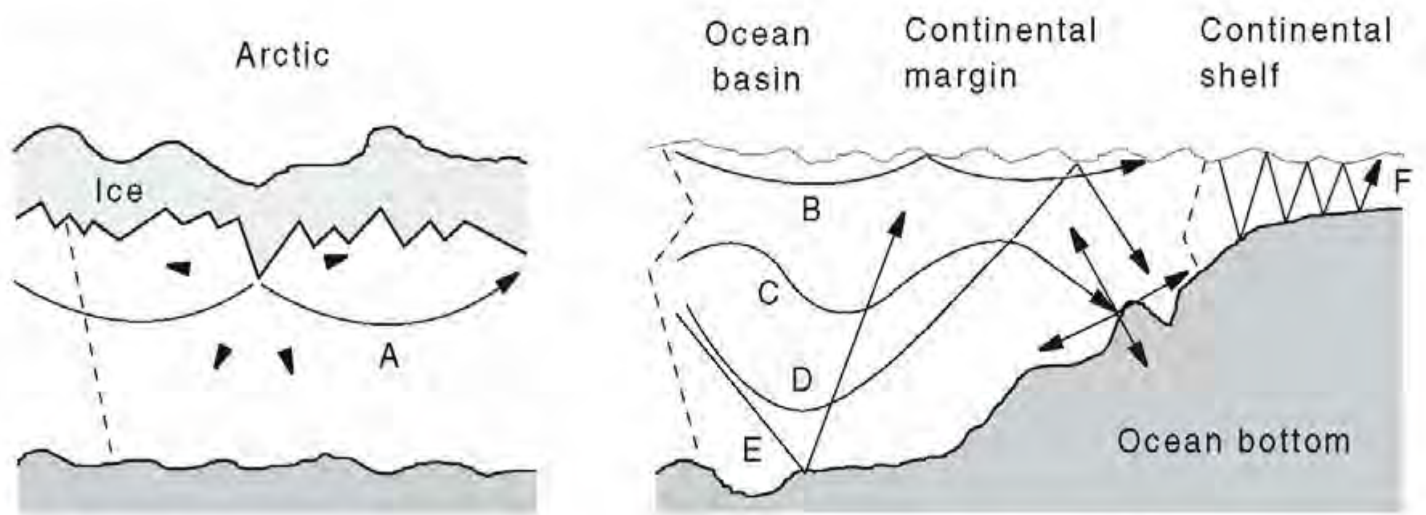
$$\frac{\cos\theta}{c} = constant,$$

Attenuation

$$A = A_0 \exp(-\alpha x),$$

$$\alpha(dB/km) = 3.3 \times 10^{-3} + \frac{0.11 f^2}{1 + f^2} + \frac{43 f^2}{4100 + f^2} + 2.98 \times 10^{-4} f^2,$$

Ocean Waveguide Propagation Paths



A. Arctic

B. Surface duct

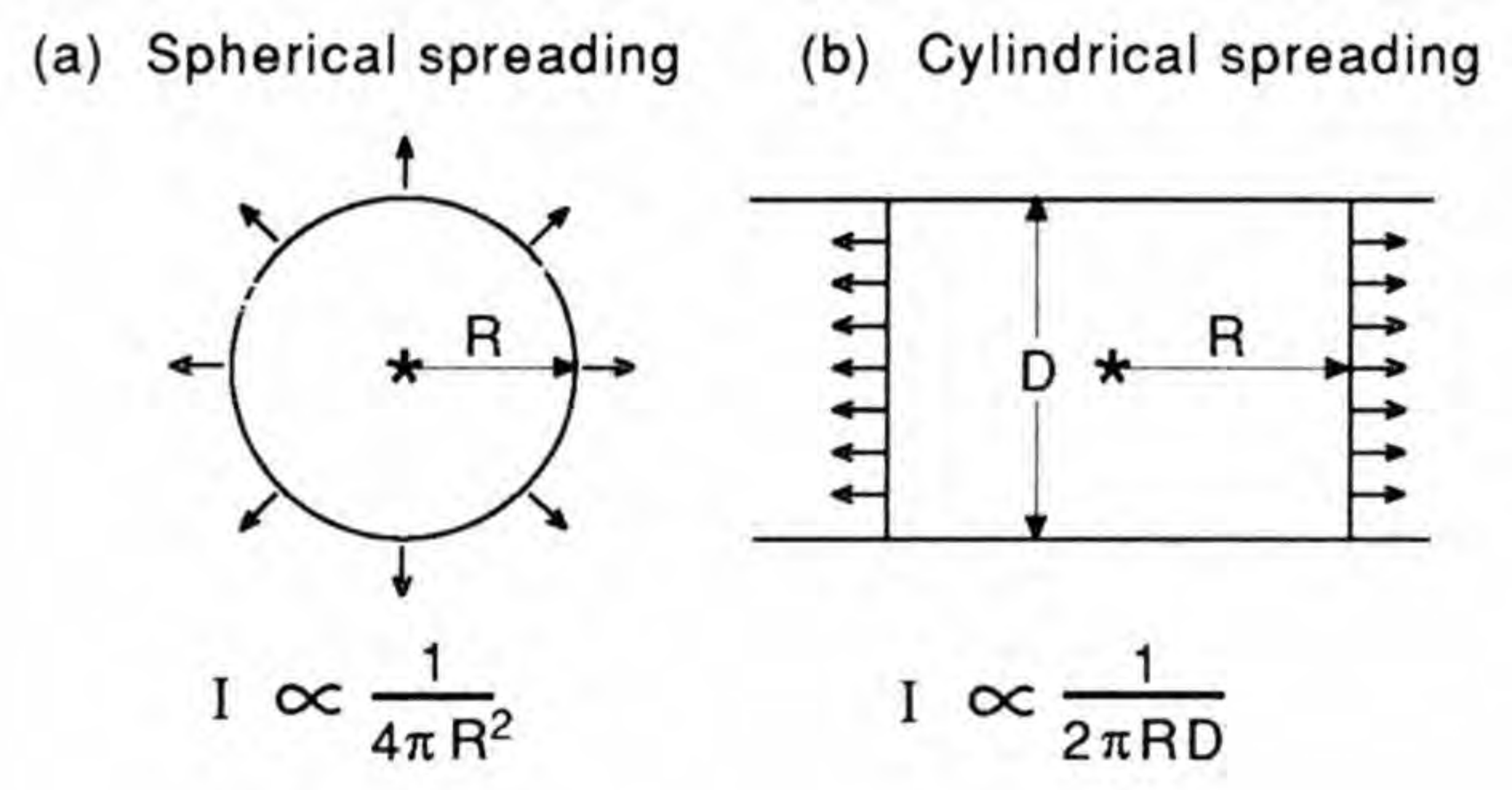
C. Deep sound channel

D. Convergence zone

E. Bottom bounce

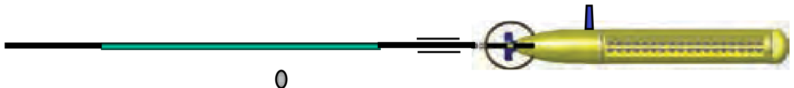
F. Shallow water

Geometric Spreading



Transmission Loss

$$TL = 20 \log_{10} \frac{p(r;z)}{p(r=1m)} = 10 \log_{10} \frac{I(r;z)}{I(r=1m)}$$



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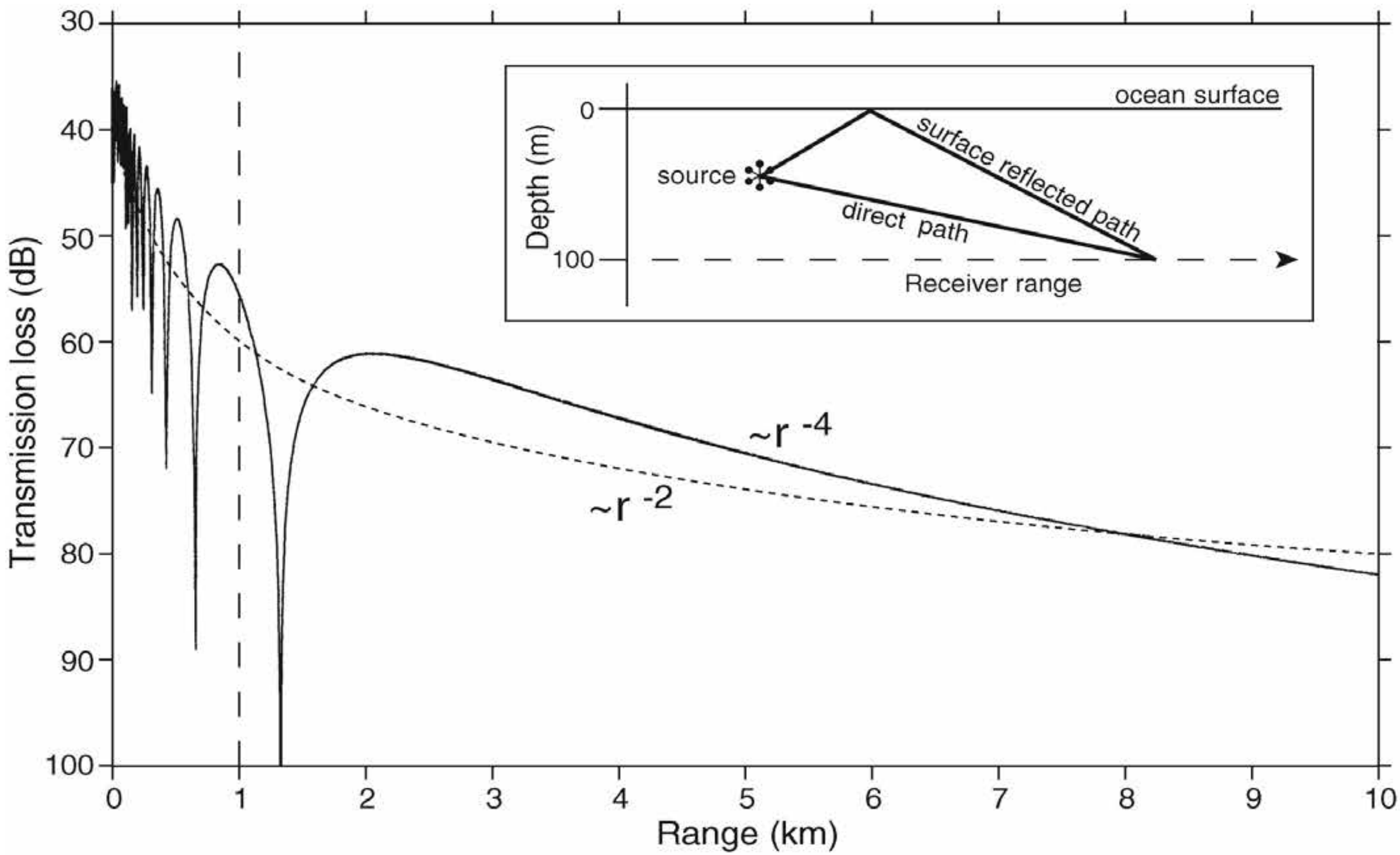
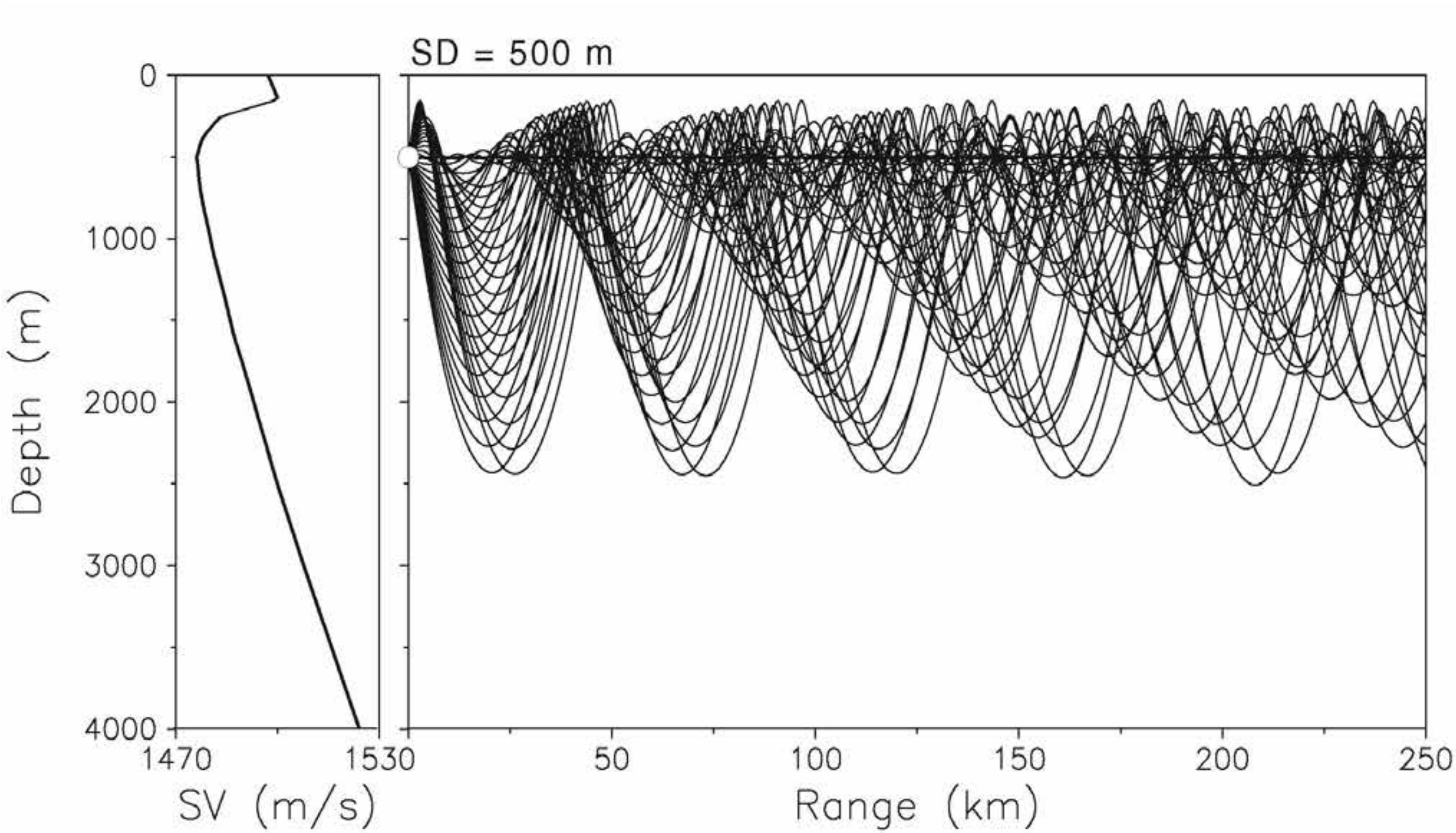
Ocean Waveguide Boundary Effects
Lloyd-Mirror Pattern



Deep Ocean Waveguide Propagation
SOFAR Channel Propagation
Norwegian Sea



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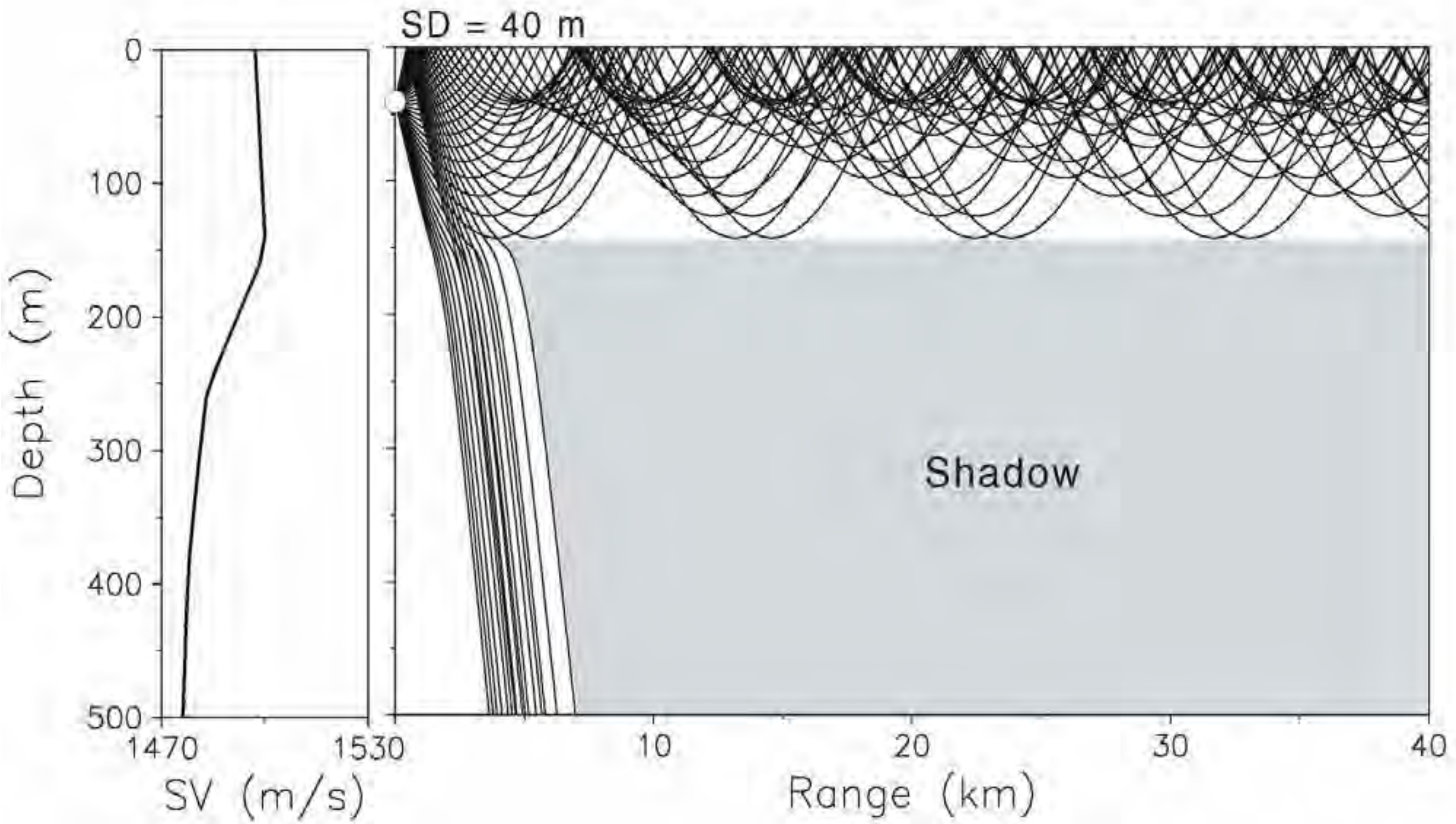
Deep Ocean Waveguide Propagation
Surface Duct Propagation
Norwegian Sea



