AREA

Adaptive Rapid Environmental Assessment

Henrik Schmidt, A.B. Baggeroer, W. Xu, D. Wang
Department of Ocean Engineering
Massachusetts Institute of Technology

Capturing Uncertainty
Final Review
Chantilly, VA
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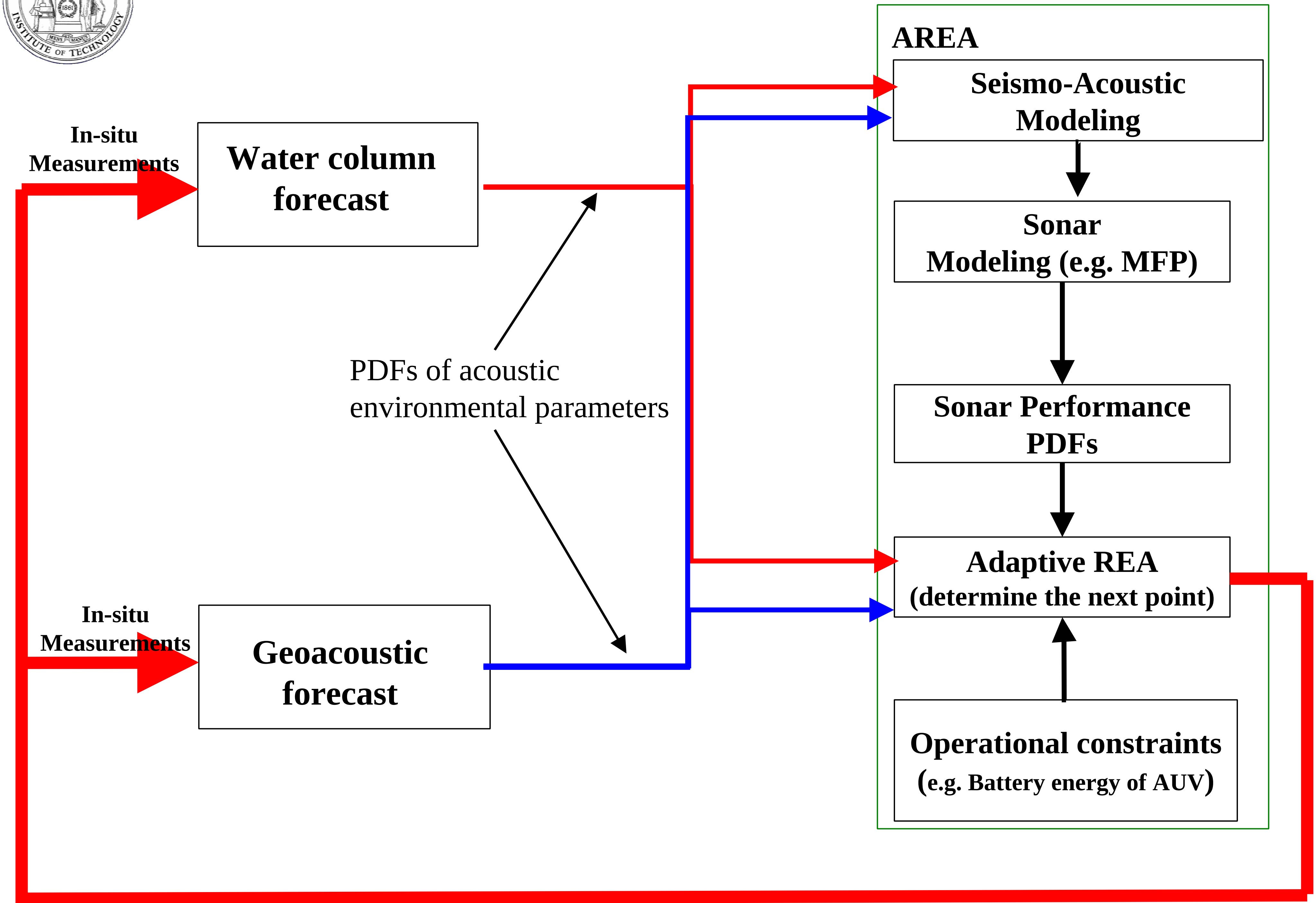
Adaptive Rapid Environmental Assessment

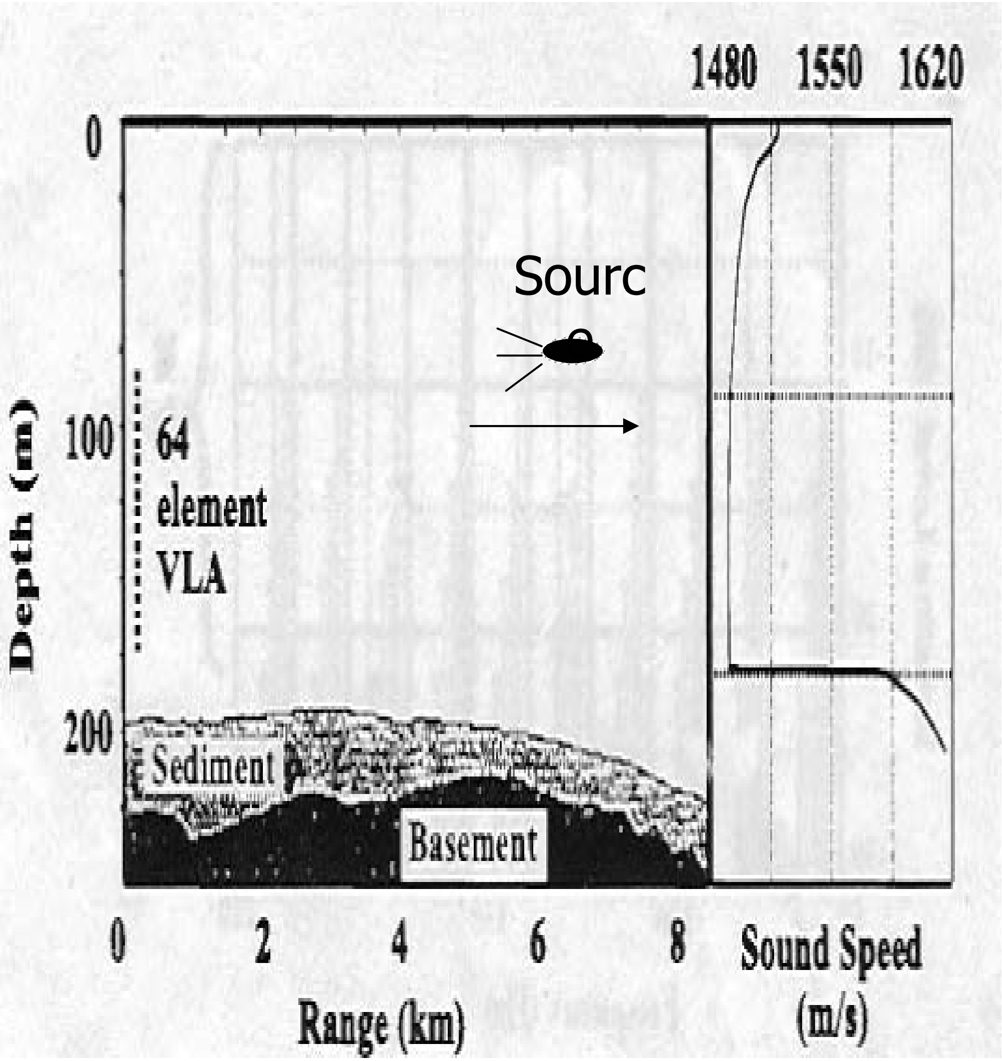


AREA

Research Strategy

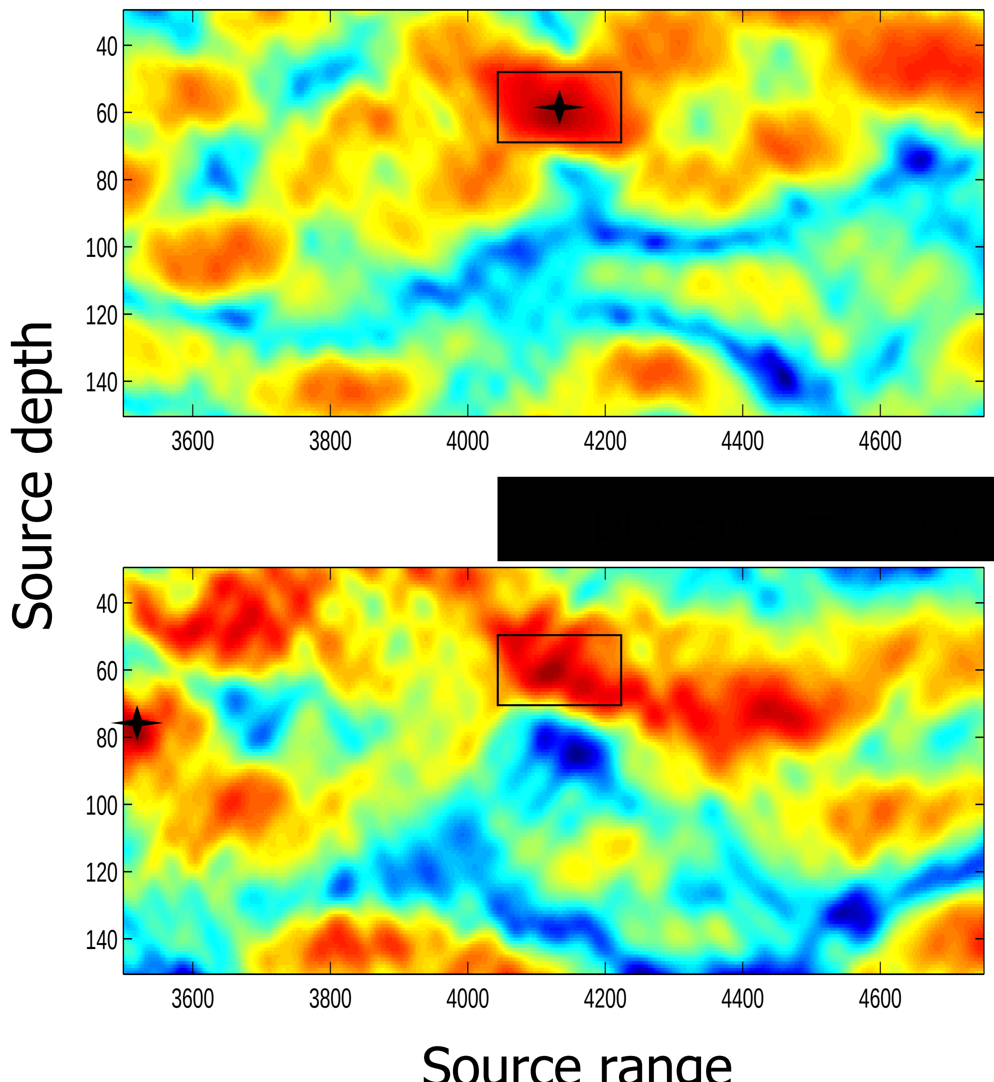
- Sonar configuration and performance metrics
  - Shallow water MFP – VLA
- Optimal Parameterization
  - System Orthogonal Functions (SOF)
    - Orthogonal or uncoupled in sonar performance statistics
    - Minimize and identify parameters to be targeted by REA
- Acoustic Data Assimilation
  - Consistent fusion of any acoustic data with other REA data
  - Inherently targets parameters most critical to sonar performance
- 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



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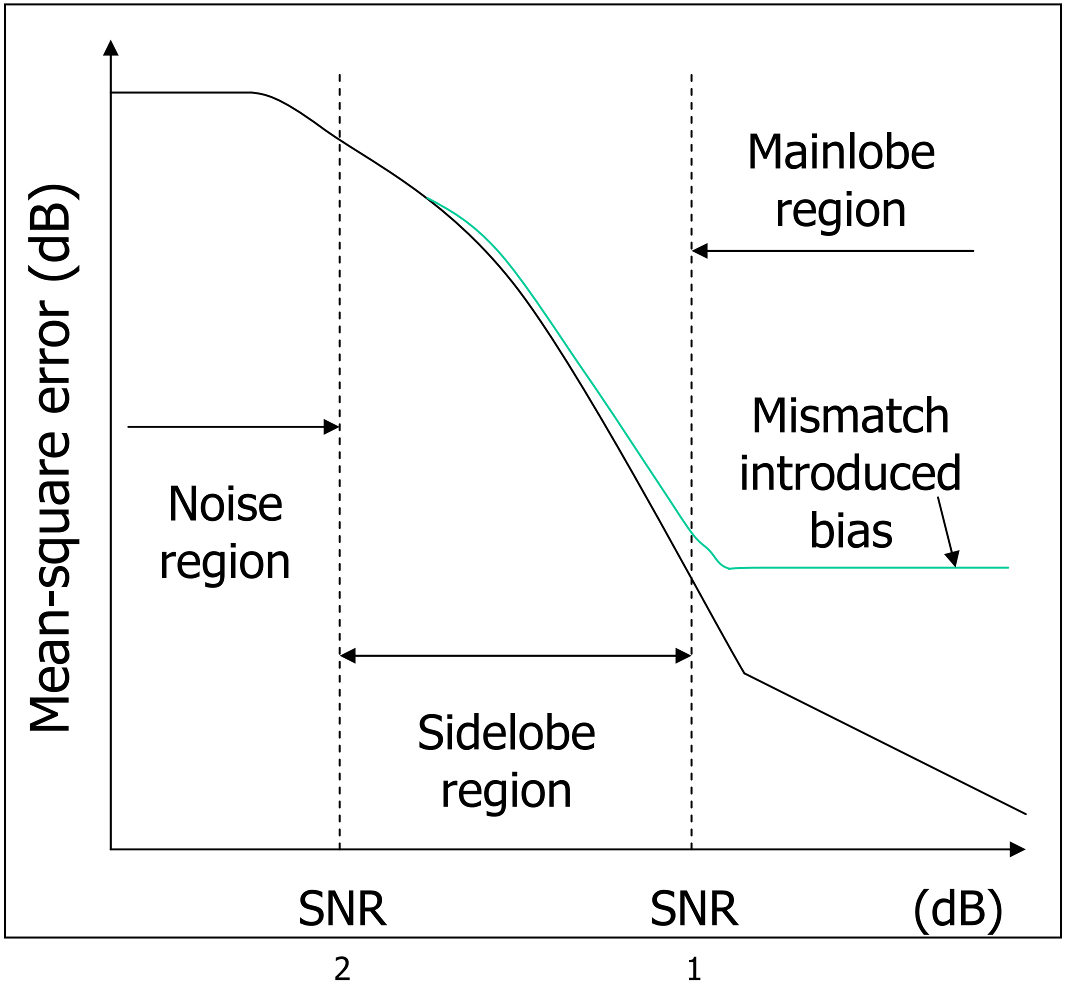
Source Localization Ambiguity Surface

