Seabed Variability and its Influence on Acoustic Prediction Uncertainty

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Research Goals

1. Assess and characterize seabed variability {in 4 dimensions; 2-3 specific environments}
    - How do critical seabed parameters vary in space/time?
    - What are the critical measurement/prediction scales?
    - How are variability/uncertainty best "captured"

2. Determine impact of the seabed variability on acoustic prediction uncertainty
    - What are the critical seabed parameters (prop/reverb/SE)?
    - How is prediction uncertainty best "captured"?

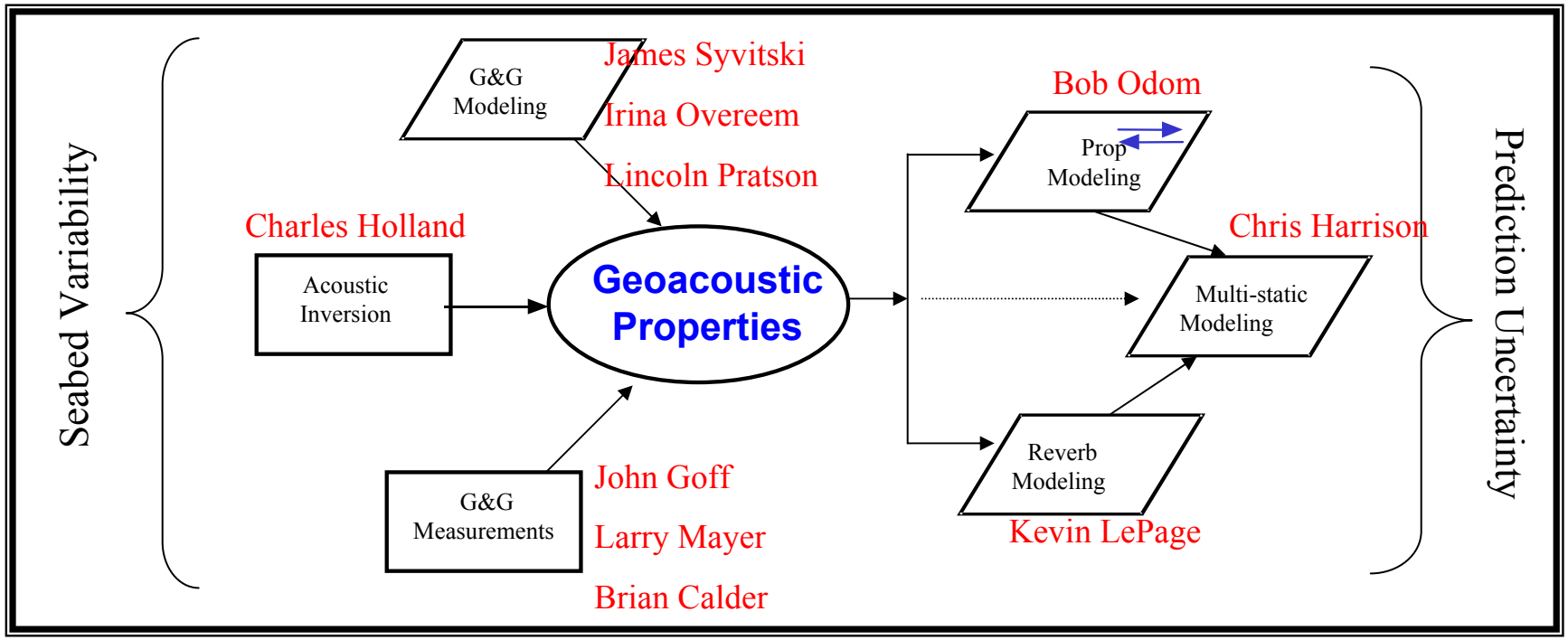
Outline

1. Overview/programmatics

2. Progress
   - G&G modeling → geoacoustics
   - Measurements of G&G&geoacoustics
   - Local acoustic measurements → geoacoustics
   - Geoacoustic uncertainty → prop uncertainty
   - Geoacoustic uncertainty → reverb uncertainty
   - Geoacoustic uncertainty → multistatic uncertainty

3. Statistical models/data available for DRI teams

Seabed Variability Team Approach



Environmental Variability * Measurement Error * Model/Inversion Error/uncertainty ⇒ Acoustic Prediction Uncertainty

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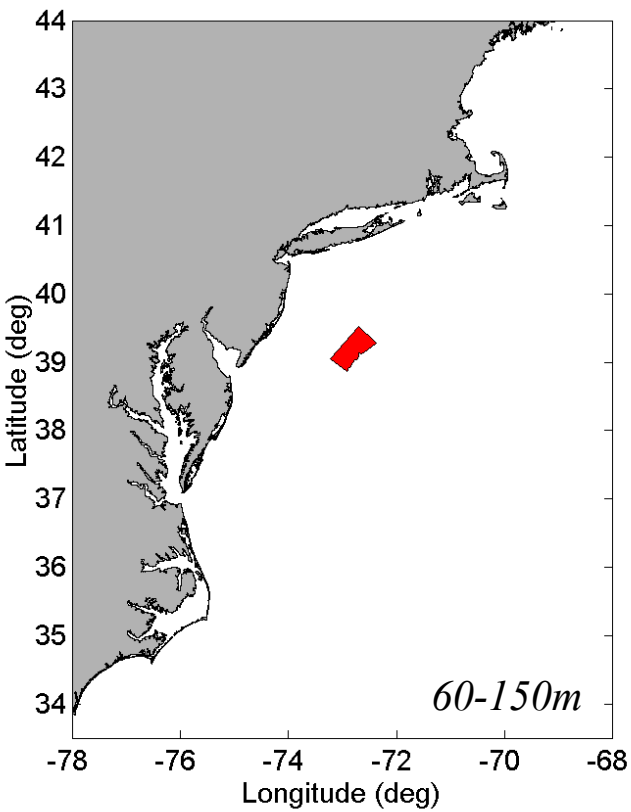
Study Areas