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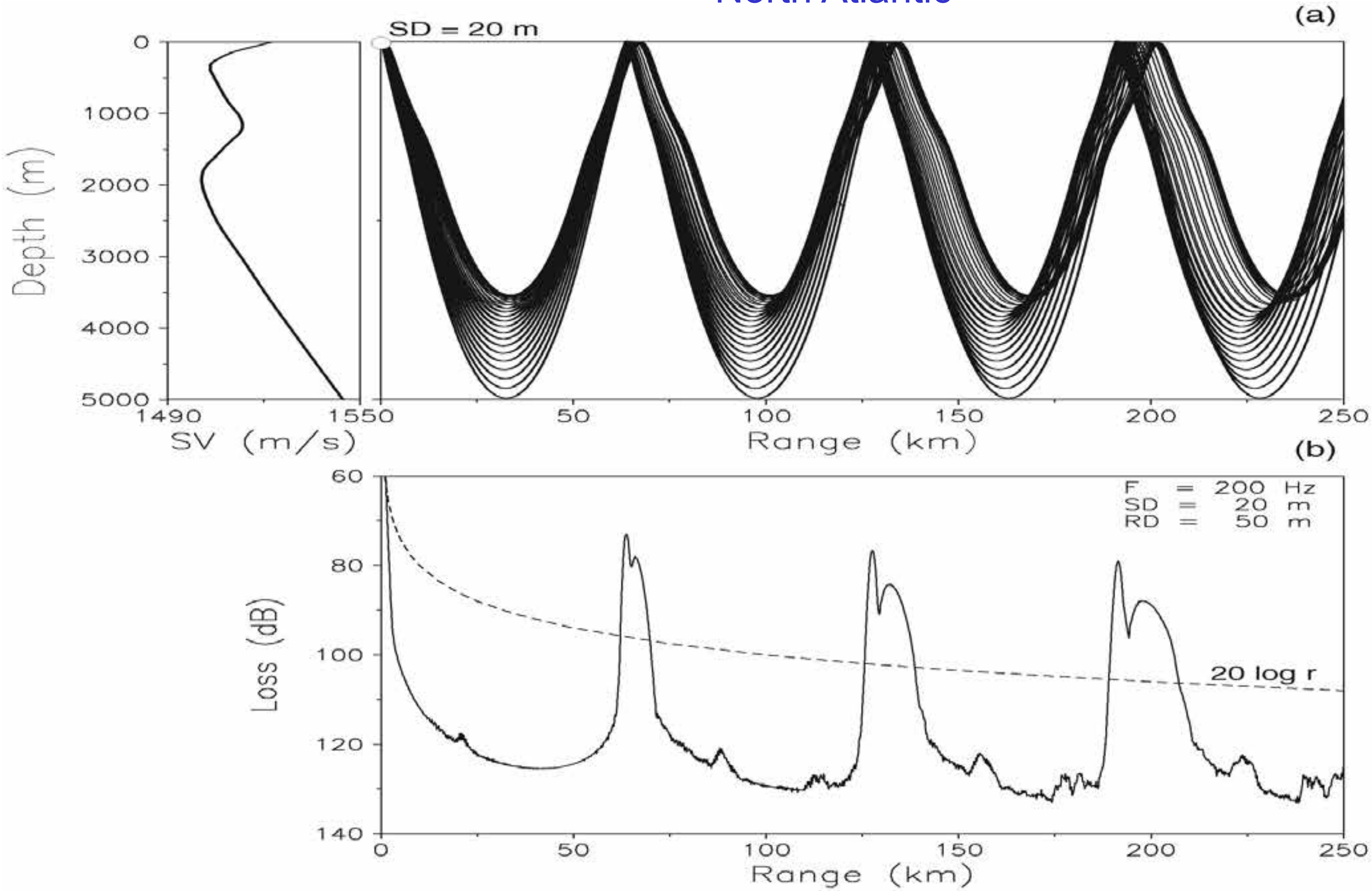
Deep Ocean Waveguide Propagation
Convergence Zone Propagation
North Atlantic



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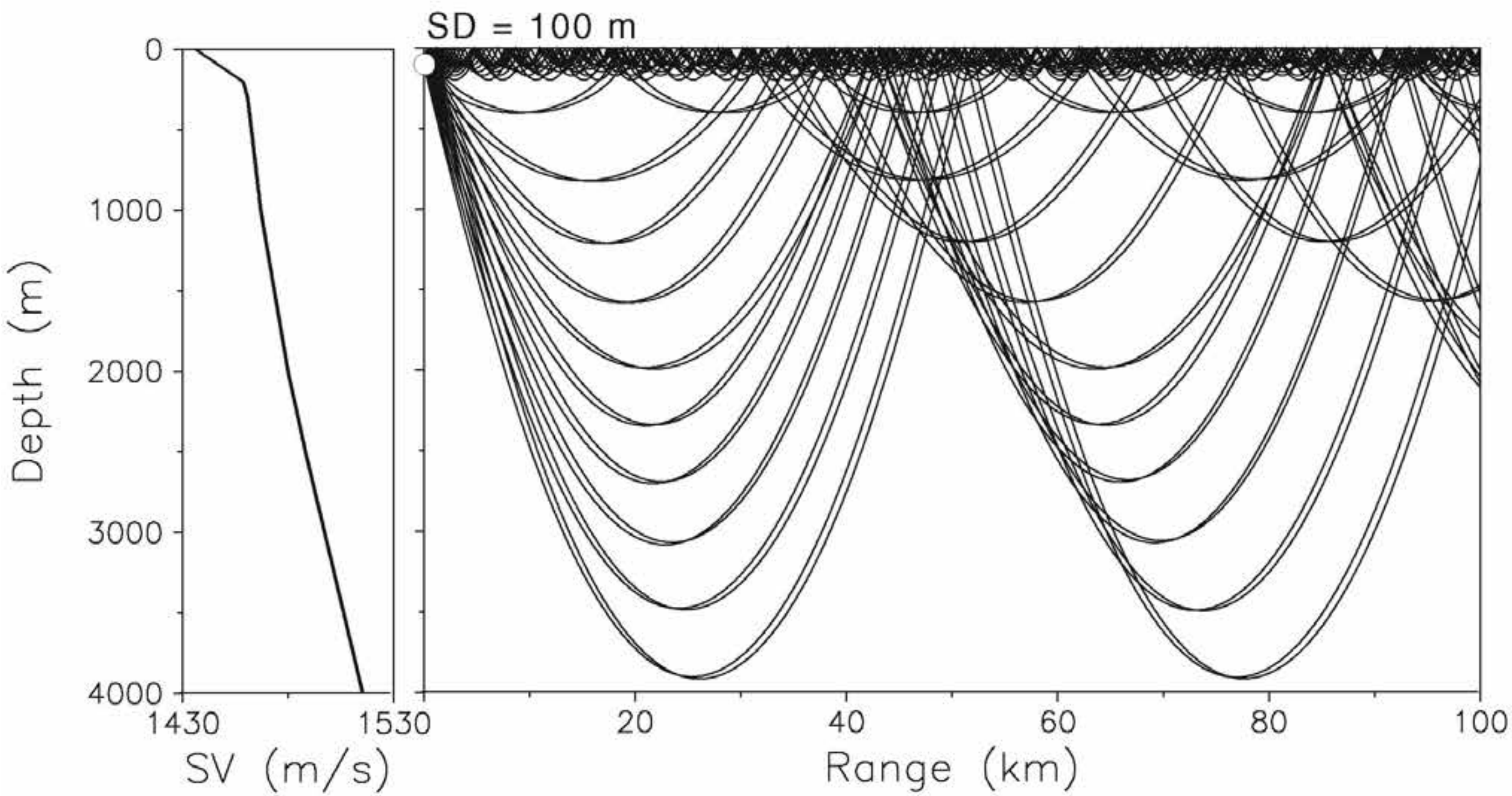
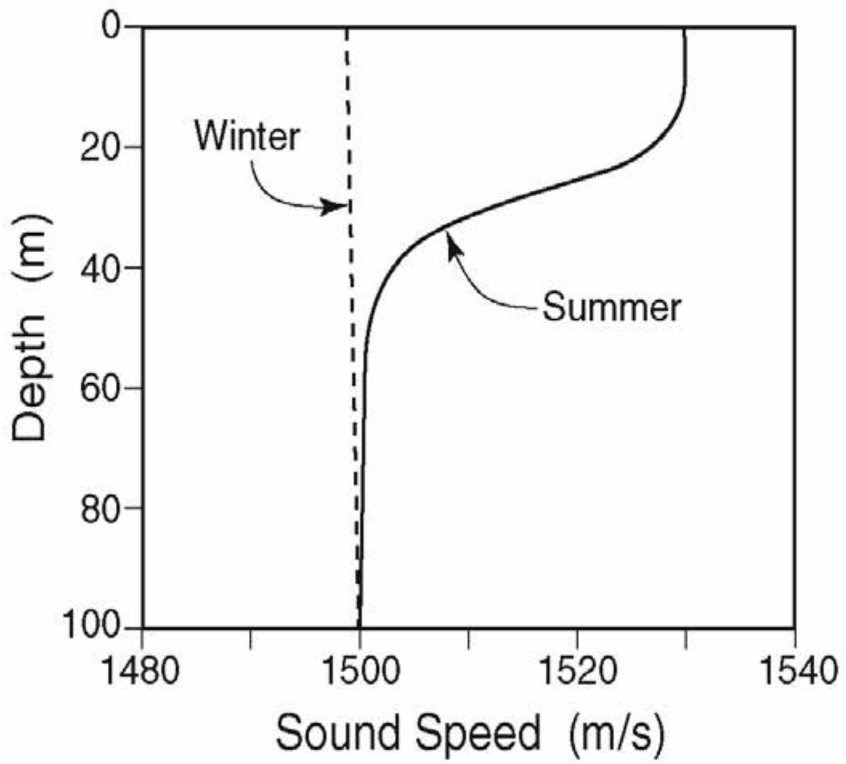
Deep Ocean Waveguide Propagation
Polar Environments
Arctic Ocean