Matched-field Performance Threshold
Parameter Mismatch

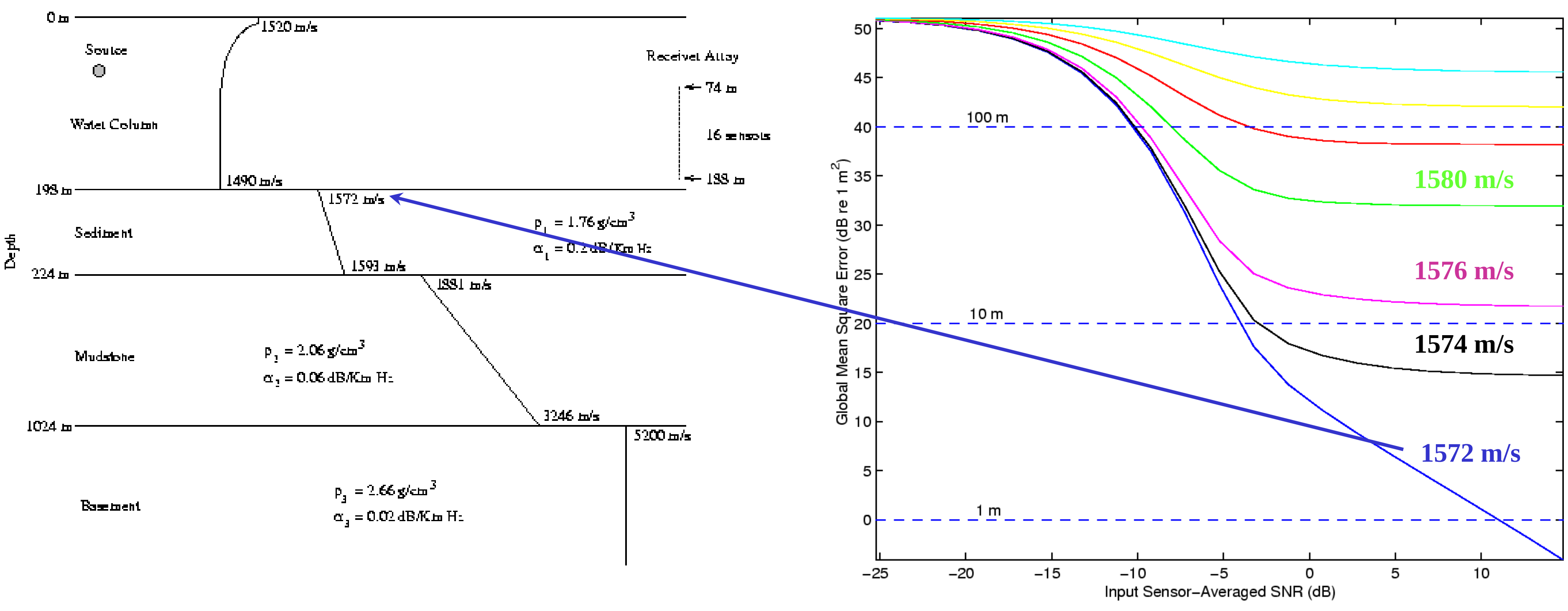
Performance analysis tools

- 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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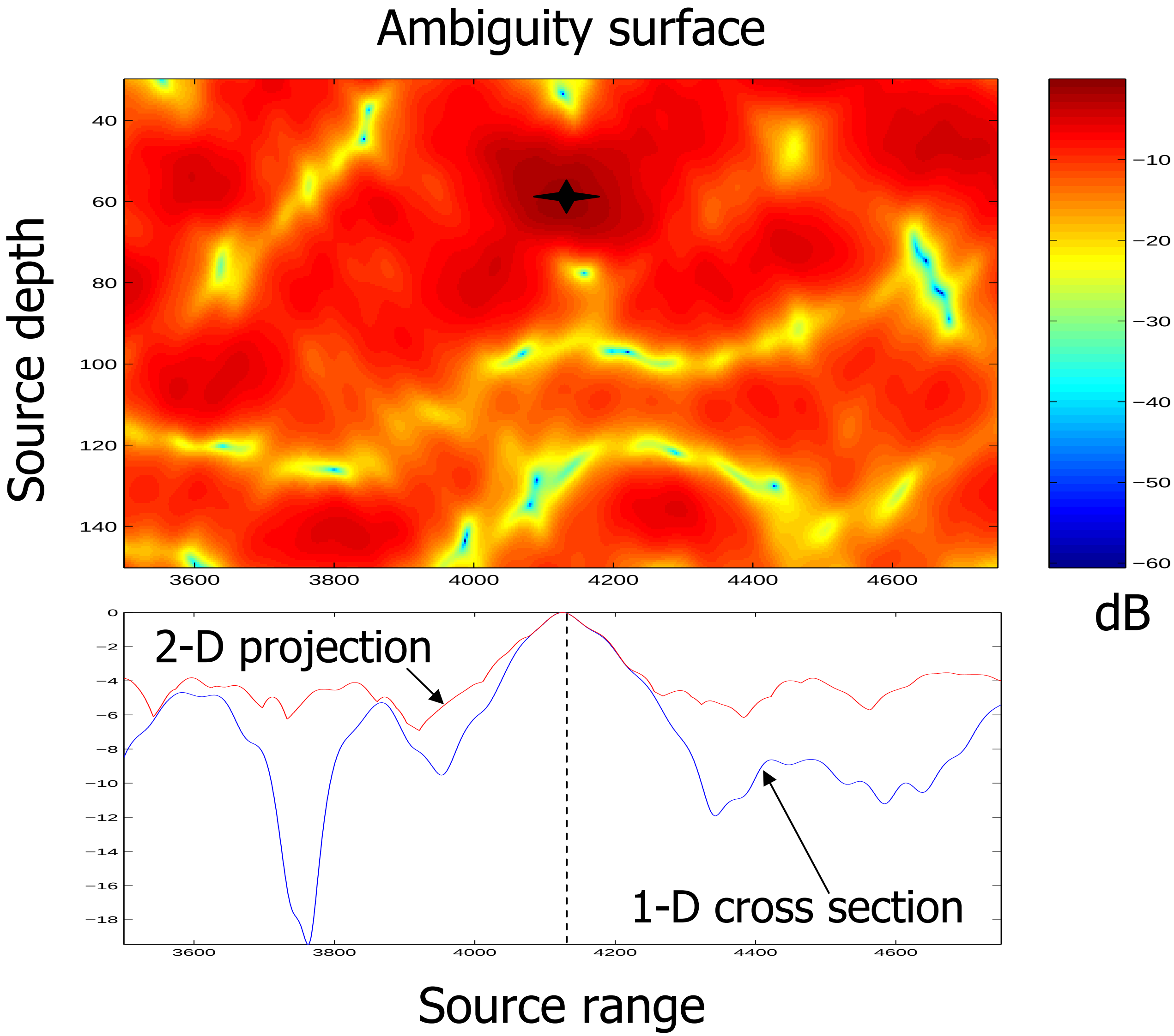
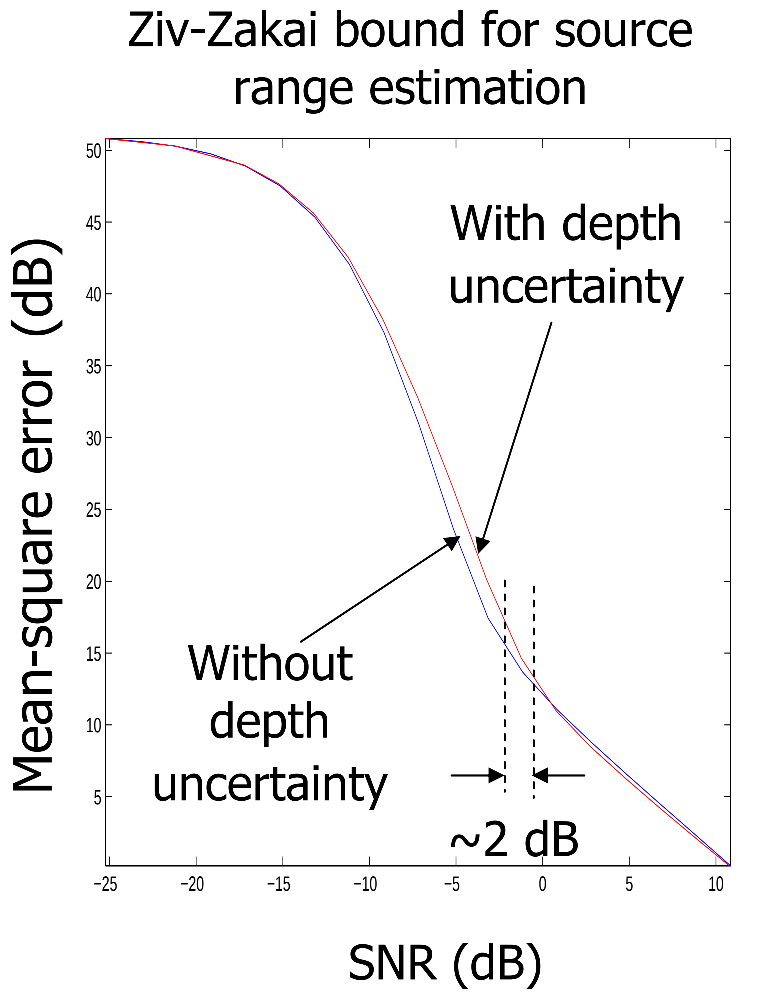
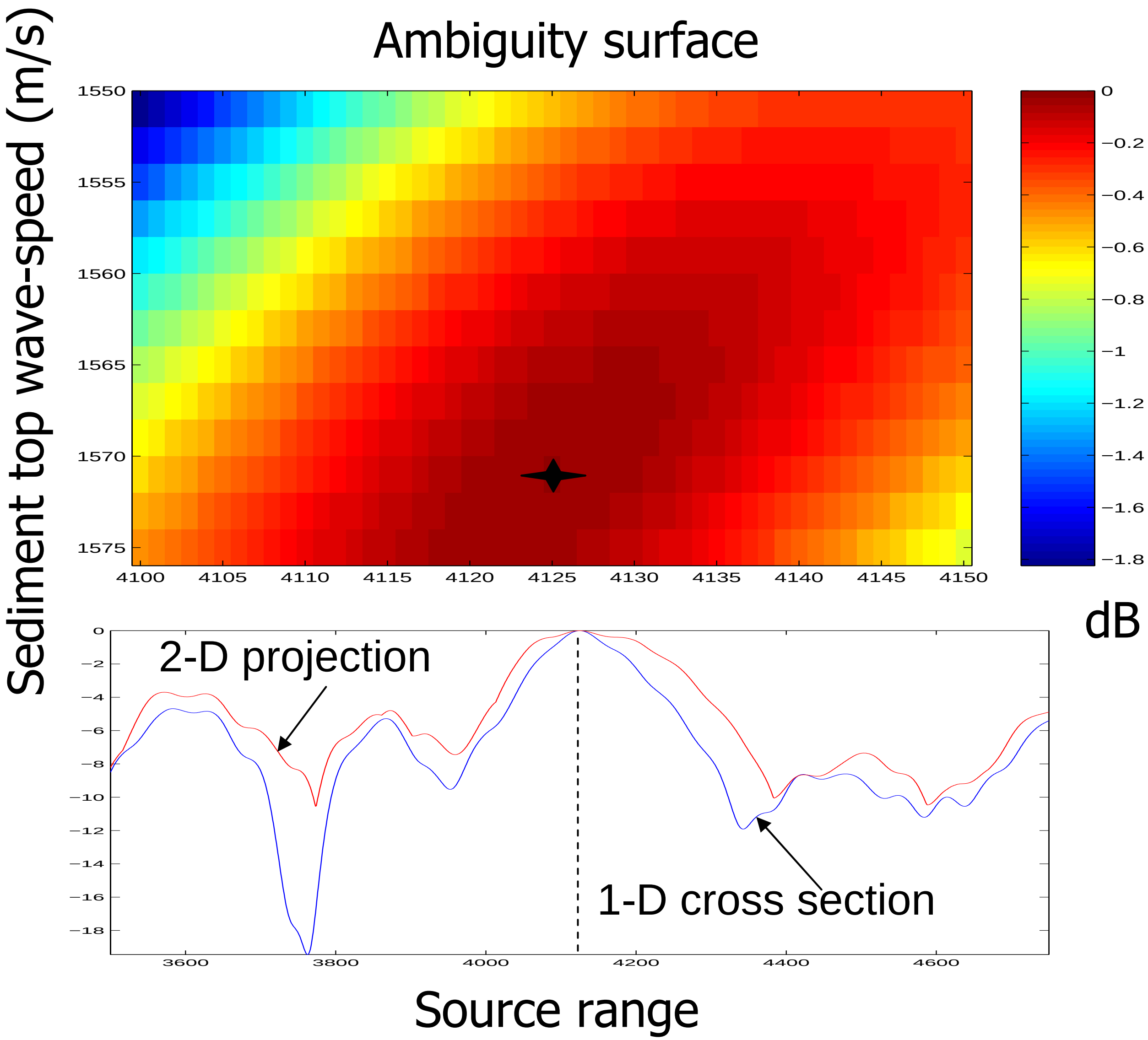
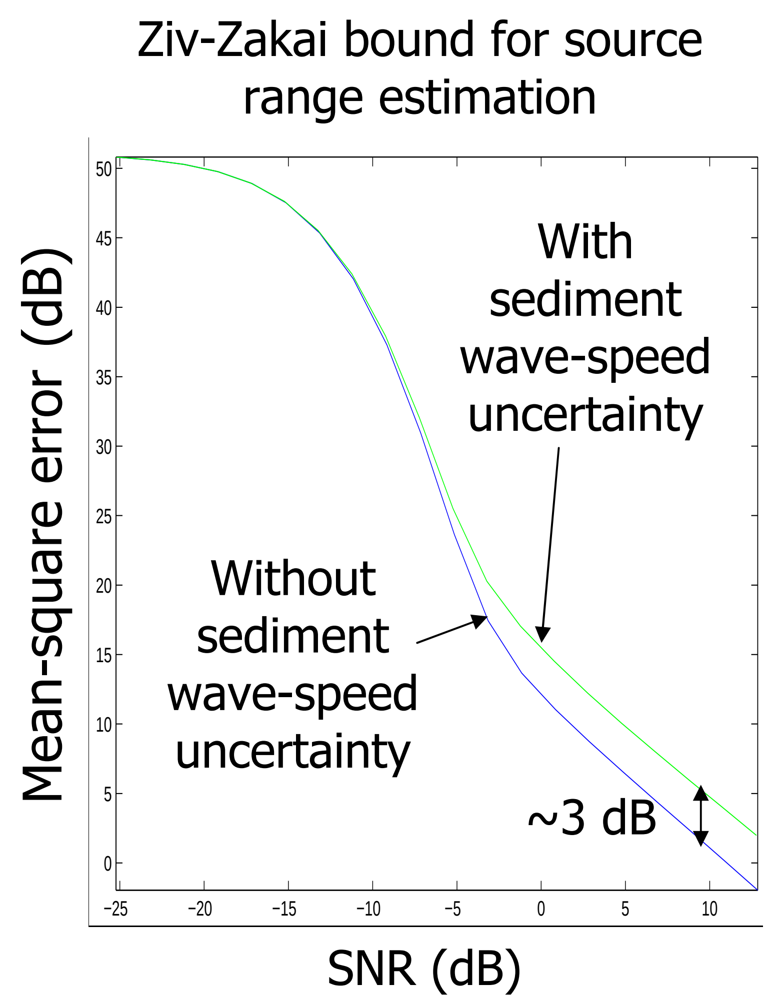
Parameter Coupling
Weak Coupling