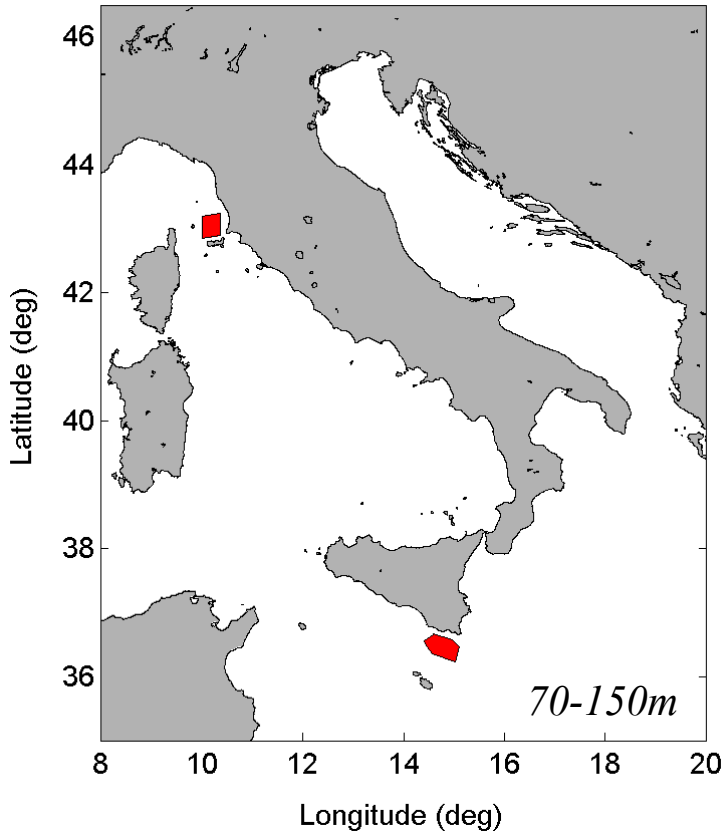
New Jersey littoral



Data:

- G&G&G
- Reflection
- Scattering
- Amb. Noise
- Propagation
- Reverberation
- Oceanography

Italian littoral



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DRI Inter-Team Interaction

Collaborative Ideas

What can Seabed team contribute to other teams?

1. Set of canonical seafloor geoacoustic models for sensitivity analyses in end-to-end system studies.

2. Site specific seabed models to aid modeling; e.g., statistical bathymetric description of the Primer area drawing on similarities with STRATAFORM site.

3. Estimates of uncertainties inherent in propagation and reverberation predictions based on uncertainties/variability of seabed geoacoustics

4. Guidance on questions/issues related to seafloor variability

Geoacoustic Extrapolation

Best geoacoustic data sets and best oceanographic data sets generally are not co-located

Seabed team has been asked to provide geoacoustic data extrapolations from NJ to Primer, ECS.

Team has discussed/argued how to proceed

Paradigm 1) provide data/statistical model for Region X: "apply at Region Y at your own risk."

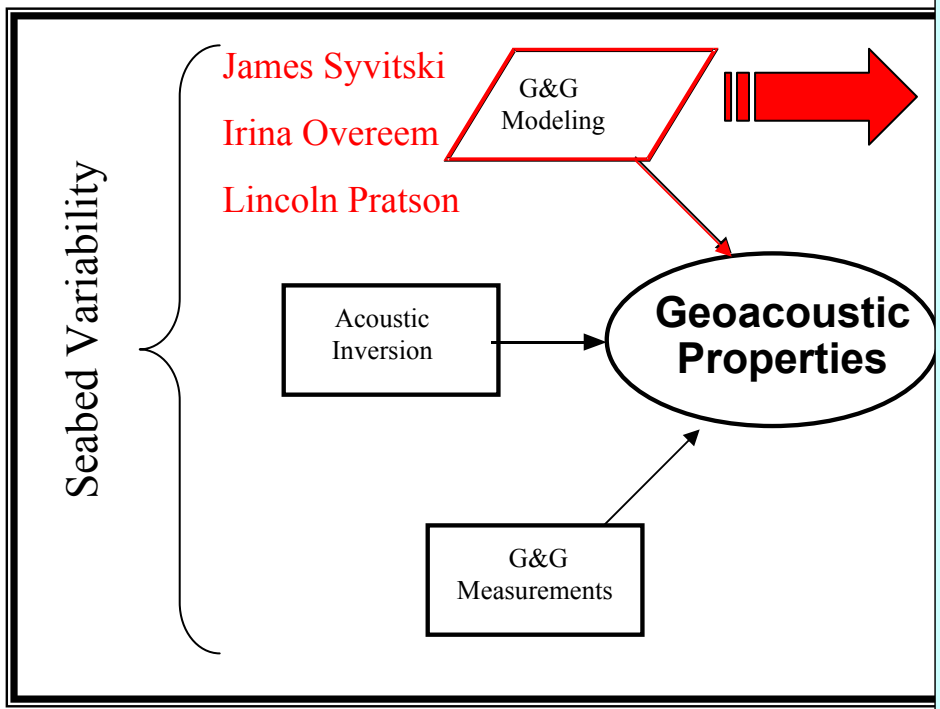
Paradigm 2) conduct a detailed G&G&G study of Region Y, and develop/adapt model based on best available knowledge

Paradigm 1.5) short G&G&G study based on collective group knowledge, provide (modified) model with recommendations, constraints

External DRI Interaction

1. GeoClutter-STRATAFORM Program
   - Tools + data on NJ shelf
2. Boundary Characterization Program
   - Tools + data in NJ shelf/ Straits of Sicily/ North Elba
3. SWAT Program
   - Collaboration on geoacoustics of NJ shelf
4. SACLANT Centre
   - Acoustic modeling (prop/reverb/multi-static)
   - data in Straits of Sicily/ North Elba

Seabed Variability Tea



Environmental Variability * Measurement Error * Model/ Error/u

SEDFLUX Model

Precip. & Temp. Data: GCM predictions, air or ground info
Drainage Basin Relief and Area, Glacier Distribution: satellite info

↓

Hydrological Model

=

daily Q, Qs, Cs, grain size, river velocity, channel size

+

Seafloor Bathymetry: GEOSAT
Ocean Climate (wind & waves): Sat & Buoy Data

↓

River Plume Models

Nepheloid Layer Model (mid water column) ↔ **Shelf Transport Model** (bottom boundary dynamics)

=

Sediment Flux, Accumulation Rate, Seafloor Properties (ρ_{bulk}, grain size) on continental margin (shelf and slope)

↓

Slope Stability Models

=

Compaction, excess pore pressure, sediment strength potential failure planes, volume of failure

↓

Sediment Gravity Flow Models

=

Seafloor Stratigraphy, Bedding Geometry & Coherency, Erosion Surfaces, Seafloor Properties (ρ_{bulk}, grain size, porosity)

+

Acoustic Source Signatures (calibrated)

