AREA

Adaptive Rapid Environmental Assessment

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Capturing Uncertainty
Final Report
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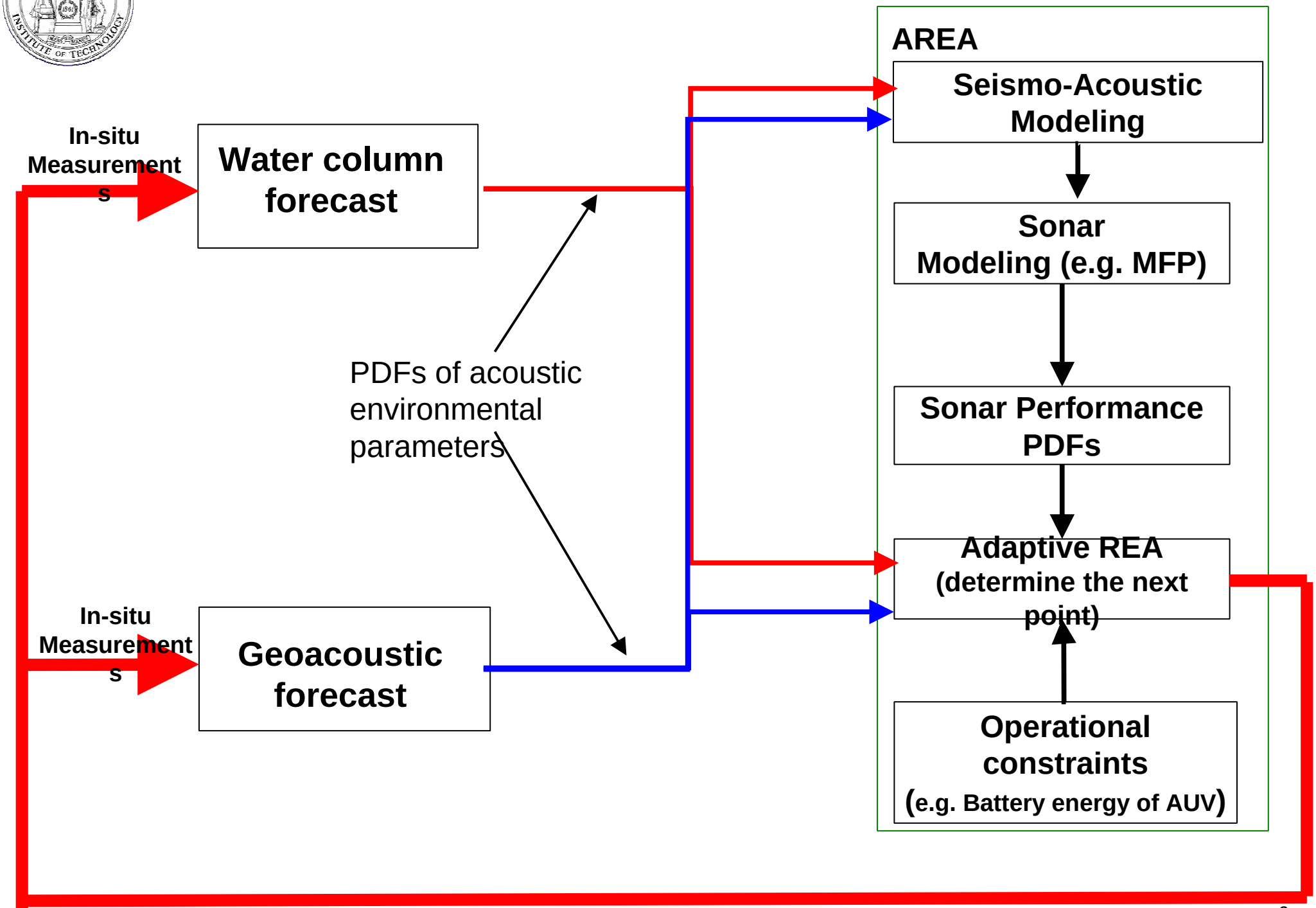
Adaptive Rapid Environmental Assessment



AREA

Research Strategy

- Sonar configuration and performance metrics
  - Shallow water MFP – VLA
- Optimal Parameterization
  - System Orthogonal Functions (SOF)
    - Orthogonal or uncoupled in sonar performance statistics
    - Minimize and identify parameters to be targeted by REA
- Acoustic Data Assimilation
  - Consistent fusion of any acoustic data with other REA data
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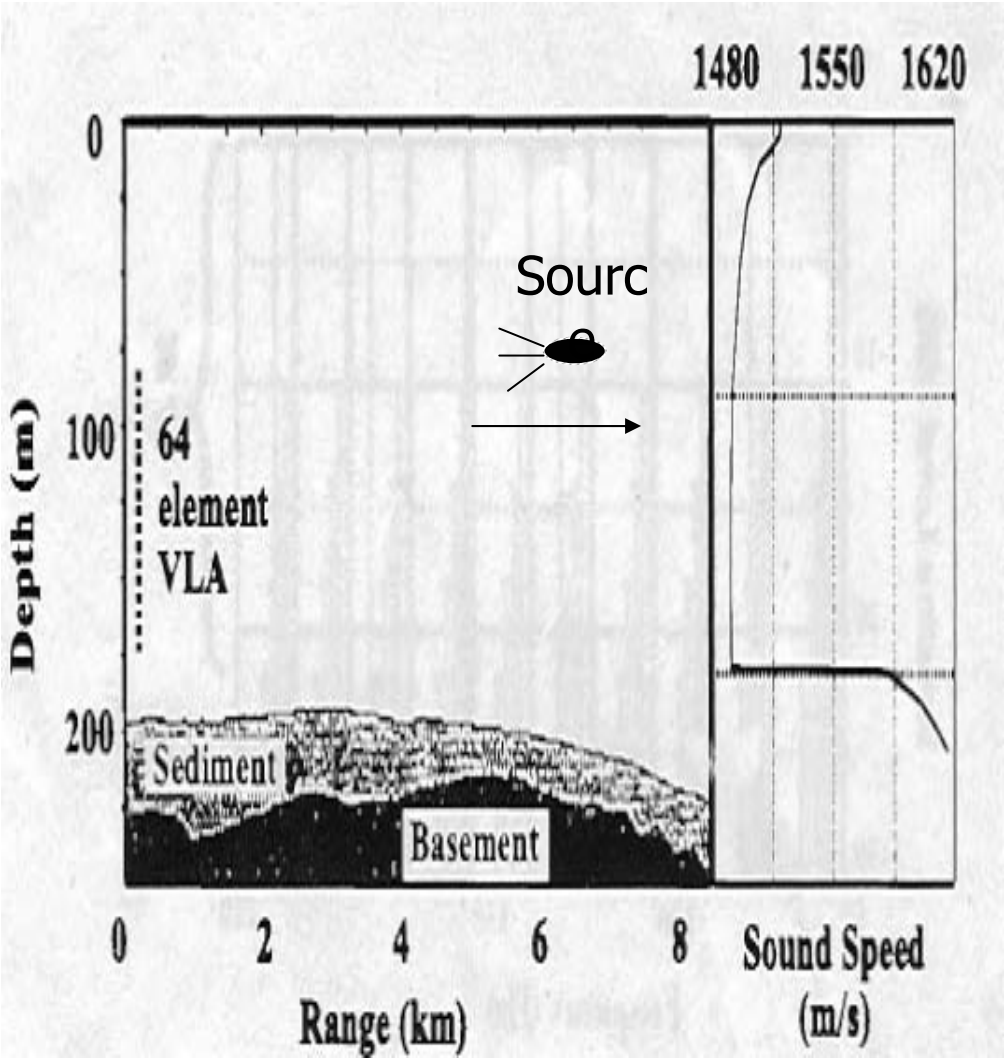
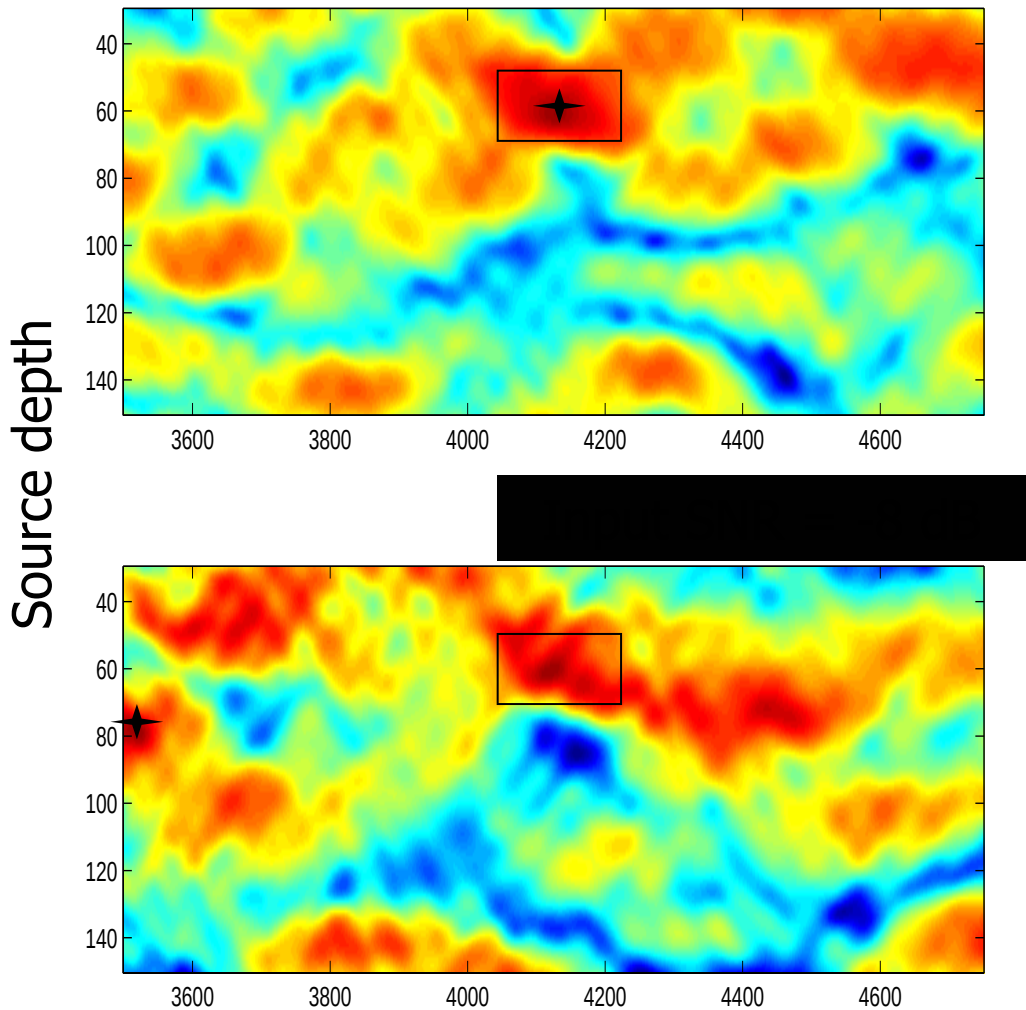
- REA Deployment Optimization
  - Non-acoustic on- and off-board sensors and platforms (e.g. AUV)
  - *Complete System Simulation* Framework

Matched Field Processing



Shallow Water Evaluation Cell Experiments
(SWellEX, Booth, *et al.*, 1996)

Input SNR = 0 dB

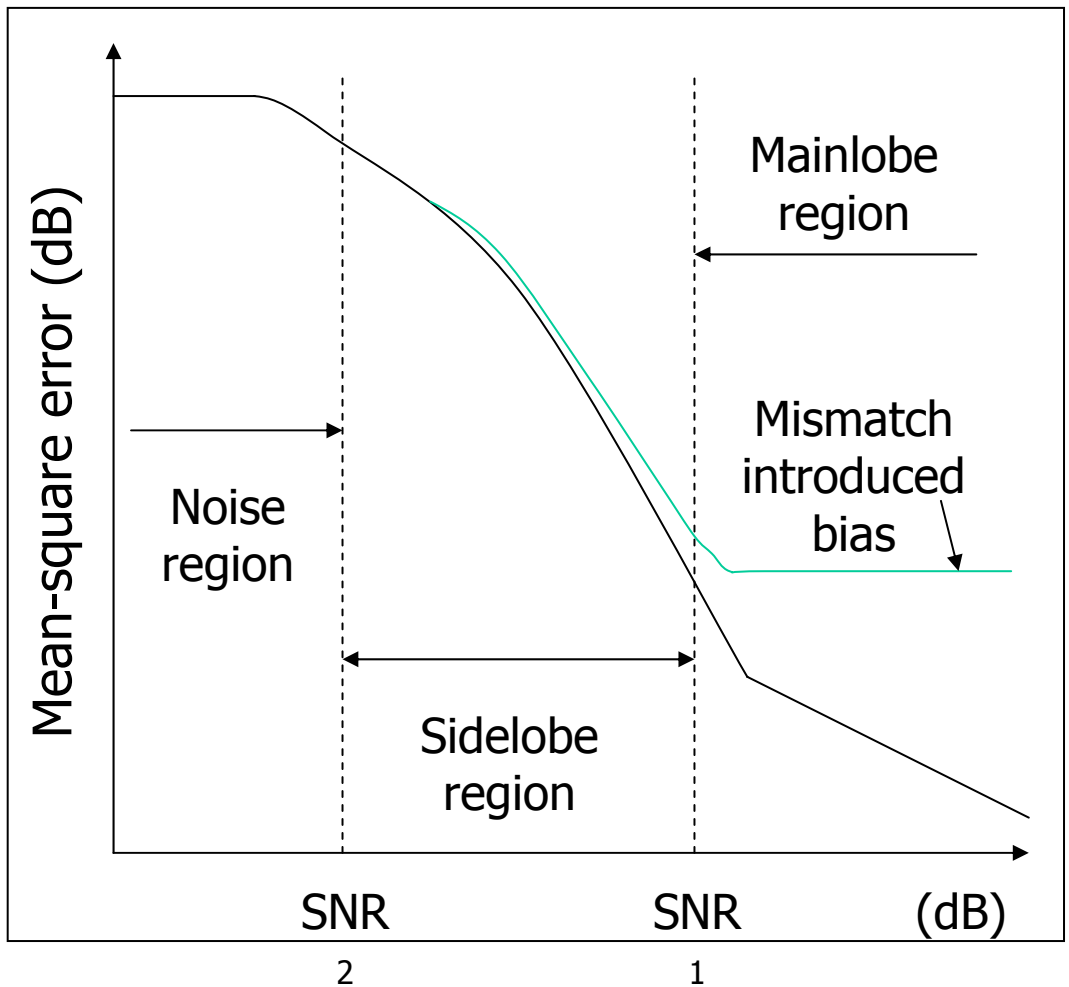


Source Localization Ambiguity Surface

Matched-field Performance Threshold Parameter Mismatch

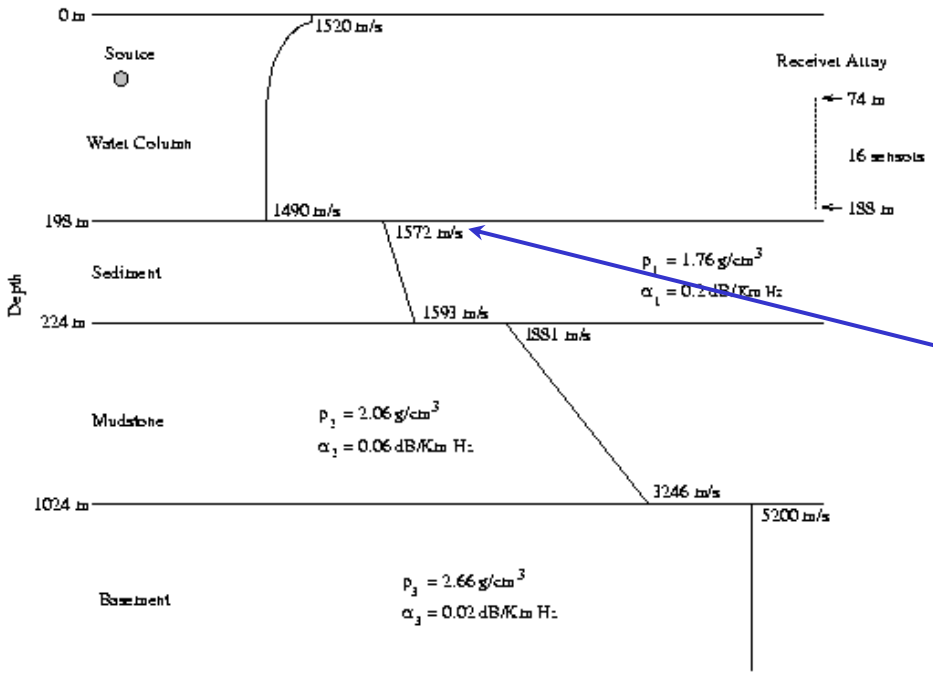
Performance analysis tools

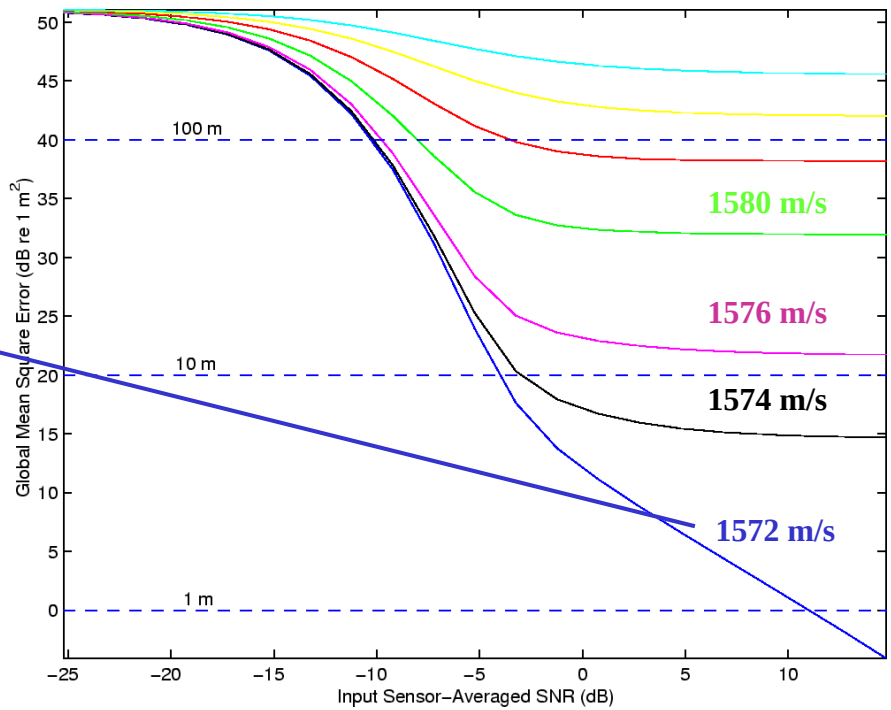
- Statistical data model
- Mean-square error
- Cramer-Rao bounds
  - High SNR
- Ziv-Zakai bound
  - All SNRs
  - Computationally intensive
- Modified Ziv-Zakai bound (Xu and Baggeroer)
  - Include the mismatch effect
- Bayesian framework
  - Random parameters