Coupling of Location and Environment
Strong Coupling





Matched Field Source Localization
Environmentally Robust Parameterization

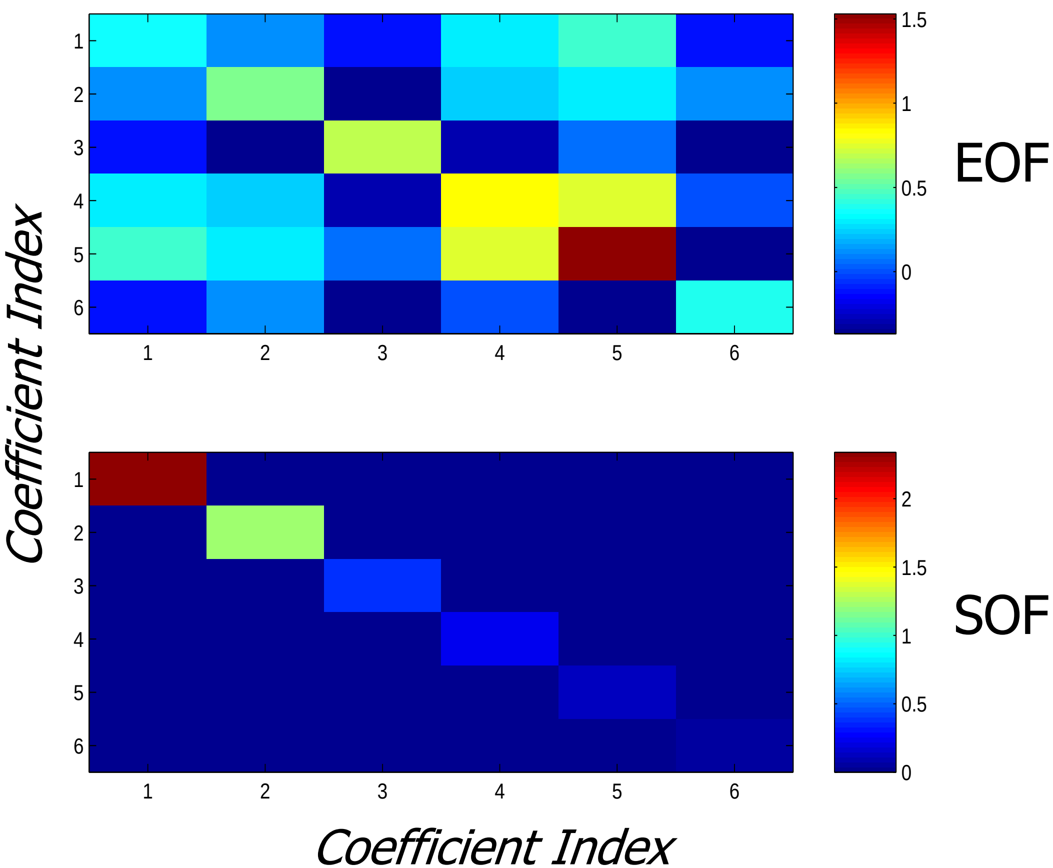
- Ignoring the environmental uncertainty could introduce significant environmental mismatch, and thus serious bias in source localization
- Environmental parameters uncoupled from source location is ideal, but impossible
- AREA: Deploy REA resources to target environmental parameters which have strongest 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

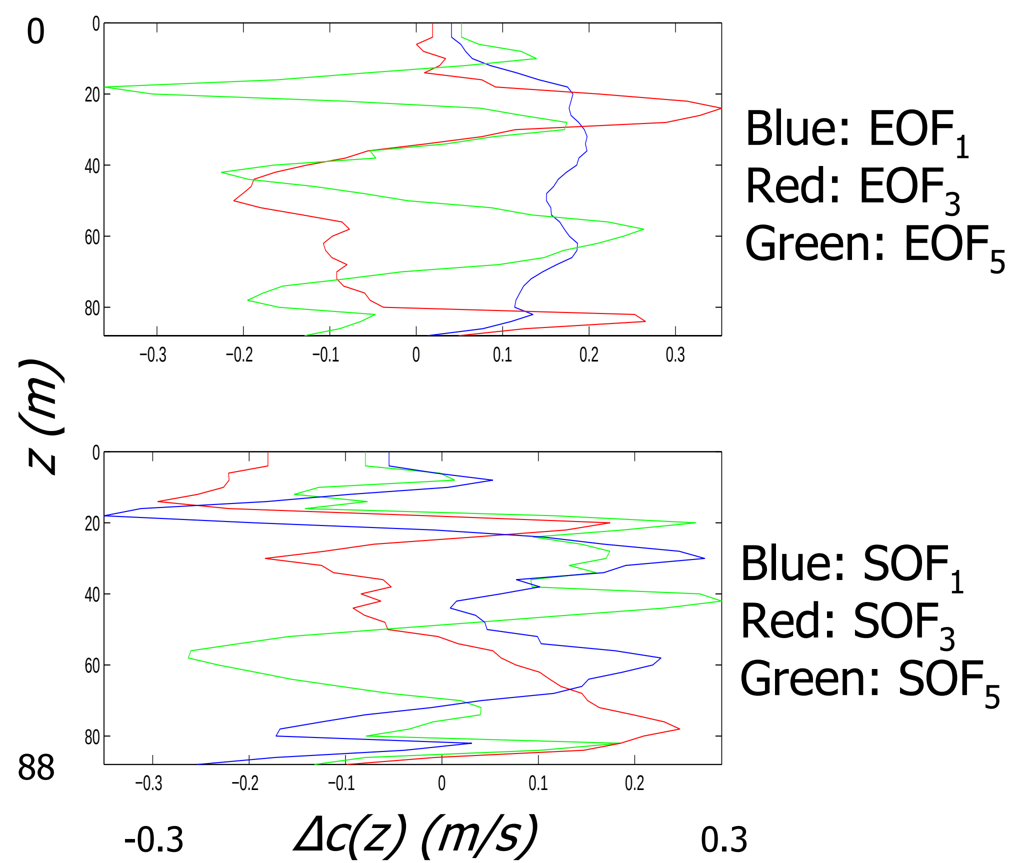
Depend on:
- Sound speed uncertainty
- Ocean waveguide properties
- Sonar Configuration

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

CRB matrix using 6 SVP coefficients

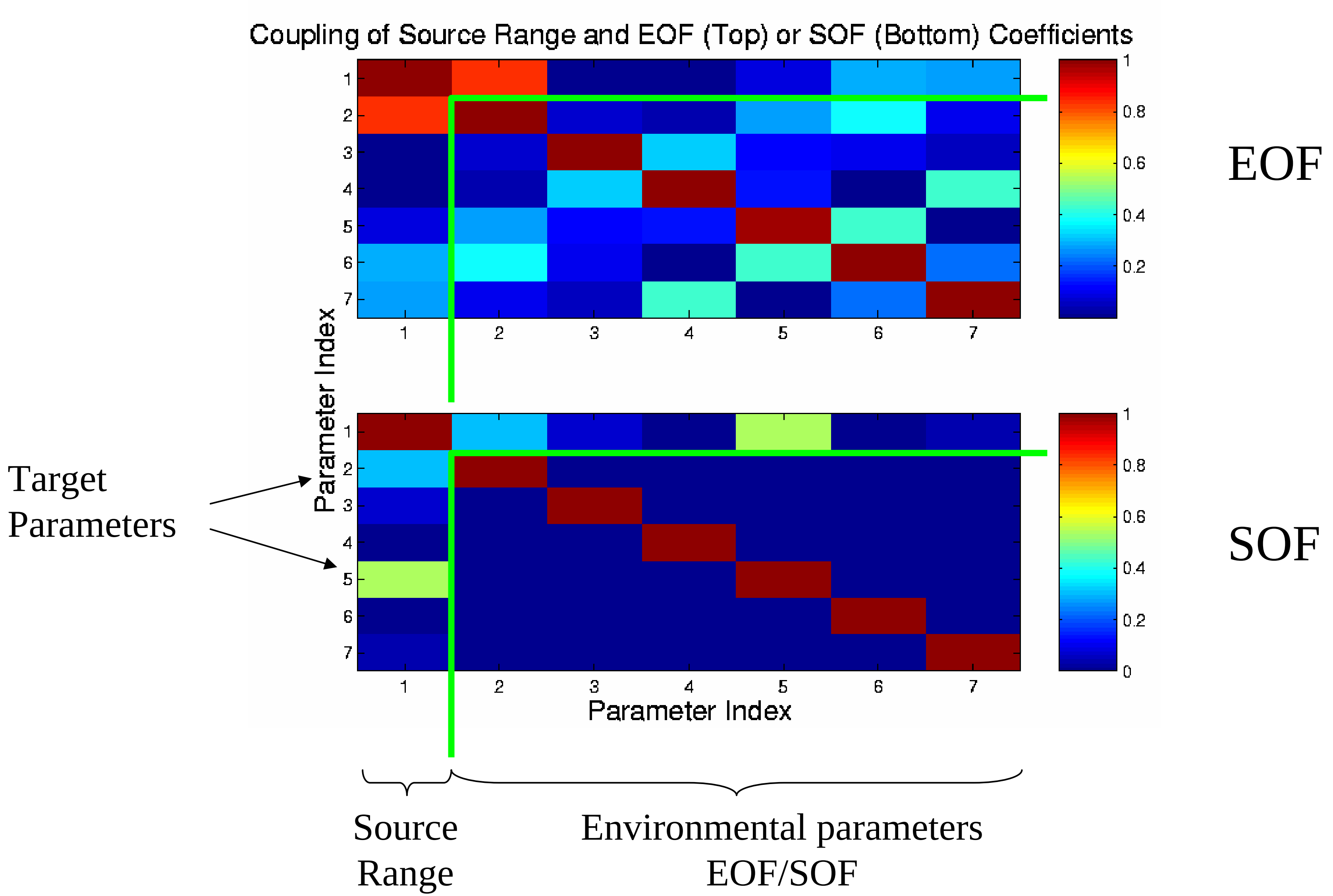


Input SNR = 0 dB



Cramer-Rao Matrix

Source Range – Environment Coupling



- 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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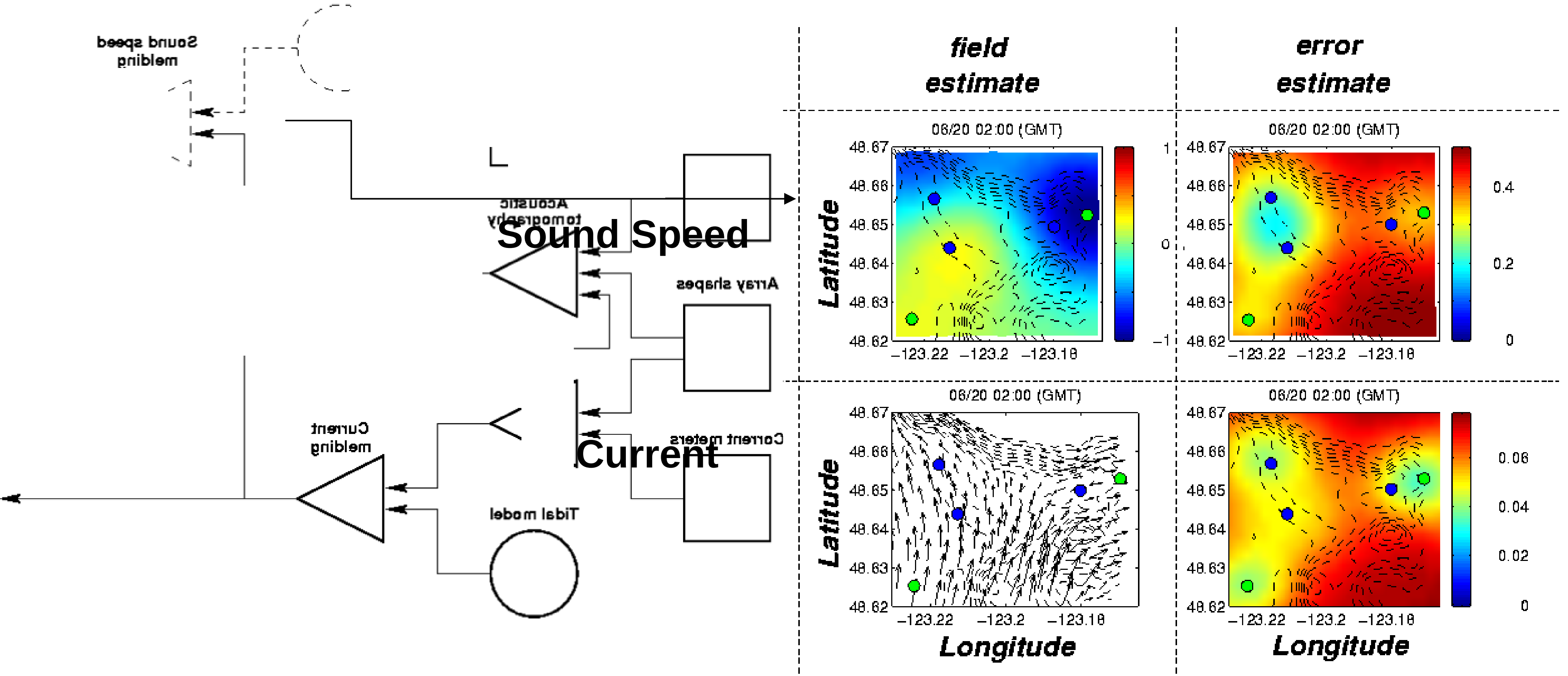
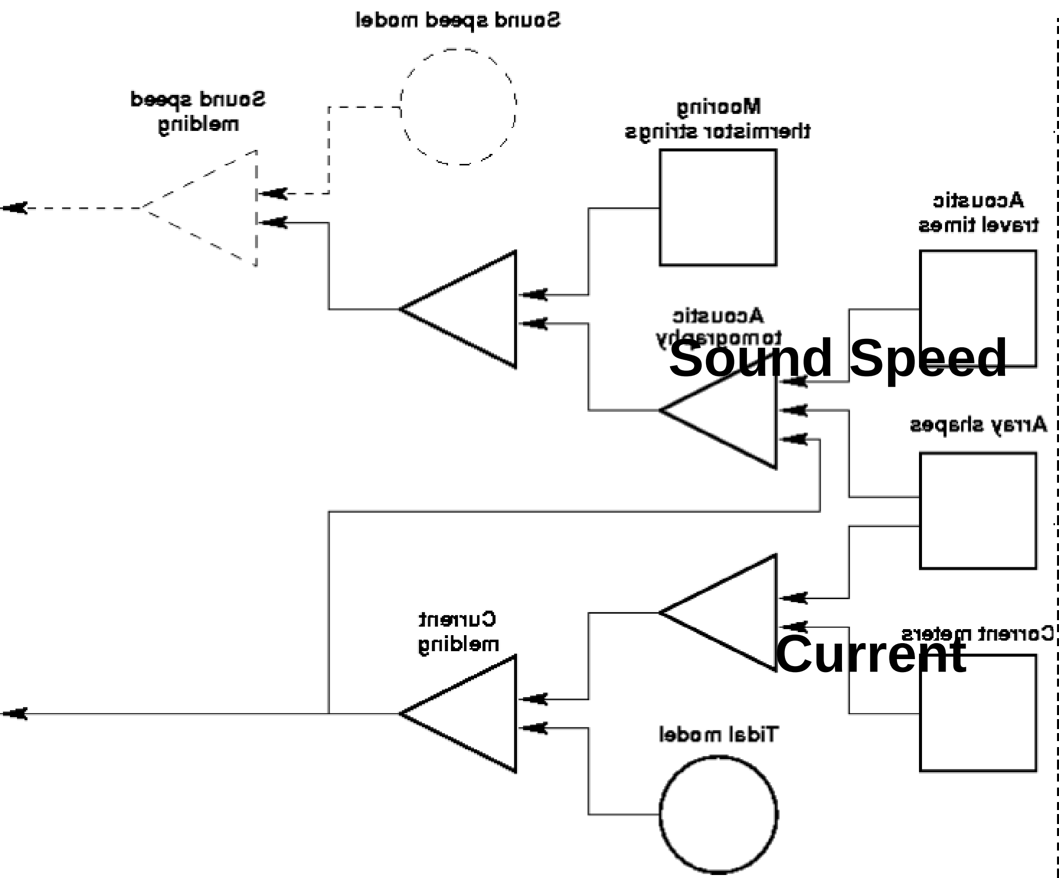
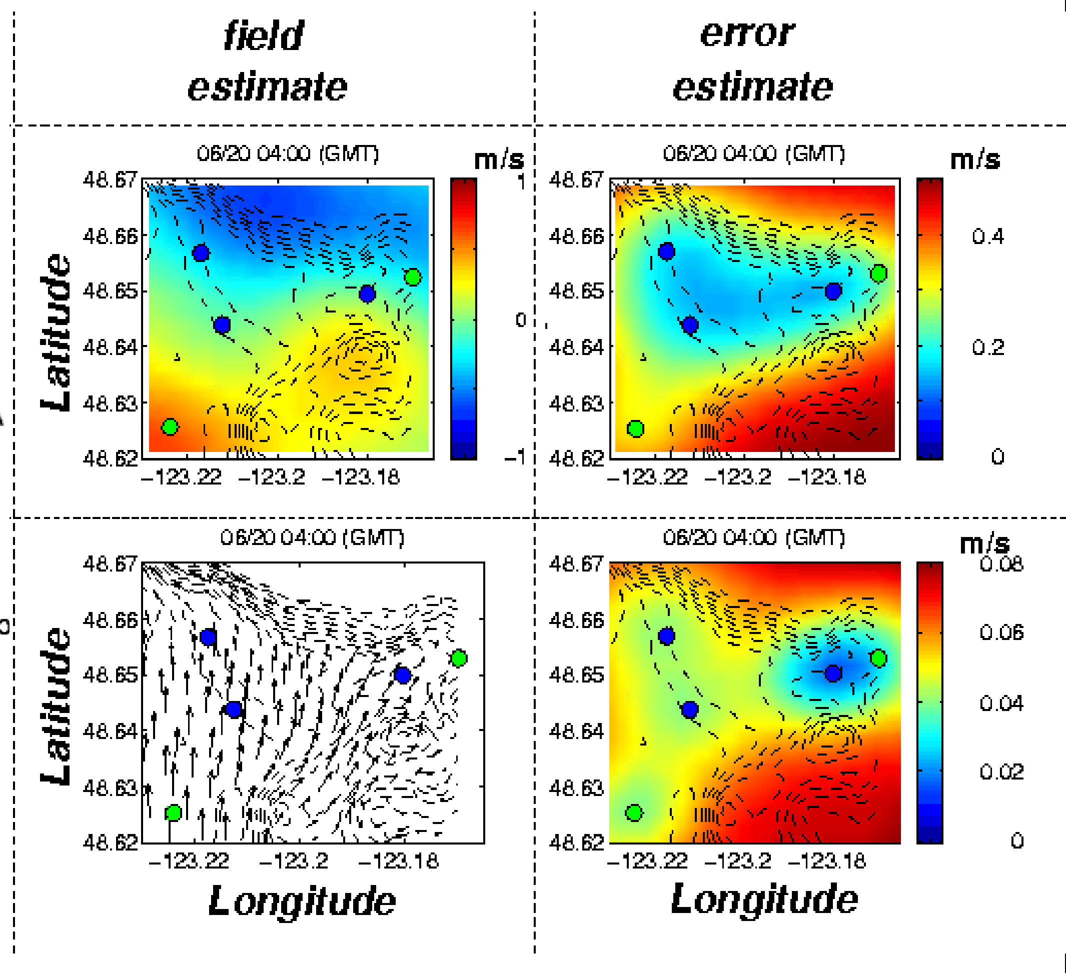
Haro Strait'96