↓

Acoustic Models

=

Reflecting Surfaces, Acoustic Absorbtion & Attenuation
Acoustic Geoclutter

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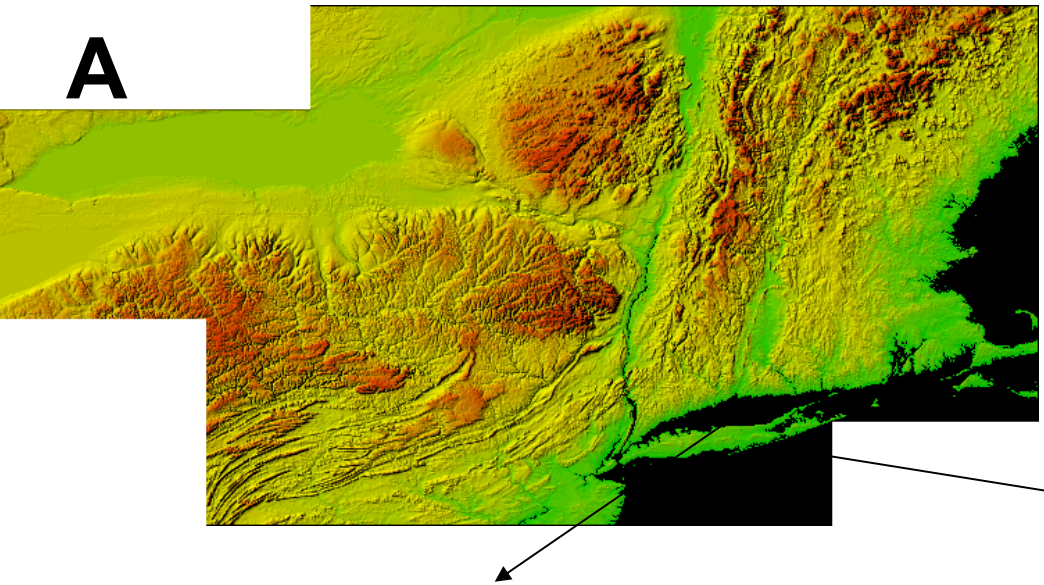
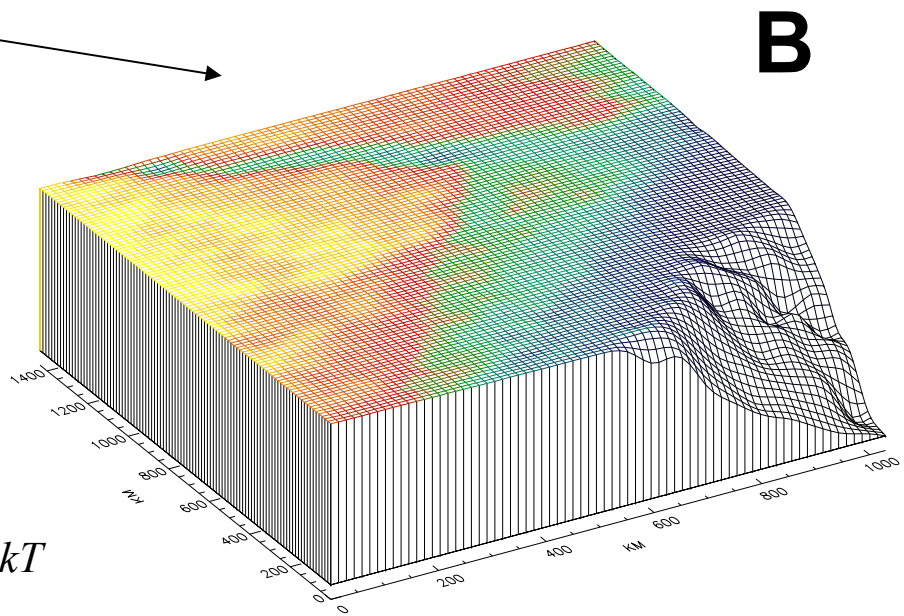
SEDFLUX inputs

NJ littoral



Paleo-seafloor model (John Goff)



A = drainage basin area 35 410 km^2
H = maximum elevation 1903 m

discharge & sediment load estimates influenced by A, H

$$\overline{Q}_s = 1.3\times10^{-4} H^{\frac{3}{2}} (\overline{Q} + Q_{ice})^{0.55} e^{kT}$$

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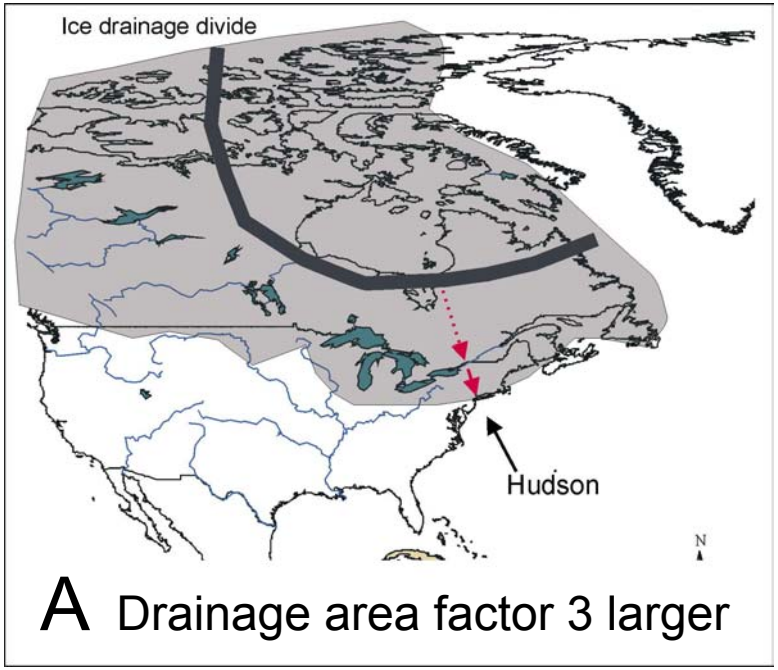
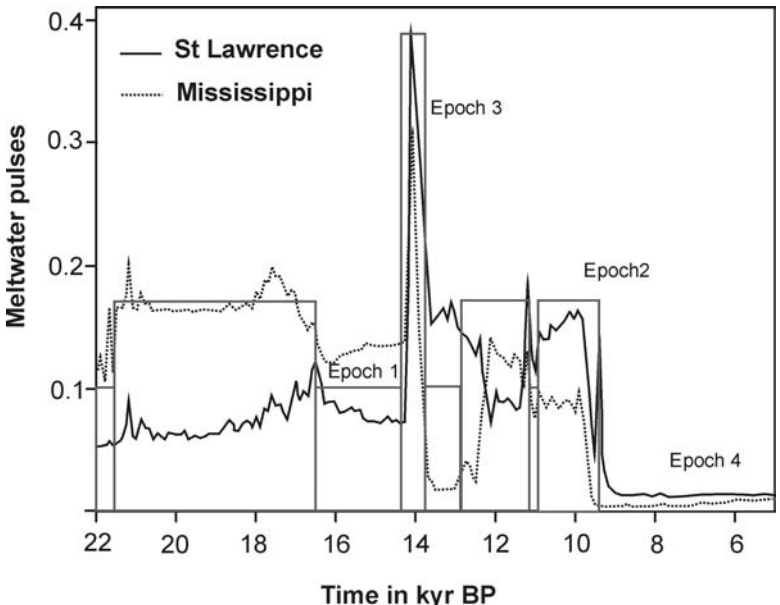
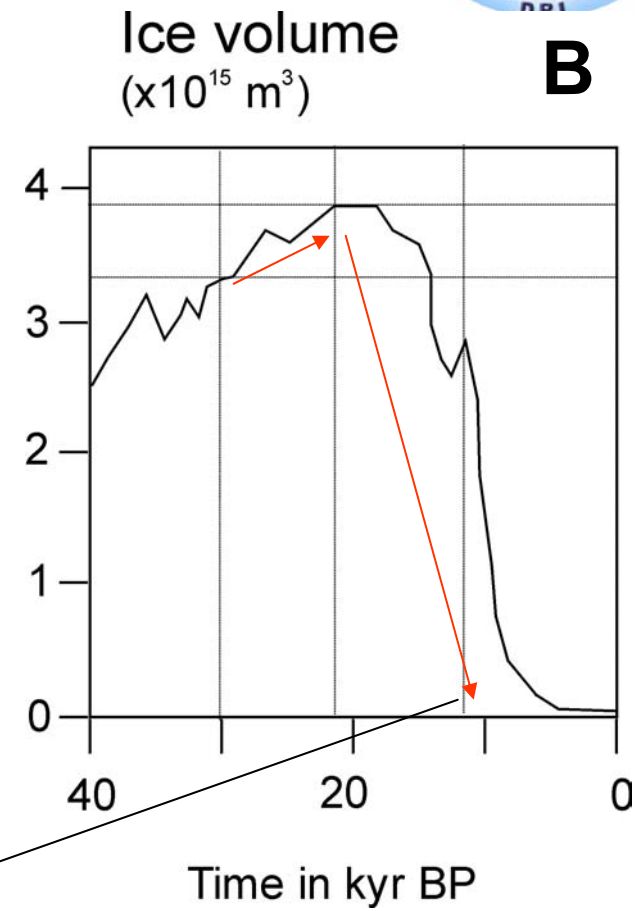
Influence of glacial conditions 30-10 yrs BP