Matched Field Processing
Environmental Parameter Mismatch

Example environmental model in SWellEX-3





High SNR: Strong environmental sensitivity

Low SNR: Weaker environmental sensitivity

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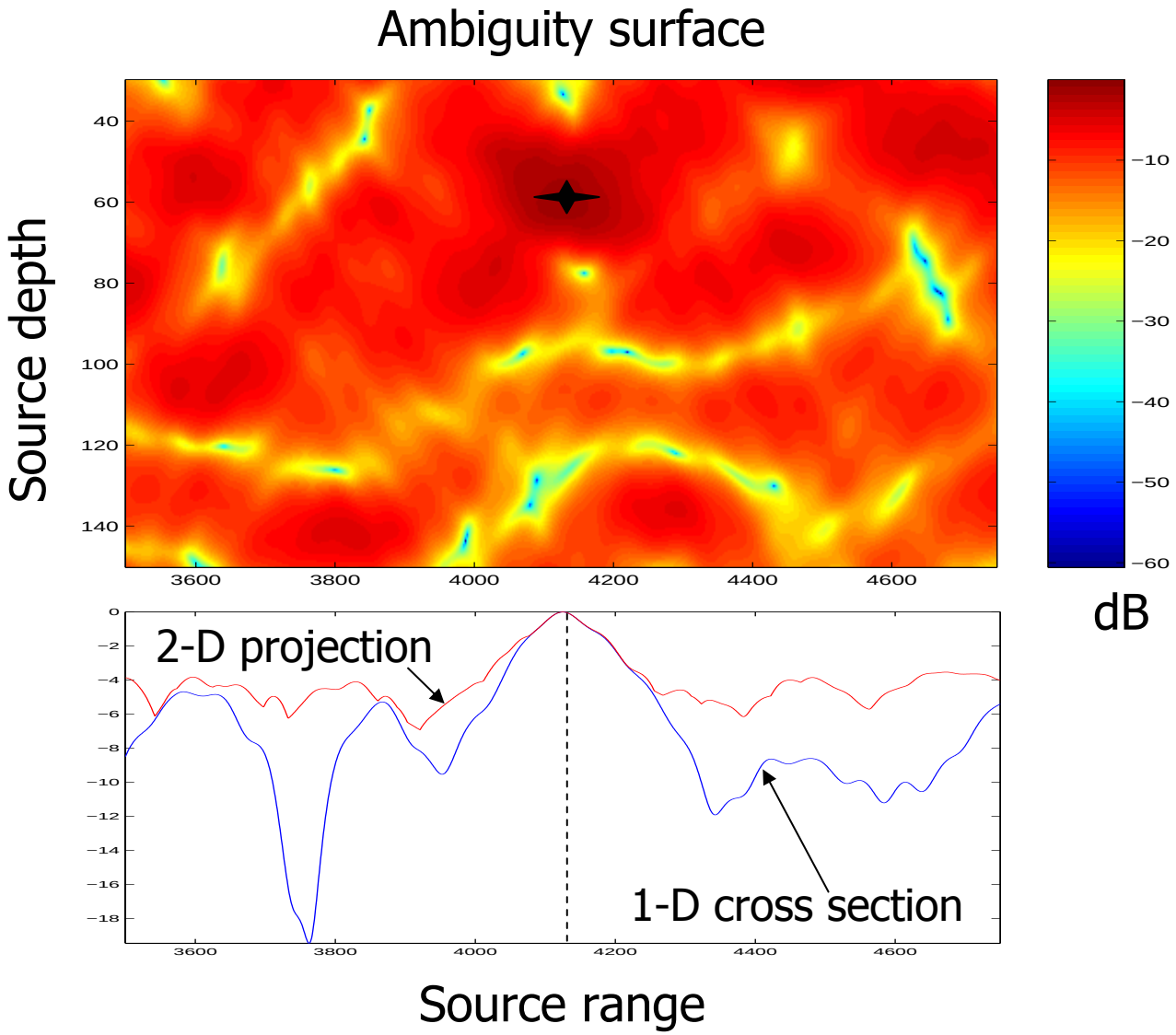
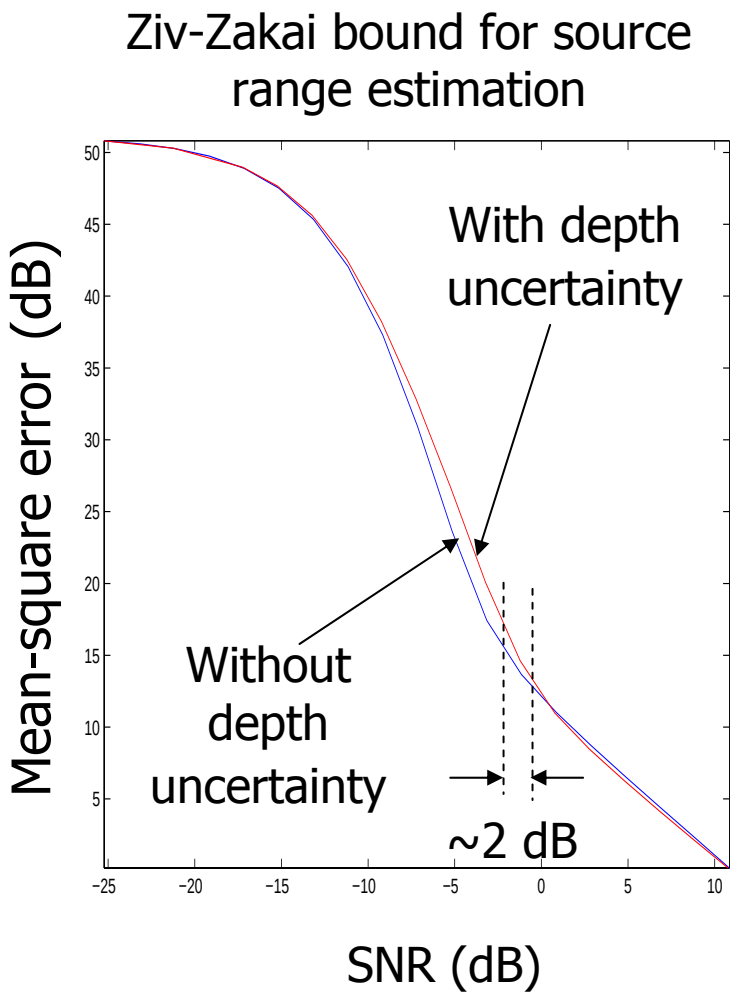
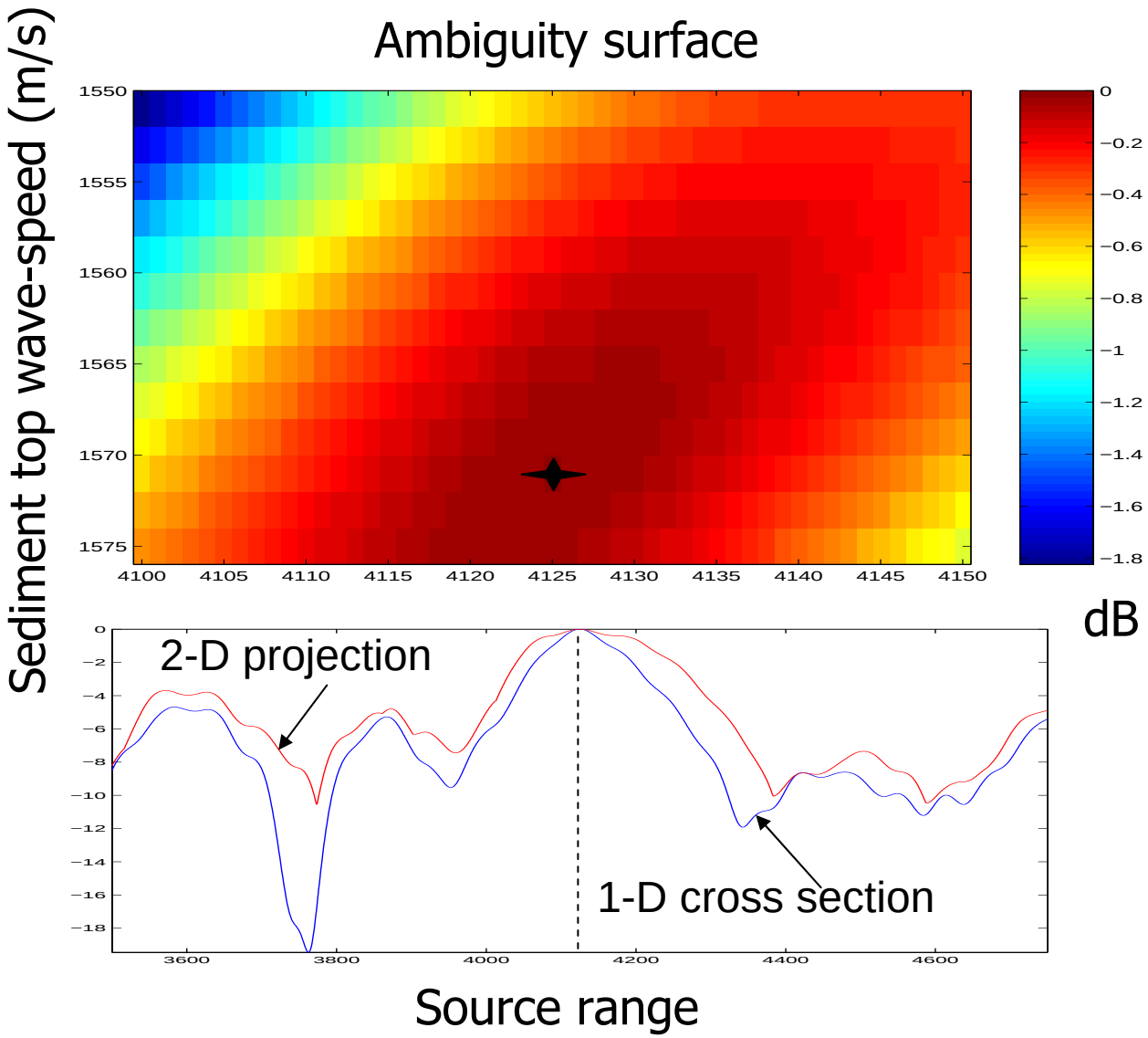
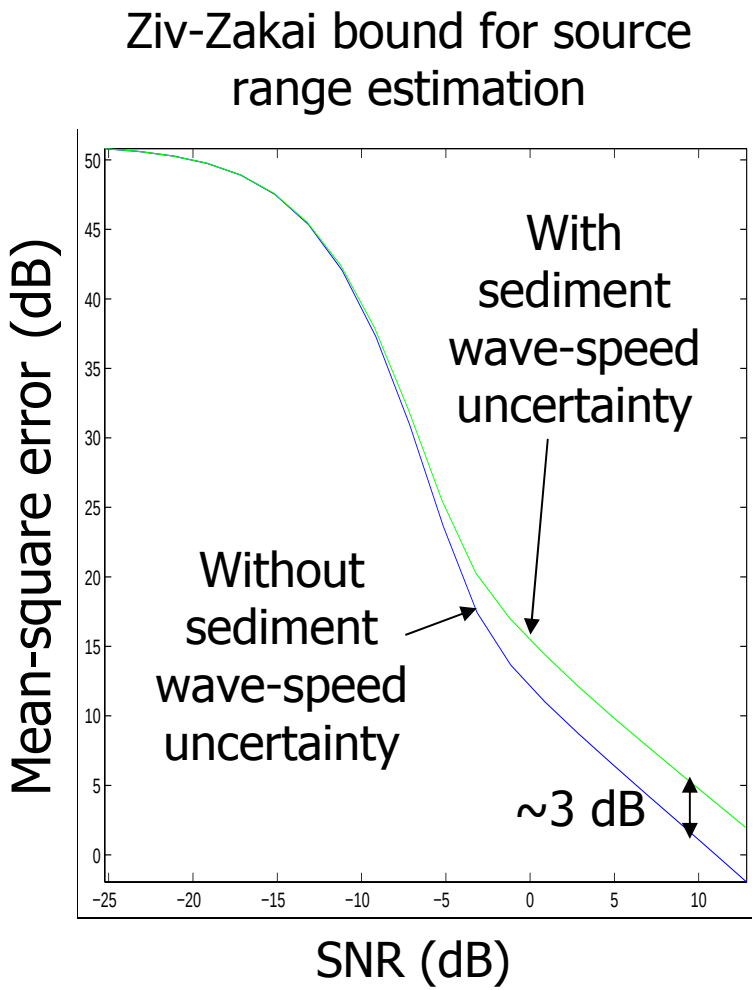
Parameter Coupling
Weak Coupling





Coupling of Location and Environment
Strong Coupling





Matched Field Source Localization
Environmentally Robust Parameterization

- Ignoring the environmental uncertainty could introduce significant environmental mismatch, and thus serious bias in source localization
- Environmental parameters uncoupled from source location is ideal, but impossible
- AREA: Deploy REA resources to target environmental parameters which have strongest coupling to source location for actual sonar system
- Decoupled environmental representation is desired:
  - Reduce the degrees of freedom
  - Isolates the relative significance of the individual parameters
  - Simplify the design of optimal adaptive sampling of environment
- Cramer-Rao bound matrix provides a framework for developing optimal acoustic parameterization

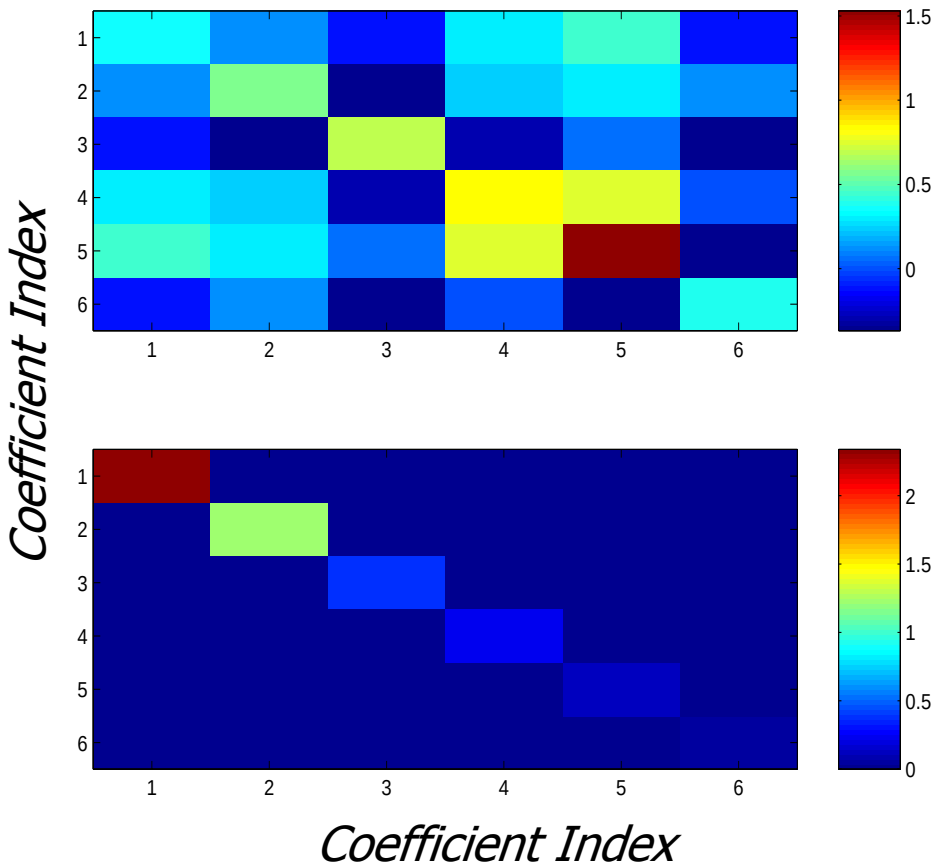
SOF
System Orthogonal Functions

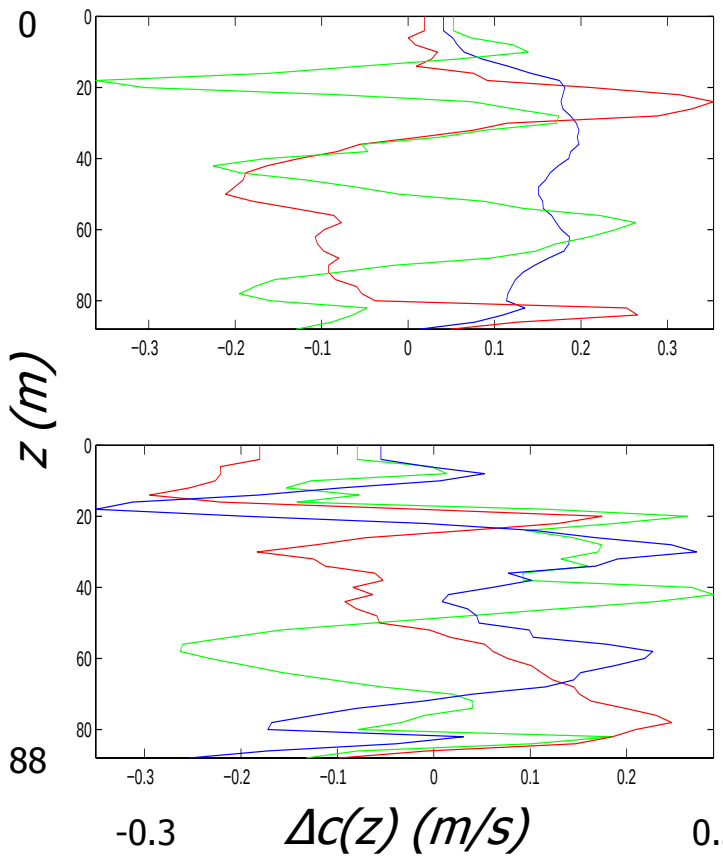
Depend on
- Sound speed uncertainty
- Ocean waveguide properties
- Sonar Configuration