Data Assimilation – No Acoustics

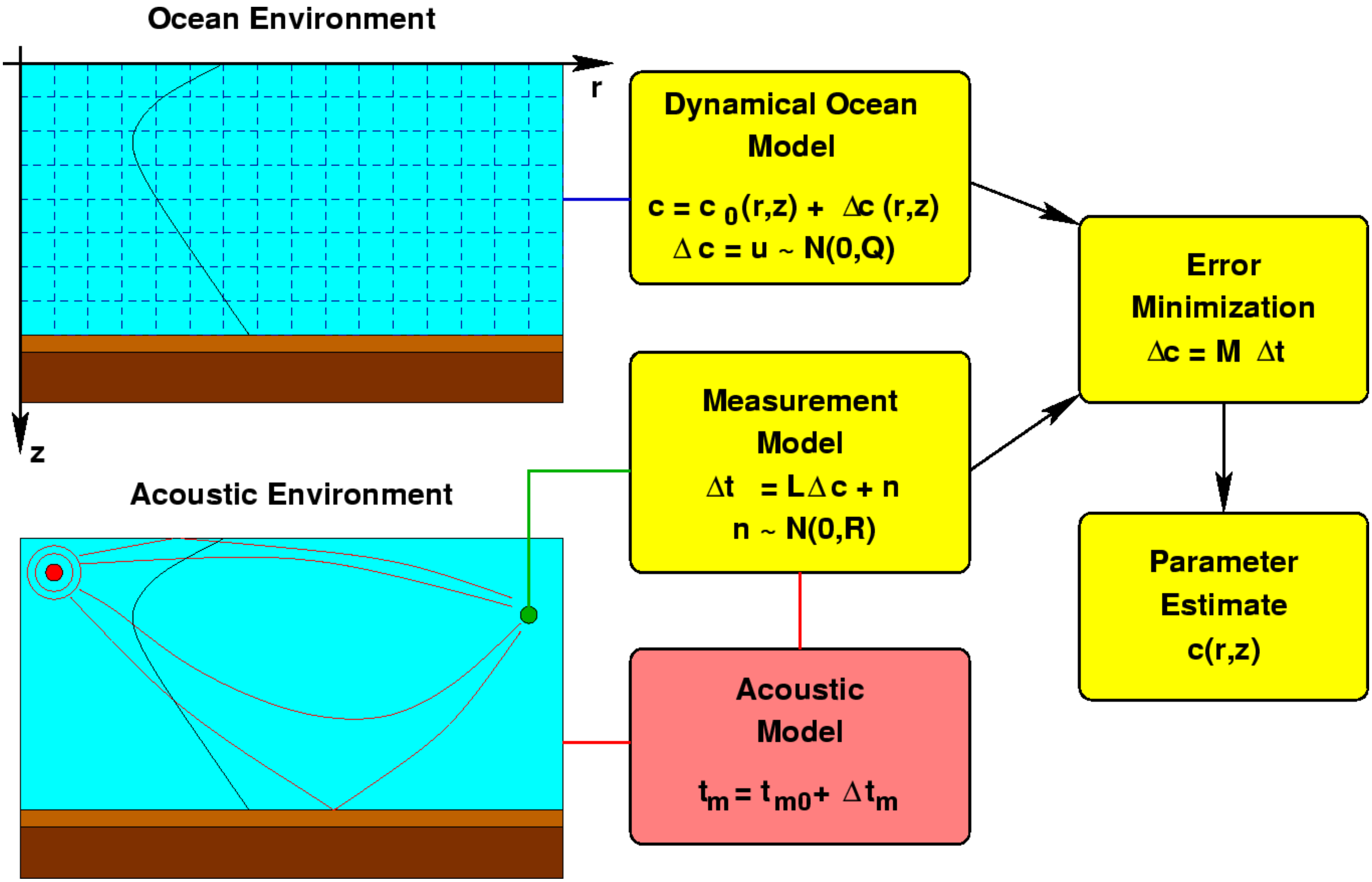


Haro Strait'96
Acoustic Data Assimilation



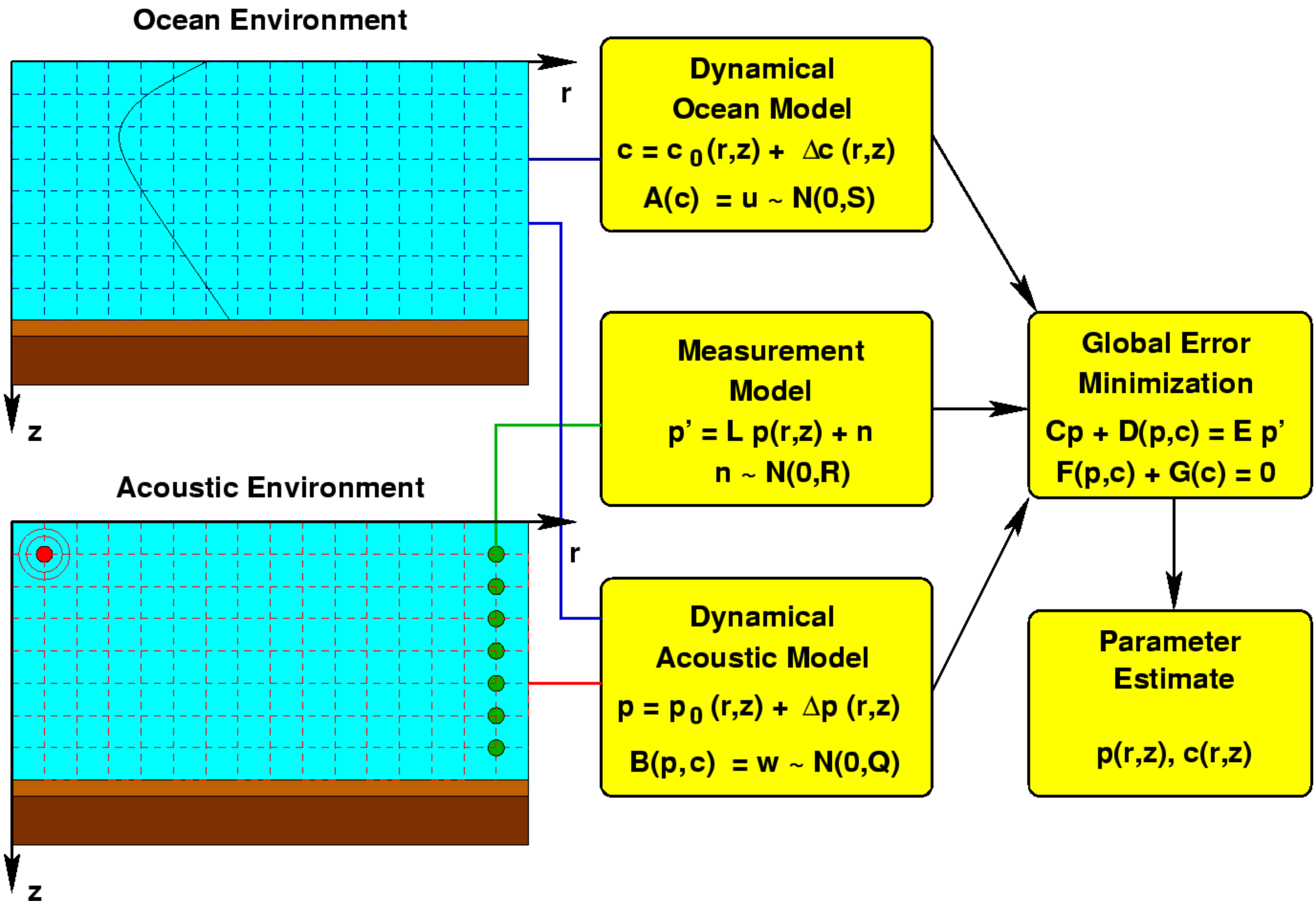


Ocean Acoustic Tomography

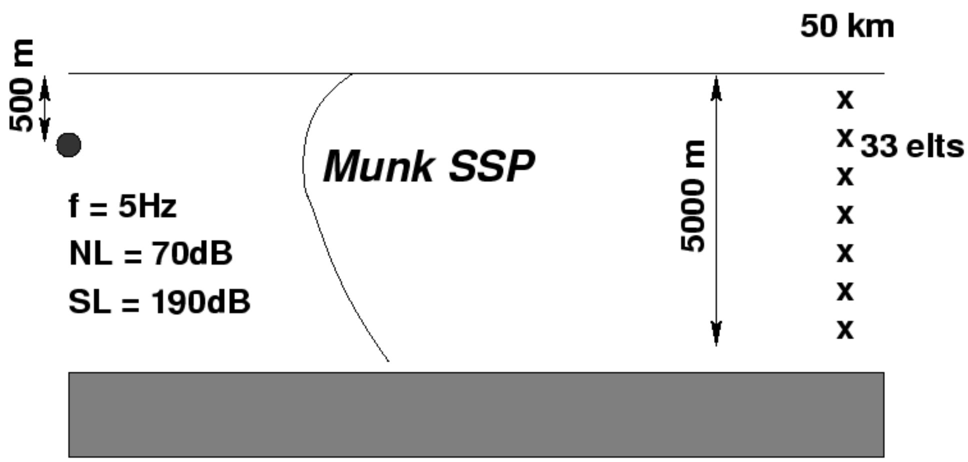


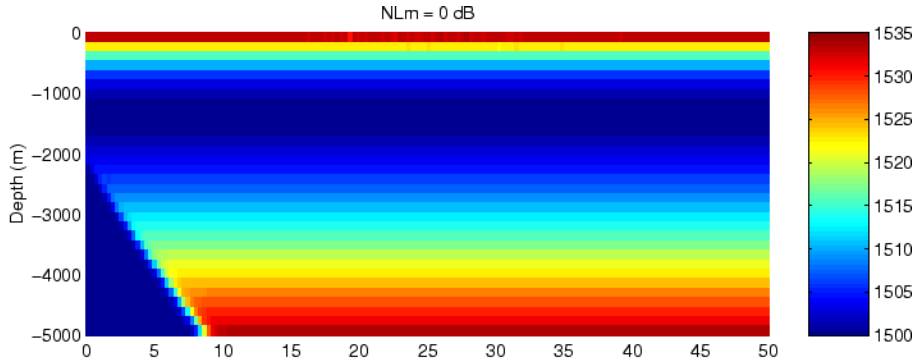
Acoustic Data Asimilation

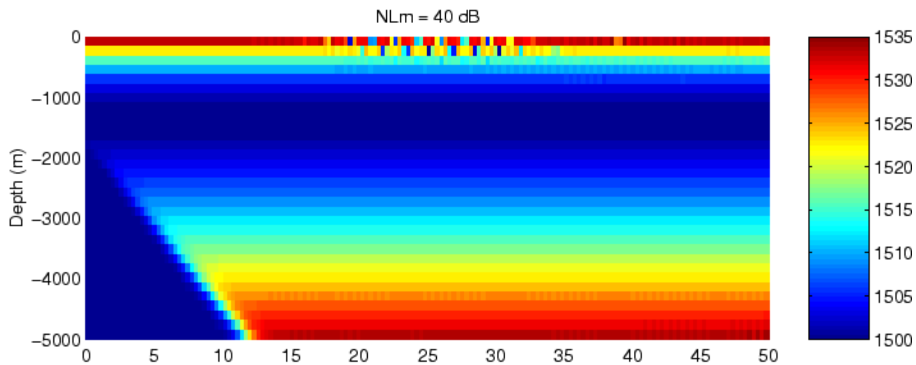
(Elisseeff, Schmidt and Xu, IEEE JOE 2002)