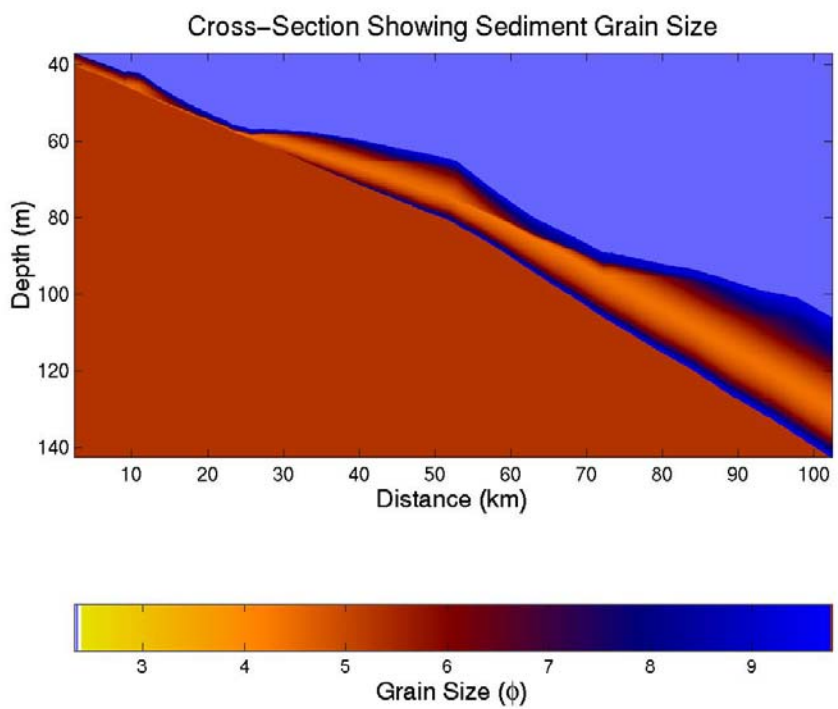


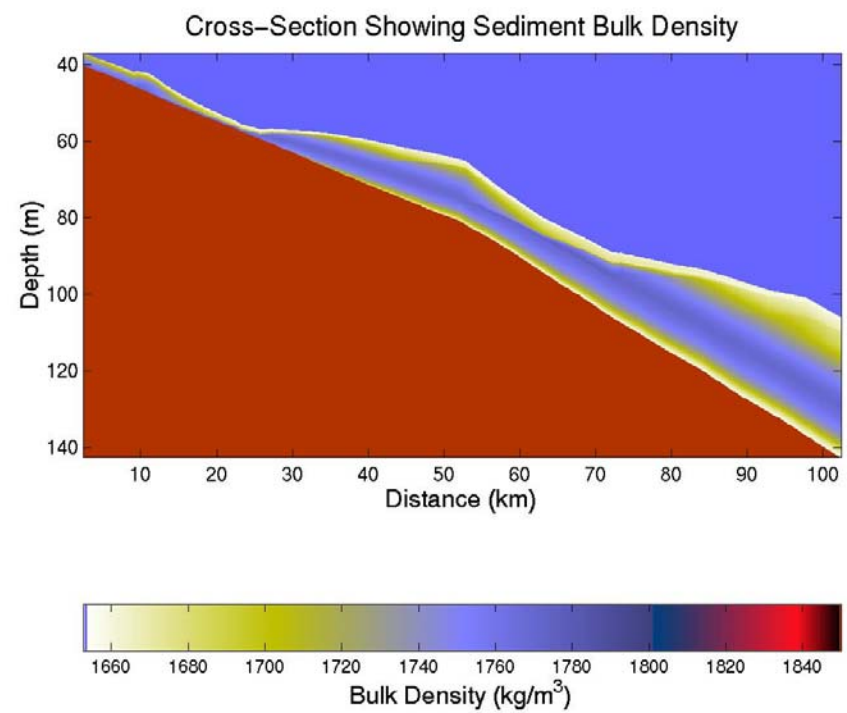




Large contribution of ice melt in pulses

SEDFLUX-results





Output resolution: vertical 0.1 m, horizontal 50 m, ~300 km profile

Grainsize, permeability, bulk density, porosity

Output files for gridcell 2400 – 4400 → 120 -240 km , shallow offshore shelf zone