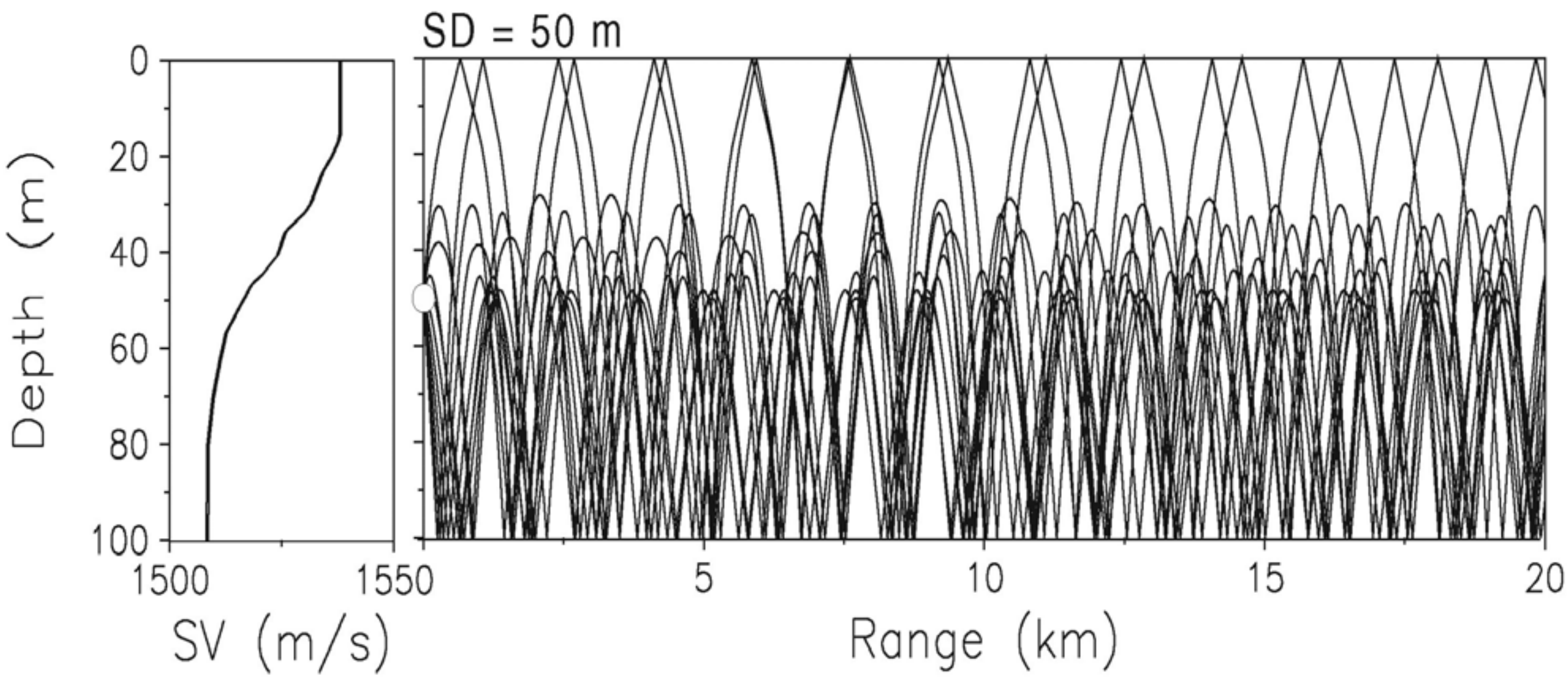


Shallow Water Seismo-Acoustics



Shallow Water Propagation

Mediterranian Summer



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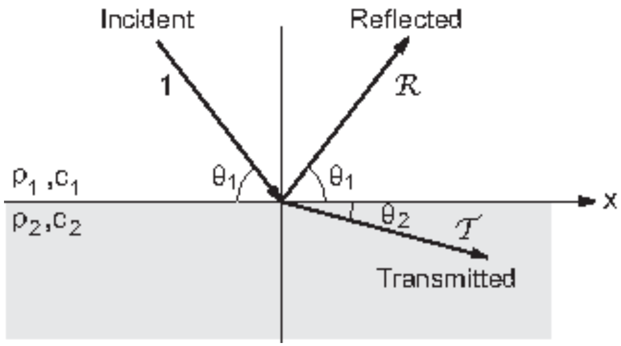
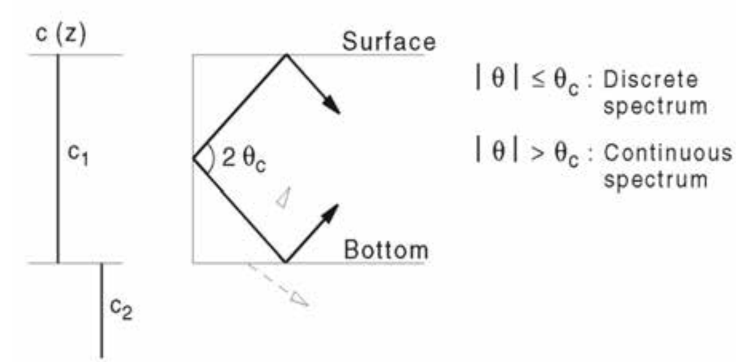
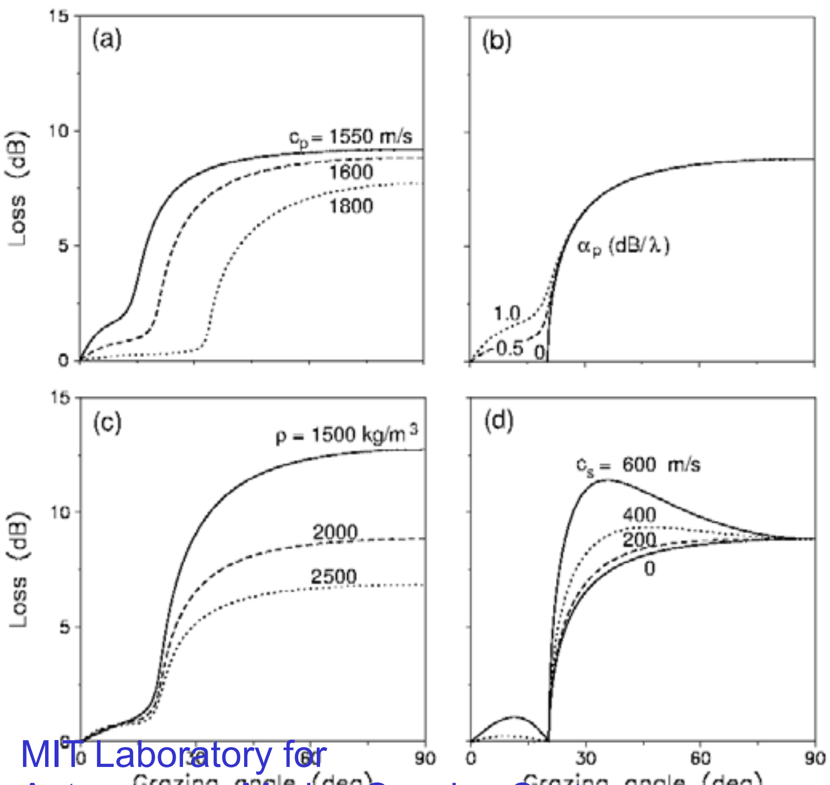
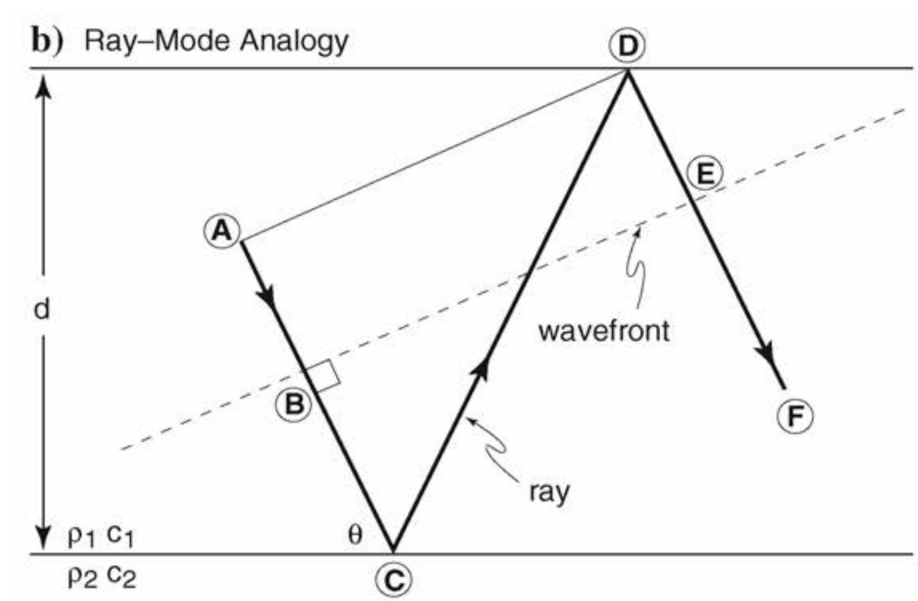
Shallow Water Acoustics
Bottom Interaction

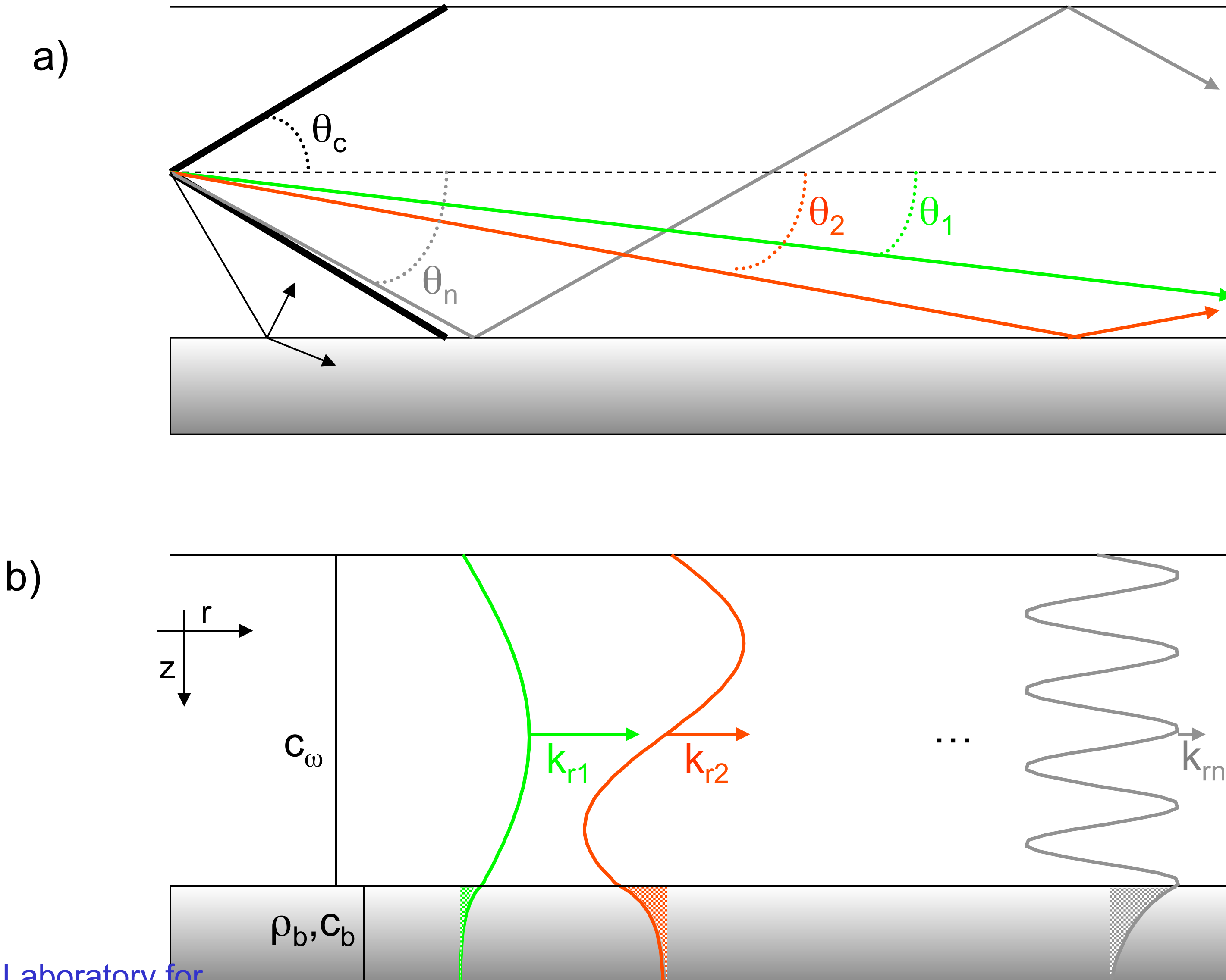






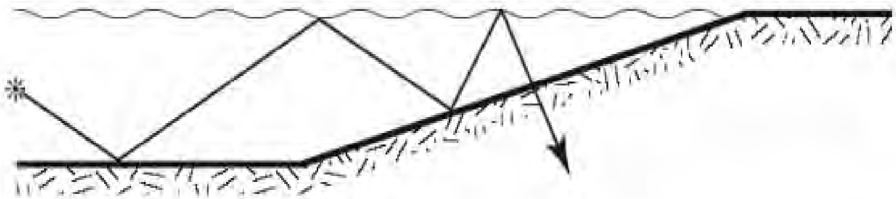


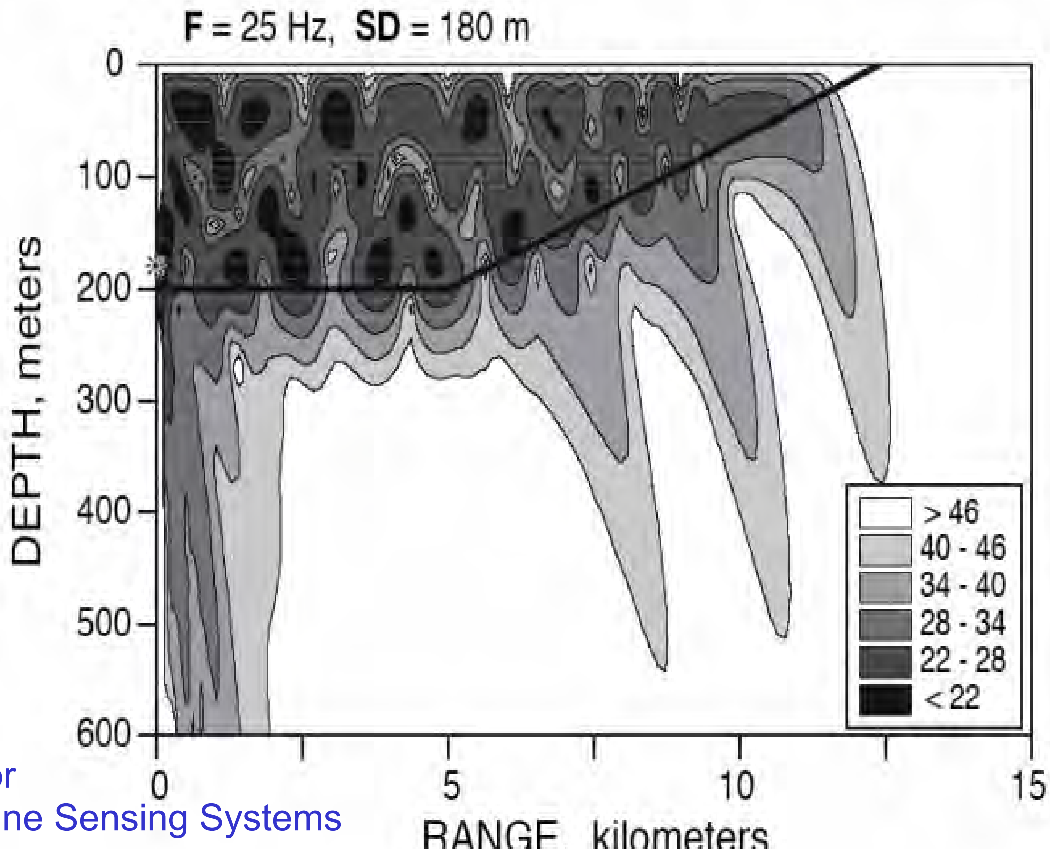
Shallow Water Propagation
Ray-Mode Analogy



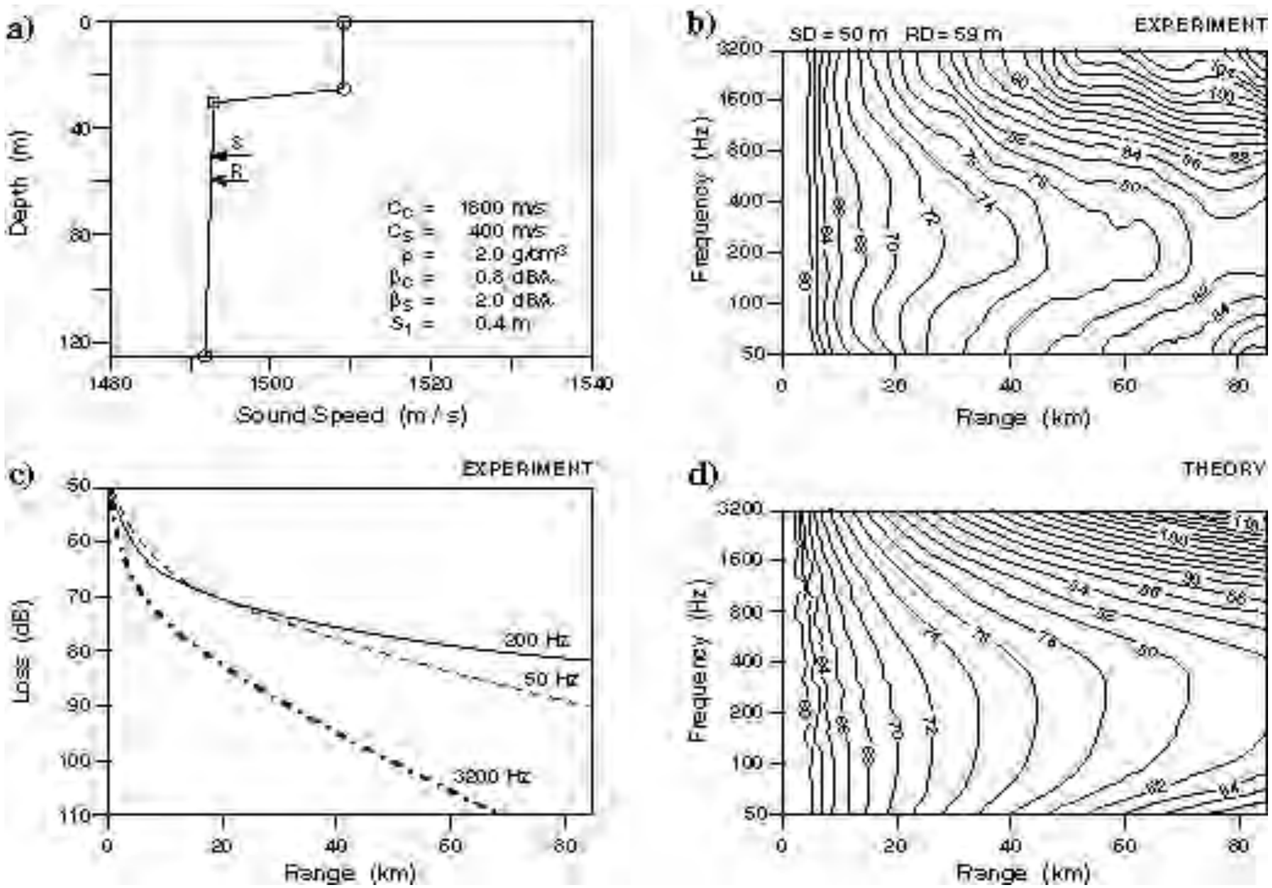
Box 2

Shallow Water Acoustics
Mode Cutoff

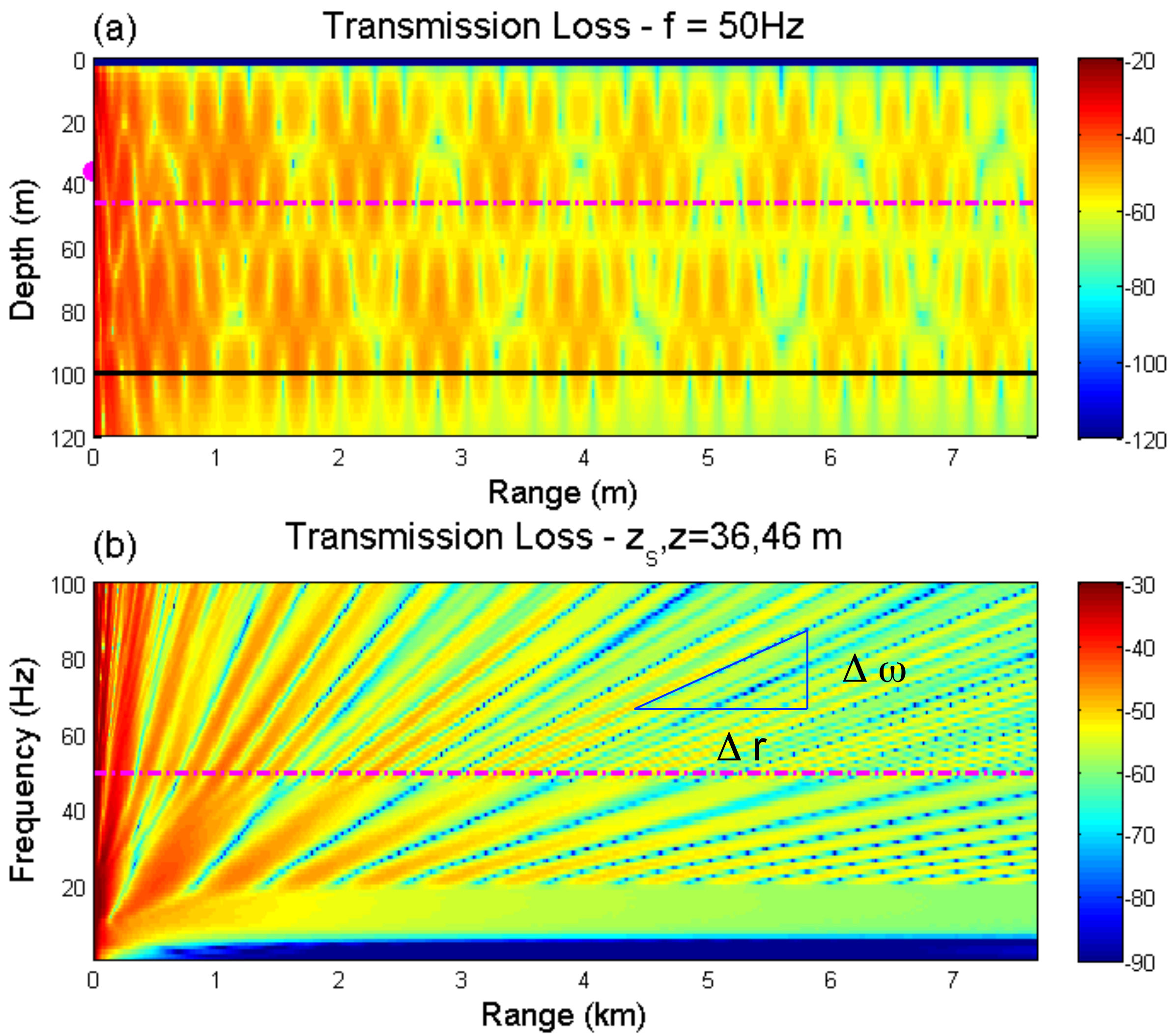




OPTIMUM FREQUENCY CURVES



Shallow Water Propagation
Modal Interference



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Waveguide Invariants

Taylor Expansion for Group of Modes

$$s_{gn} = s_g + \frac{ds_g}{ds_p}(s_{np} - s_p) \,,$$

Frequency-Range TL Maxima

$$\frac{\Delta r}{\Delta \omega} = -\frac{r}{\omega}\frac{ds_g}{ds_p} \,.$$

Waveguide Invariant

$$\frac{1}{\beta} \equiv -\frac{ds_g}{ds_p} = -\left(\frac{v}{u}\right)^2 \frac{du}{dv} \,,$$