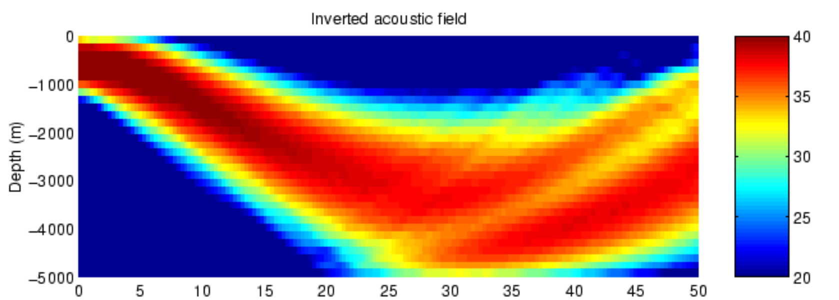


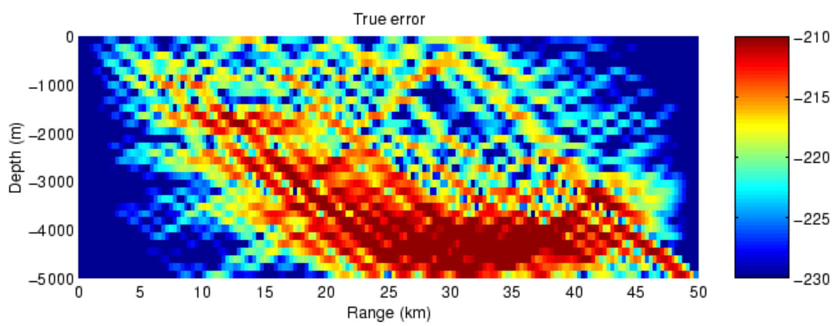
Acoustic Data Assimilation
Simulation Validation

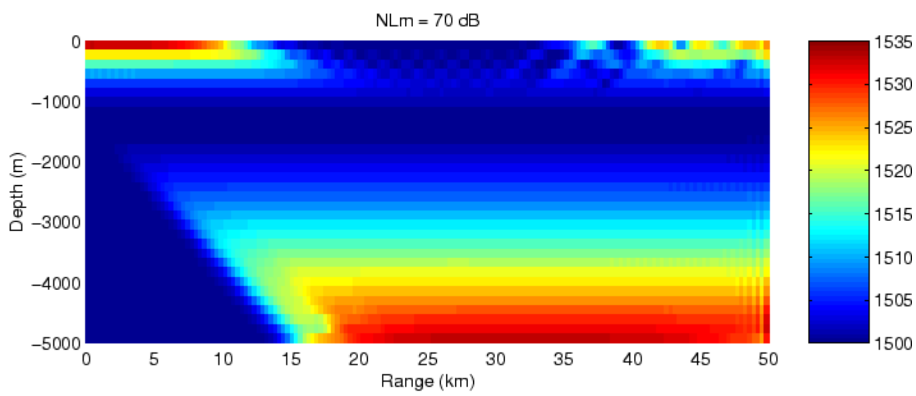












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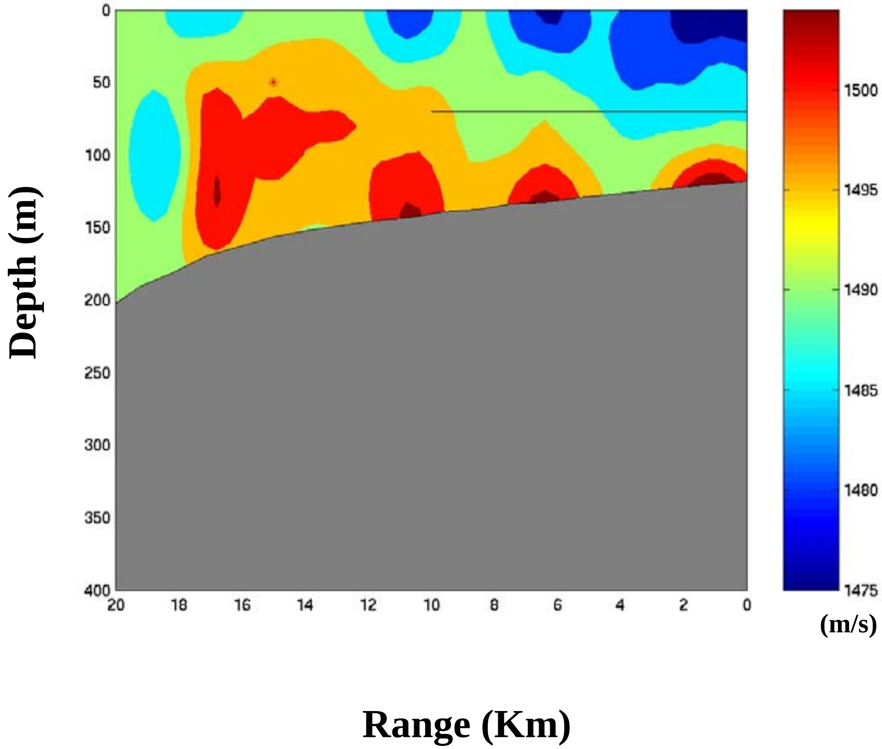
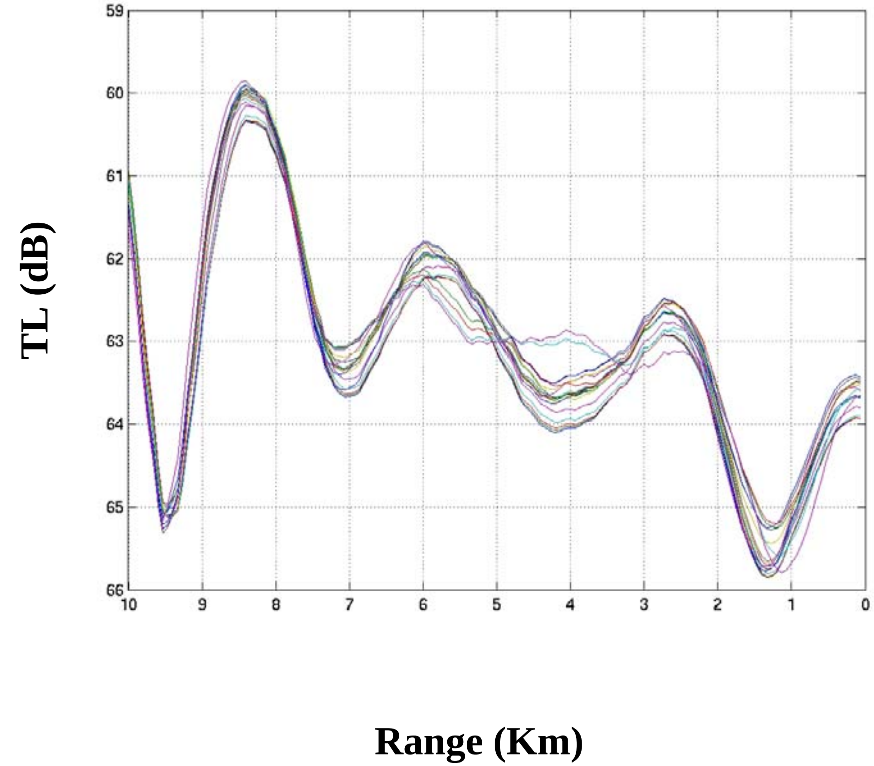
Random Ocean Variability

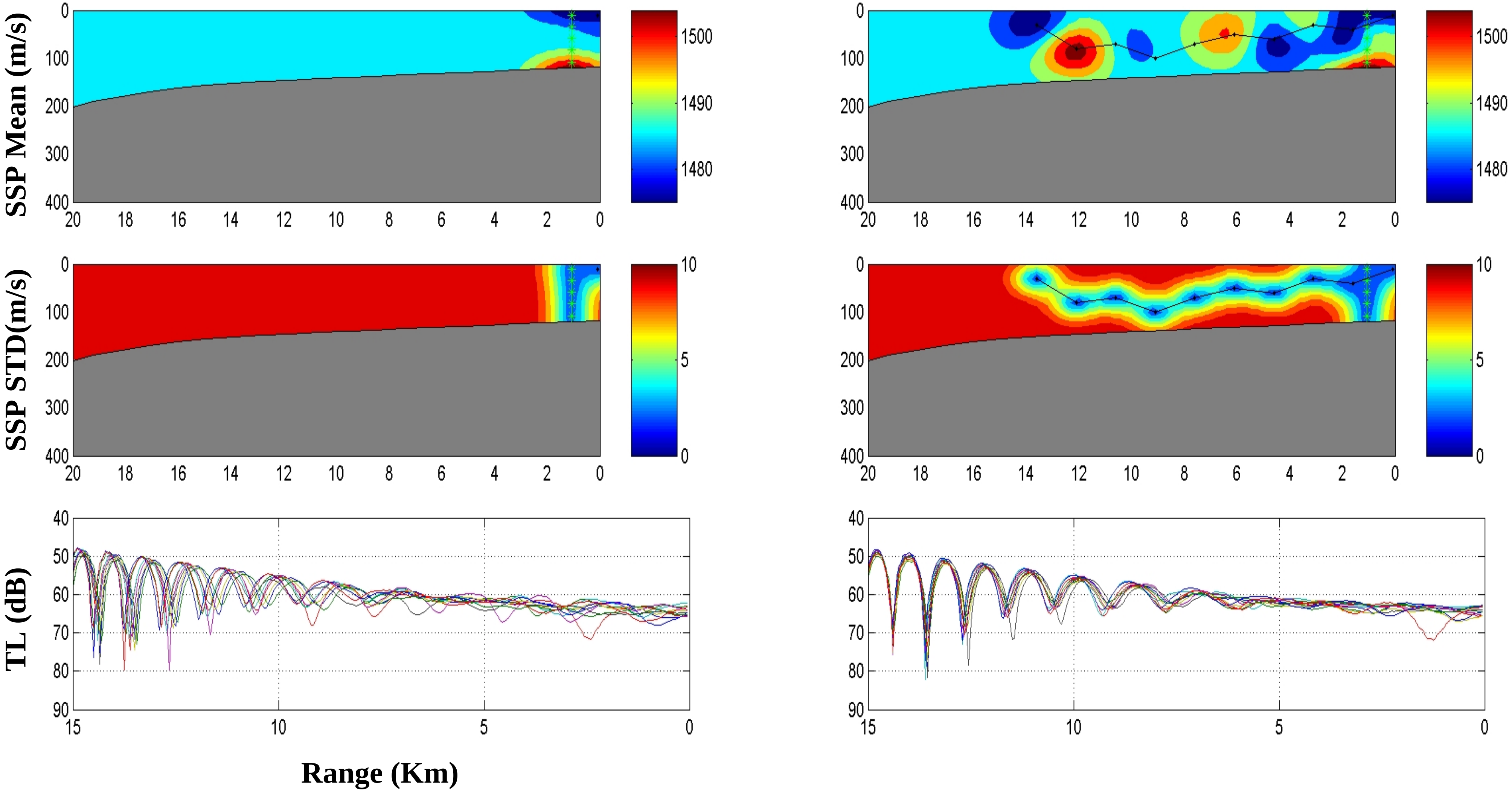
Ocean Sound Speed Profile Variation Over Time



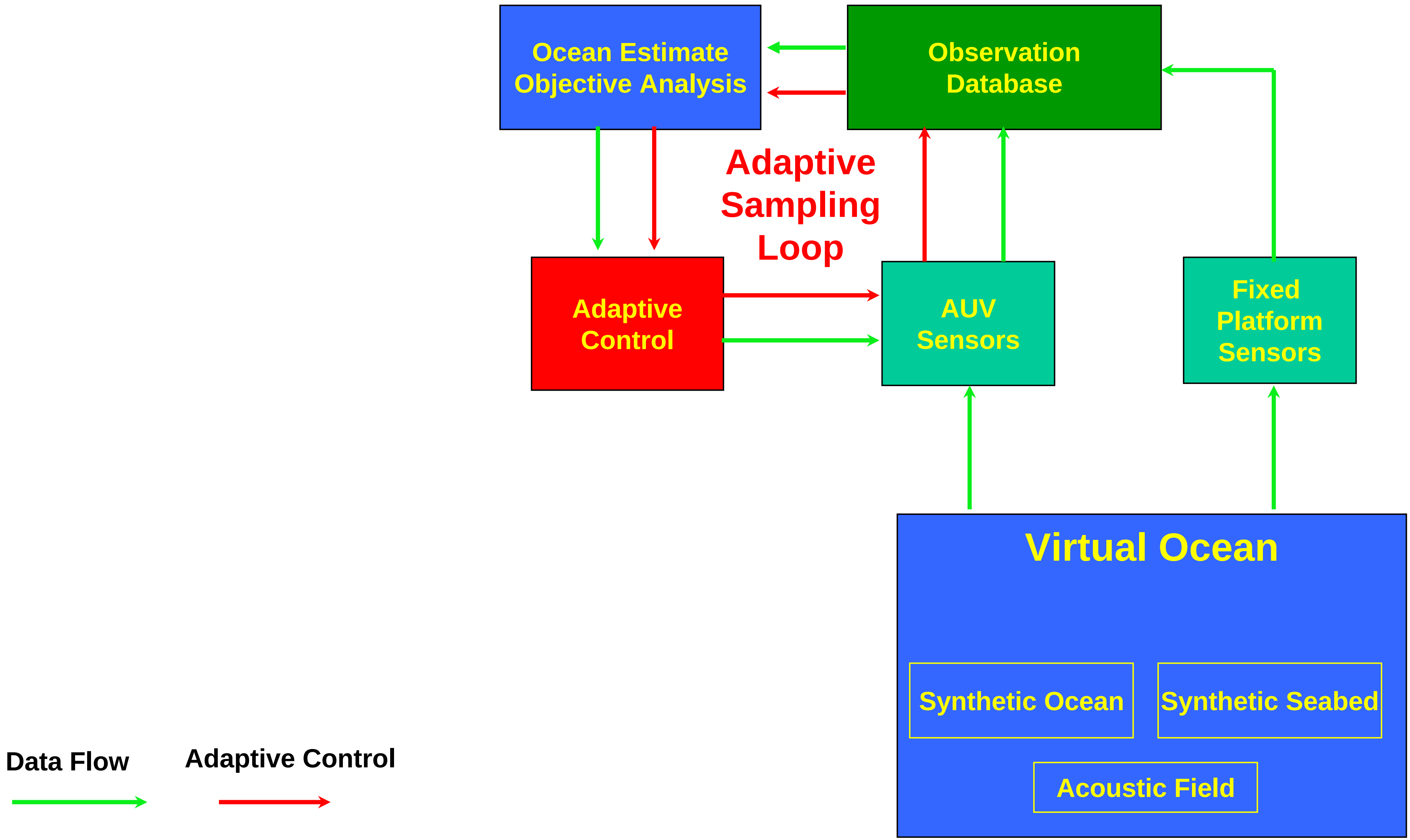
Transmission Loss Variation (50 HZ)