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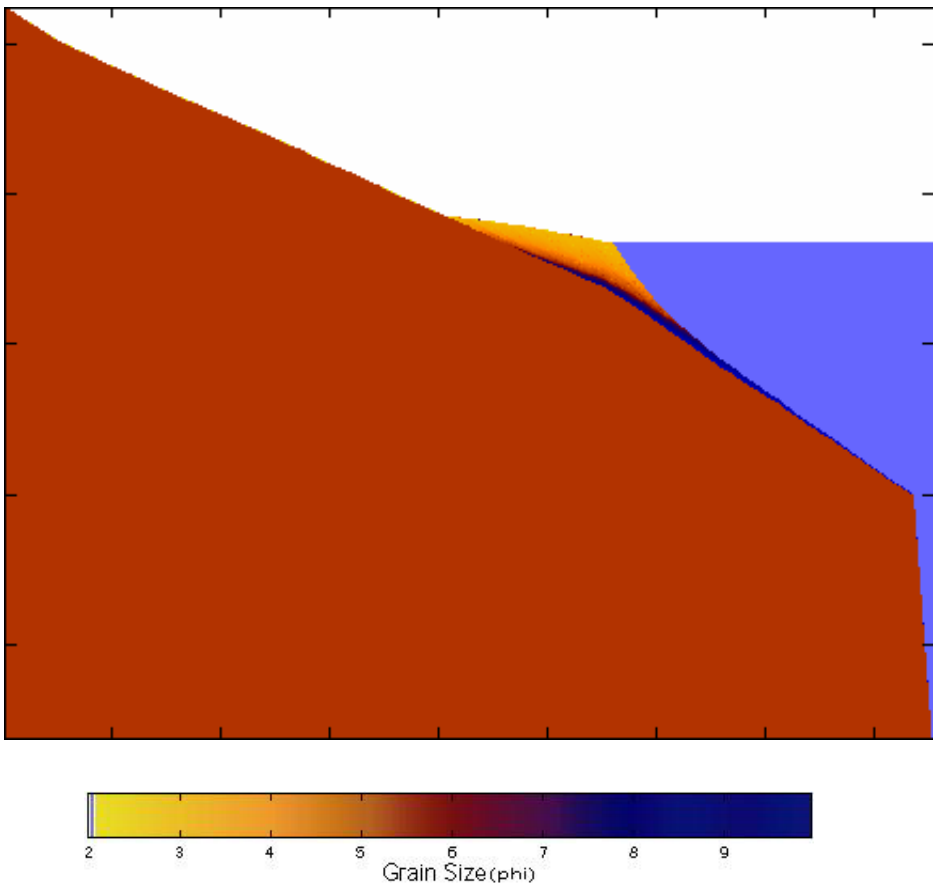
Sensitivity experiments



- SEDFLUX processes 4 runs: avulsion, diffusion, bedload dumping, floodplain sedimentation

- Slope geometry 4 runs: geometries based on profiles from pseudo-horizon

- Discharge and sediment load 3 runs with variation in input sediment
  - coarser sediment input
  - coarse fraction only in melting stage of glacial higher

- Extreme events (glacial lake outbursts)

  4 runs with different bed-load input/ floodplain sedimentation

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SEDFLUX → Geoacoustics

Kuster-Toksöv

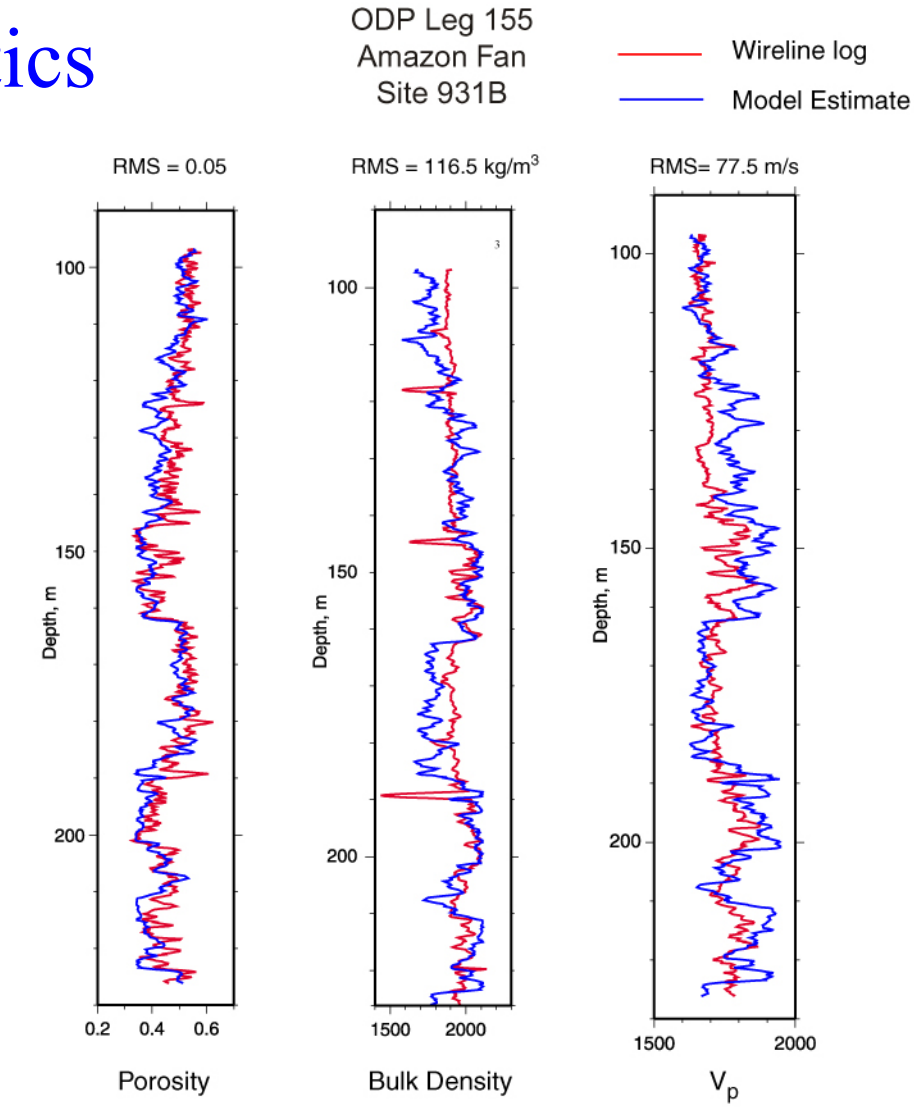
$$\left(K^*_{KT} - K_m\right)\frac{\left(K_m + \frac{4}{3}\mu_m\right)}{\left(K^*_{KT} + \frac{4}{3}\mu_m\right)} = \sum_{i=1}^{N} x_i\left(K_i - K_m\right)P$$

$$\left(\mu^*_{KT} - \mu_m\right)\frac{\left(\mu_m + \frac{4}{3}\zeta_m\right)}{\left(\mu^*_{KT} + \frac{4}{3}\zeta_m\right)} = \sum_{i=1}^{N} x_i\left(\mu_i - \mu_m\right)Q$$

Berryman

$$\sum_{i=1}^{N} x_i\left(K_i - K^*_{SC}\right)P = 0$$

$$\sum_{i=1}^{N} x_i\left(\mu_i - \mu^*_{SC}\right)Q = 0$$



Assumptions:

- Binary mixture of sands and clays with fixed grain properties.
- Pore fluid is a brine.