$$\frac{\Delta \omega}{\Delta r} = \beta \frac{\omega}{r} \,,$$

$$\frac{\omega}{\omega_0} = \left(\frac{r}{r_0}\right)^{\beta} \,.$$

Ideal Waveguide

$$k_{rn} \equiv \omega / v_n = k \cos\theta_n = (\omega/c)\cos\theta_n$$

Phase and Group velocity

$$v_n = \frac{\omega}{k_r} = \frac{c}{\cos\theta_n}$$

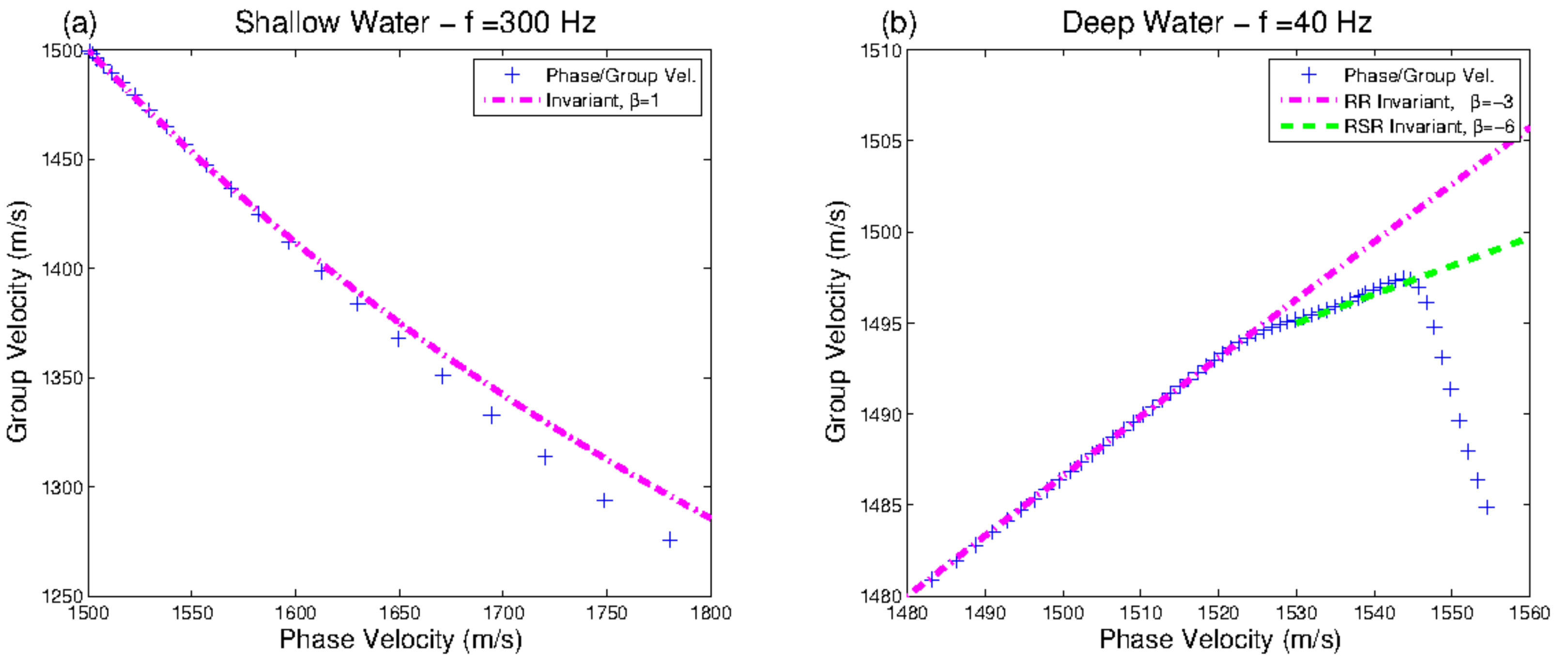
$$u_n = c \cos\theta_n$$

$$\beta = \cos^2\theta \,.$$

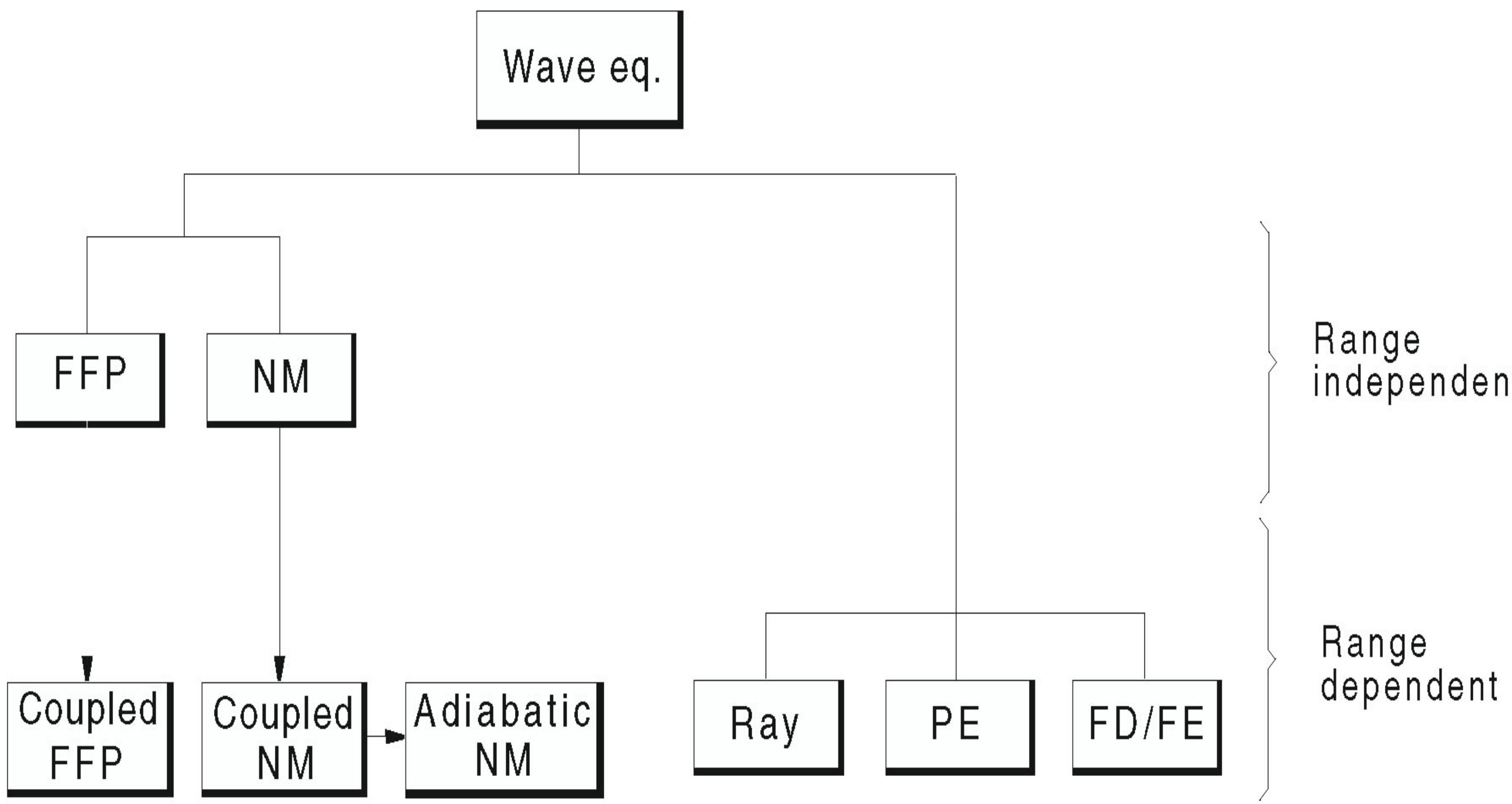
Small grazing angles

$$\beta \approx 1$$

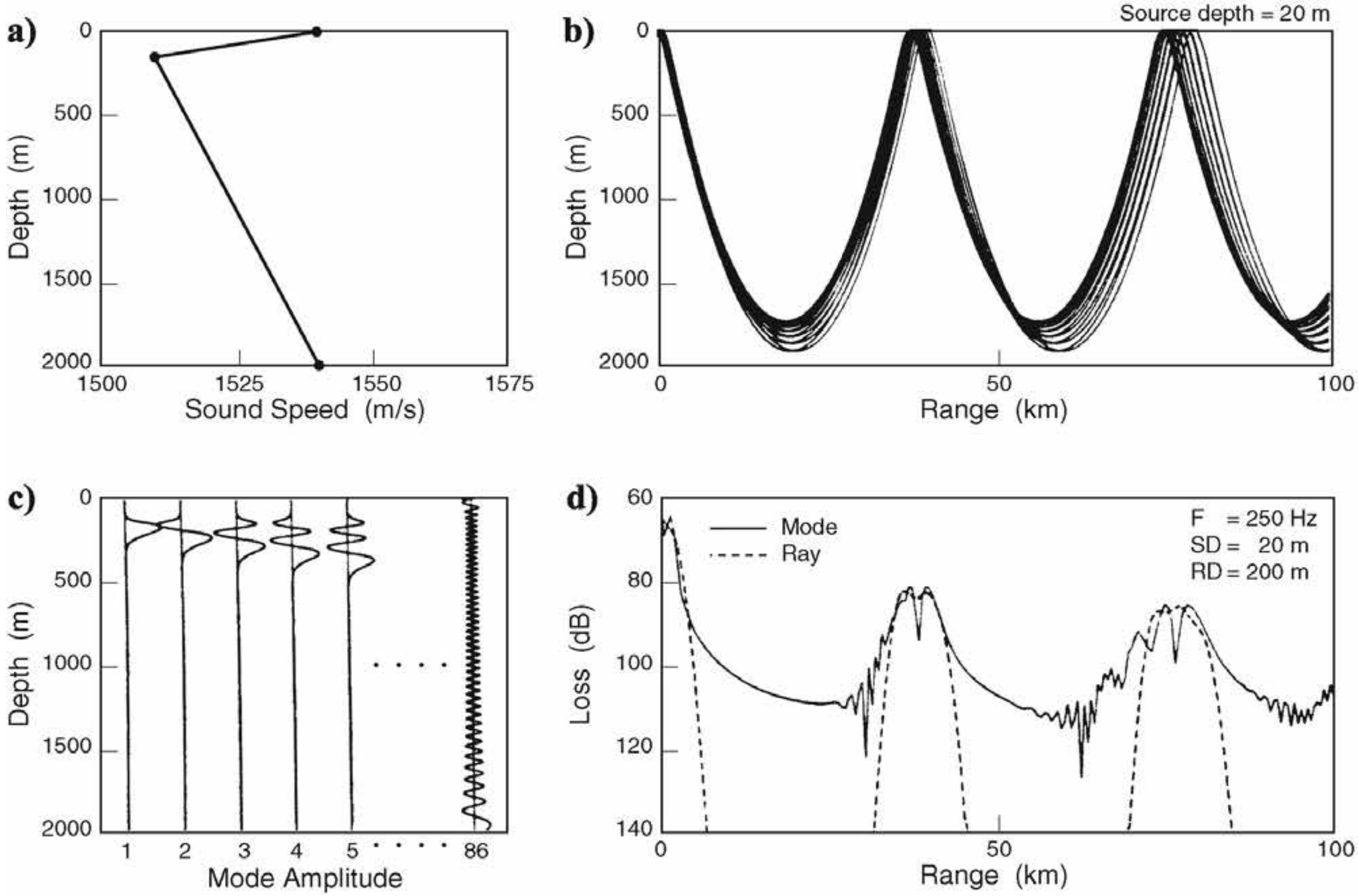
Waveguide Invariants



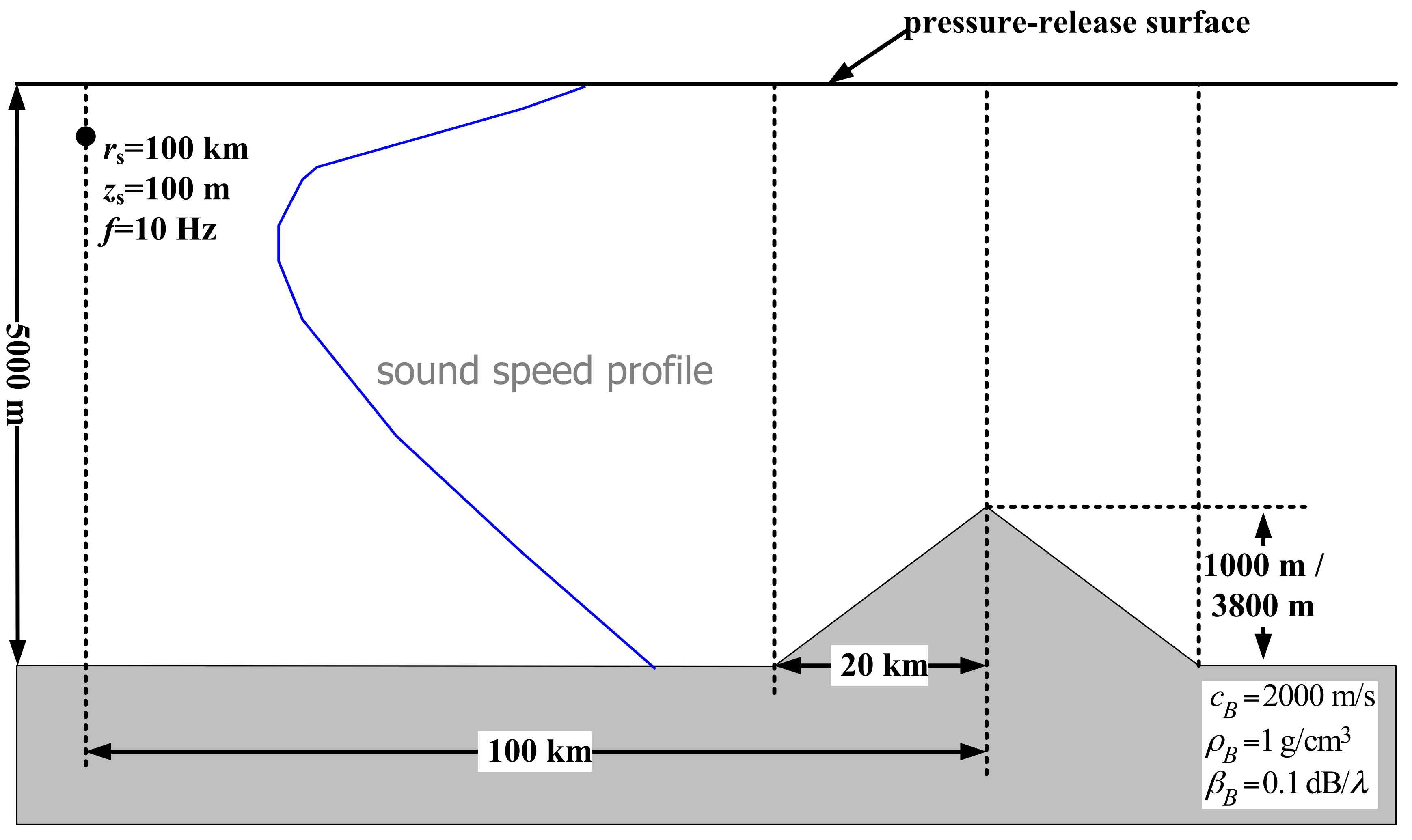
Hierarchy of Underwater Acoustic Propagation Models