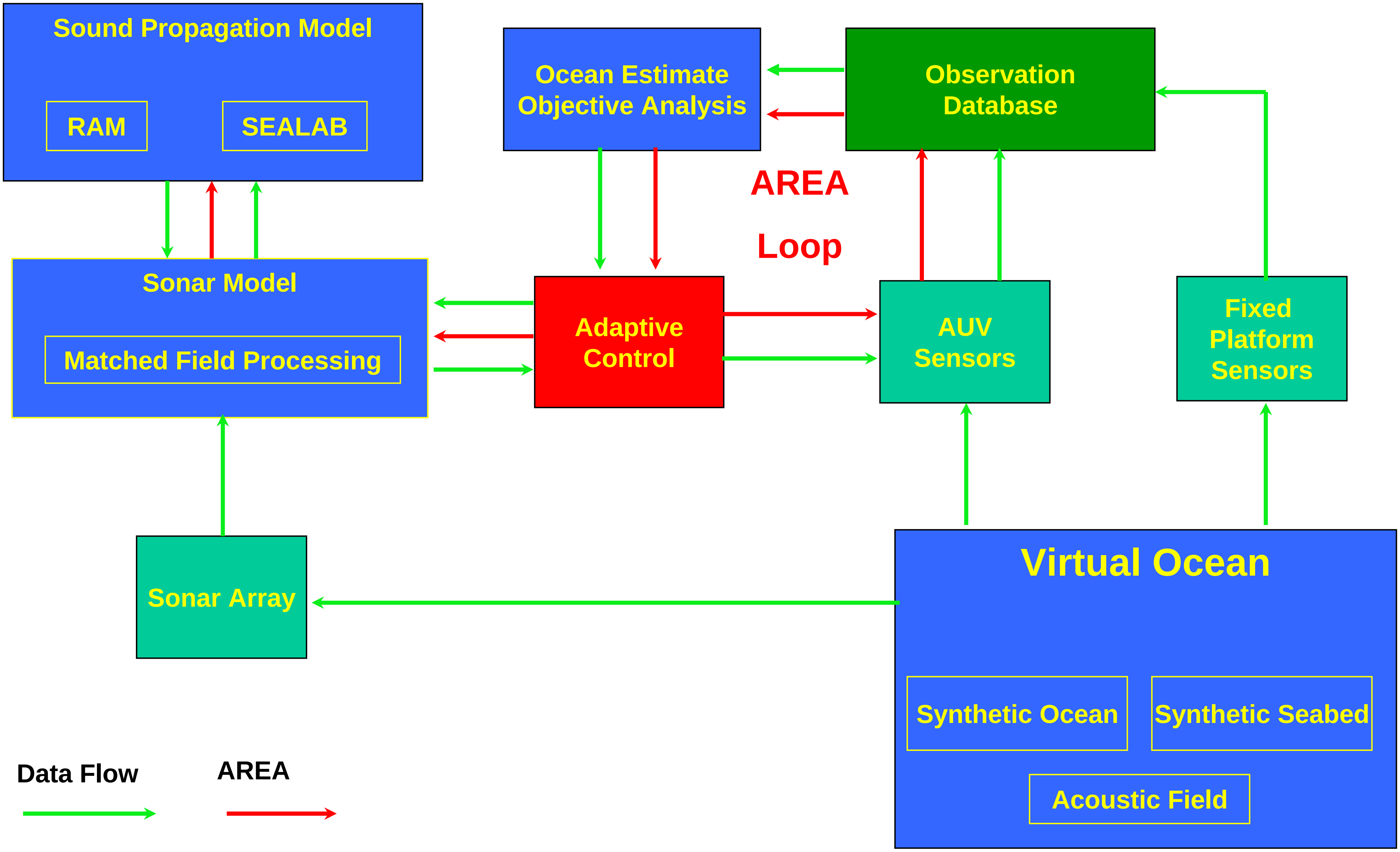
AREA Ideal Objective:
Minimize Sonar Performance Prediction Uncertainty



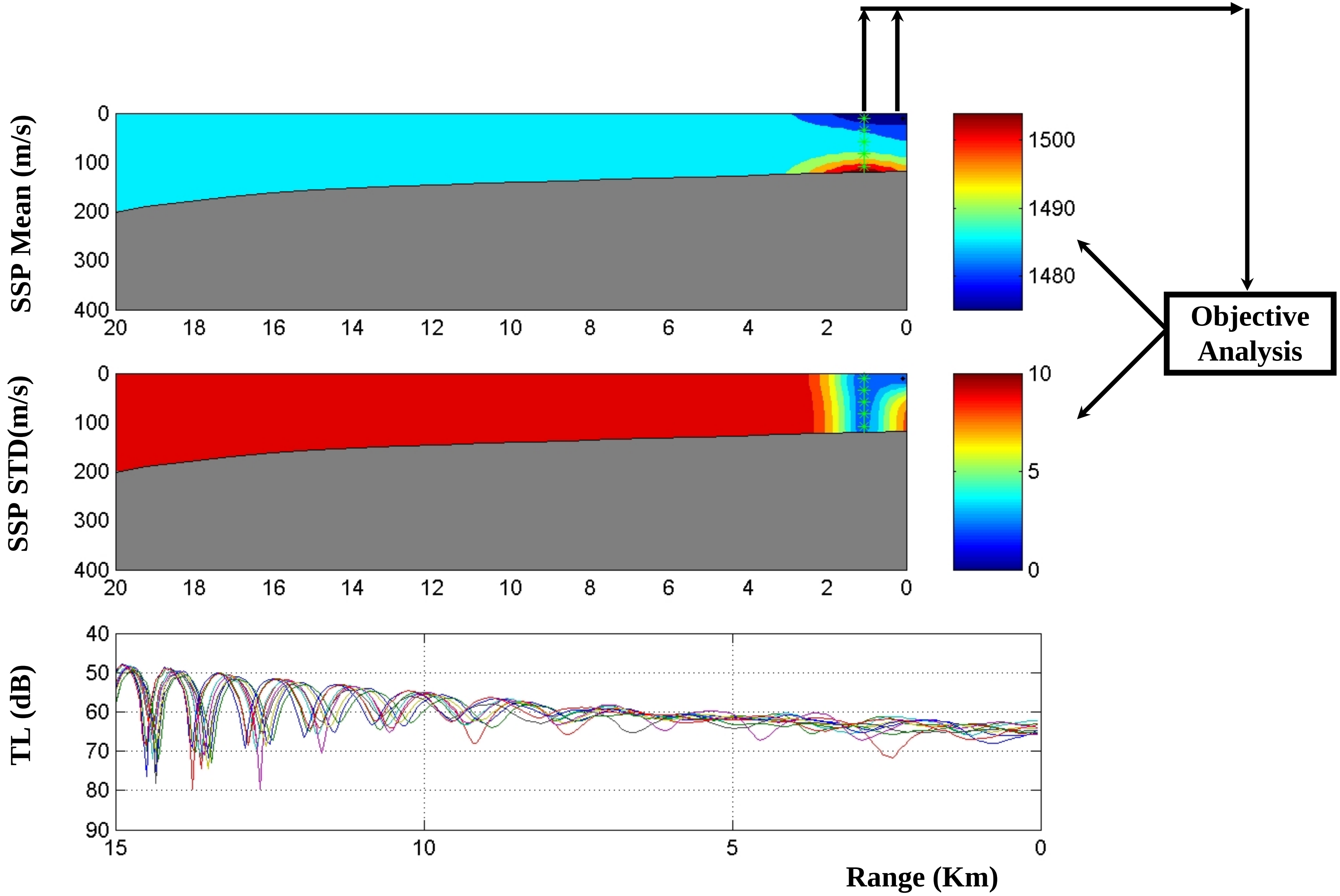
Adaptive Oceanographic Sampling
Complete System Simulation Framework



AREA
Complete System Simulation Framework



AREA: Acoustic Adaptive Sampling



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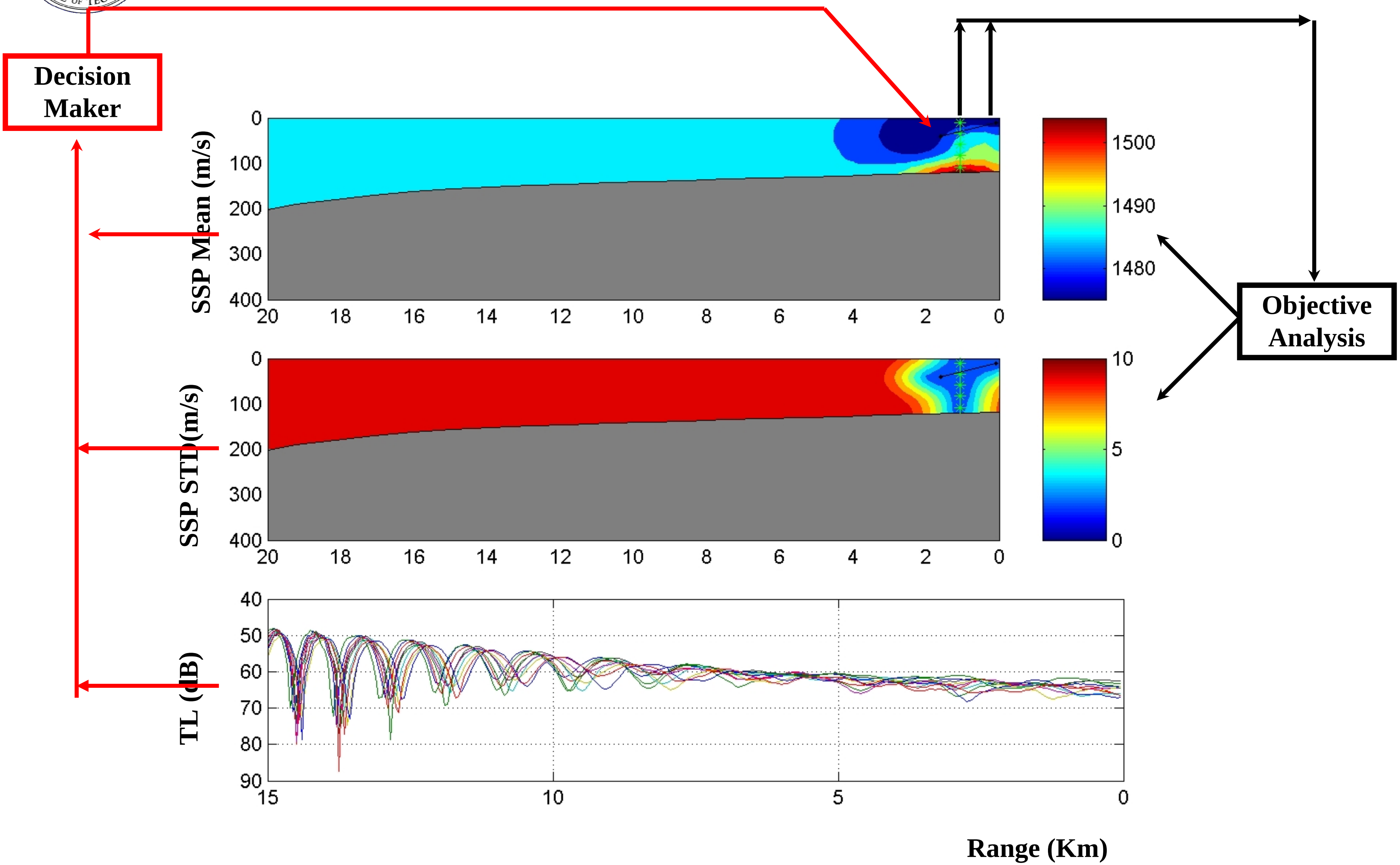