Isovelocity channel + Shelf Break Primer SVP statistics (G. Potty *et al.*, 2000)

CRB matrix using 6 SVP coefficients

Input SNR = 0 dB



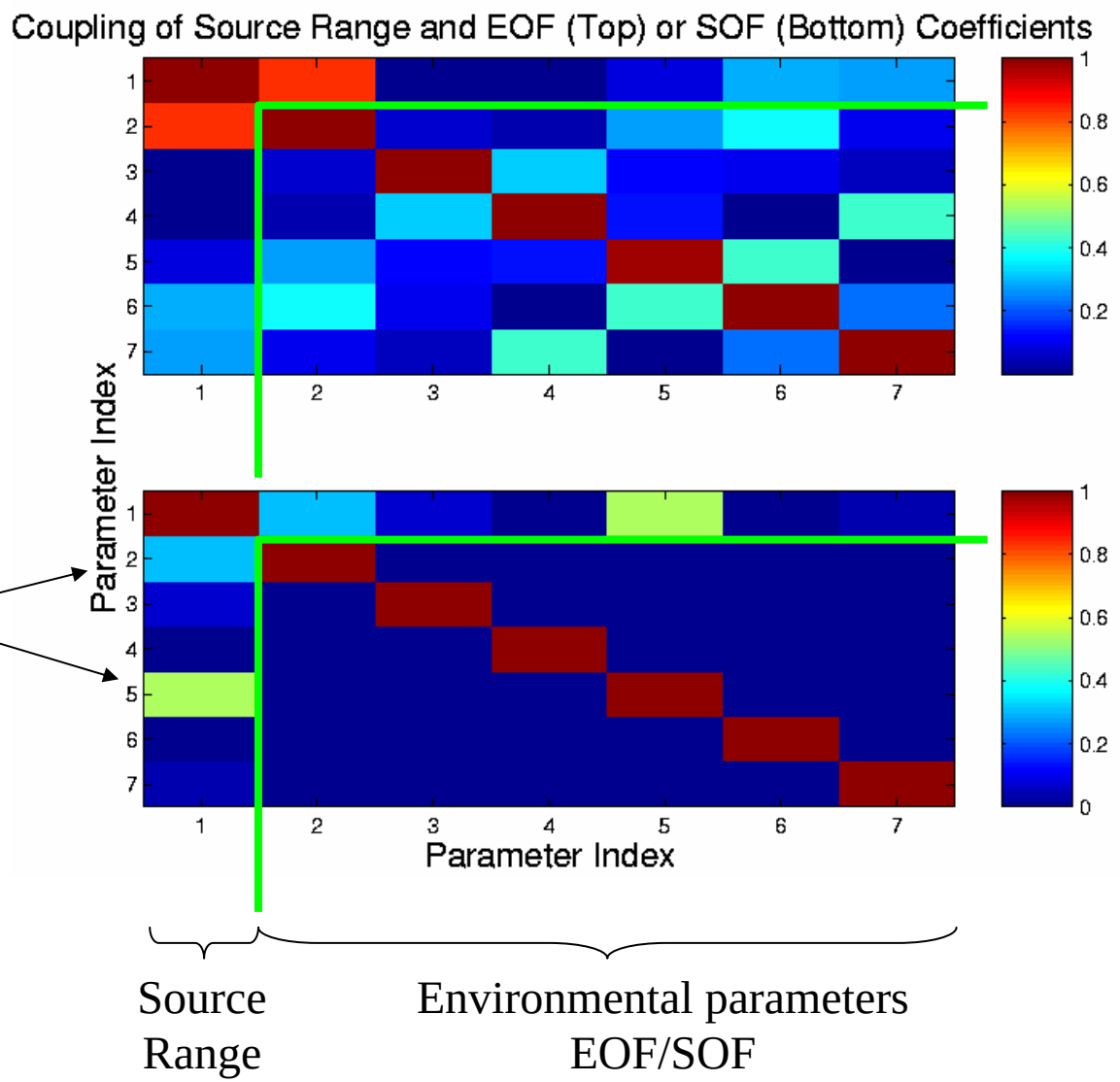


Blue: EOF_1
Red: EOF_3
Green: EOF_5

Blue: SOF_1
Red: SOF_3
Green: SOF_5

Cramer-Rao Matrix

Source Range – Environment Coupling



EOF

SOF

Target Parameters

Source Range

Environmental parameters EOF/SOF

▪W. Xu and H. Schmidt, "System-orthogonal functions for sound velocity profile perturbation," Submitted for publication in *IEEE Journal of Oceanic Engineering*.

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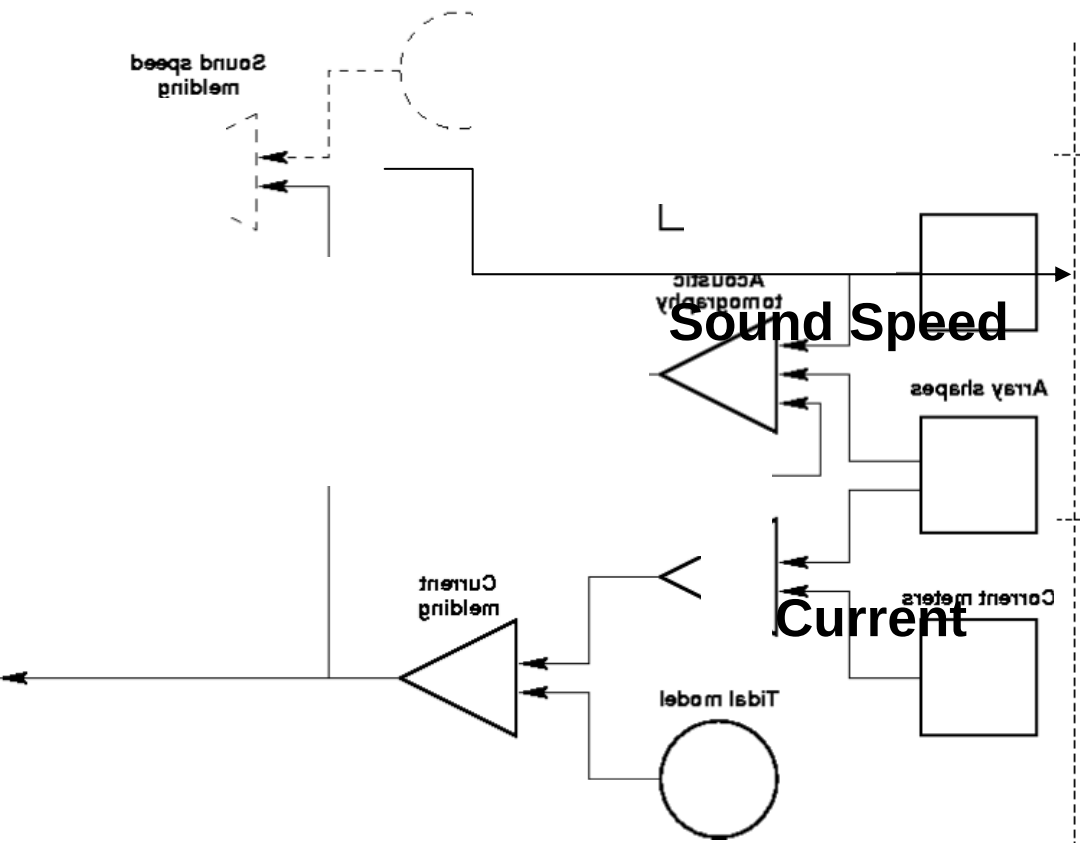
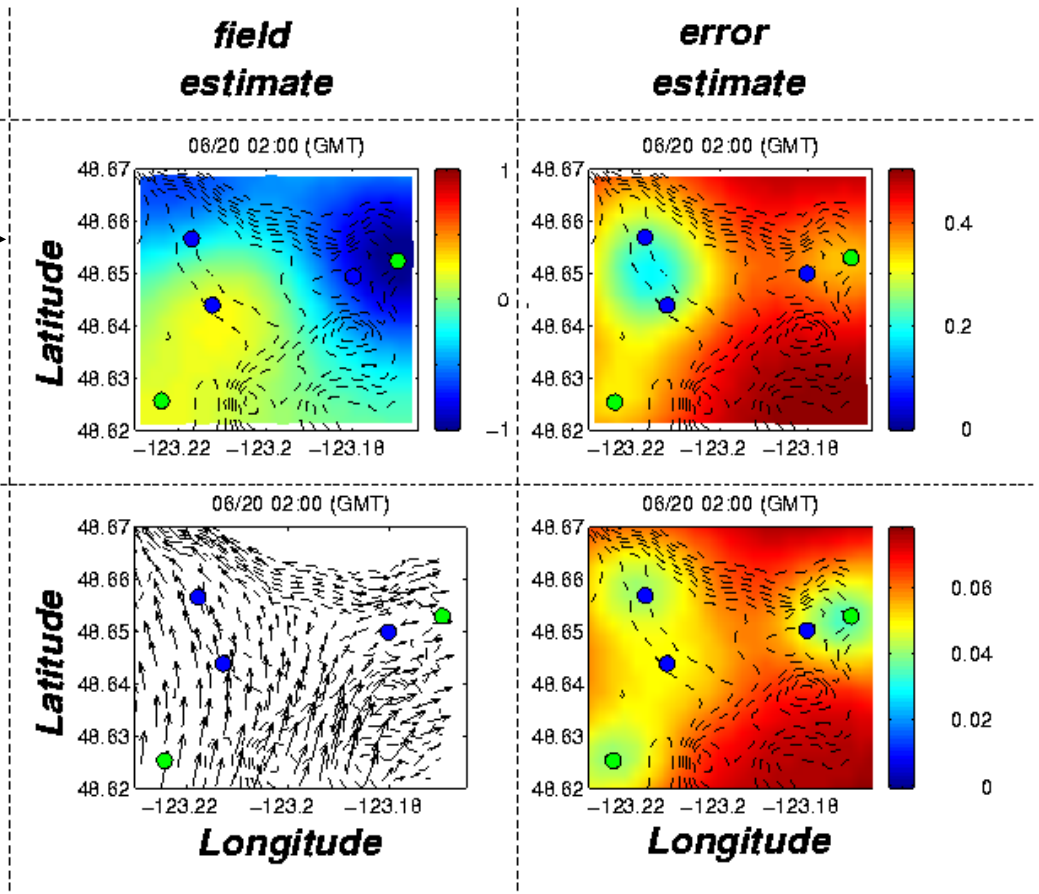
Haro Strait'96
Data Assimilation – No Acoustics