Model Consistency
Normal Modes and Rays



3D Propagation Around Conical Seamount



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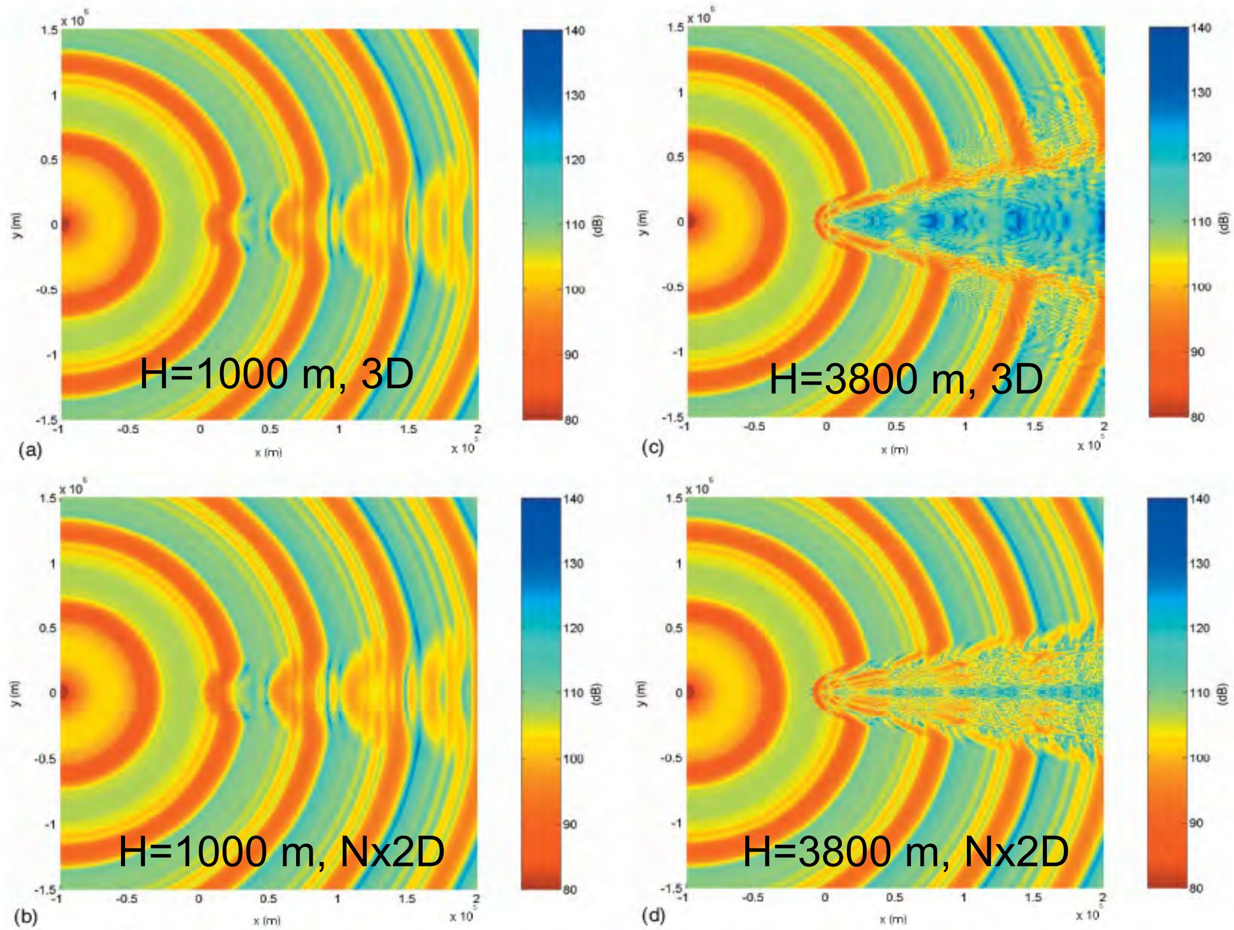
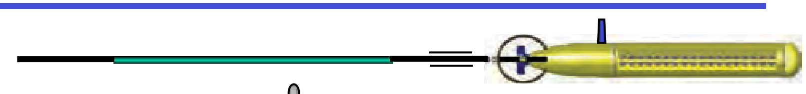
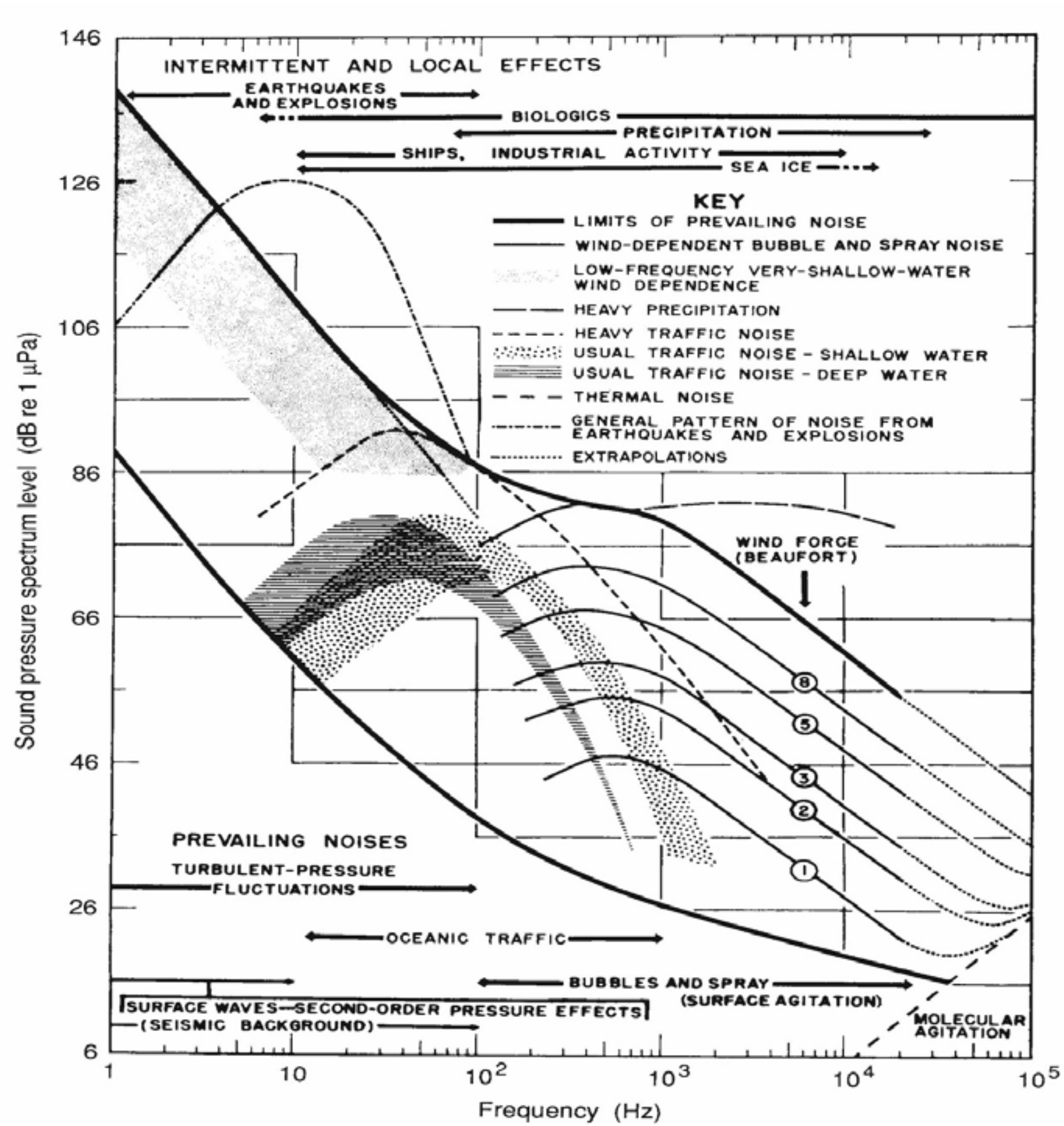
Comparison between 3D and Nx2D solutions

TL in the horizontal plane at depth 300 m. The source frequency is 10 Hz.





AMBIENT NOISE SPECTRA
Wenz Curves



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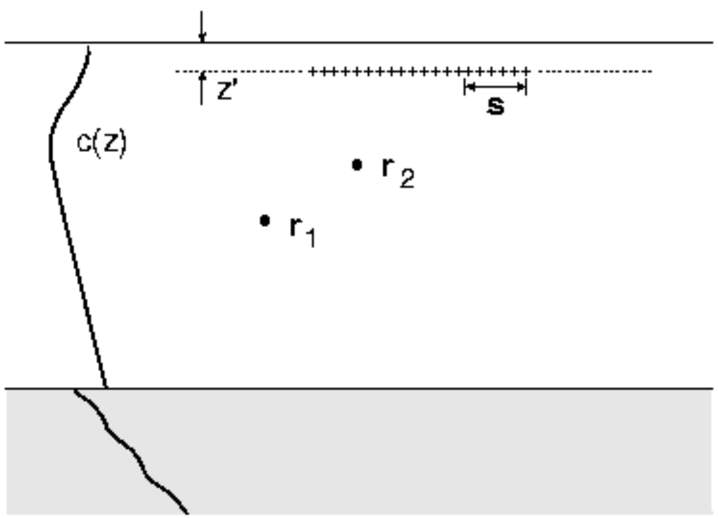
Surface Noise in a Stratified Ocean



Helmholtz Equation - Horizontal Source Distribution

$$(\nabla^2 + k^2)\,\phi_\omega(\mathbf{r}, z) = -S_\omega(\mathbf{r}')\,\delta(z - z')\,,$$

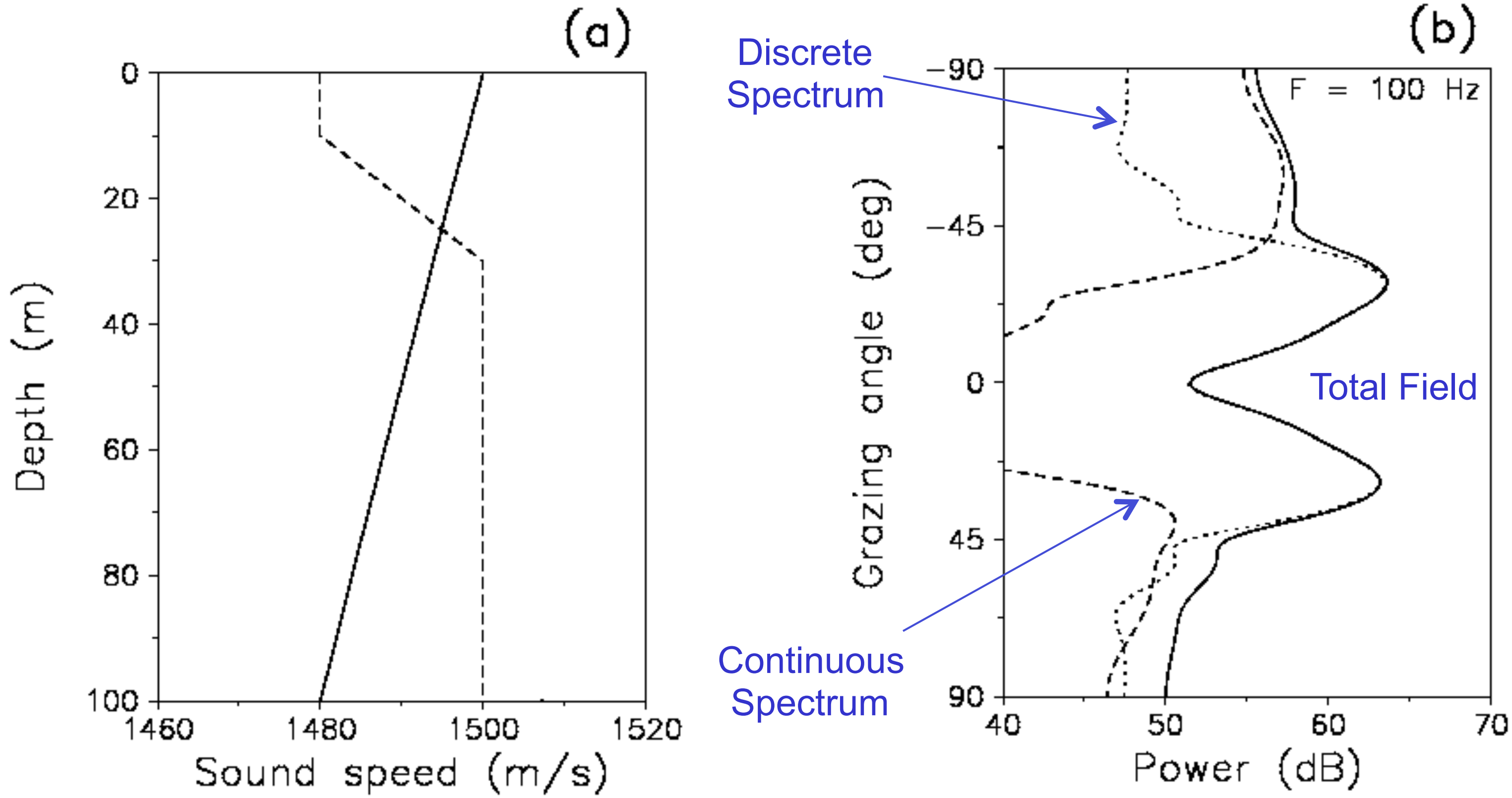
Solution

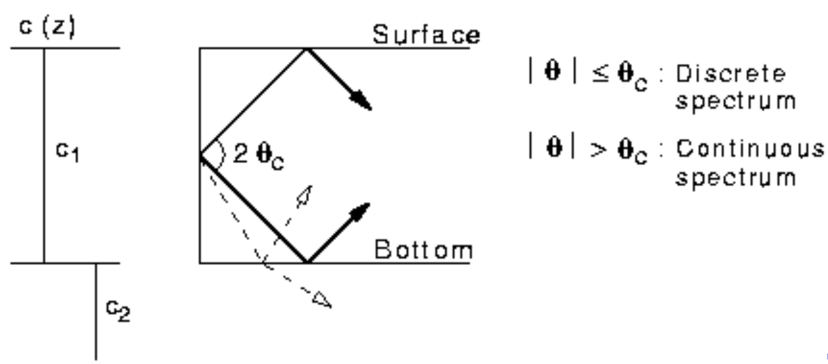
$$\phi(\mathbf{r}, z) = \int S(\mathbf{r}')\,g(\mathbf{r}, \mathbf{r}'; z, z')\,d^2\mathbf{r}',$$

Green's function

$$(\nabla^2 + k^2)\,g(\mathbf{r}, \mathbf{r}'; z, z') = -\delta^2(\mathbf{r} - \mathbf{r}')\,\delta(z - z')\,,$$