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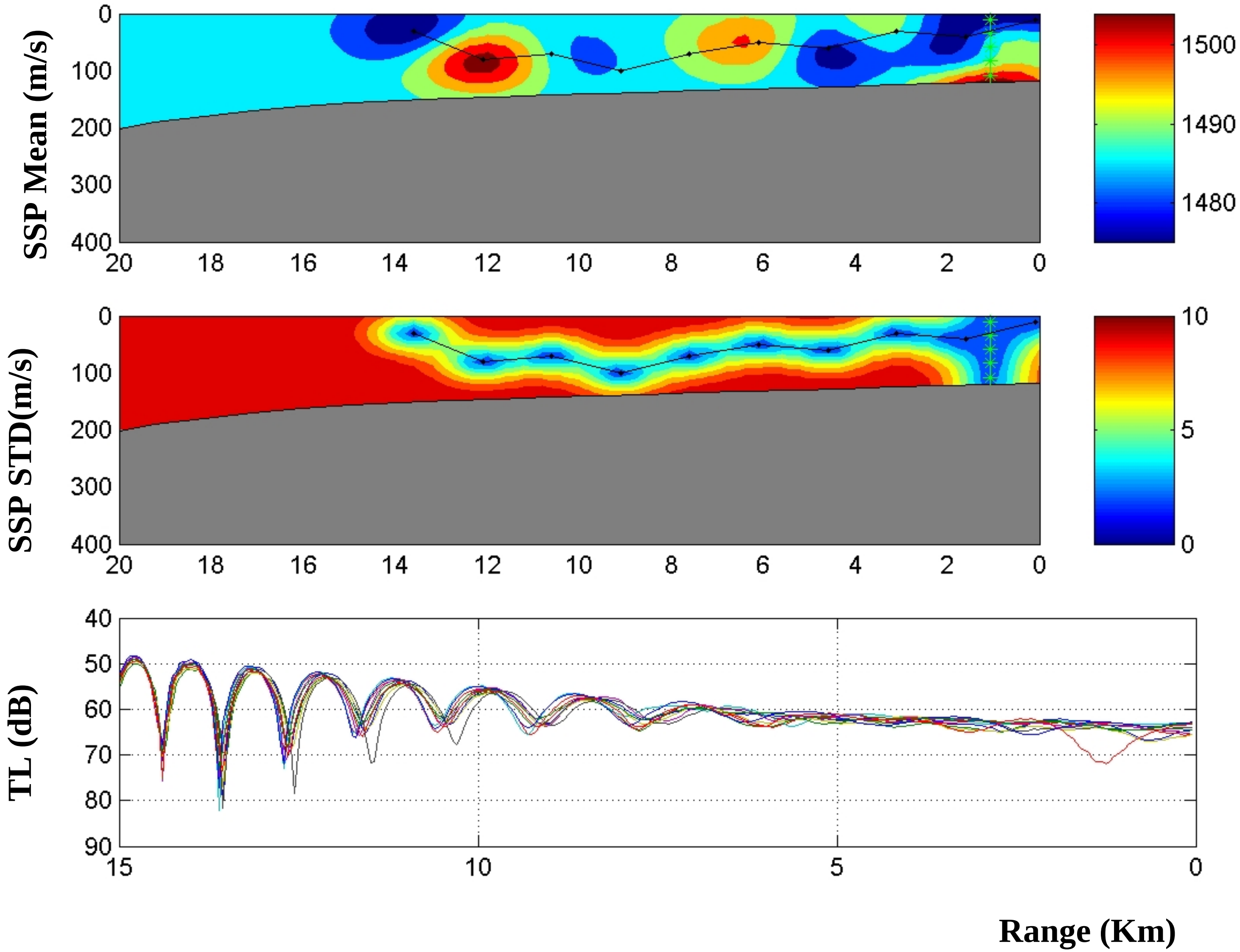
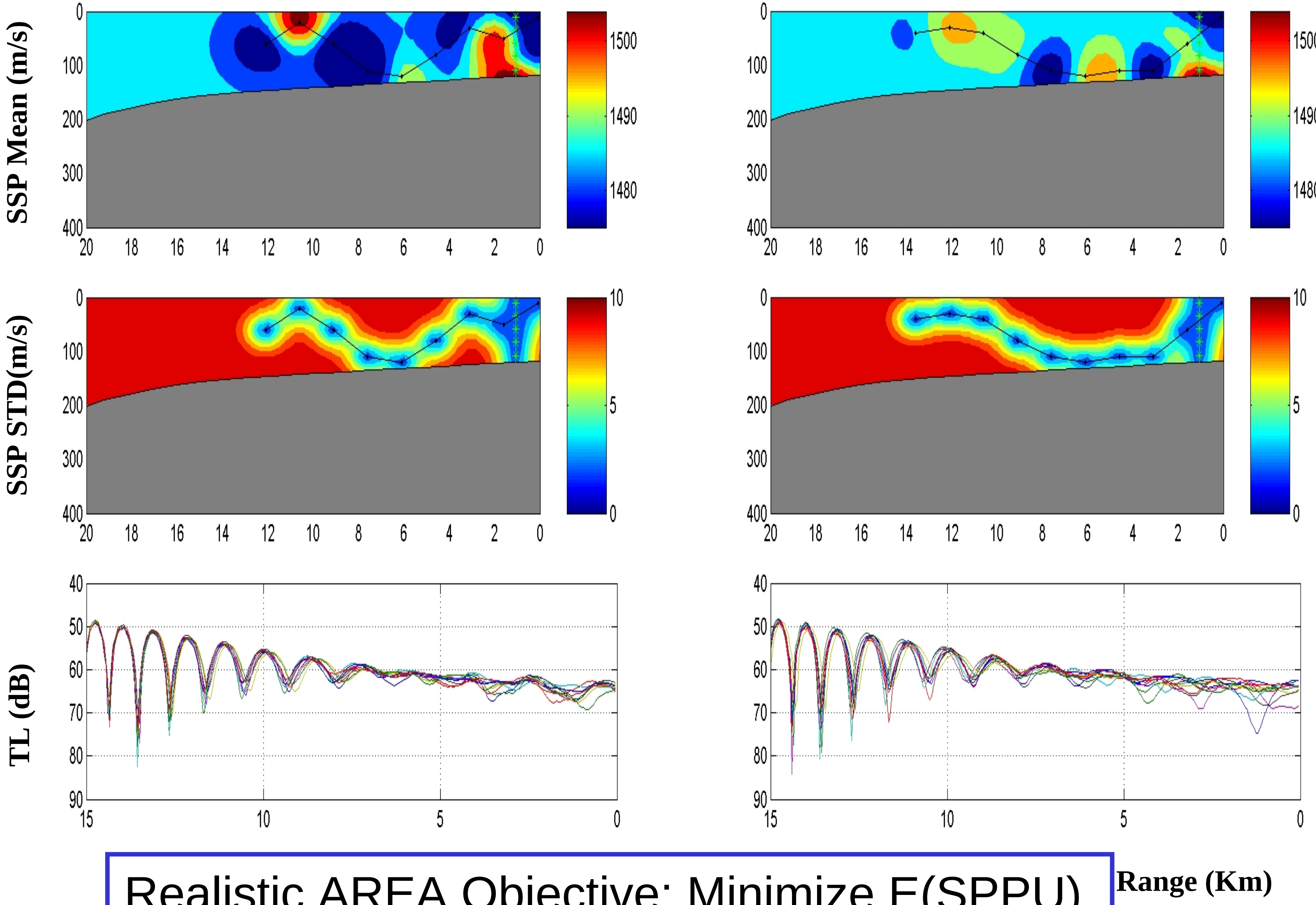
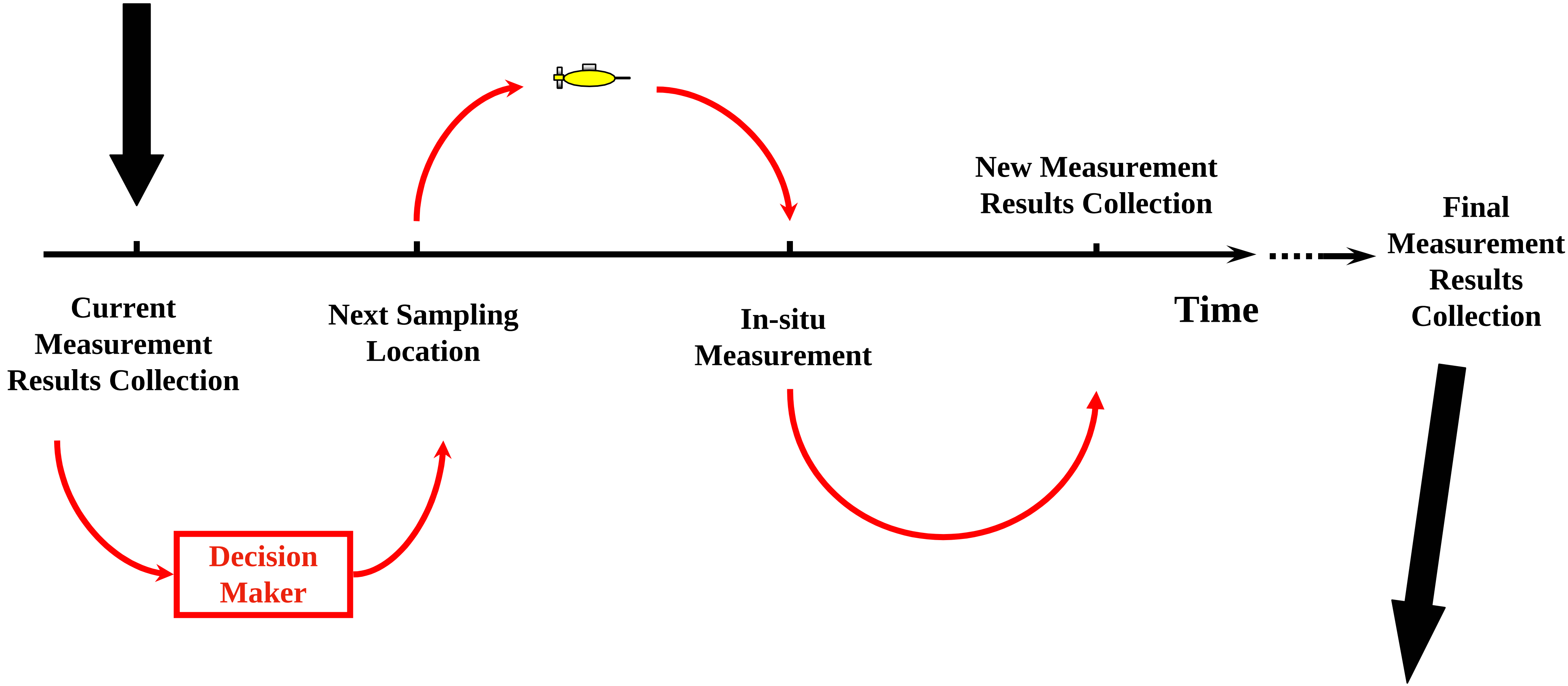


Random Ocean
Minimizing SPPU Impossible



Realistic AREA Objective: Minimize E(SPPU)

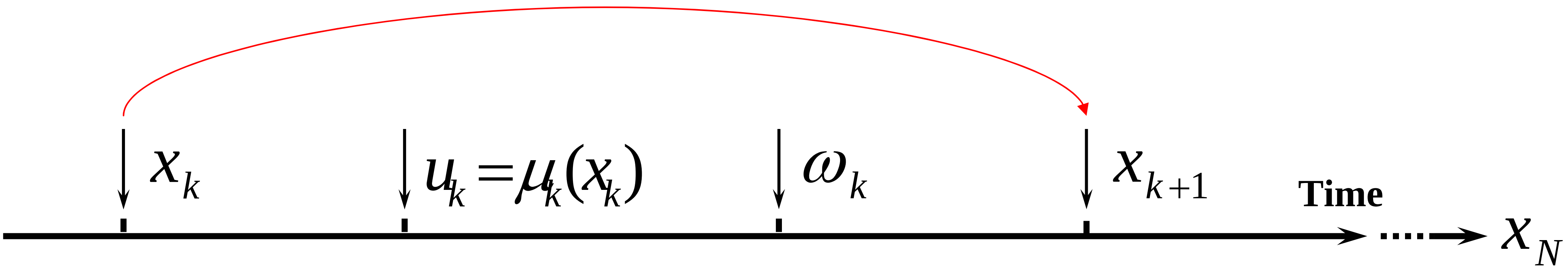
Sequential Decision Making



Objective: min E{ SPP Uncertainty}

Dynamic Programming

cost per stage : $g_k(x_k, u_k, \omega_k)$



x: state u: control ω: random disturbance

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

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

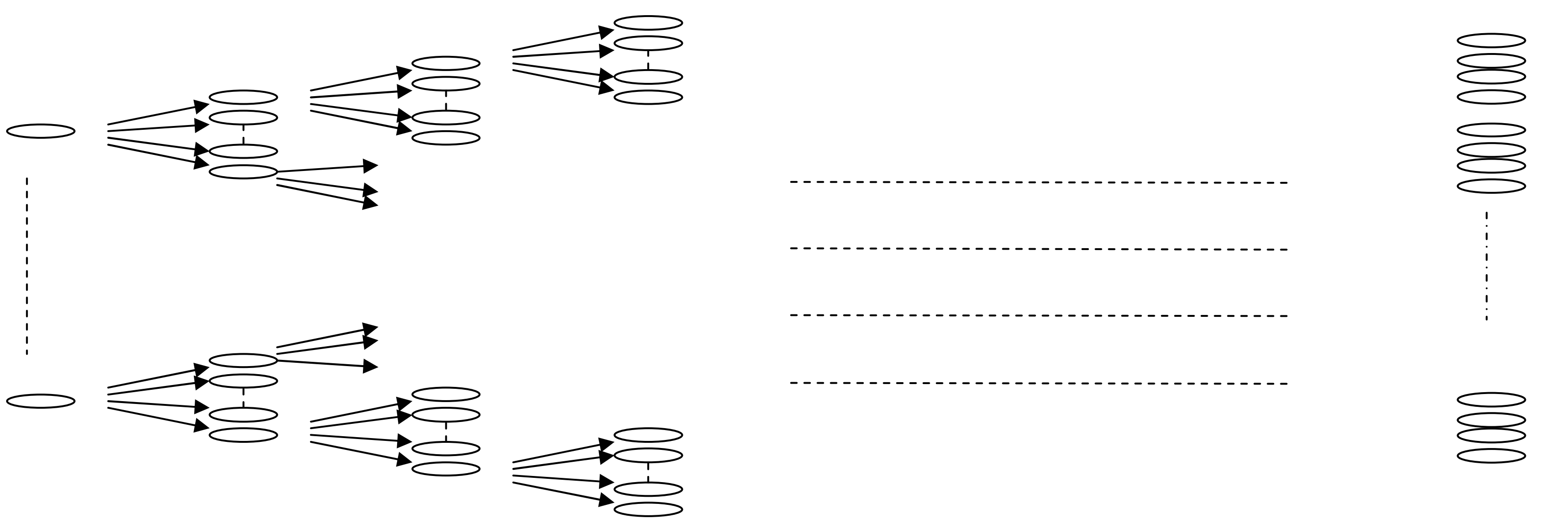
$$\{\mu_0(x_0), \mu_1(x_1)\cdots \mu_{N-1}(x_{N-1})\} \xrightarrow{\min} E\left\{ g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k, \omega_k) \right\}$$

AREA as DP Problem

- State: A matrix containing all initial measurement results and all in-situ measurement results.

Initial State x_0 $\qquad$ x_1 $\qquad$ **Terminal State** x_N

$$\begin{bmatrix} r_1 & r_2 & \cdots & r_n \\ z_1 & z_2 & \cdots & z_n \\ c_1 & c_2 & \cdots & c_n \end{bmatrix} \longrightarrow \begin{bmatrix} r_1 & r_2 & \cdots & r_n & r_{n+1} \\ z_1 & z_2 & \cdots & z_n & z_{n+1} \\ c_1 & c_2 & \cdots & c_n & c_{n+1} \end{bmatrix} \longrightarrow \cdots\cdots \longrightarrow \begin{bmatrix} r_1 & r_2 & \cdots & r_n & r_{n+1} & \cdots & r_{n+N} \\ z_1 & z_2 & \cdots & z_n & z_{n+1} & \cdots & z_{n+N} \\ c_1 & c_2 & \cdots & c_n & c_{n+1} & \cdots & c_{n+N} \end{bmatrix}$$



AREA as DP Problem

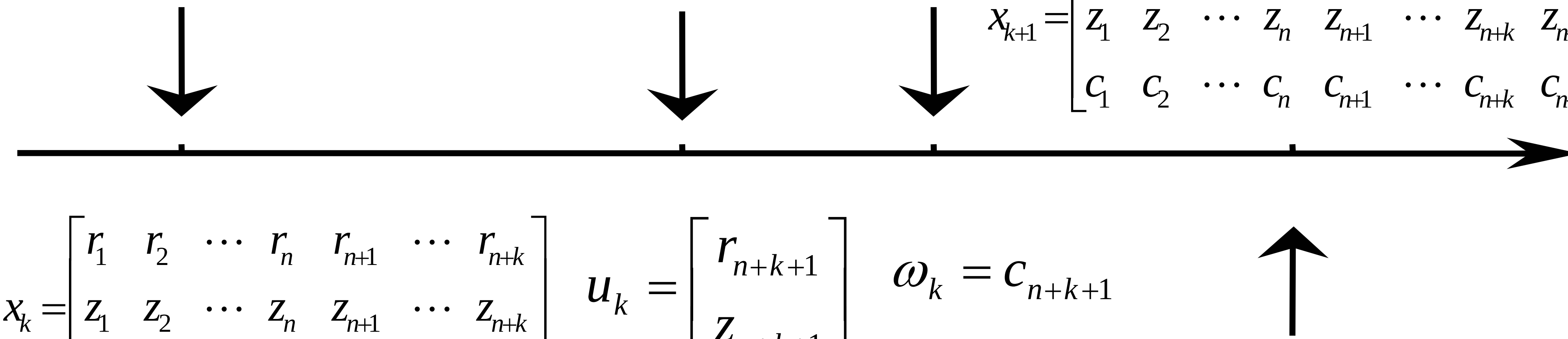
- Control: A vector containing next sampling location constrained by AUV's performance.