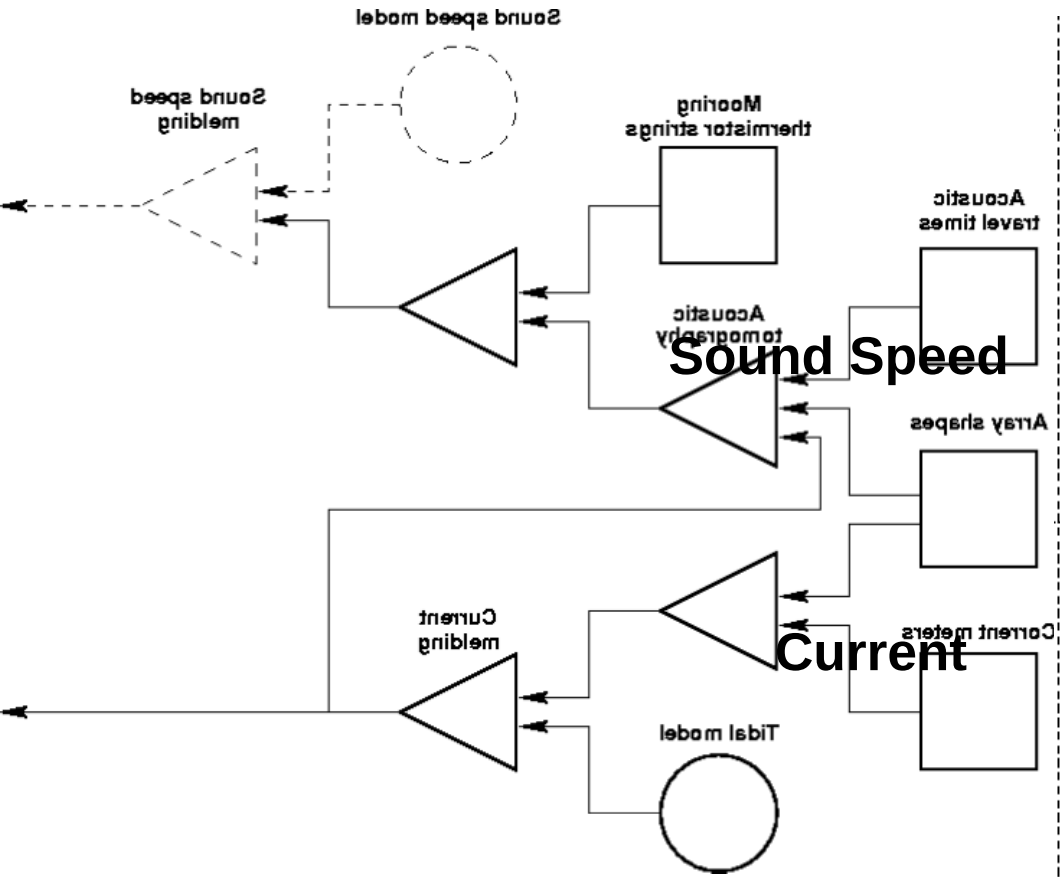


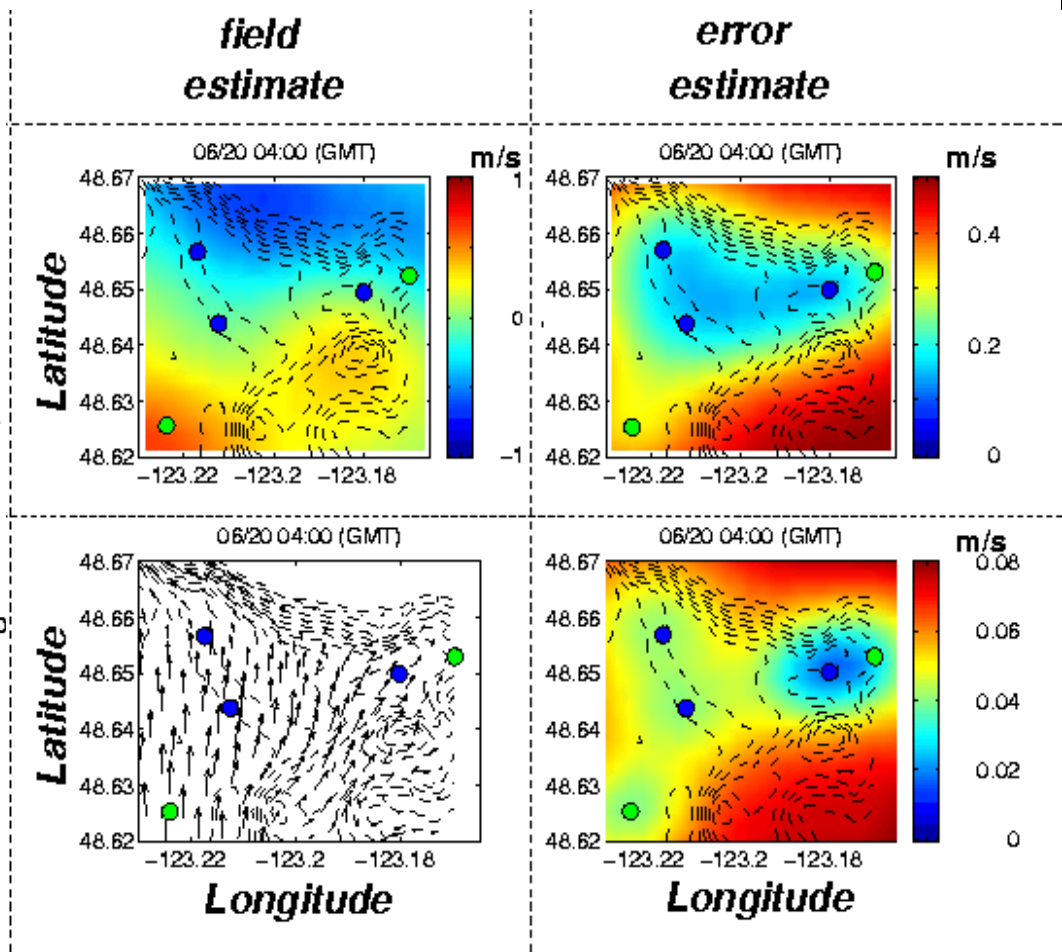
Sound Speed

Current

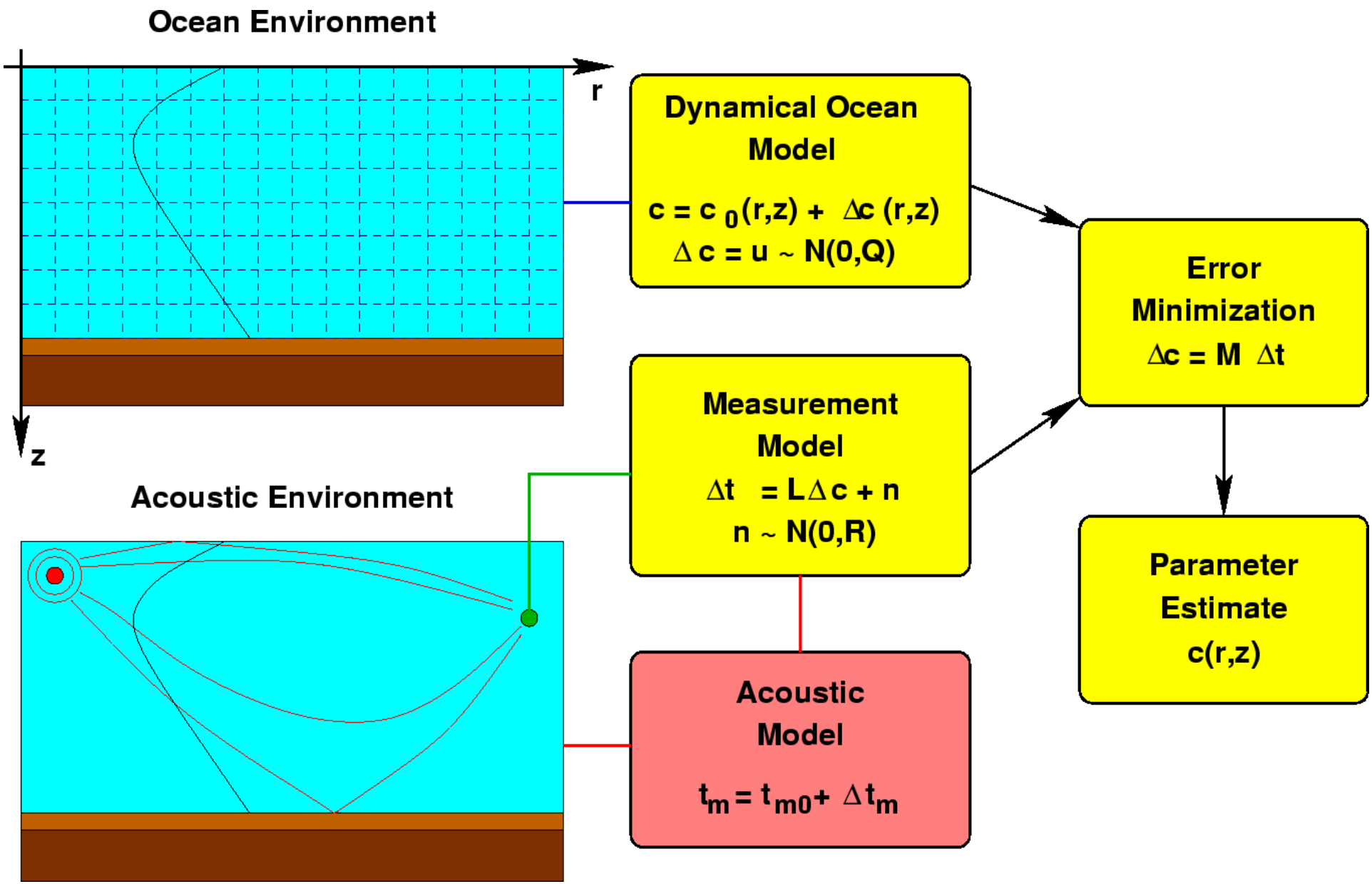


Haro Strait'96
Acoustic Data Assimilation



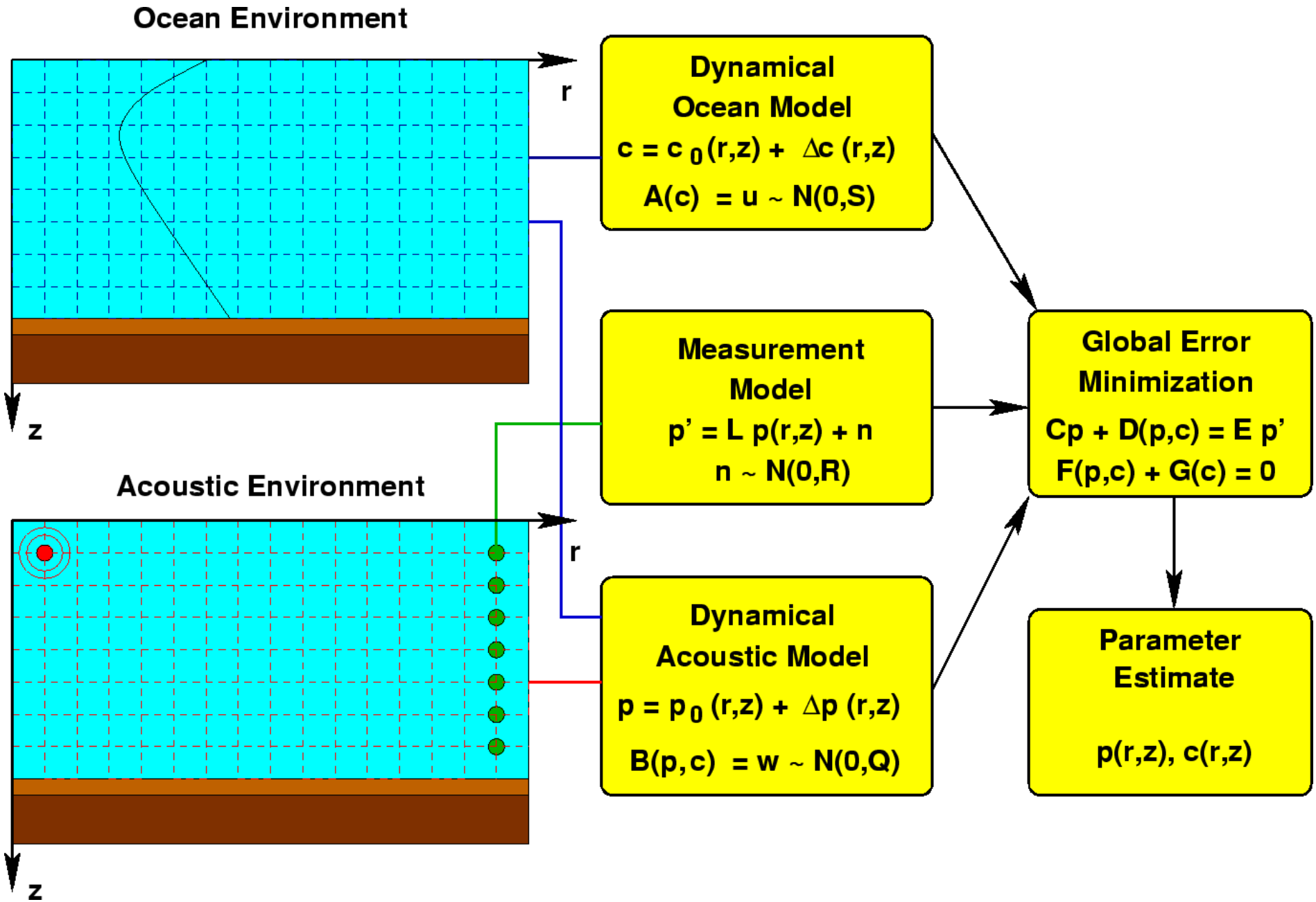


Ocean Acoustic Tomography



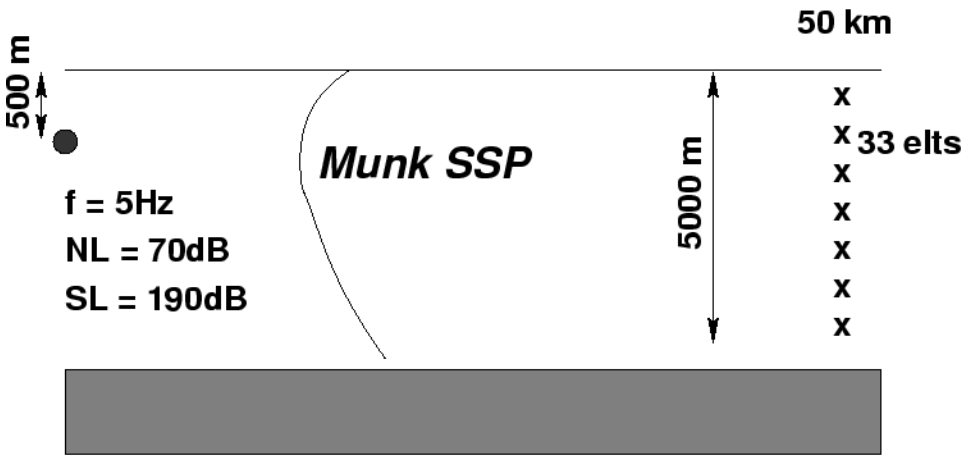
Acoustic Data Asimilation

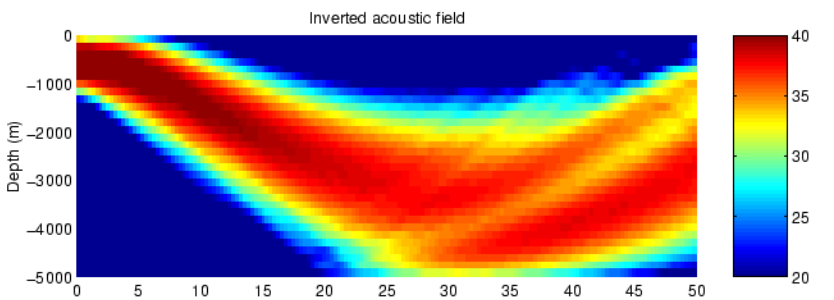
(Elisseeff, Schmidt and Xu, IEEE JOE 2002)

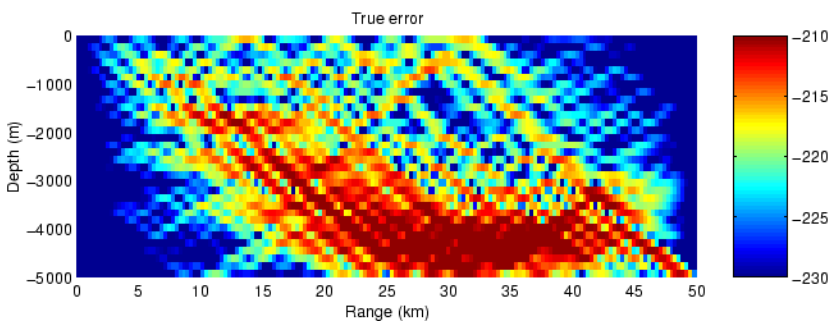


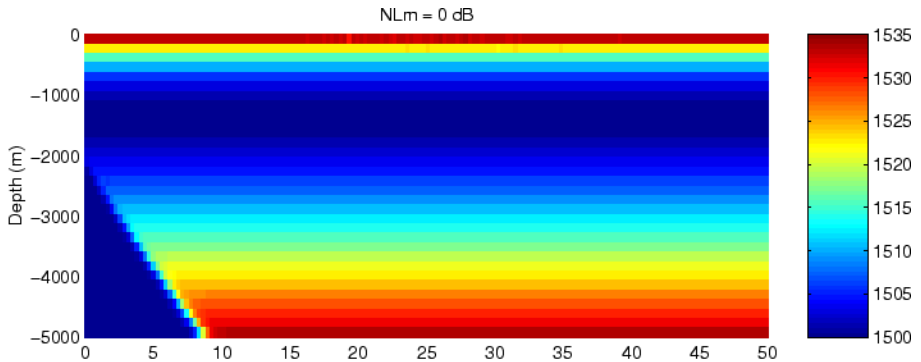
Acoustic Data Assimilation

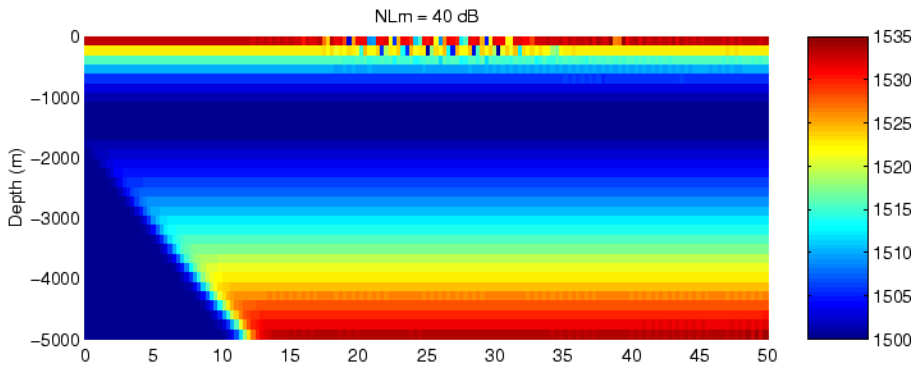
Simulation Validation

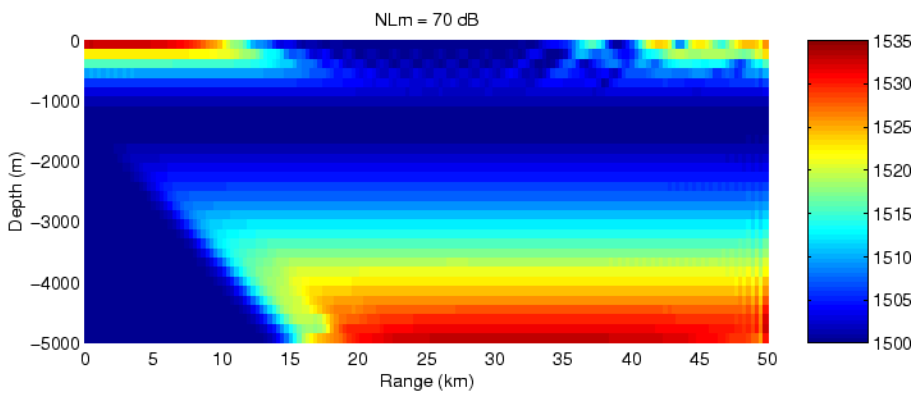












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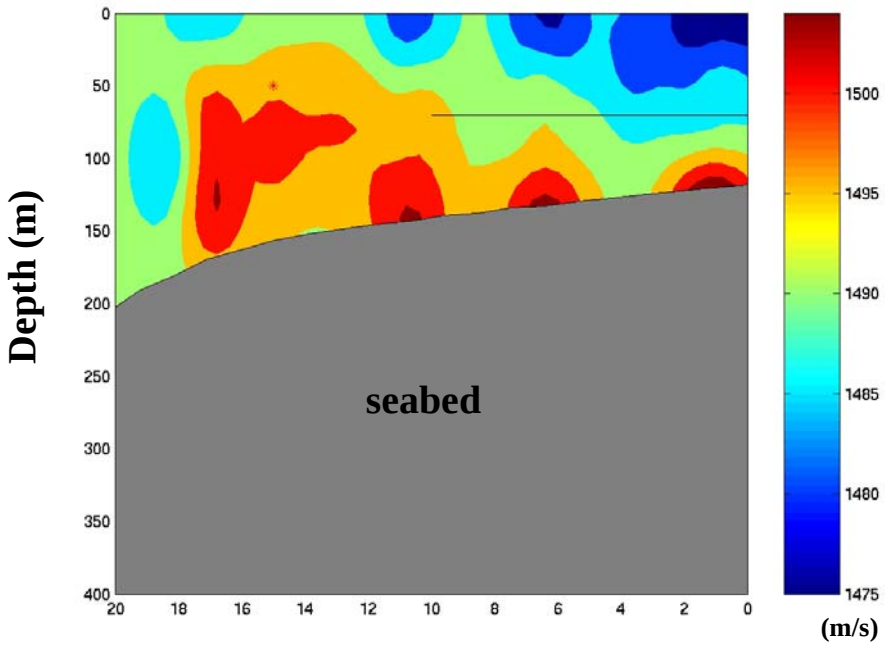
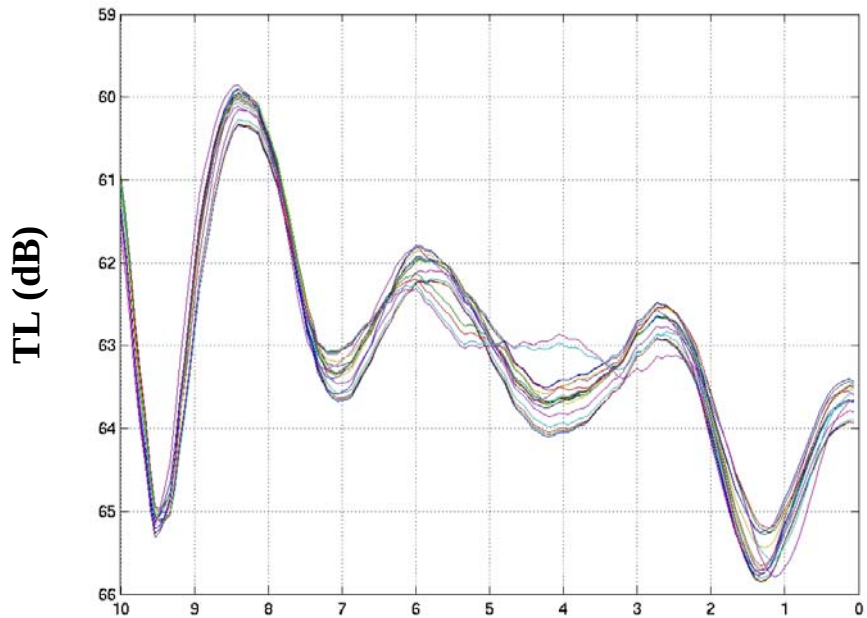
Random Ocean Variability