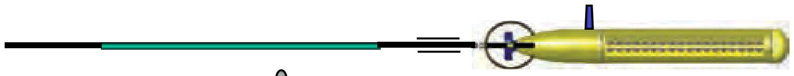
Surface Noise in a Stratified Ocean



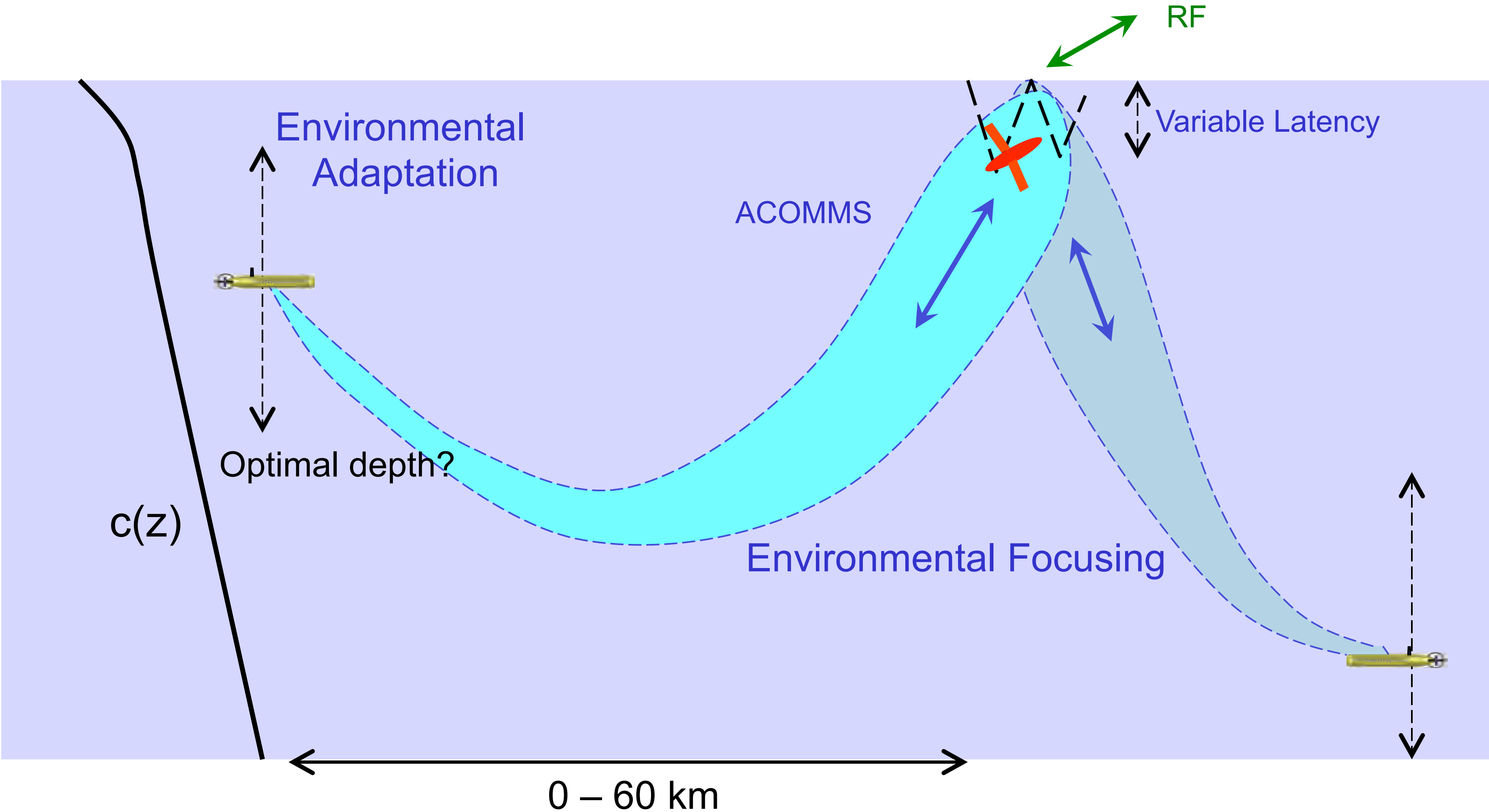


Nested Autonomy

Model-Based Environmental Acoustic Adaptation

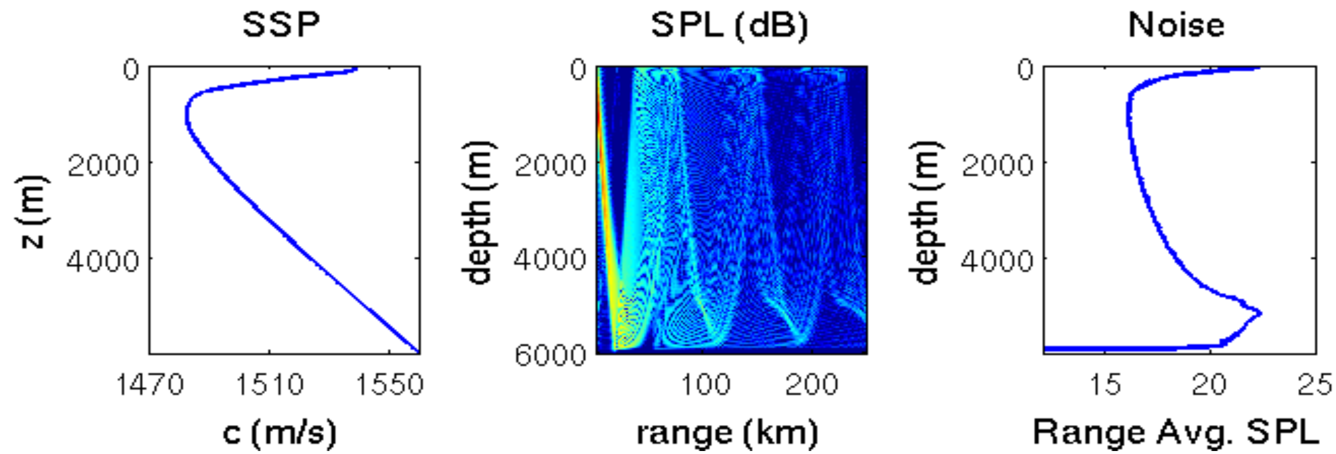


Deep Ocean Sensing and Communication Environmental Adaptation

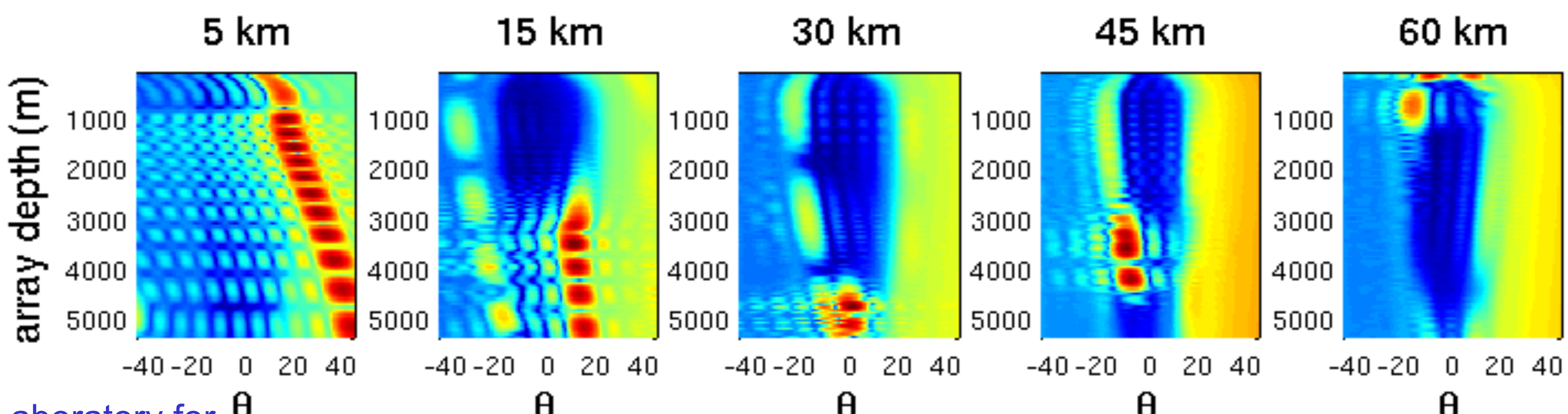


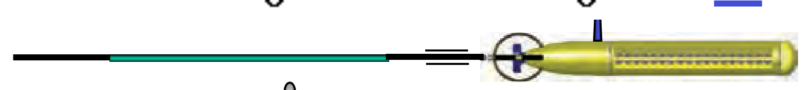
Extending Sonar Range through Depth Adaptation

Full Angular Spectrum Signal and Noise Modeling

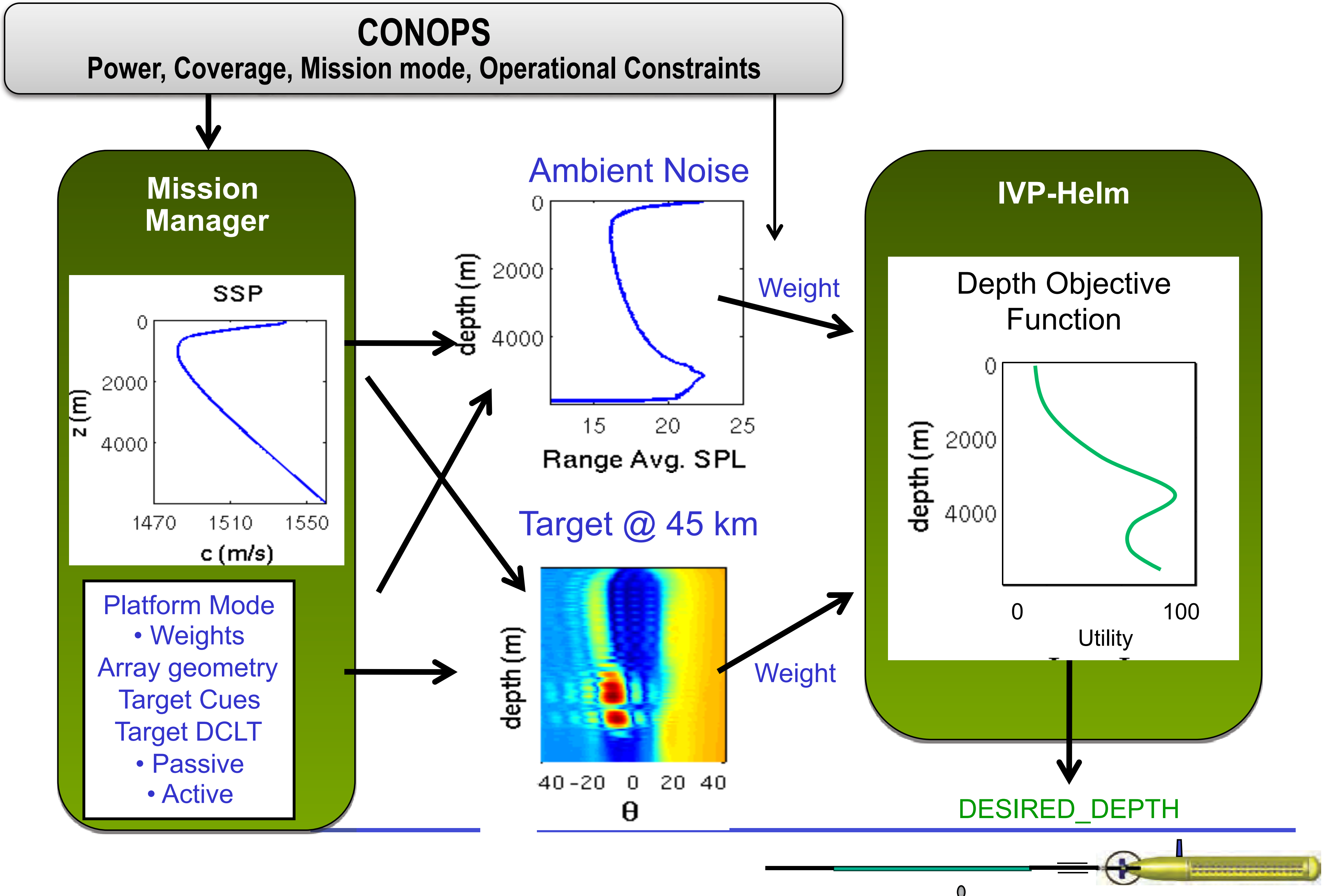


RAP Path Extension by Vertical Mobility





Model-based Environmental Adaptation



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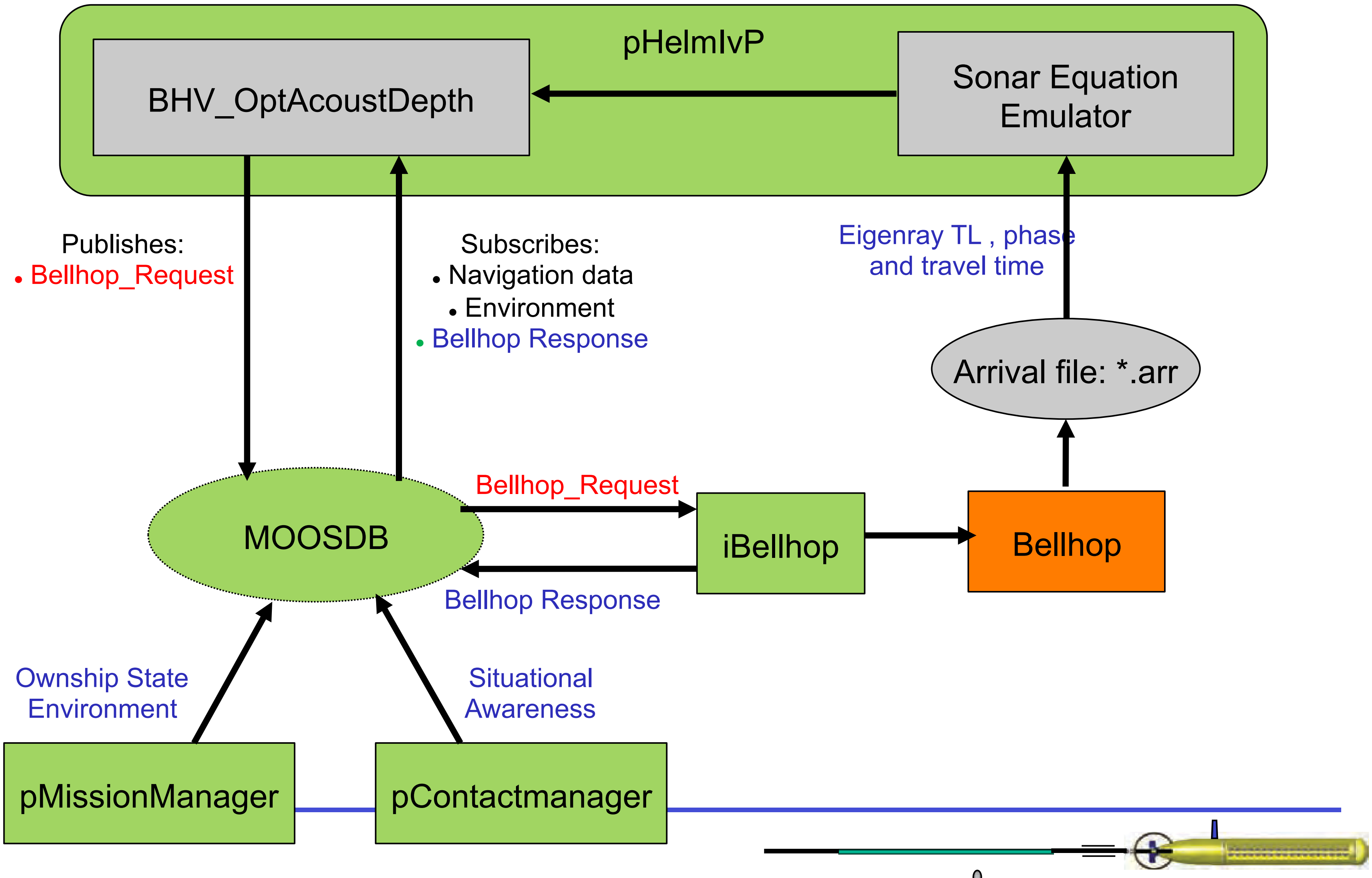
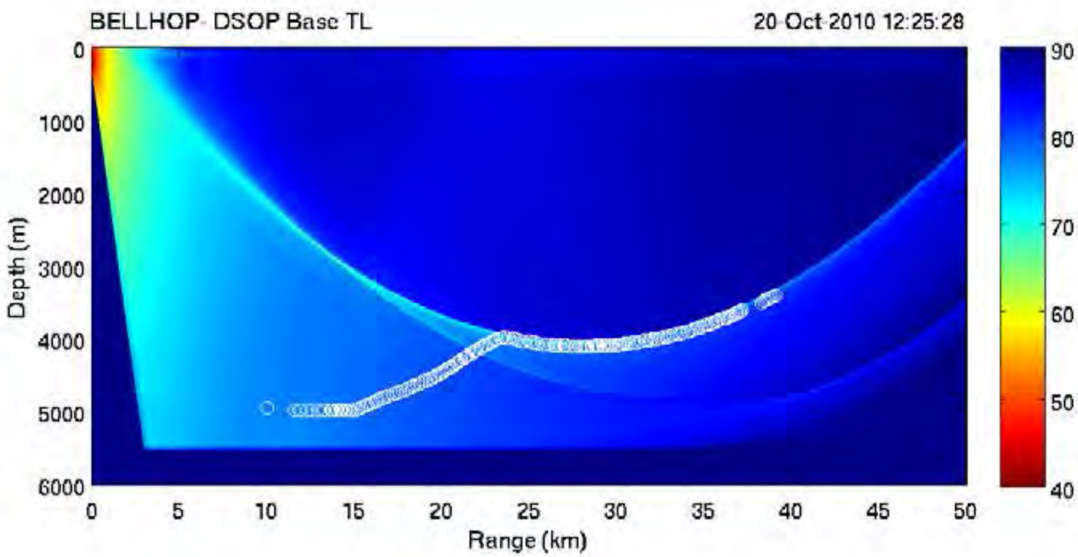
Embedded Environmental Modeling



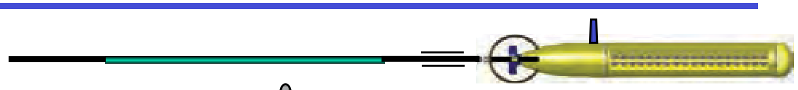
Acoustic Tracking with Depth Adaptation



Transmission Loss

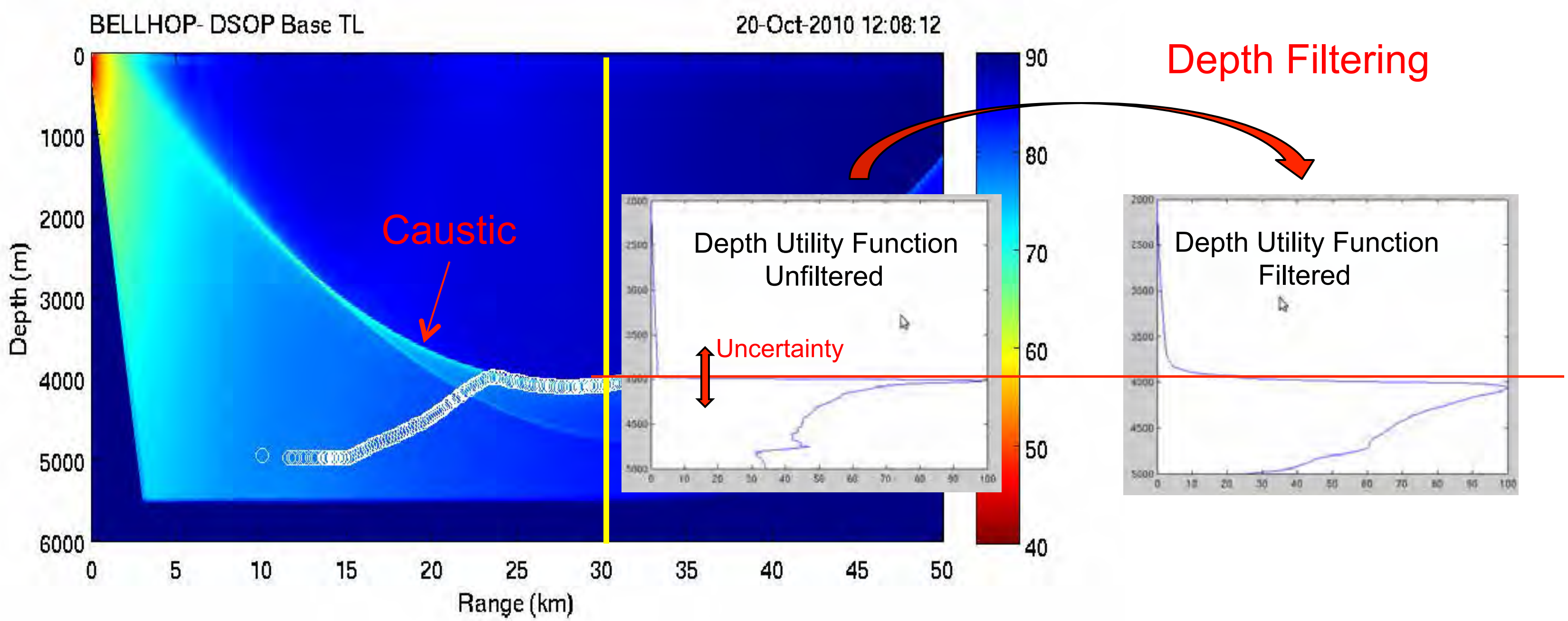
Source depth: 200 m
Source speed: 16 kn
Frequency: 800-1000 Hz

- Prosecute CONOPS
- Detection: Dive to depth with maximum predicted signal excess (SE), align broadside to surveillance bearing, level, fire sonar, drift and adapt to target cue for next ping.
- Tracking: After detection, maintain depth and track source in bearing and range until it moves out towards ½ CZ, then change depth dynamically to depth with max SE for forecast of source track.