Independent Variable:

- Clay content estimated from gamma ray log.

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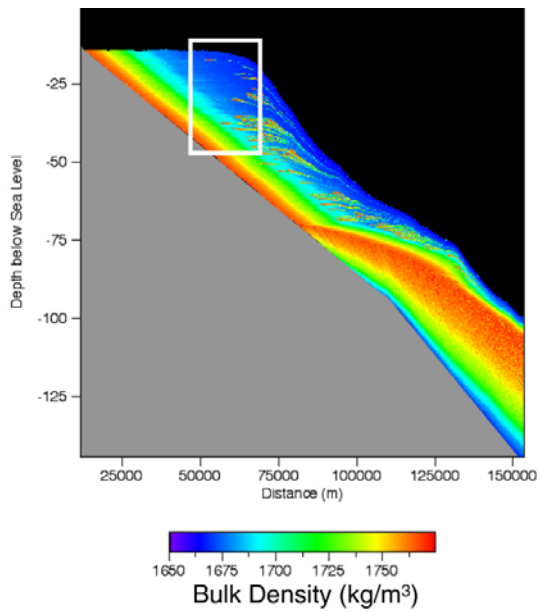
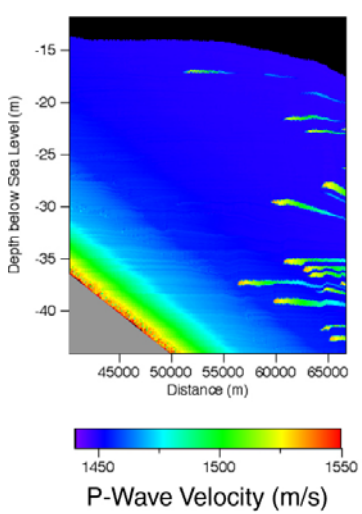
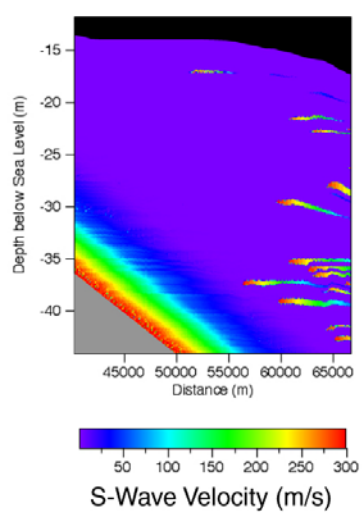
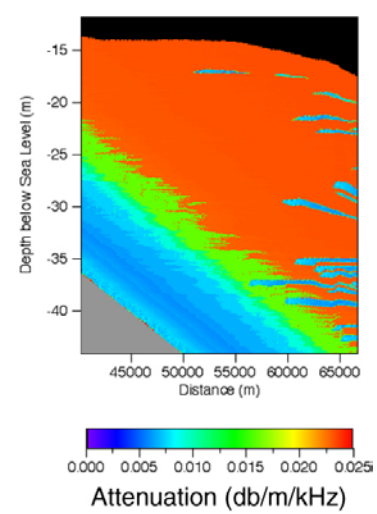
SEDFLUX → Geoacoustics



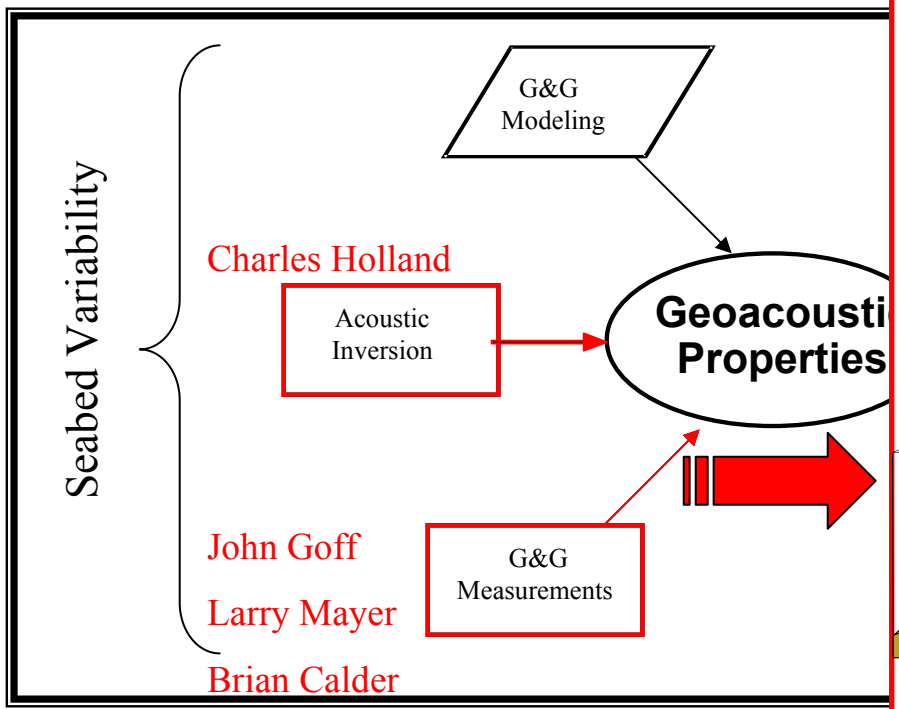
Fluctuations in the Laurentide ice-sheet melting responsible for fine-scale structure