Water Sound Speed Profile Variation Over Time



Range (Km)

Transmission Loss Variation (50 Hz)

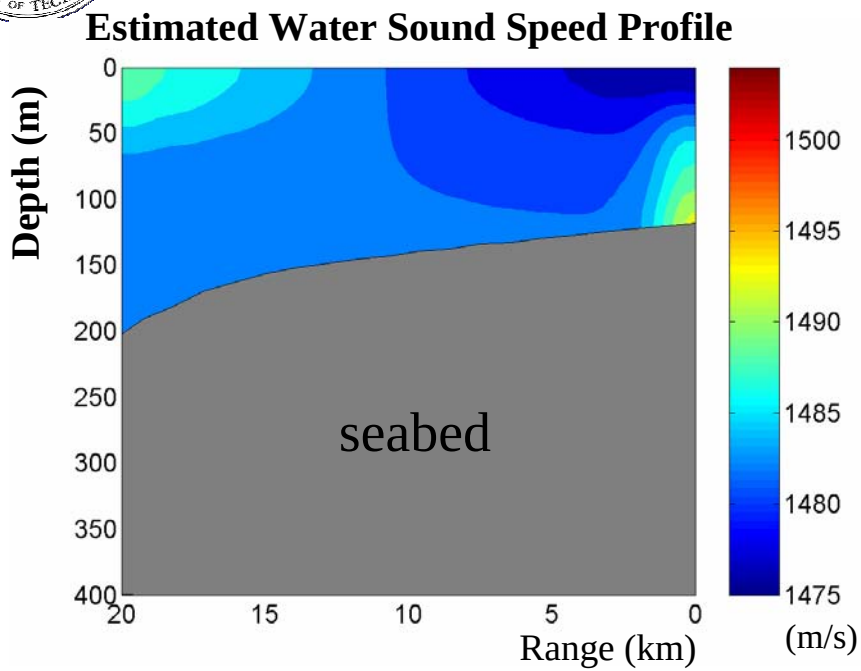


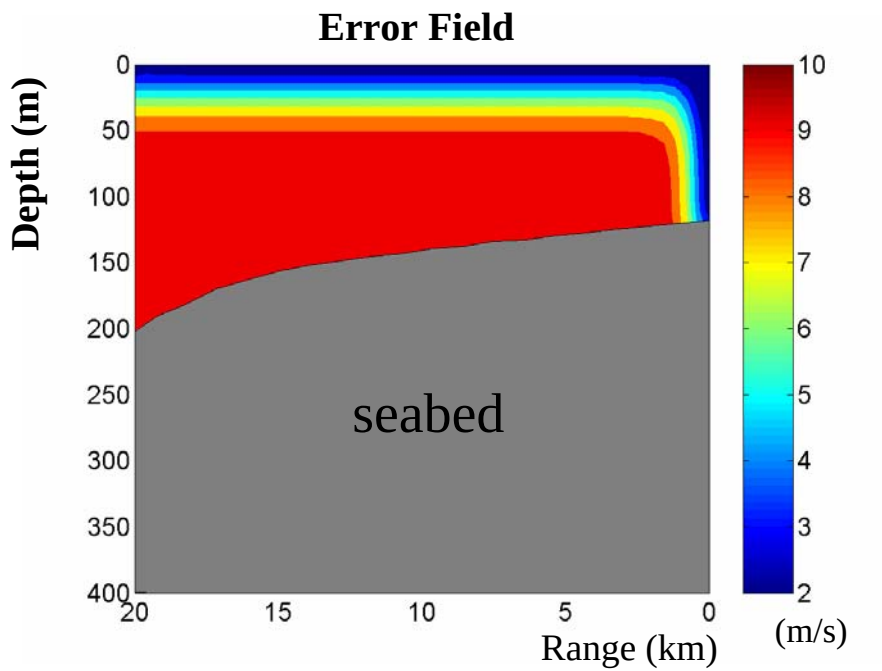
Range (Km)