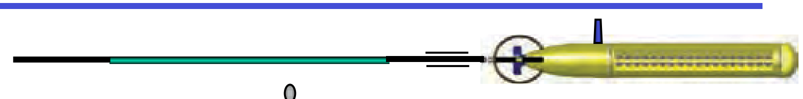


Hold-at-Risk Autonomy

Robust Model-based Adaptation



- Depth-filtering of utility function
- Avoid non-symmetric caustics – Must stay on ‘good side’
- Filtering consistent with statistics of environmental acoustics



Nested Autonomy

Field Deployment Examples

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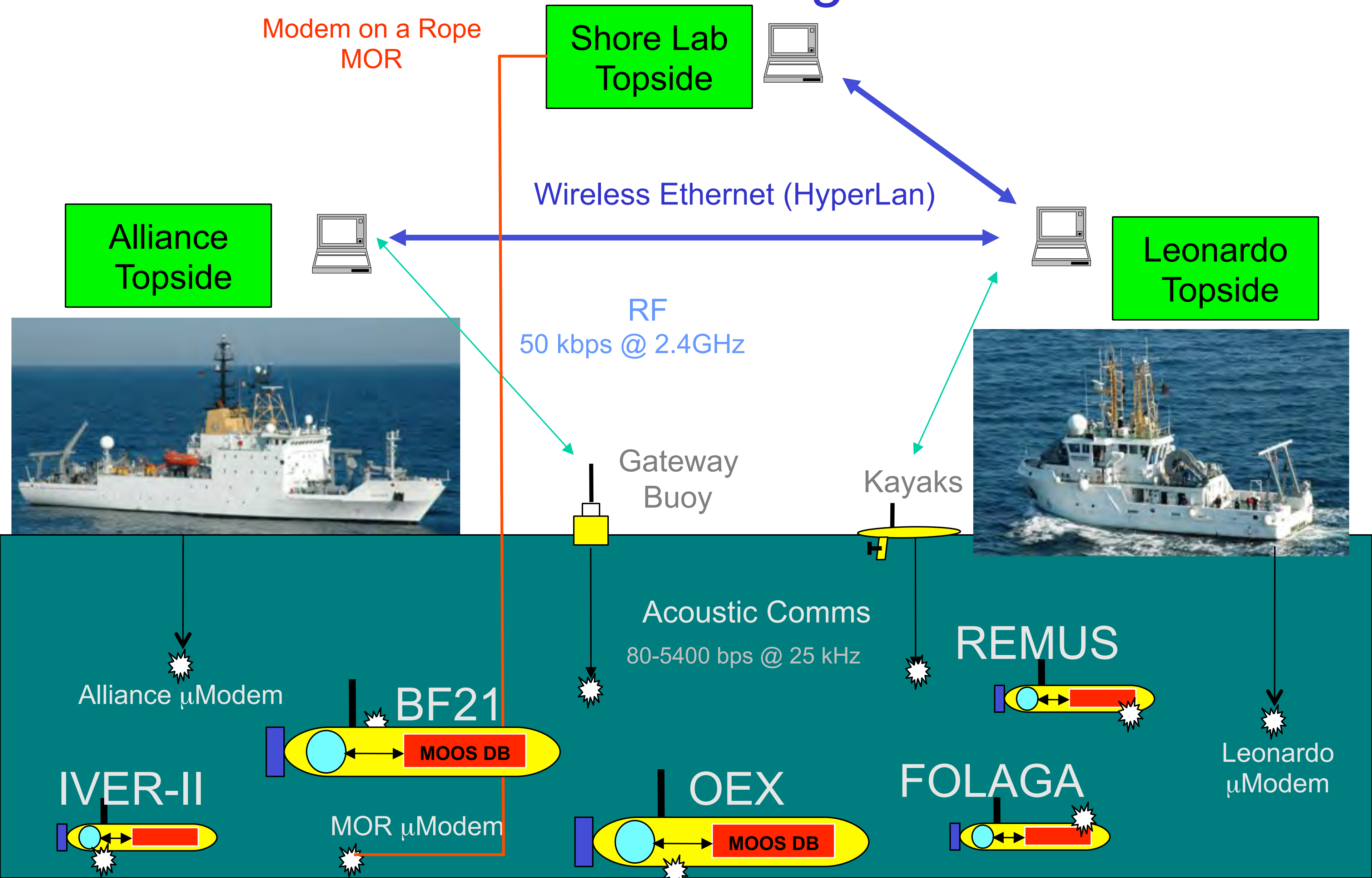
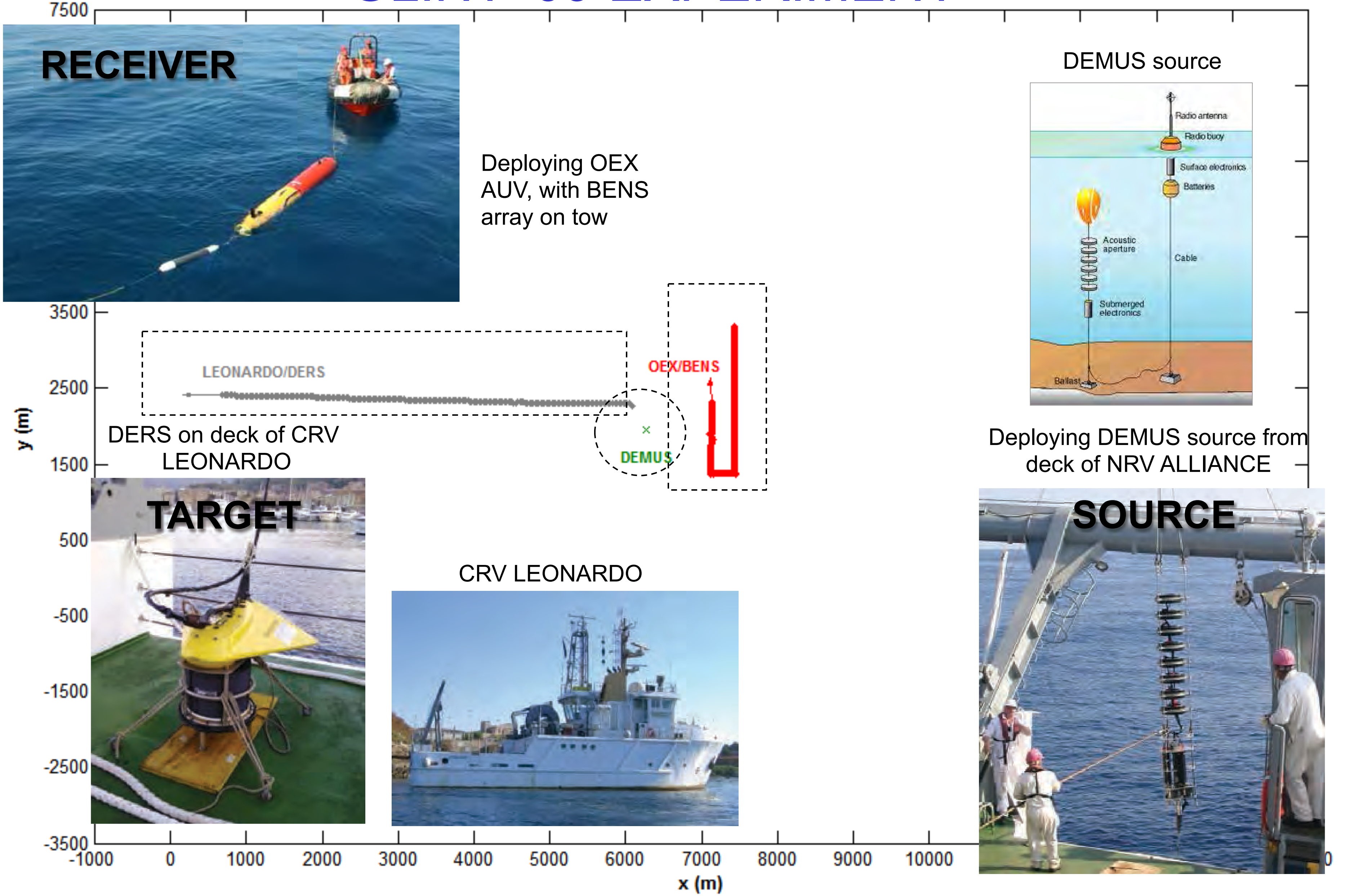
GLINT'08 – '10

Generic Littoral Interoperable Network Technology

GLINT08
Autonomous Sensing Network

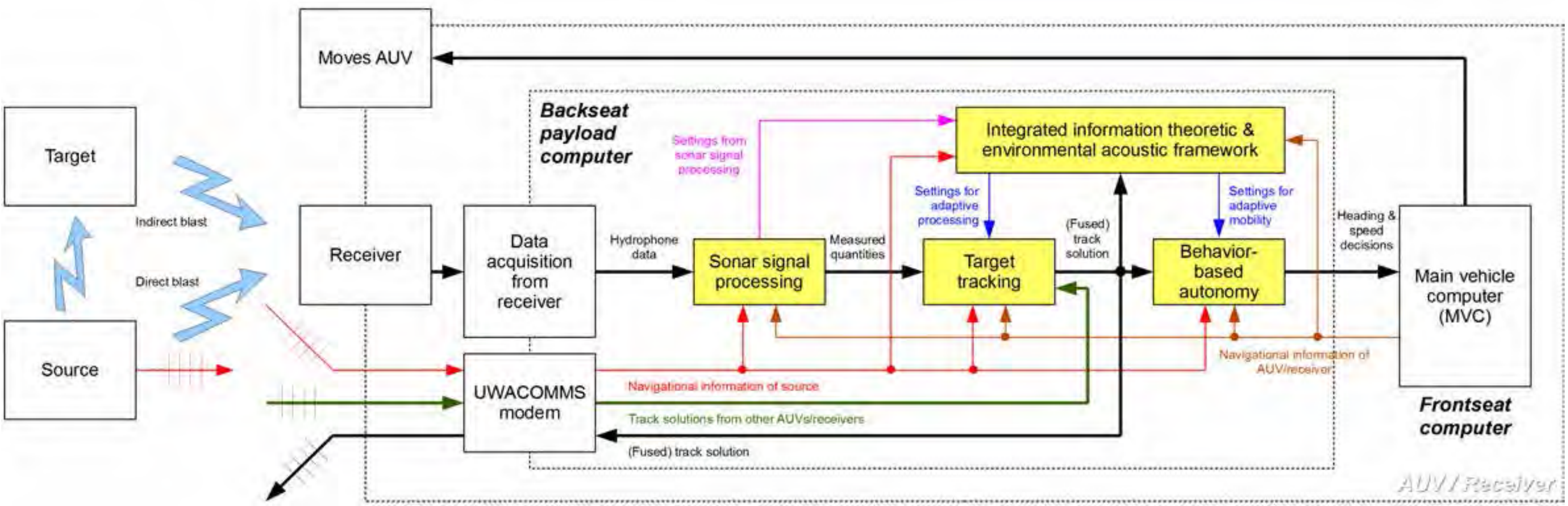


Multistatic-Active target Tracking
GLINT '09 EXPERIMENT



Integrated, Adaptive Multistatic Processing and Control Framework

Raymond Lum (PhD 2/12)



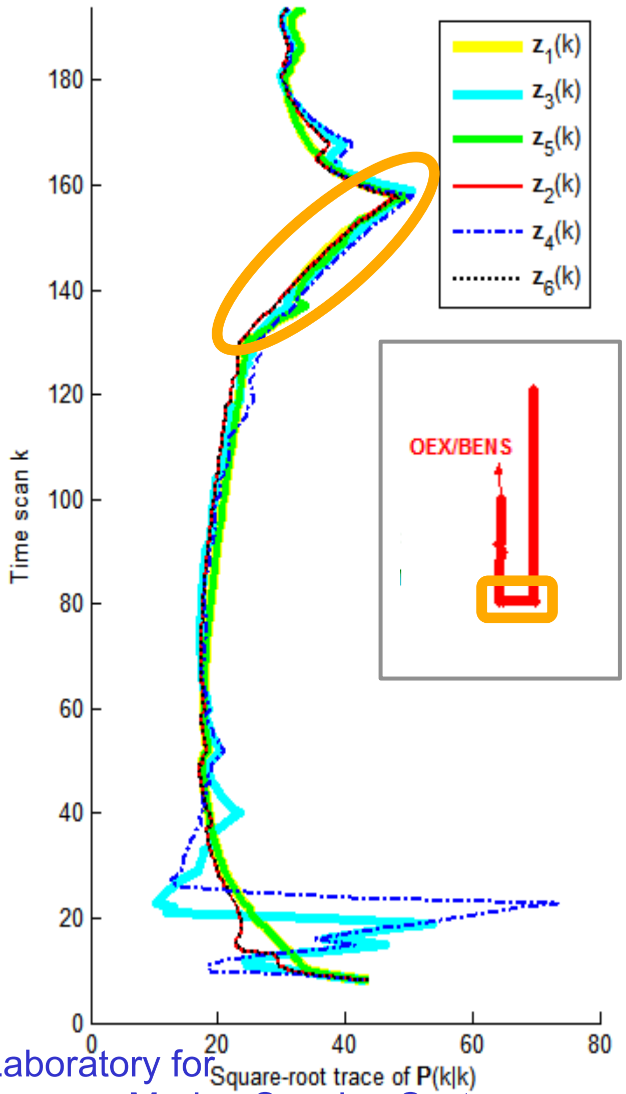
Key algorithms

- Sonar signal processing
- Target tracking
- Behavior-based autonomy
- Integrated information theoretic & environmental acoustic framework