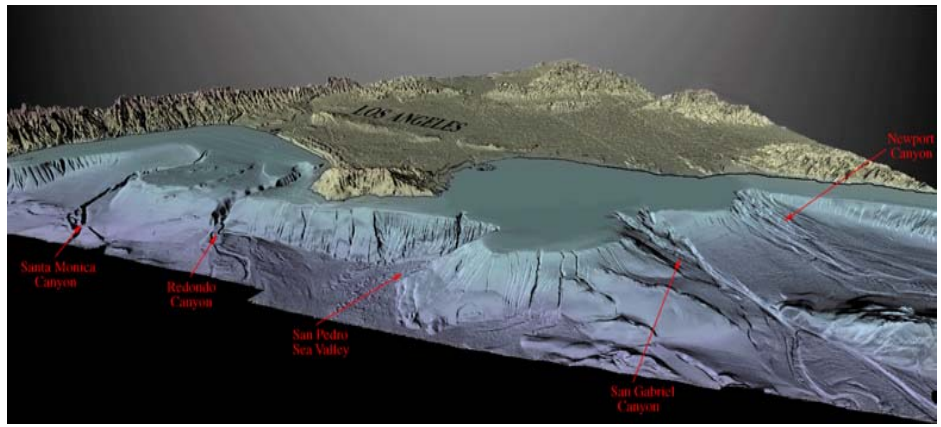


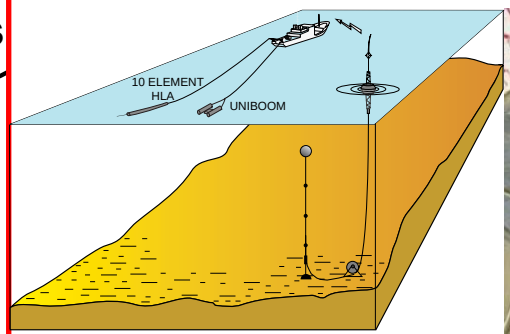


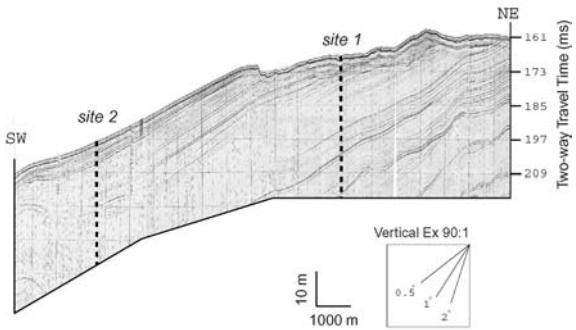


Seabed Variability Team Approach









Environmental Variability * Measurement Error * Mod Error

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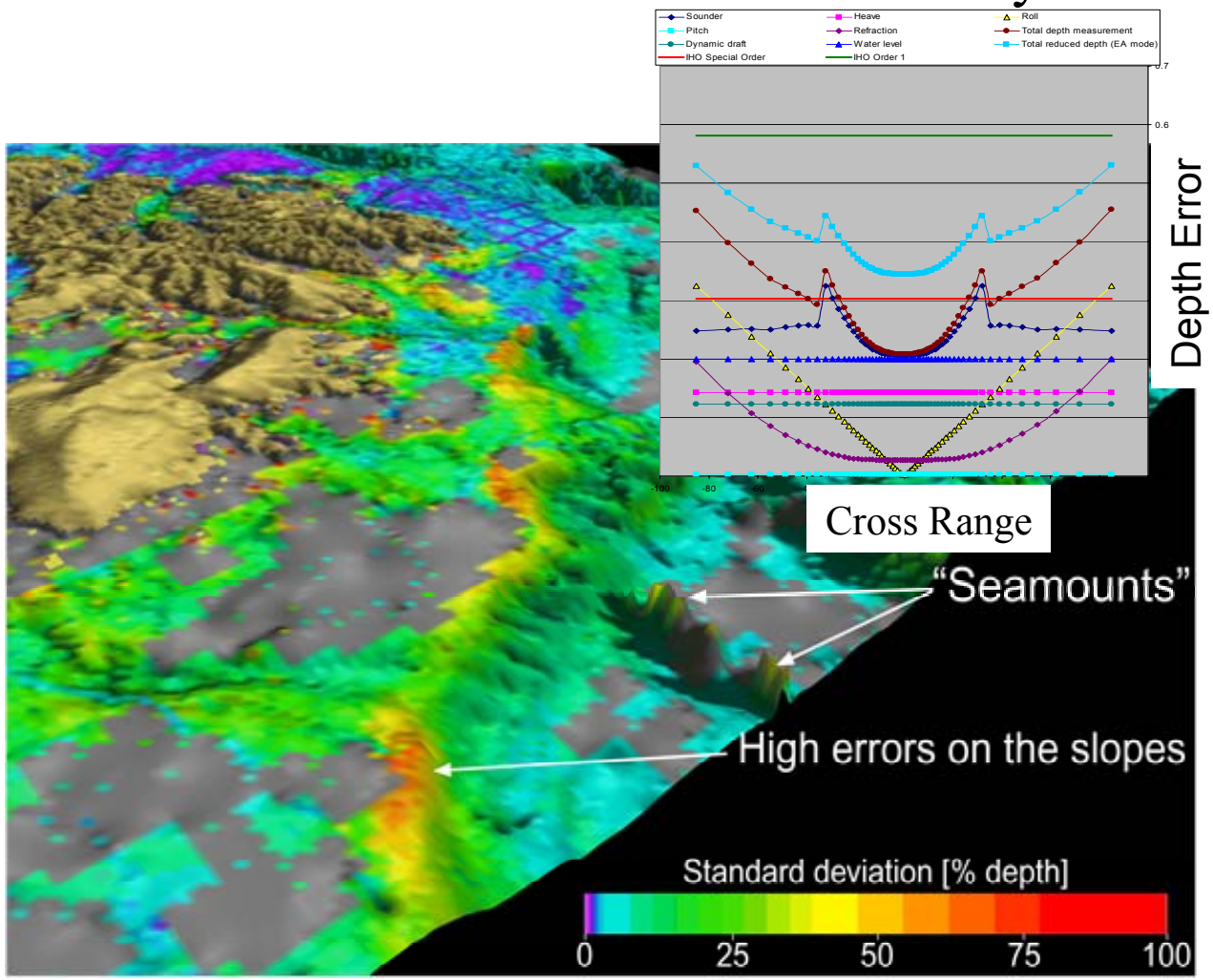
Bathymetric Uncertainty

Error Analysis



Detailed uncertainty estimates are possible when system specific data is available

Bathymetric uncertainty can also be estimated for historical data

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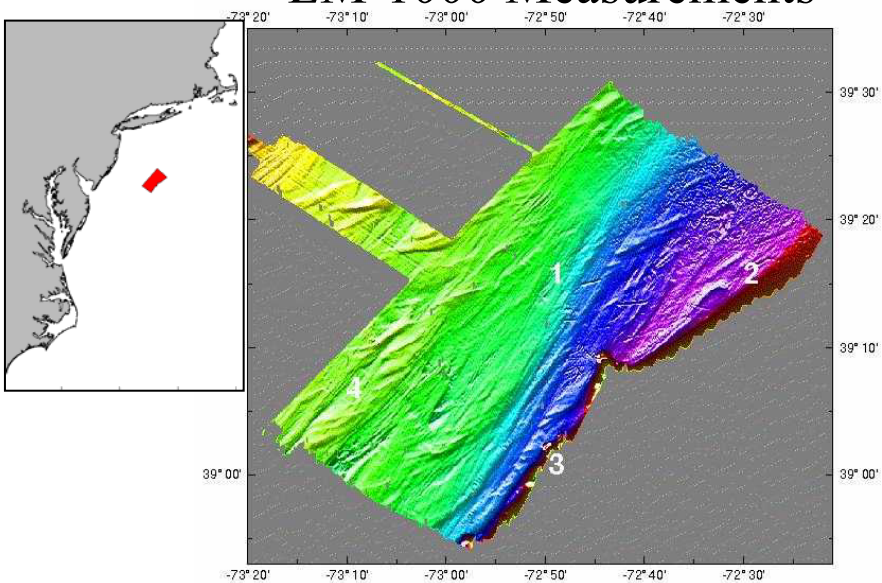
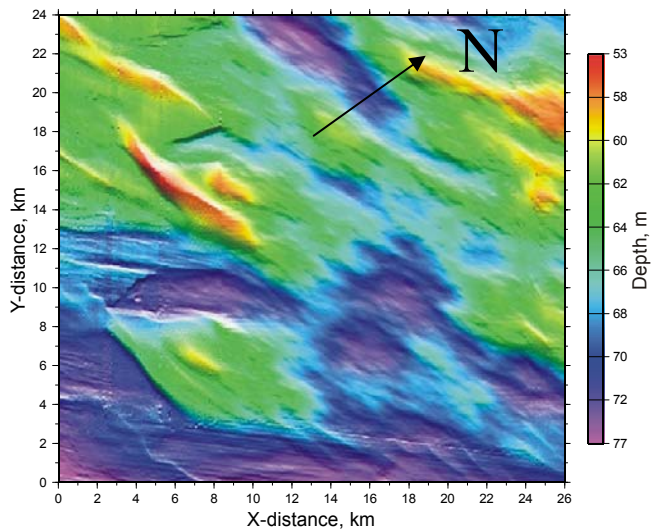
Statistical Modeling for NJ Sand Ridges