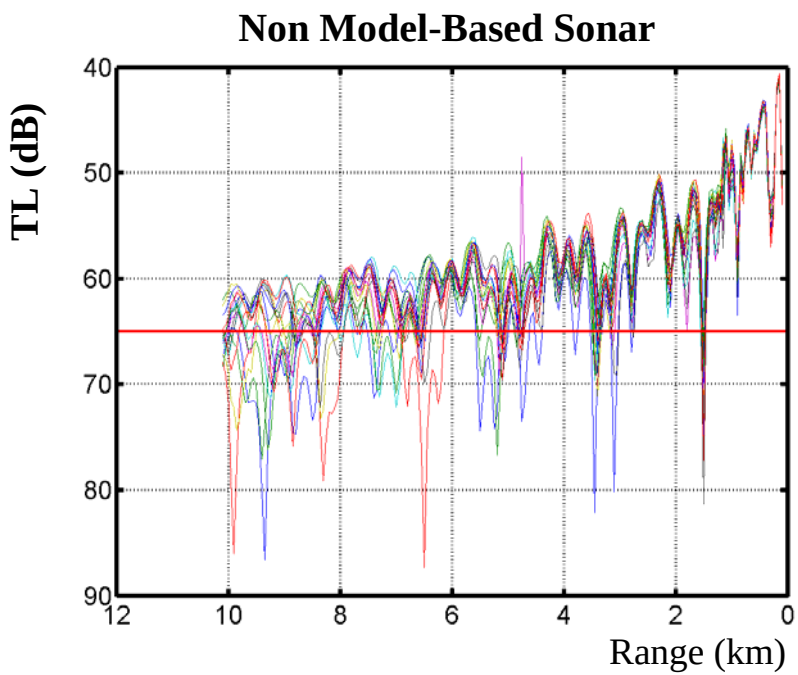
* Source location

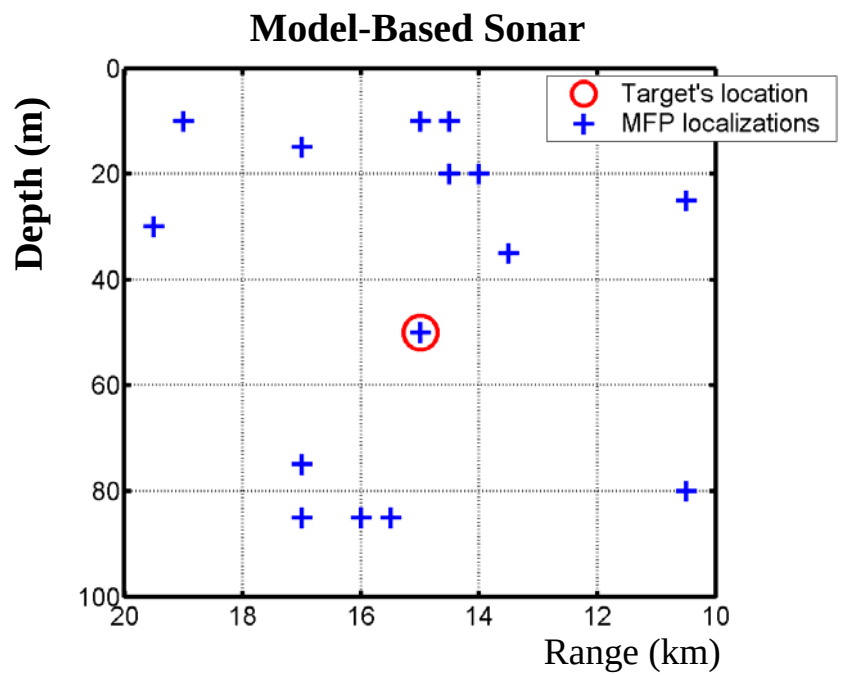
--- Receivers' location

Ocean Environment Uncertainties VS. Sonar Performance

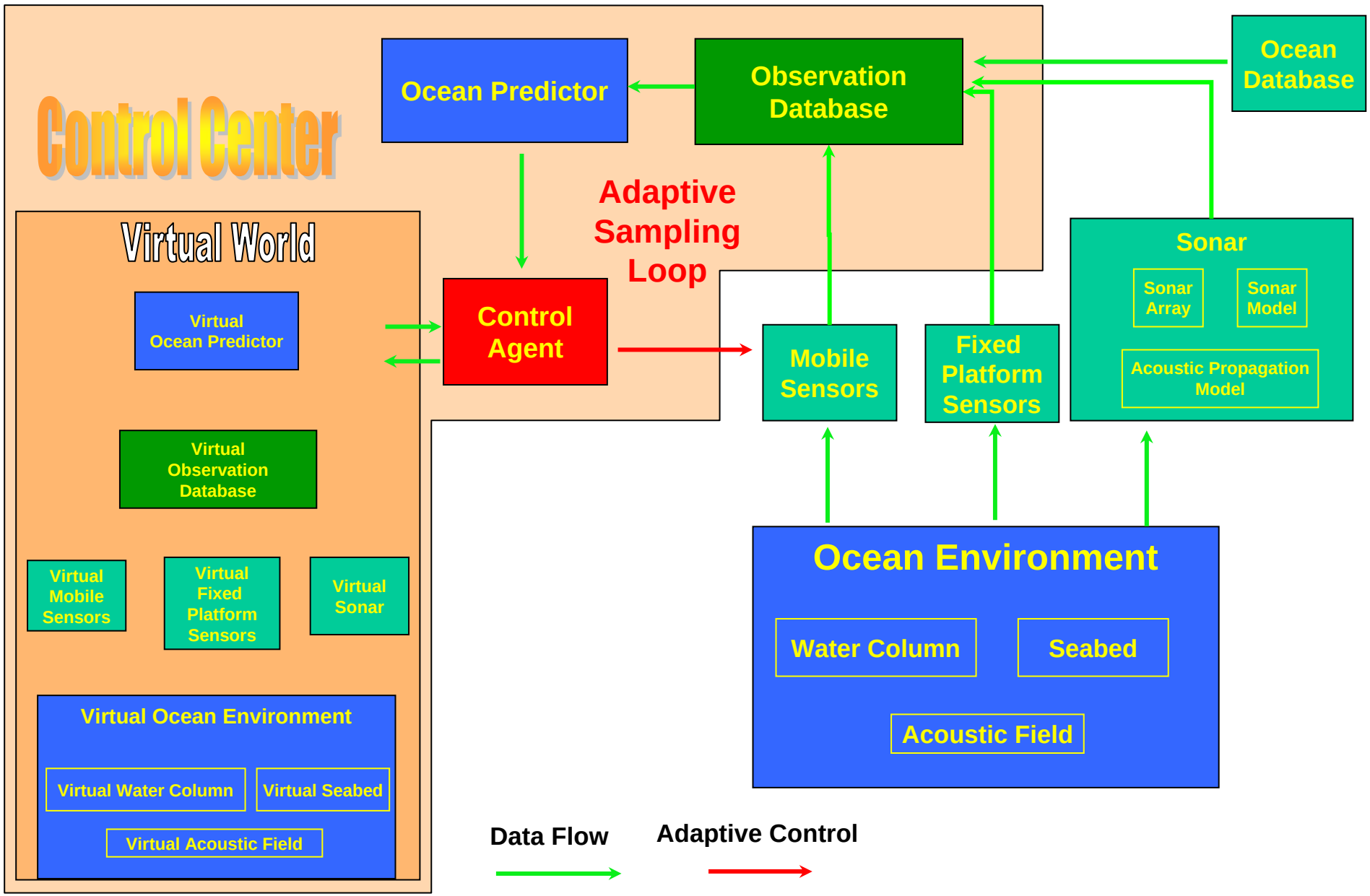




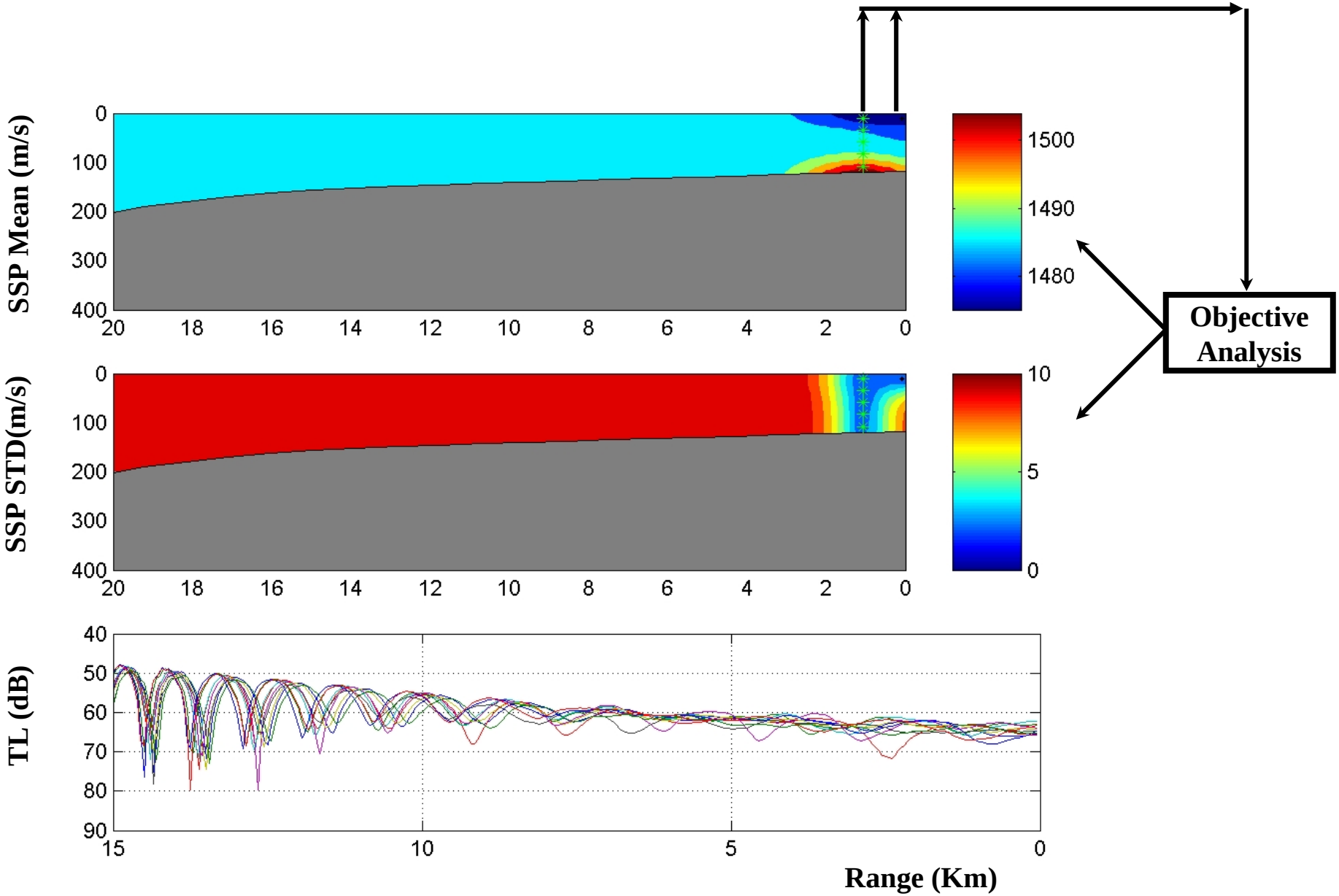




Adaptive Rapid Environmental Assessment System



AREA: Acoustic Adaptive Sampling



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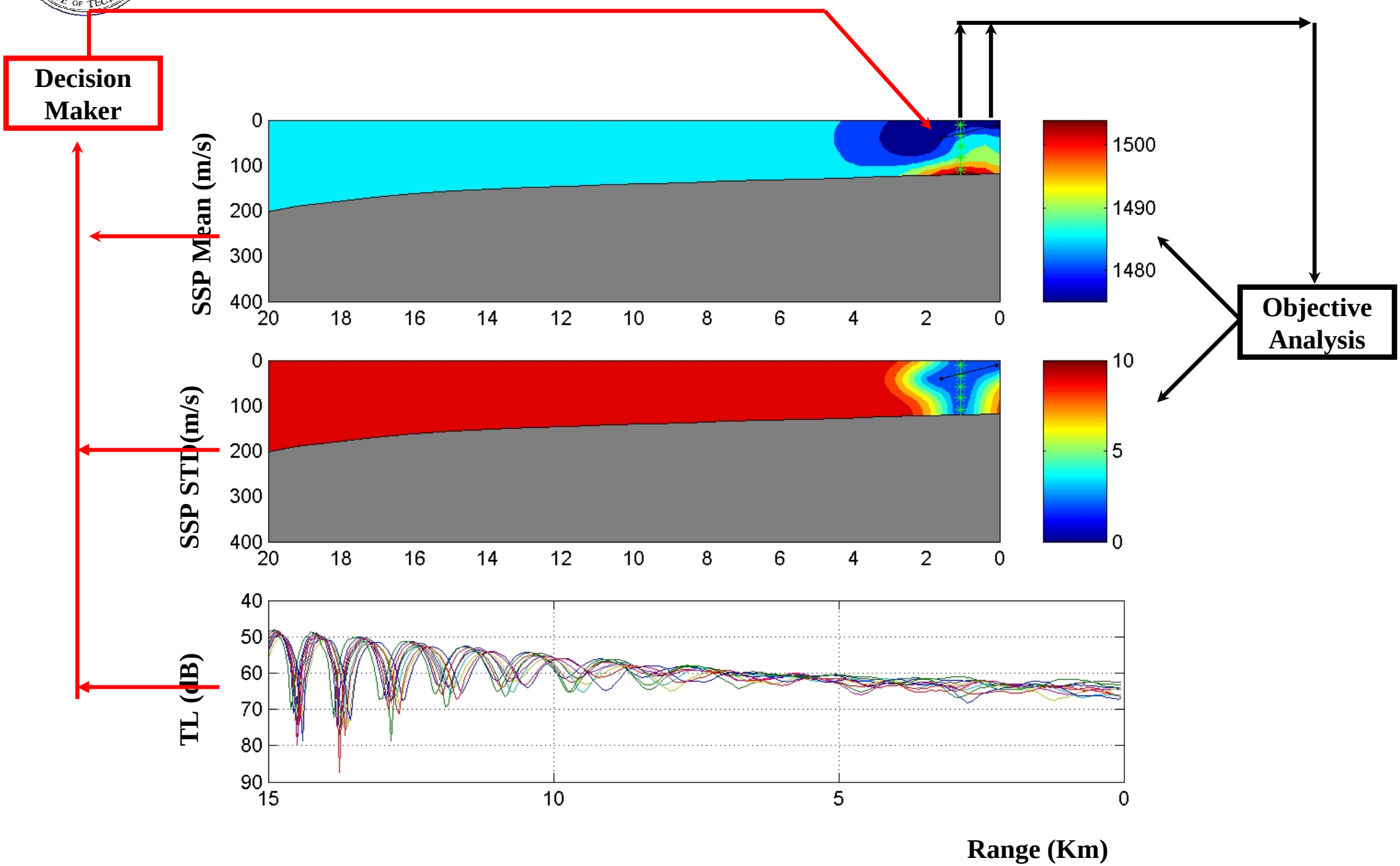

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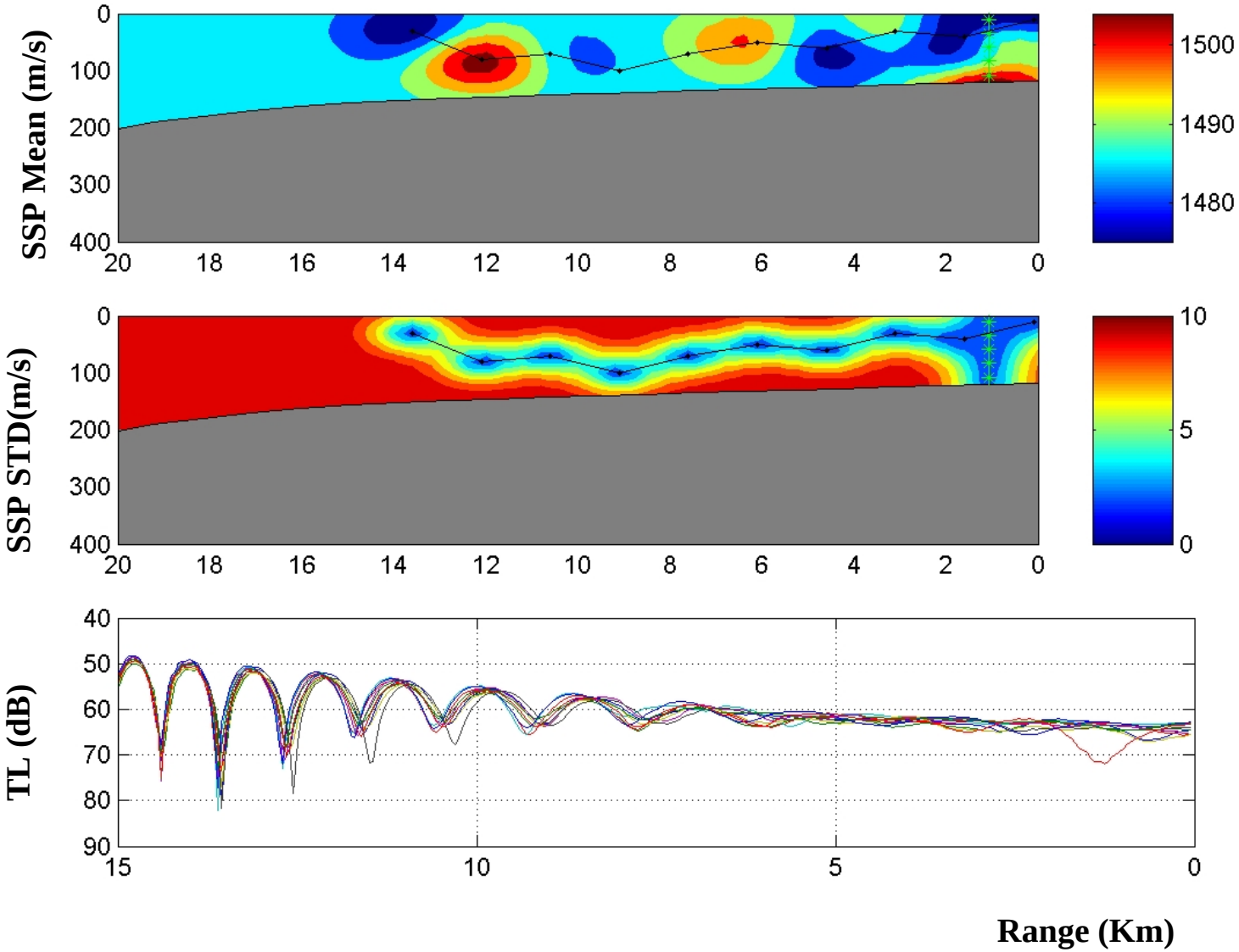
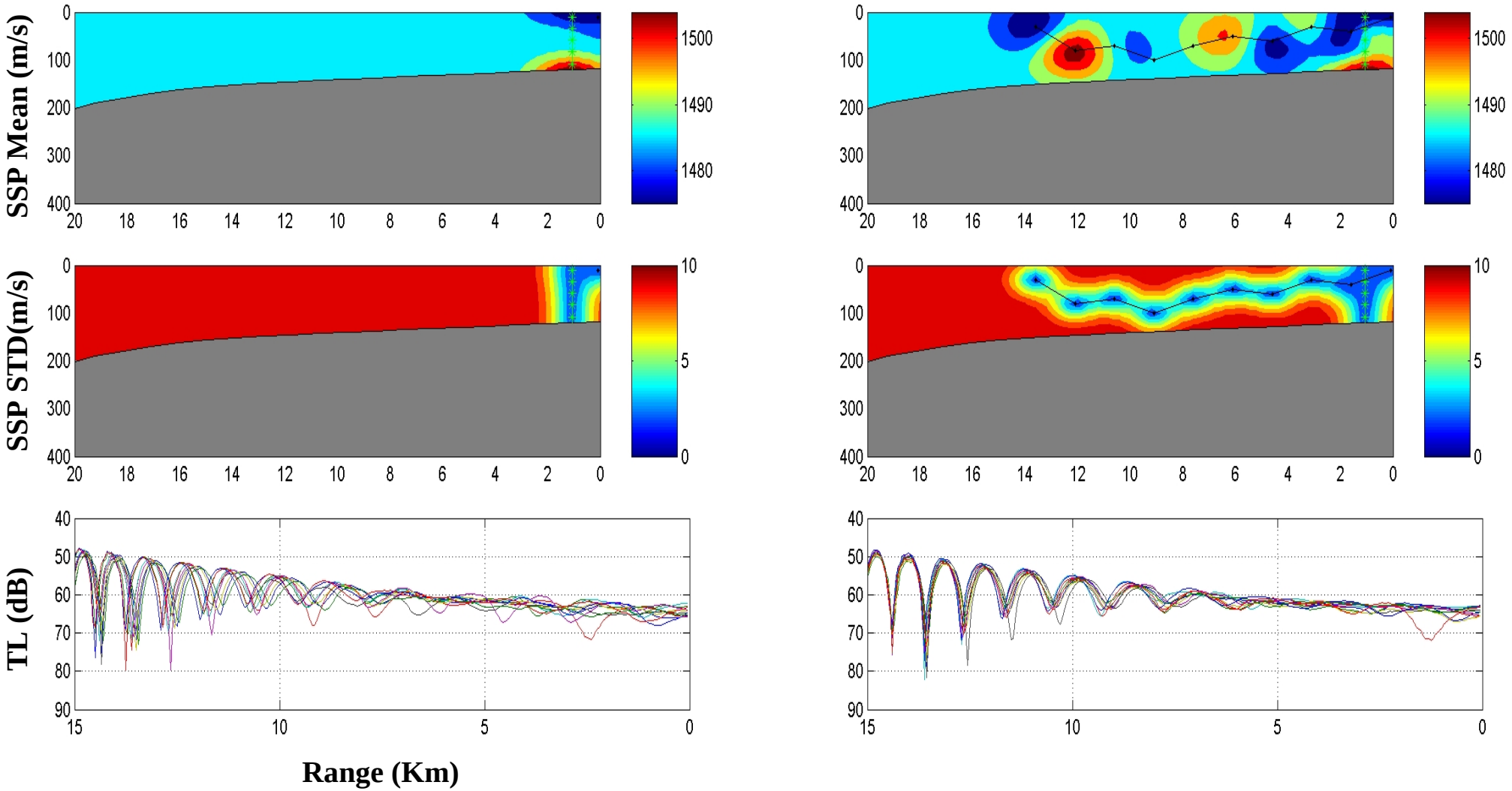
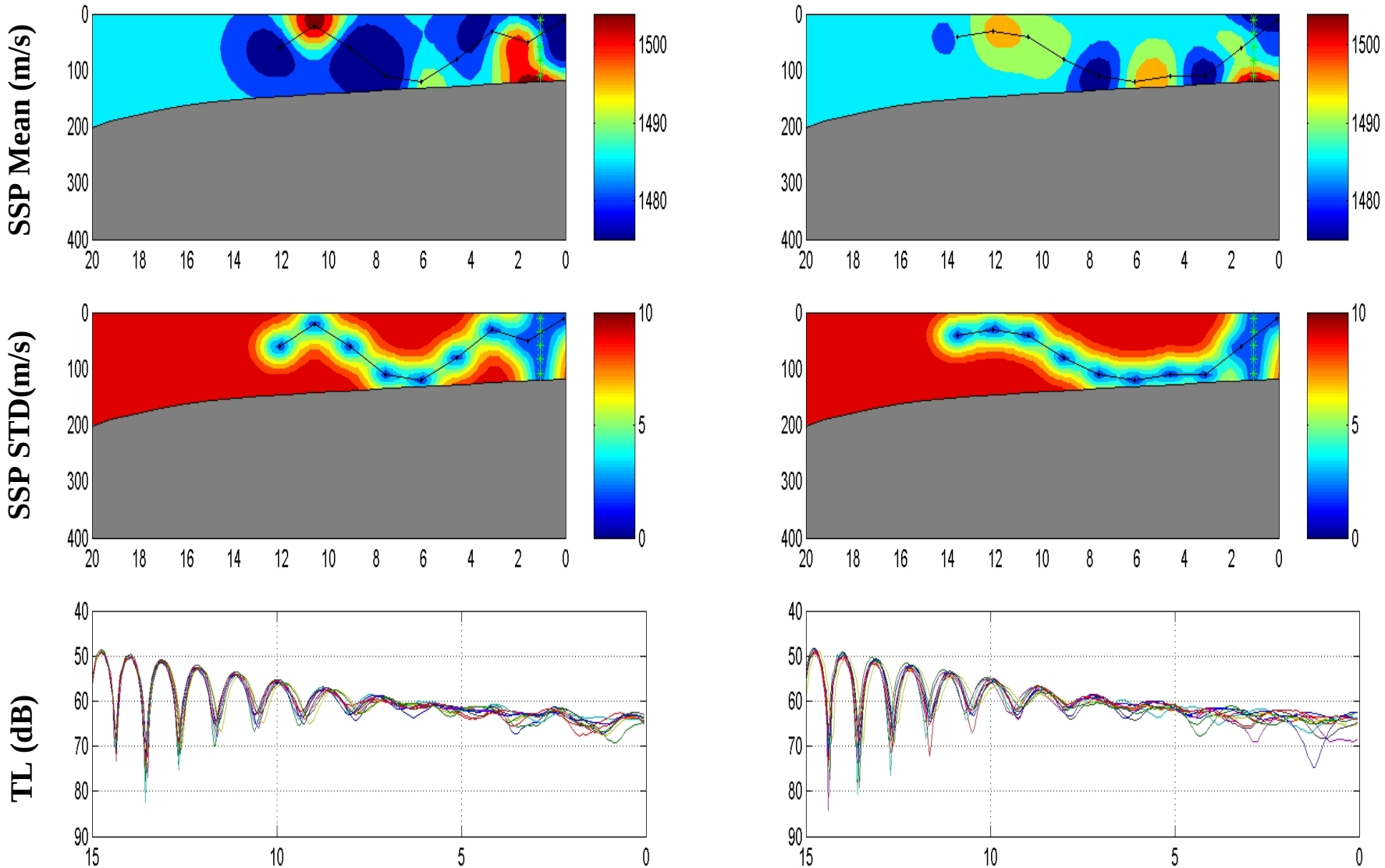


AREA Ideal Objective:
Minimize Sonar Performance Prediction Uncertainty

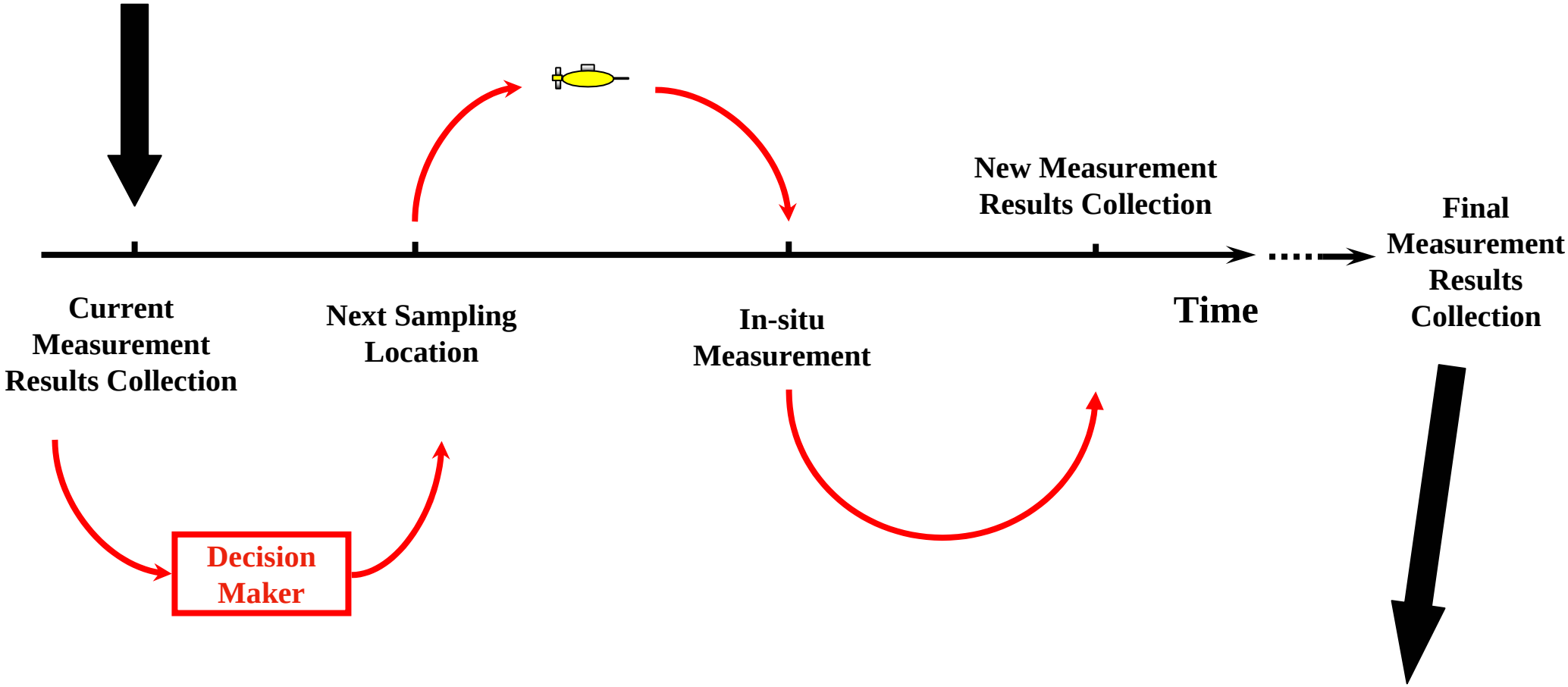


Random Ocean
Minimizing SPPU Impossible



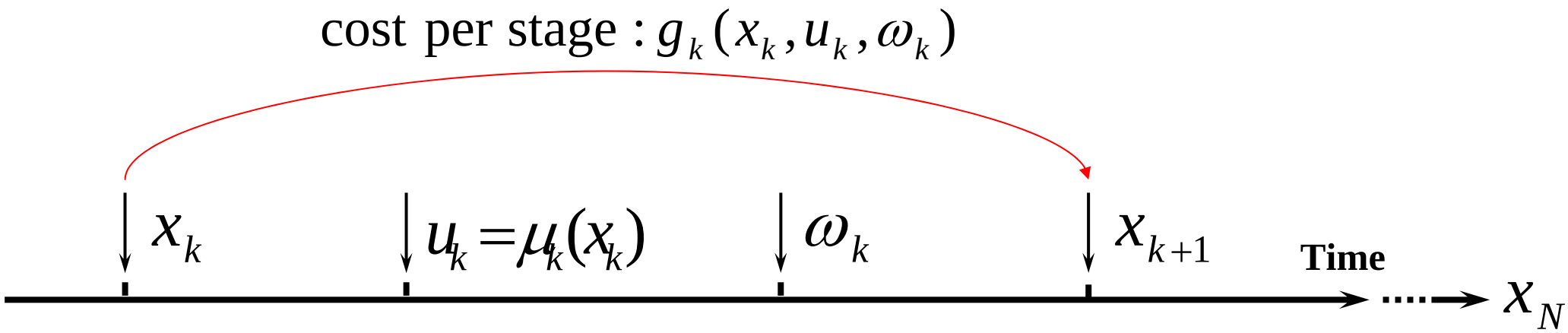
Realistic AREA Objective: Minimize E(SPPU)