$$u_k = \begin{bmatrix} r_{n+k+1} \\ z_{n+k+1} \end{bmatrix}$$

- Disturbance: Sound speed measurement at next sampling location. $P_k(\omega_k \mid x_k, u_k)$ can be determined from the Objective Analysis.

$$\omega_k = c_{n+k+1}$$

AREA as DP Problem



$$x_{k+1} = \begin{bmatrix} r_1 & r_2 & \cdots & r_n & r_{n+1} & \cdots & r_{n+k} & r_{n+k+1} \\ z_1 & z_2 & \cdots & z_n & z_{n+1} & \cdots & z_{n+k} & z_{n+k+1} \\ c_1 & c_2 & \cdots & c_n & c_{n+1} & \cdots & c_{n+k} & c_{n+k+1} \end{bmatrix}$$

$$x_k = \begin{bmatrix} r_1 & r_2 & \cdots & r_n & r_{n+1} & \cdots & r_{n+k} \\ z_1 & z_2 & \cdots & z_n & z_{n+1} & \cdots & z_{n+k} \\ c_1 & c_2 & \cdots & c_n & c_{n+1} & \cdots & c_{n+k} \end{bmatrix} \quad u_k = \begin{bmatrix} r_{n+k+1} \\ z_{n+k+1} \end{bmatrix} \quad \omega_k = c_{n+k+1}$$

- Cost:

$$g_k(x_k, u_k, \omega_k) = 0;$$

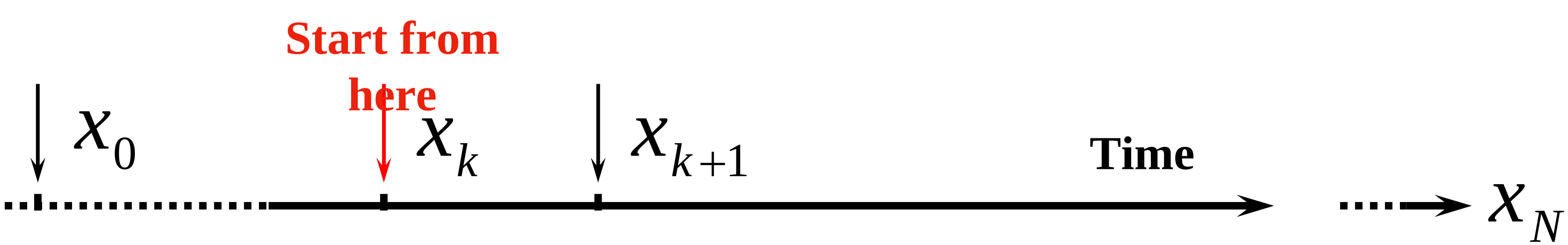
$$g_N(x_N) = \text{final transmission loss uncertainty}$$

Conventional DP

- By Conventional DP Algorithm:

$$\mu_k^*(x_k) = \arg \min_{u_k \in U_k(x_k)} \; E_{\omega_k}\left\{ g_k(x_k, u_k, \omega_k) + J_{k+1}(f_k(x_k, u_k, \omega_k)) \right\}$$

$J_k(x_k)$ is optimal cost-to-go function at stage k which requires very intensive computation.



$$J_k(x_k) = \min \; E\left\{ \sum_{i=k}^{N-1} g_i(x_i, u_i, \omega_i) + g_N(x_N)) \right\}$$

Solved by Approximate DP

- By 1 Step Look Ahead Algorithm:

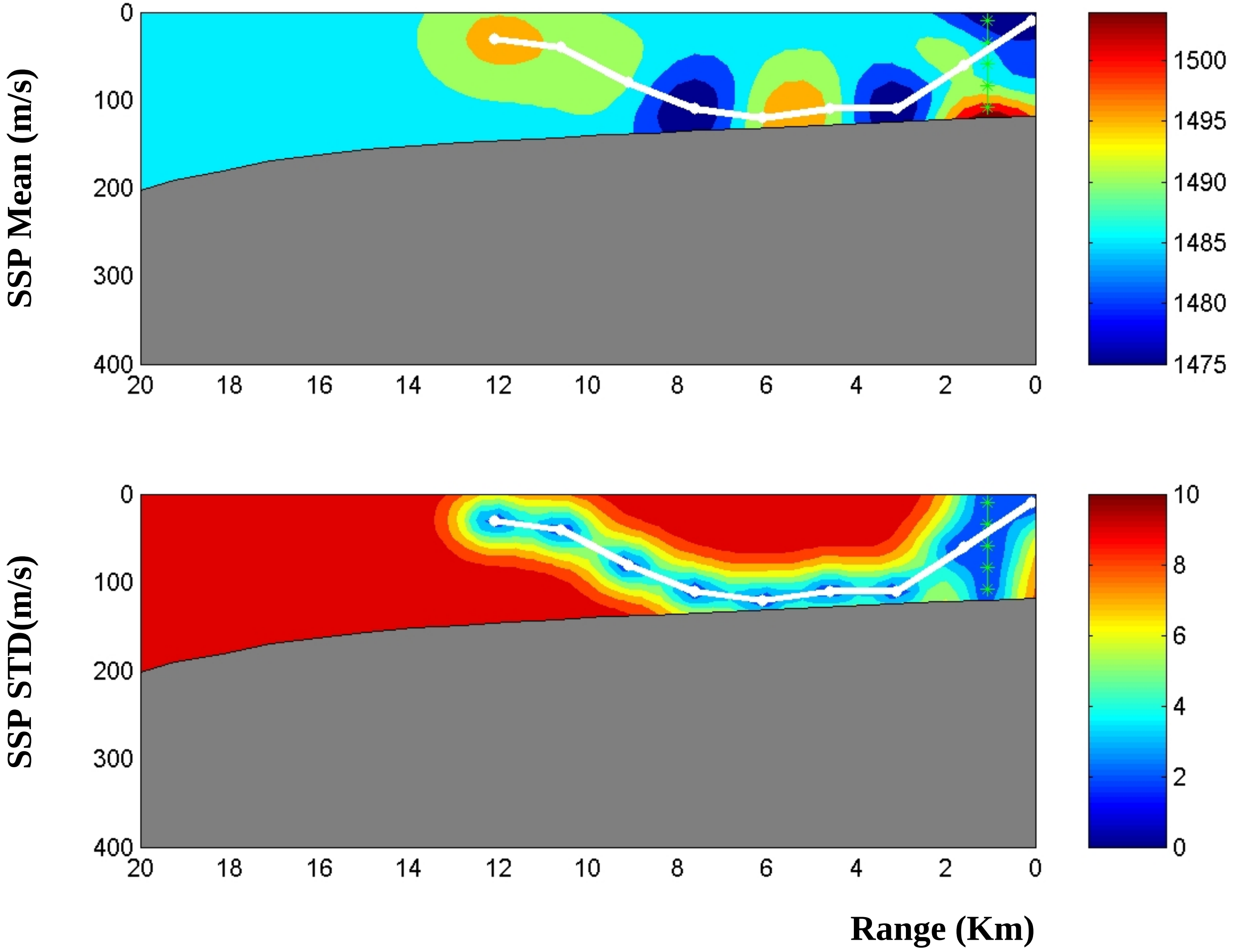
$$\tilde{\mu}_k(x_k) = \arg \min_{u_k \in U_k(x_k)} \underset{\omega_k}{E} \left\{ g_k(x_k, u_k, \omega_k) + \tilde{J}_{k+1}(f_k(x_k, u_k, \omega_k)) \right\}$$

Approximate optimal cost-to-go function $\tilde{J}_k(x_k)$ is needed.

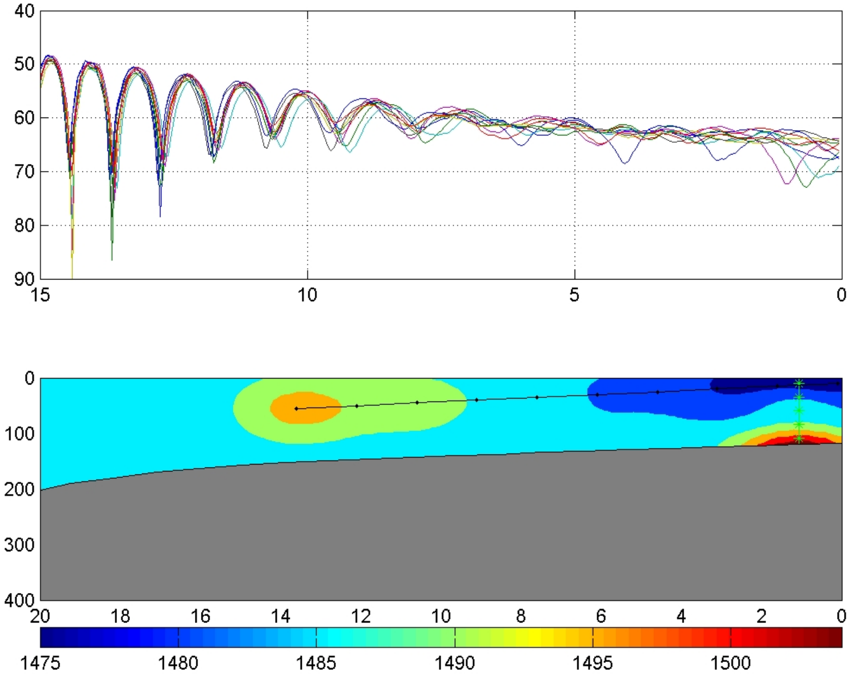
$\tilde{J}_k(x_k)$ could be obtained by heuristic methods such as the greedy algorithm.

Rollout Algorithm Based on Greedy Algorithm

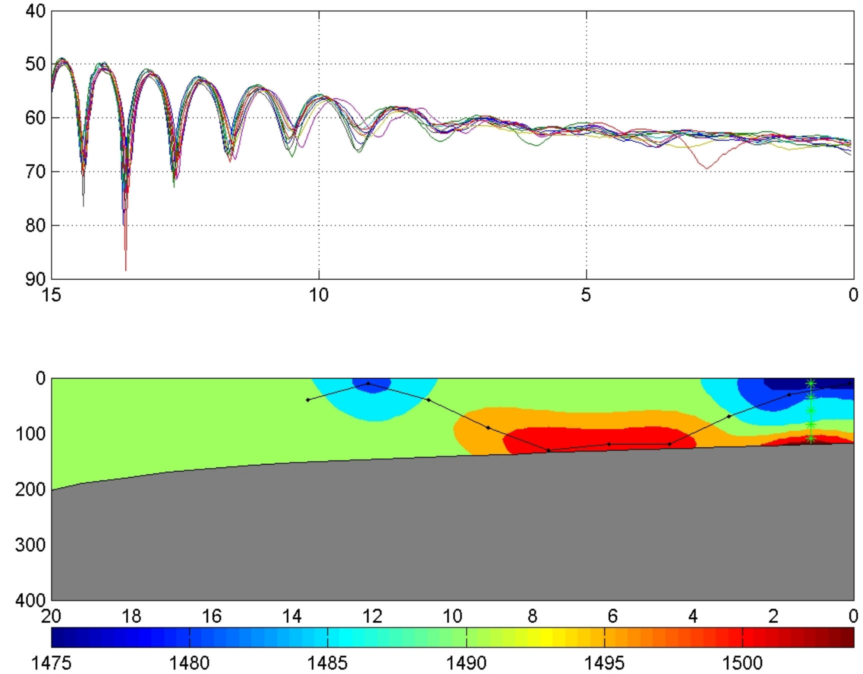
$$\tilde{\mu}_k(x_k) = \arg \min_{u_k \in U_k(x_k)} \underset{\omega_k}{E}\left\{\tilde{J}_{k+1}(f_k(x_k, u_k, \omega_k))\right\}$$

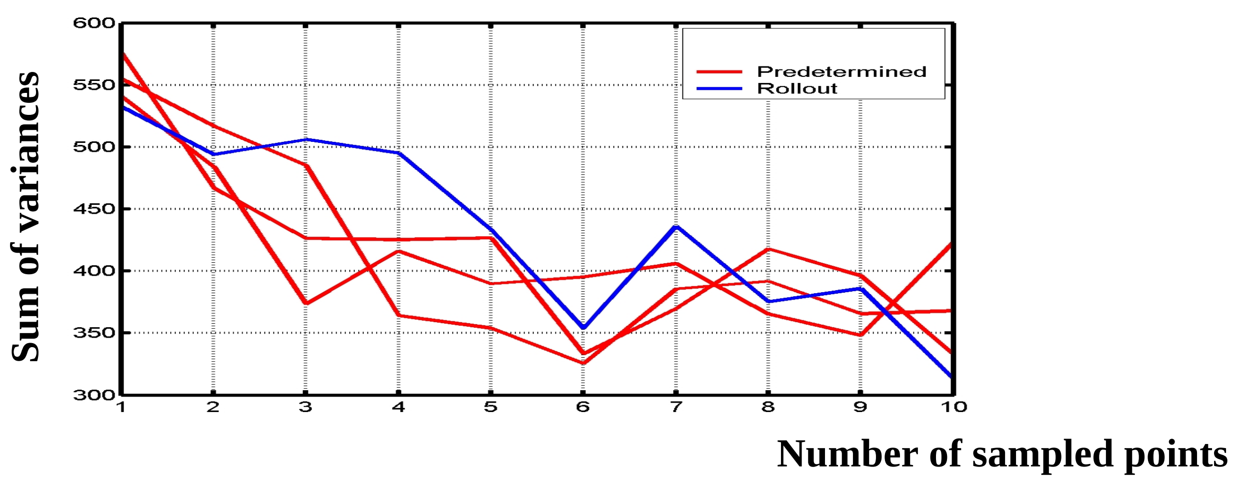


Predetermined Path



Rollout based on greedy algorithm





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 parameters
  - Journal paper published

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: 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, pp275-282, 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, pp2716, 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*, pp448-452, 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*, pp507-514, 2002.
- H. Schmidt, “AREA: Adaptive Rapid Environmental Assessment,” in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, pp587-594, 2002.
- W. Xu and C. D. Richmond, "Quantitative ambiguity analysis for matched-field source localization under spatially-correlated noise field," to appear in *Proc. of IEEE/MTS OCEANS'03*, 2003.
- W. Xu, A. B. Baggeroer, and K. L. Bell, “A bound on mean-square estimation error with background parameter mismatch,” to appear in *IEEE Trans. Information Theory* (accepted).
- W. Xu, A. B. Baggeroer, and C. D. Richmond, “Bayesian bounds for matched-field parameter estimation,” in revision for *IEEE Trans. Signal Processing*.
- W. Xu and H. Schmidt, "System-orthogonal functions for sound velocity profile perturbation,“ Being revised 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," in preparation for *IEEE Journal of Oceanic Engineering*.

AREA

2004 Plans

- AREA Concept development
  - Dynamic Programming Adaptive Control
  - Acoustic Rapid Environmental Assessment - SUSHI
- AREA Simulation framework development
  - Integrate MINI-HOPS for real-time data assimilation
  - Integrate with ADAPTS distributed computational environment for multi-disciplinary ocean forecasting
  - Initiate the incorporation of Acoustic Data Assimilation
  - Integrate system orthogonal function parameterization
- Transitions
  - ADA /MINI-HOPS
    - NSF-ITR
    - AOSN-III MURI
  - High Fidelity Sonar modeling
    - PLUS –ONR/

Capturing Uncertainty
Transition Potential

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