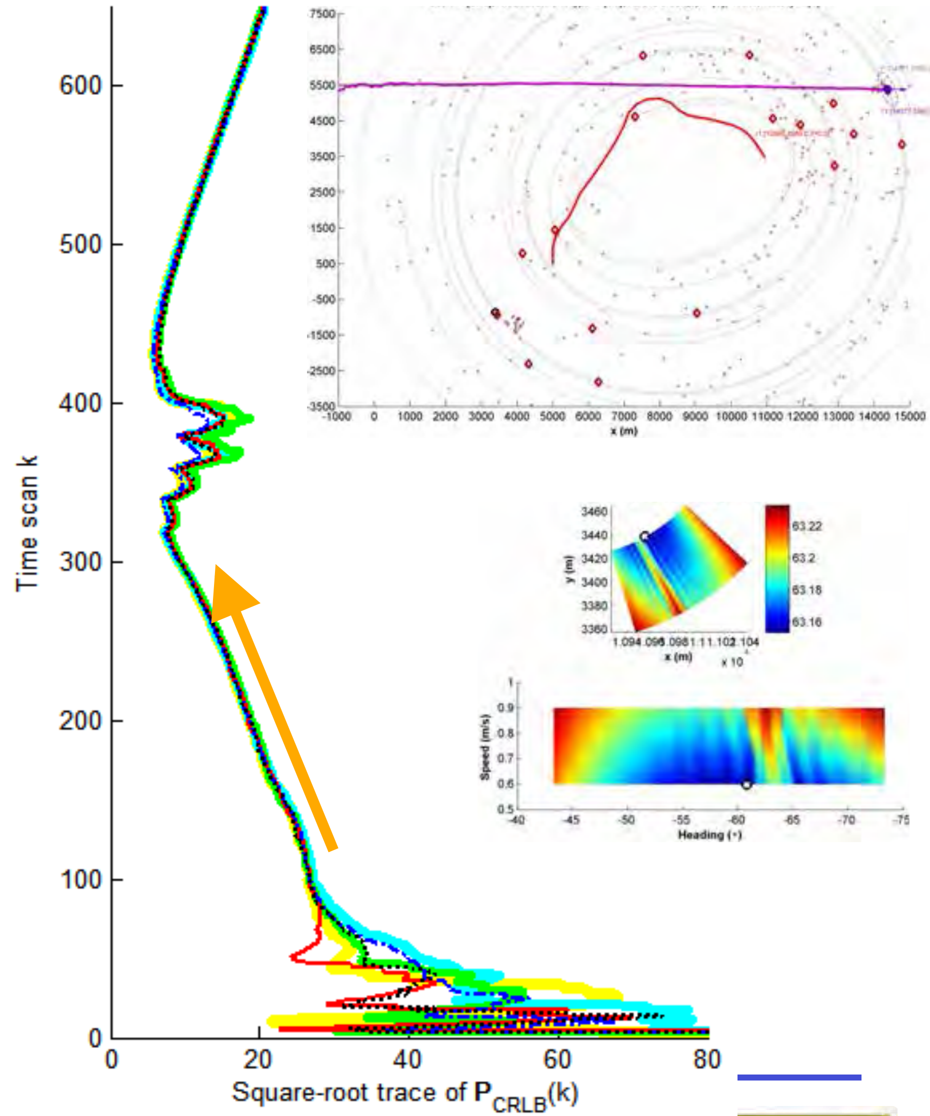
Performance Evaluation

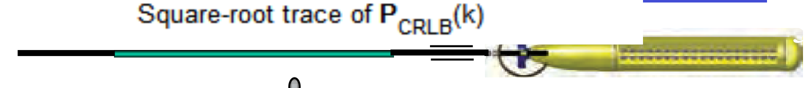
Tracking Error Covariance

Racetrack

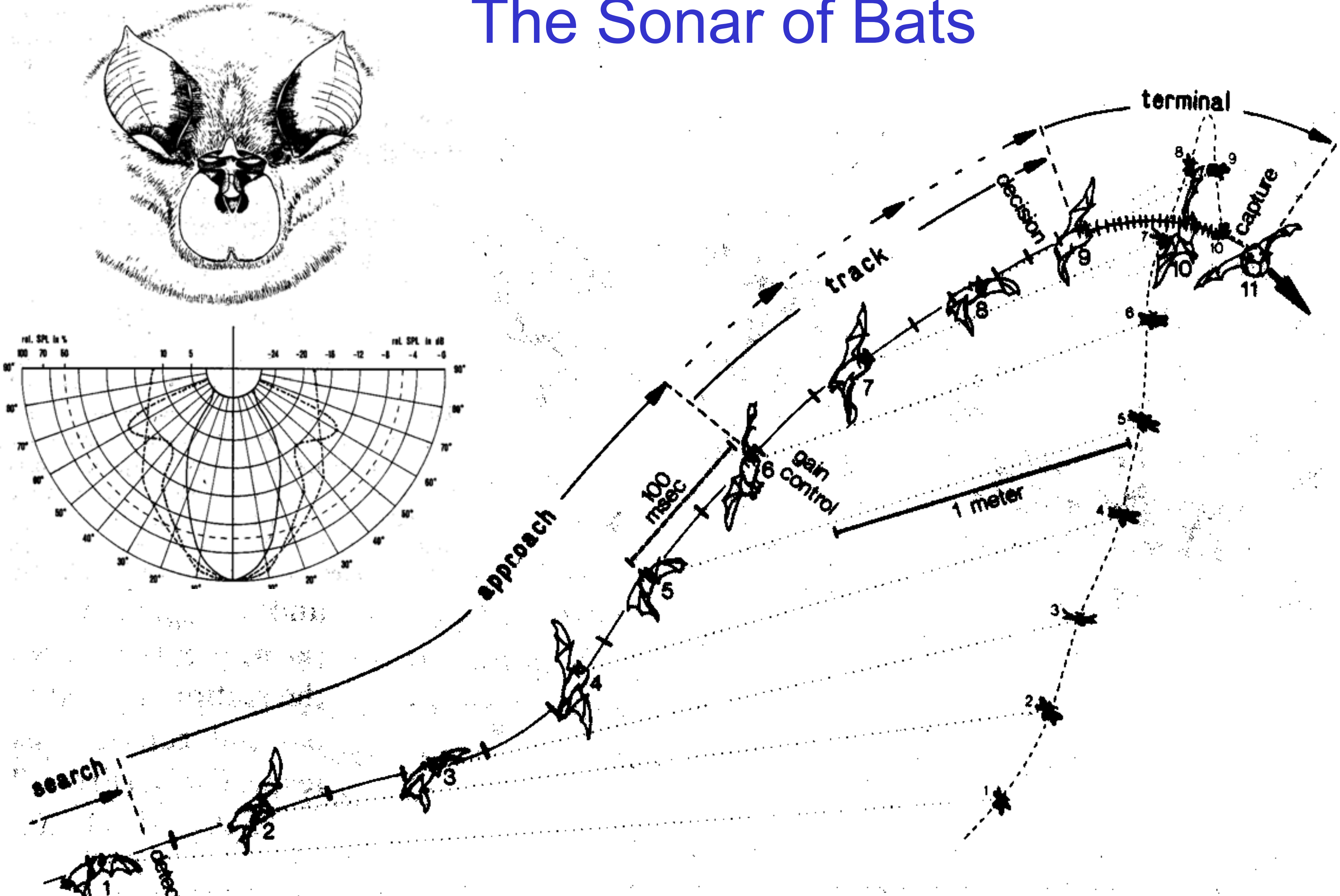


Adaptive



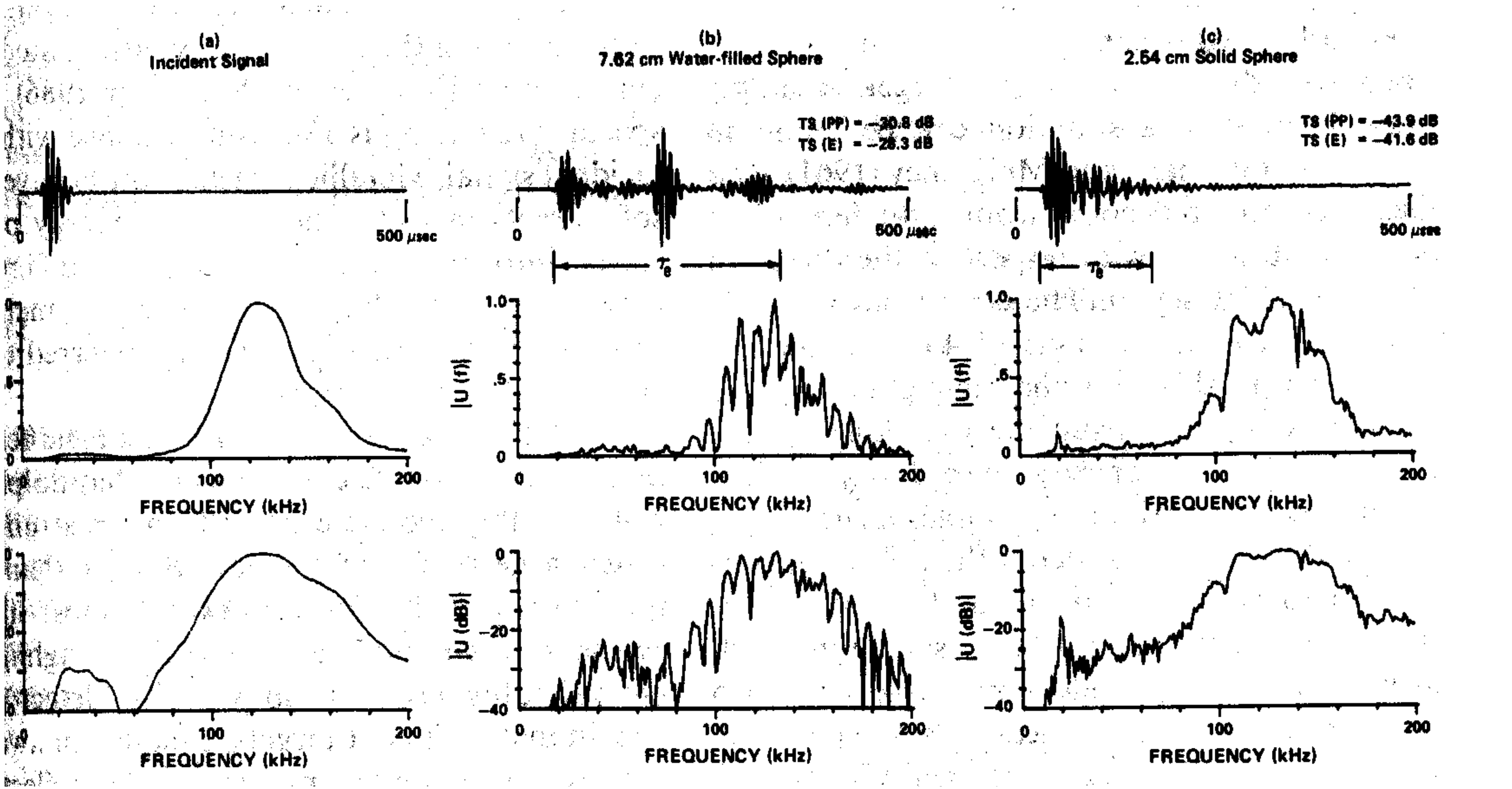


The Sonar of Bats



Figures from “The Sonar of Dolphins” by W. Au (Springer Verlag, 1993)

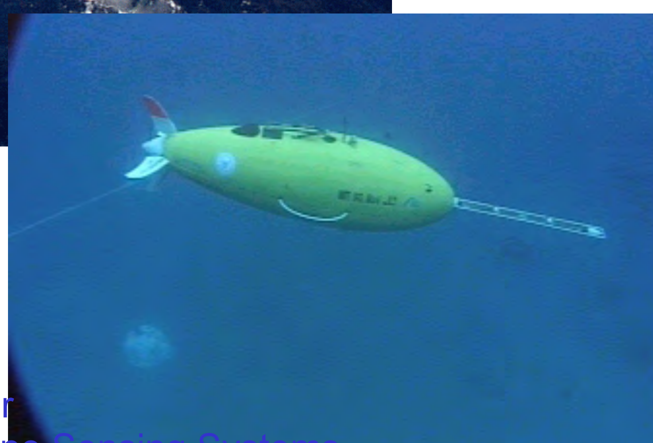
Dolphin Sonar
Reflection from Objects

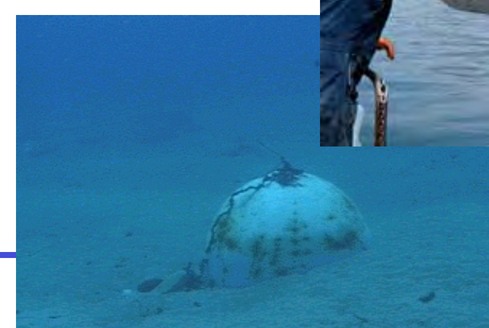


Figures from “The Sonar of Dolphins” by W. Au (Springer Verlag, 1993)

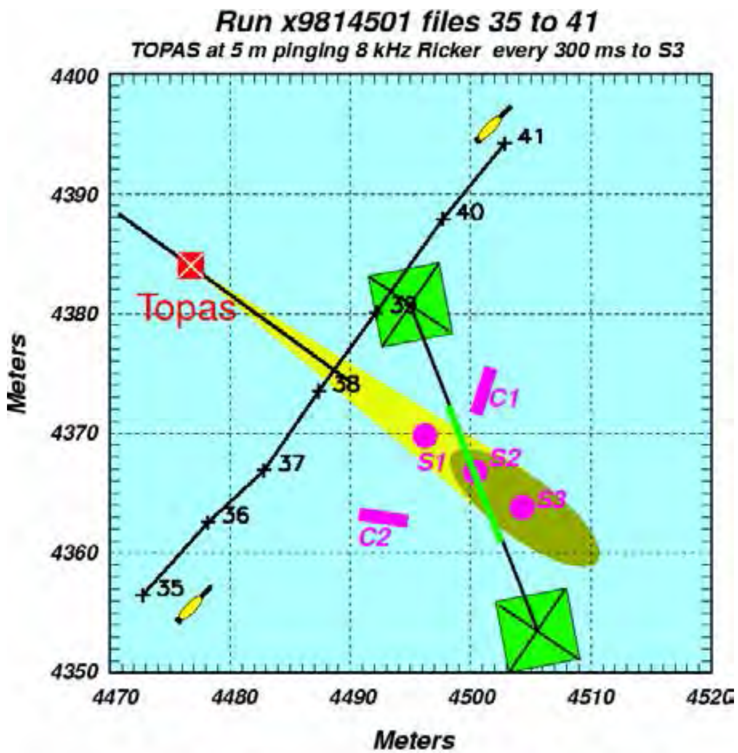
GOATS' 98
Odyssey II Bi-static Receiver Platform

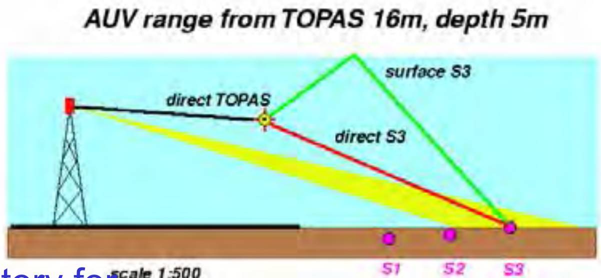


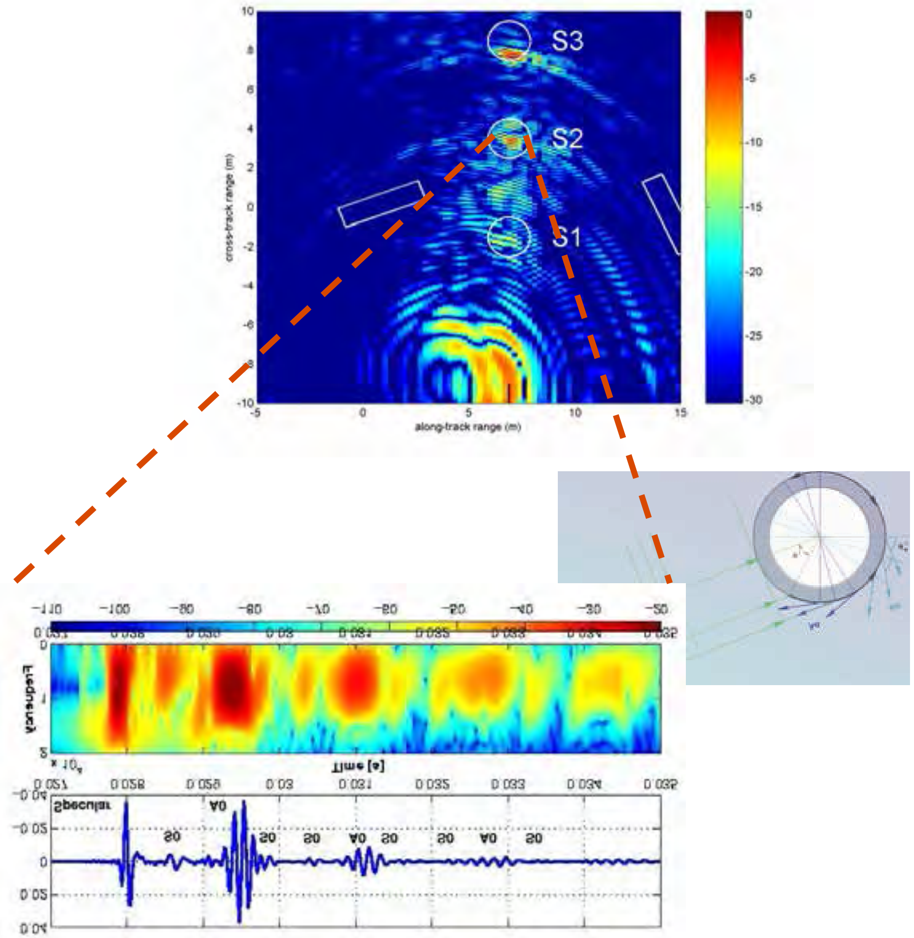


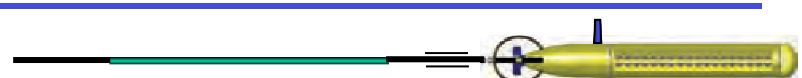
GOATS' 98 Experiment
Automated, Bistatic SAS Imaging





Super-critical Insonification





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Summary

- Intelligent autonomy is crucial to the performance of distributed undersea sensing systems
  - Adaptation and collaboration may compensate for less capable sensing capabilities
  - Communication channel capacity many orders of magnitude lower than for air-and land-based systems
  - Full integration of sensing, modeling, and control required so mission can be accomplished with no or intermittent communication
  - Behavior-based autonomy key enabler for integrated sensing, modeling and control.
  - MOOS-IvP is an open-source, highly portable autonomy software supporting advanced, behavior-based, adaptive and collaborative autonomy.
  - High-fidelity acoustic simulation linked with autonomy system is a key tool for development of distributed autonomy

Waveguide Invariants

Frequency Perturbation

$$\omega + \Delta\omega$$

Range Perturbation

$$r + \Delta r$$

TL Contour Slope

$$\Delta f / \Delta r$$

TL and Intensity

$$\mathrm{TL}(r, z, \omega) = 10 \log_{10}(I(r, z, \omega))$$

$$\Delta f / \Delta r = \frac{1}{2\pi} \Delta\omega / \Delta r$$

Frequency-Range TL Maxima

$$\Delta I(r;\omega) = \frac{\partial}{\partial\omega}\Delta\omega + \frac{\partial}{\partial r}\Delta r = 0$$

$$\frac{\Delta\omega}{\Delta r} = -\frac{\partial I}{\partial r} \Big/ \frac{\partial I}{\partial\omega} .$$

Modal Sum Intensity

$$I(r, z; \omega) \propto \left(\sum_n B_n^2 + 2 \sum_{m \neq n} B_m B_n \cos[(k_{rm} - k_{rn}) r] \right) ,$$

Range-dependent Mode Amplitudes

$$B_{m,n} = r^{-1/2} A_{m,n}$$

Partial Derivatives

$$\frac{\partial I}{\partial r} = -\omega \sum_{m,n} B_n B_m \left(s_{pm} - s_{pn} \right) \sin((k_{rm} - k_{rn})\, r),$$

$$\frac{\partial I}{\partial \omega} = -r \sum_{m,n} B_n B_m \left(s_{gm} - s_{gn} \right) \sin((k_{rm} - k_{rn})\, r),$$

Modal Phase and Group Slowness

$$s_{pn} = 1/v_n = k_n/\omega$$

$$s_{gn} = 1/u_n = \partial k_n / \partial \omega$$