Sequential Decision Making



Objective: min E{ SPP Uncertainty}

Dynamic Programming



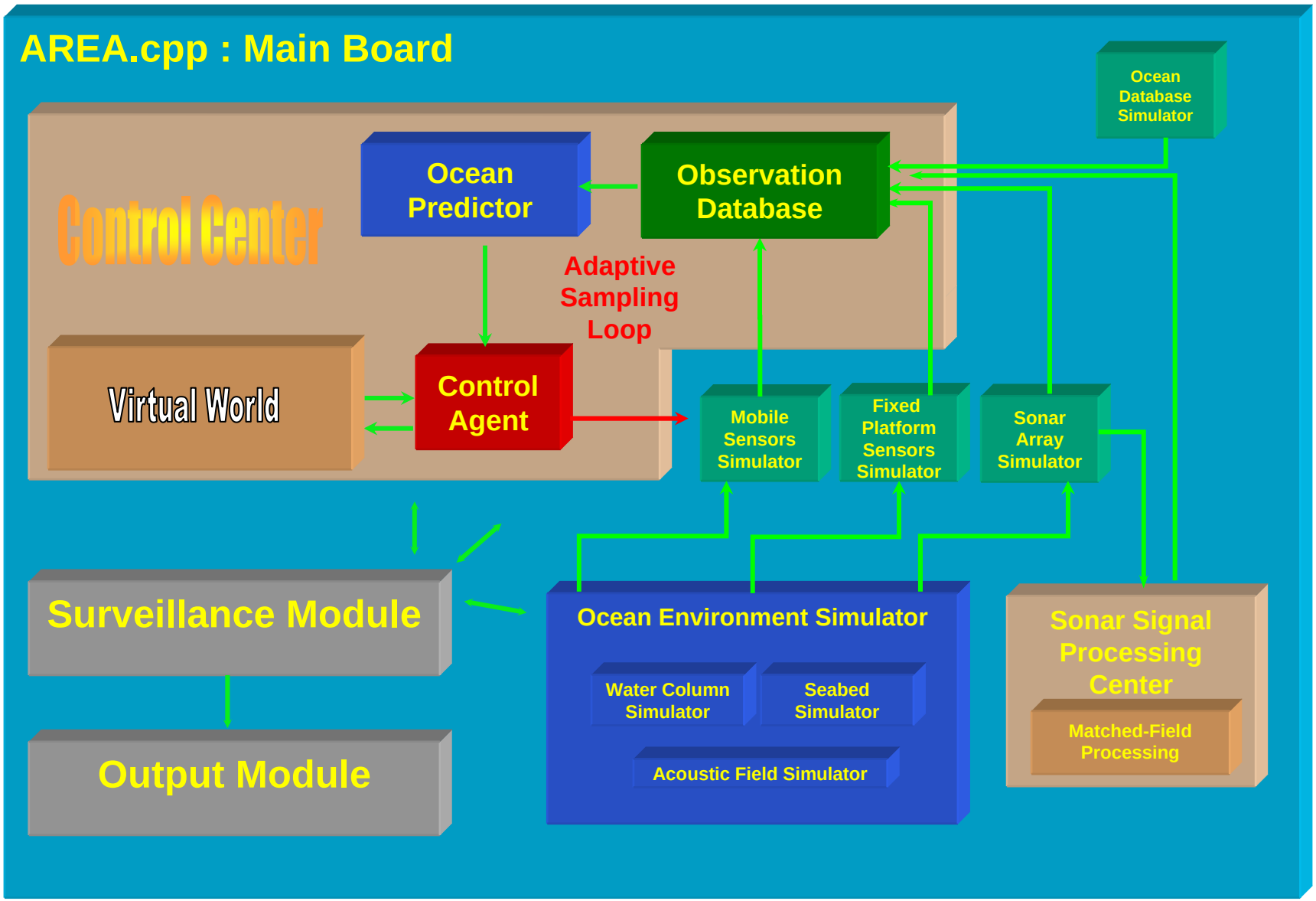
x: state u: control ω: random disturbance

$P_k(\omega_k \mid x_k, u_k)$

state equation : $x_{k+1} = f_k(x_k, u_k, \omega_k)_{k=0,1,2\cdots N-1}$

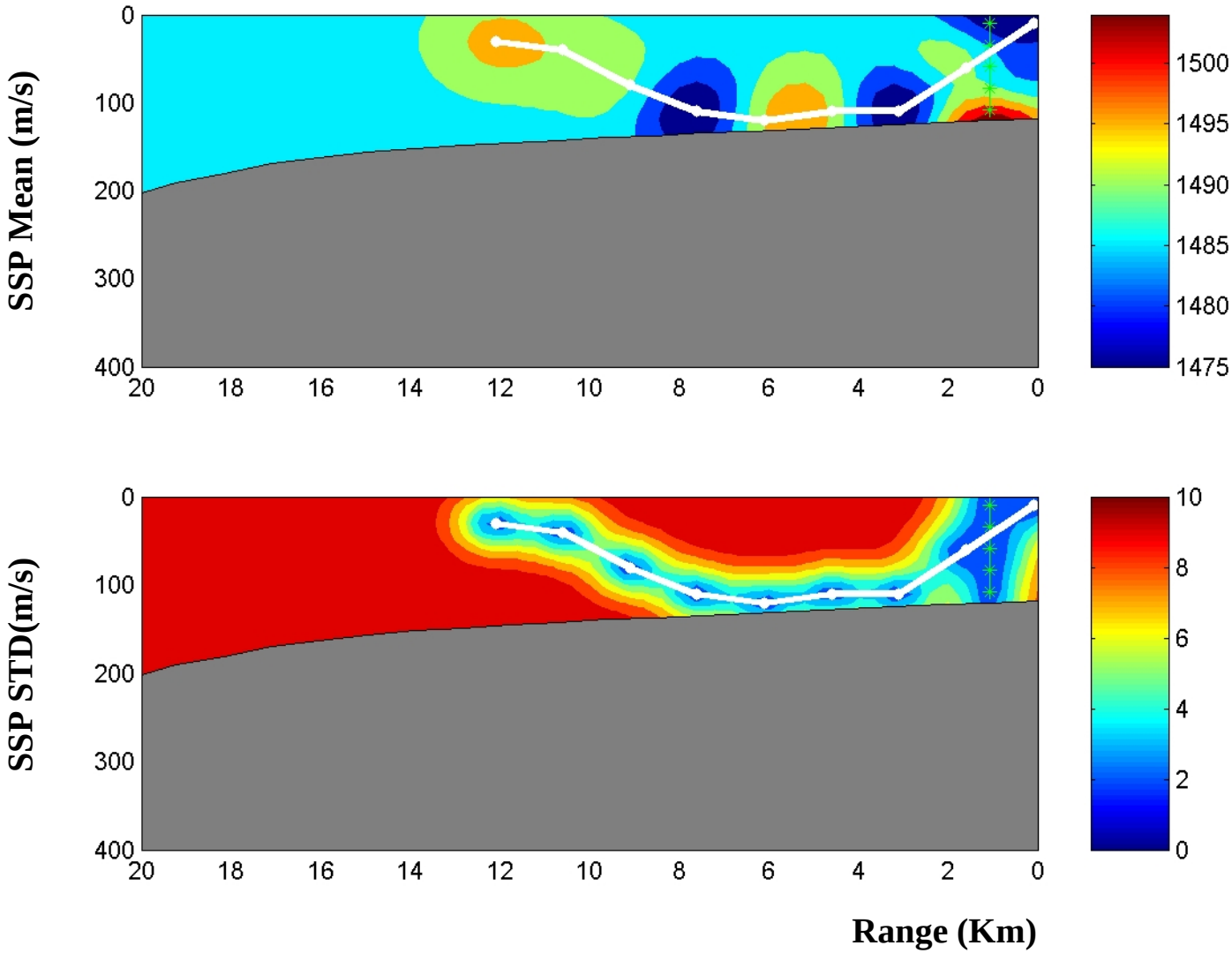
$$\{\mu_0(x_0), \mu_1(x_1) \cdots \mu_{N-1}(x_{N-1})\} \xrightarrow{\min} E\left\{ g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k, \omega_k) \right\}$$

Adaptive Rapid Environmental Assessment Simulation Framework



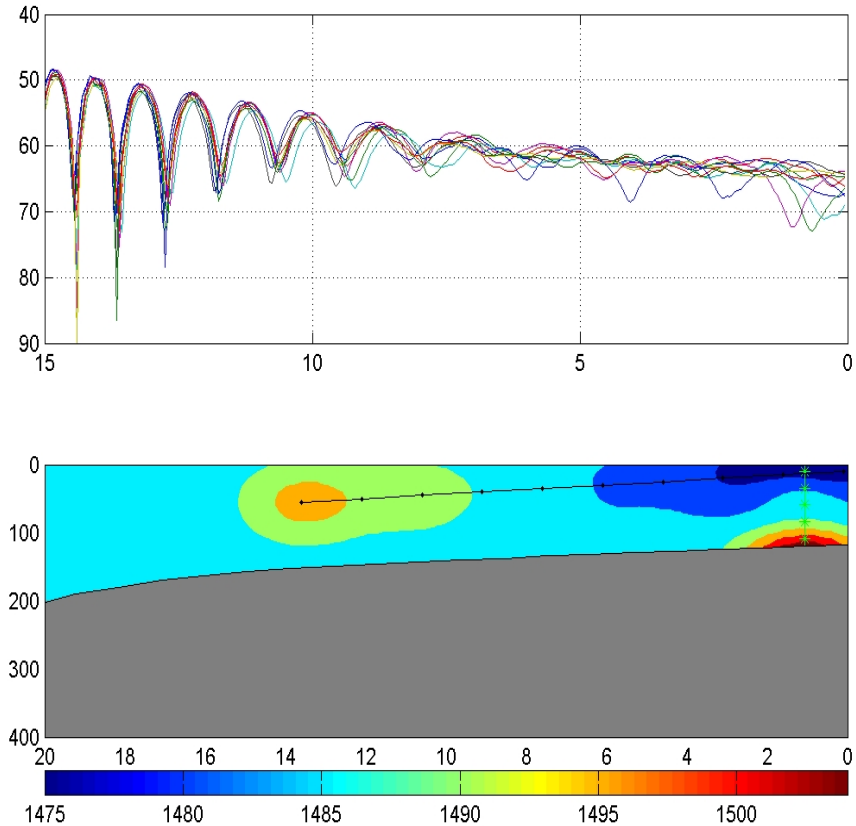
Rollout Algorithm Based on Greedy Algorithm

$$\tilde{\mu}_k(x_k) = \arg \min_{u_k \in U_k(x_k)} \; E_{\omega_k}\left\{\tilde{J}_{k+1}(f_k(x_k, u_k, \omega_k))\right\}$$

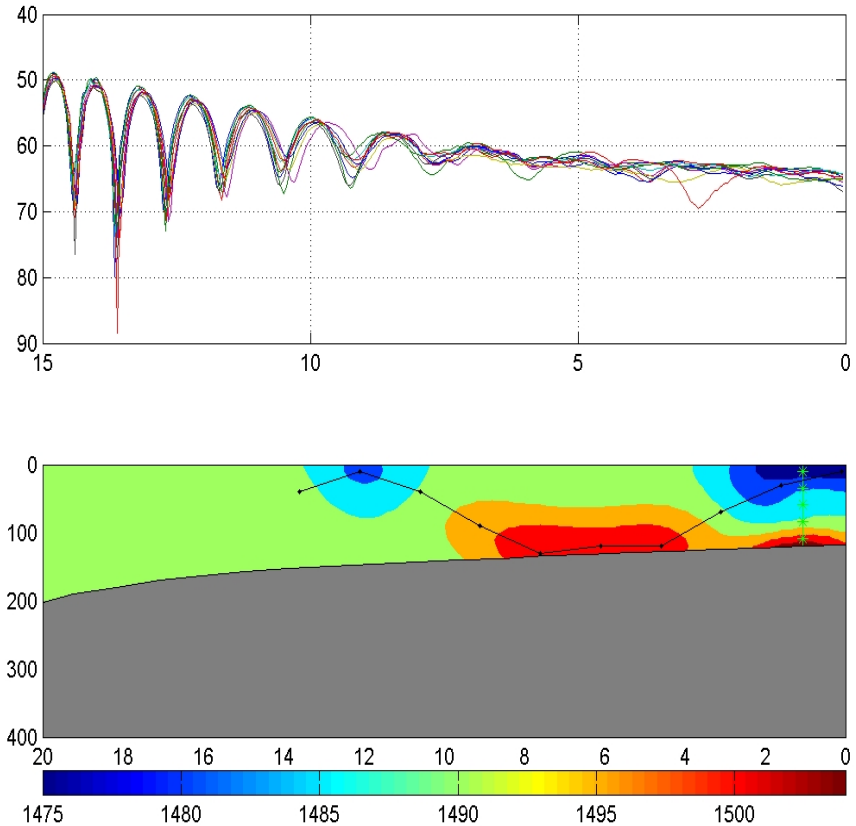


Example 1

Predetermined Path



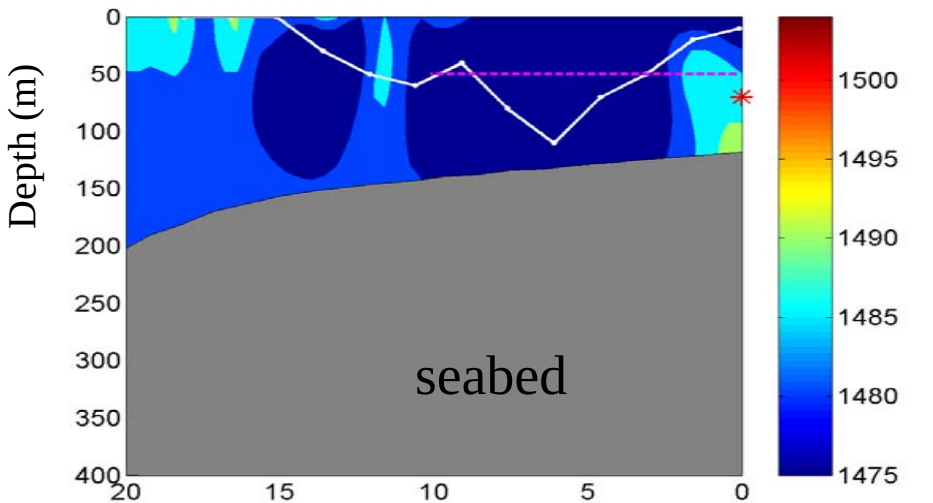
Rollout algorithm based on greedy algorithm



Example 2

Rollout algorithm based on greed algorithm

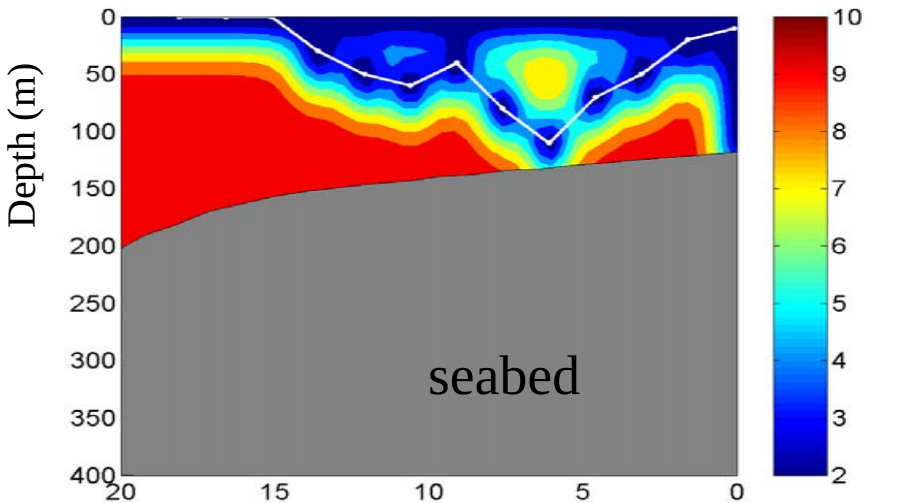
Estimated Water Sound Speed Profile



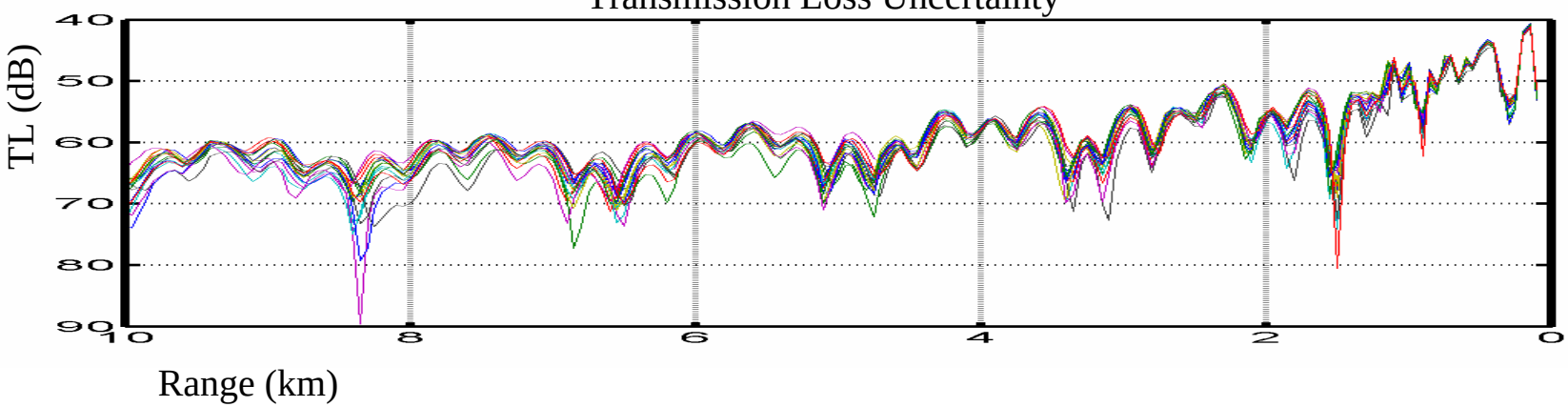
* Receiver location

--- Sources' location

Error Field



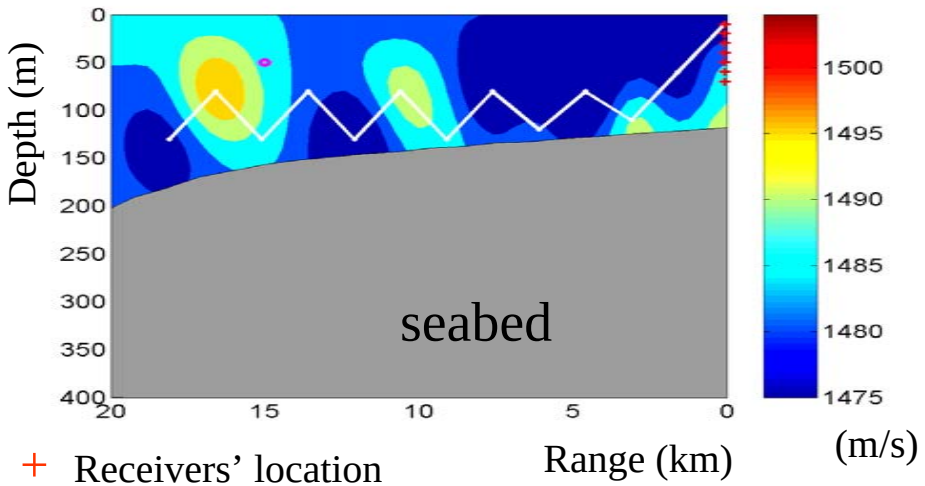
Transmission Loss Uncertainty



Example 3

Greedy Algorithm

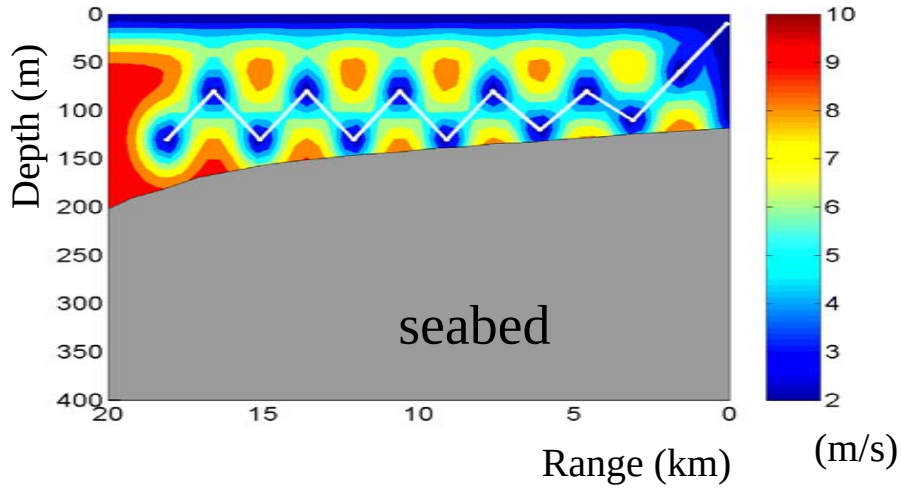
Estimated Water Sound Speed Profile



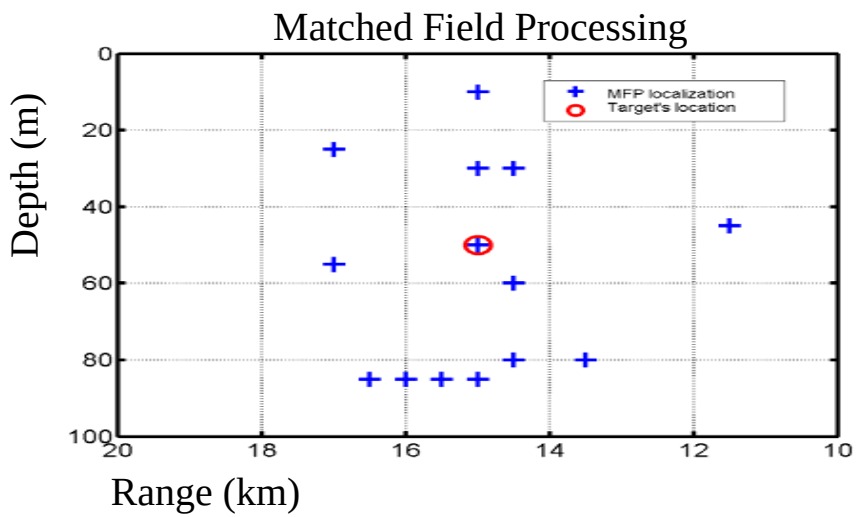
+ Receivers' location

o Source location

Error Field



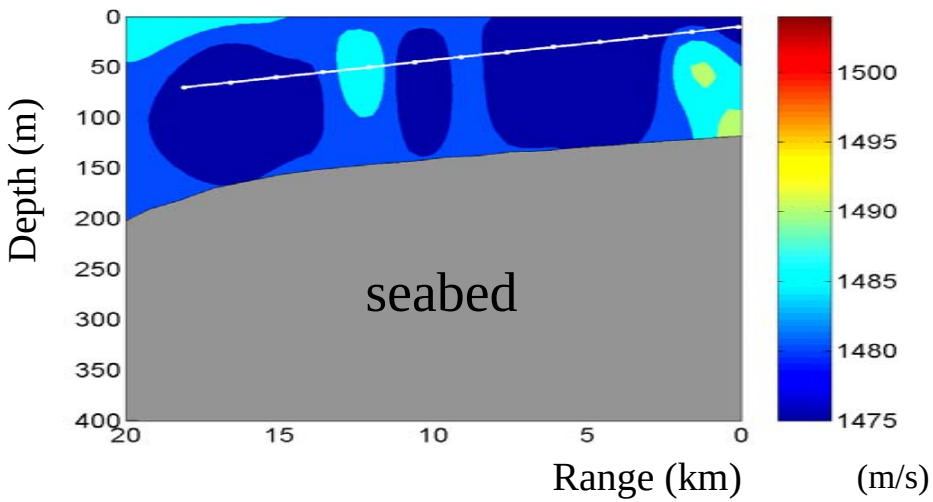
Matched Field Processing



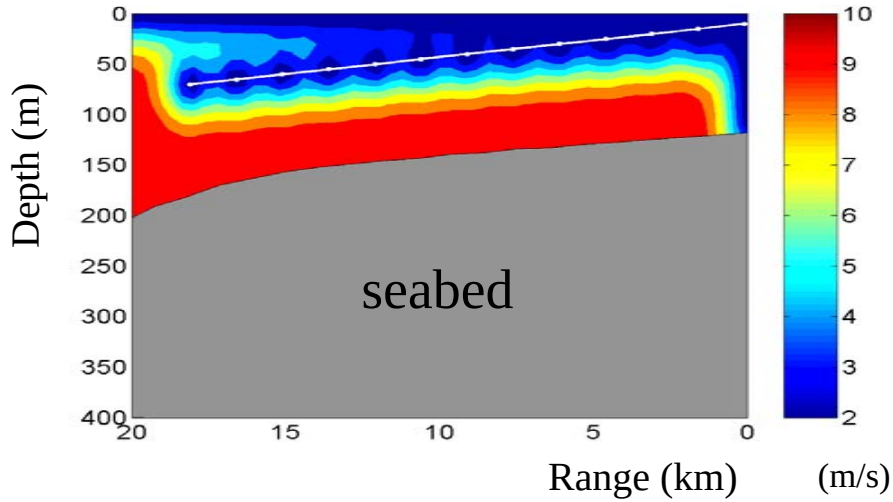
Example 4

Predetermined path
(cost=4746.3 m/s)

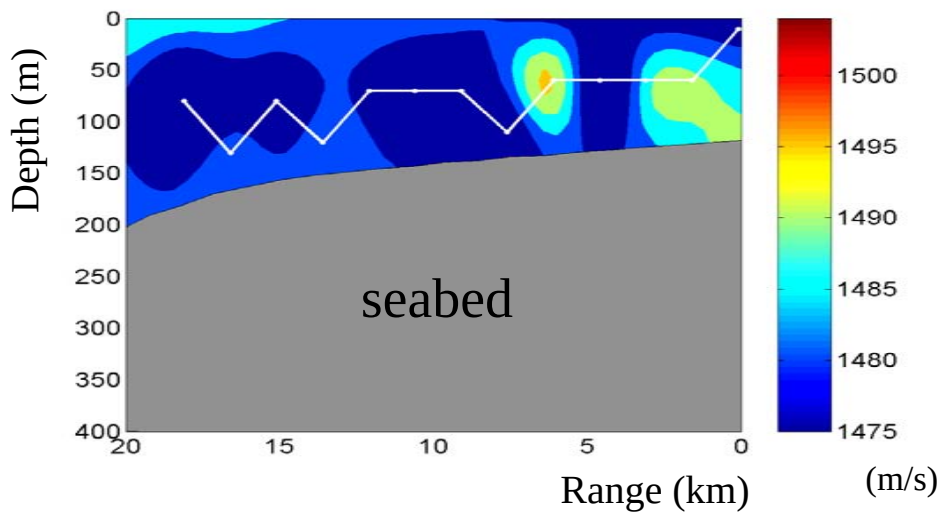
Estimated Water Sound Speed Profile

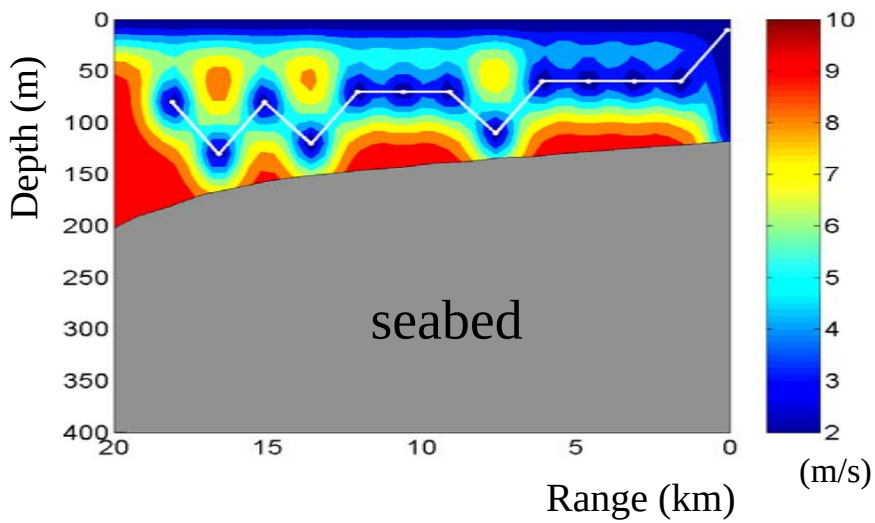


Error Field



Rollout algorithm based on greed algorithm
(cost=4307.8 m/s)





AREA
Accomplishments-I

- Quantitative Sonar Performance Assessment
  - Non-local performance bounds
  - Several Journal publications completed (Xu etal)
- Optimal through-the-sonar parameterization
  - SOF: Uncoupled in sonar response
  - Quantifies environmental sensitivity
  - Identifies parameters to be targeted by REA resources
  - Journal paper in revision
- Through-the-sonar Acoustic Data Assimilation (ADA)
  - Consistent fusion of acoustic and non-acoustics data
  - Inherently estimates most critical environmental

AREA
Accomplishments-II

- AREA Simulation Framework Prototype
  - Modular, structured MATLAB-C++ framework
  - HOPS compatible
  - Hi-Fi Sonar modeling
    - RAM
    - SEALAB
  - Dynamic Programming decision-maker prototype
  - Next: ADAPTS MURI 04-08
    - Integrate with Mini-HOPS
    - Efficient on-board sonar model
    - On-board implementation and demonstration in MURI’06

Capturing Uncertainty
MIT Publications

- P. Elisseeff, H. Schmidt, and W. Xu, “Ocean acoustic tomography as a data assimilation problem,” *IEEE Journal of Oceanic Engineering*, Vol. 27, No. 2, pp 275-282, 2002.
- W. Xu and A. B. Baggeroer, “Quantitative ambiguity analysis for matched-field parameter estimation,” *J. Acoust. Soc. Am.*, Vol. 110, No. 5, Pt. 2, pp 2716, 2001.
- W. Xu, A. B. Baggeroer, and H. Schmidt, “Quantitative ambiguity analysis for matched-field source localization,” *Proc. of Asilomar Conference on Signals, Systems, and Computers*, pp 448-452, 2002.
- A.B. Baggeroer and H. Schmidt, “Performance Bounds on the Detection and Localization in a Stochastic Ocean,” in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, pp 507-514, 2002.
- H. Schmidt, “AREA: Adaptive Rapid Environmental Assessment,” in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, pp 587-594, 2002.
- W. Xu and C. D. Richmond, "Quantitative ambiguity analysis for matched-field source localization under spatially-correlated noise field," *Proc. of IEEE/MTS OCEANS'03*, Vol. 2, pp 922-927, 2003.
- W. Xu, A. B. Baggeroer, and K. L. Bell, “A bound on mean-square estimation error with background parameter mismatch,” *IEEE Trans. Information Theory*, Vol. 50, No. 4, pp 621-632, 2004.
- W. Xu, A. B. Baggeroer, and C. D. Richmond, “Bayesian bounds for matched-field parameter estimation,” *IEEE Trans. Signal Processing* (In press).
- W. Xu and H. Schmidt, "System-orthogonal functions for sound velocity profile perturbation,“ Accepted for publication in *IEEE Journal of Oceanic Engineering*.
- W. Xu, A. B. Baggeroer, and H. Schmidt, "Performance analysis on matched-field source localization: Simulations and experimental results," Submitted for publication in *IEEE Journal of Oceanic Engineering*.

Capturing Uncertainty Transitions

- New Uncertainty-Mitigating Operational Paradigms
  - Intelligent, Mobile Off-board Sensor Networks.
    - Sonobouys → Underwater robotic networks
    - Sensors on Platforms → Sensing Systems
  - Integrated Sensing, Modeling, Processing and Platform Control
    - Environmentally Adaptive Sonar Technology (EAST)
    - Sonar-Adaptive Environmental Assessment (ADAPT MURI, PLUS)
    - Target-Adaptive Synthetic Array Apertures (PLUS)
    - Multi-platform Autonomous Collaborative Sensing (PLUS)
    - Platforms as Virtual Sensors (nested processing) (PLUS)
- Research Needs
  - Robust Parameterization
  - Acoustic Data Assimilation
  - Autonomous Network Navigation and Control
  - Multi-static, model-based sonar processing
  - Multidisciplinary Synergies