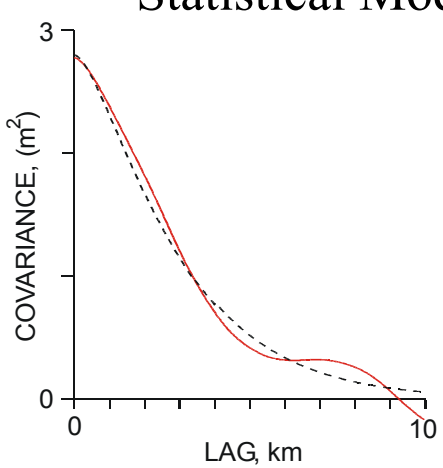
EM-1000 Measurements

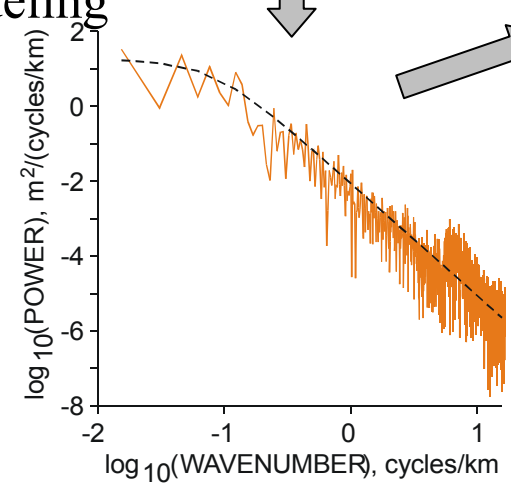


Conditional Simulation



Statistical Modeling





Variance: 2.8 m^2 (rms: 1.7 m)

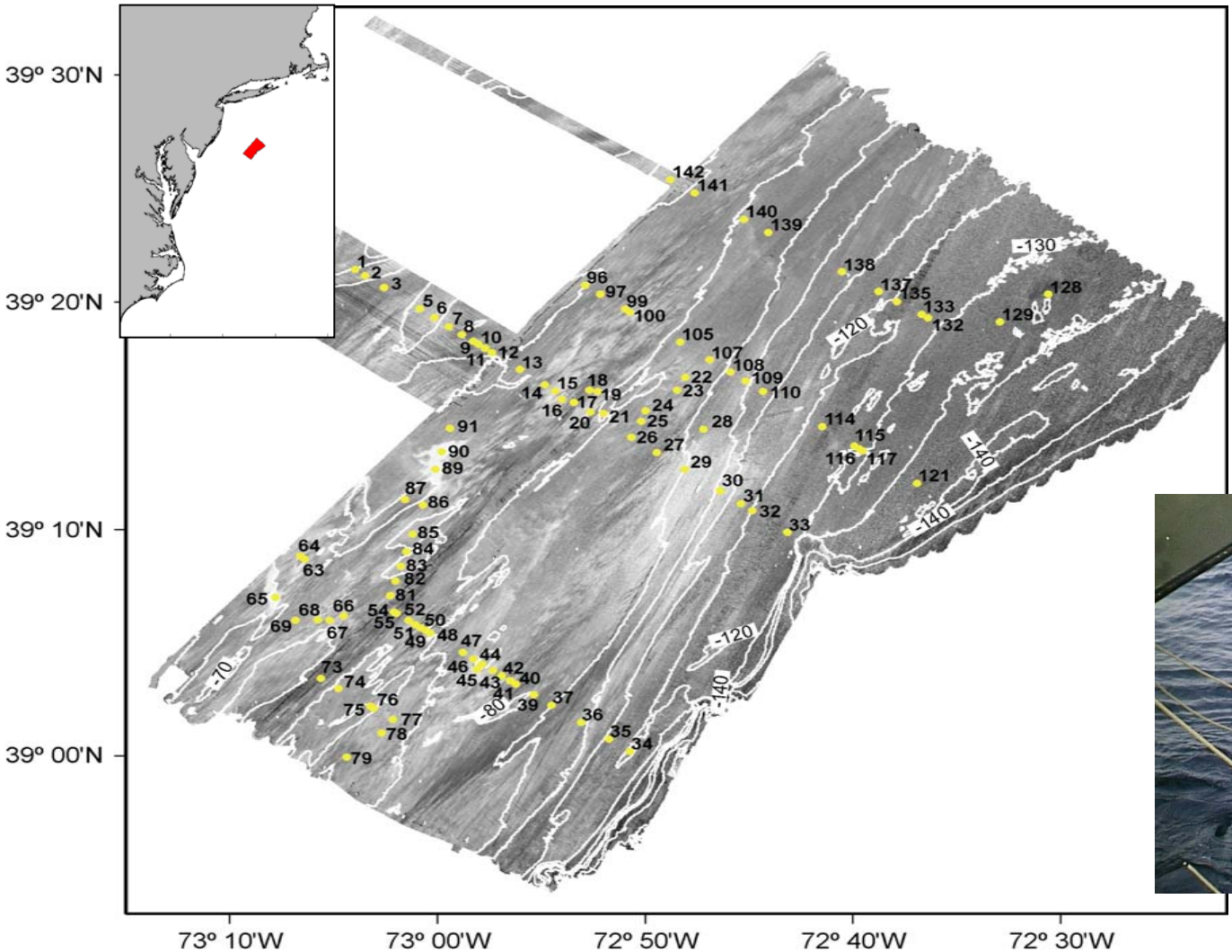
Characteristic Width : 2.7 km

Characteristic Length : 7 km

Strike Azimuth: N65ºE

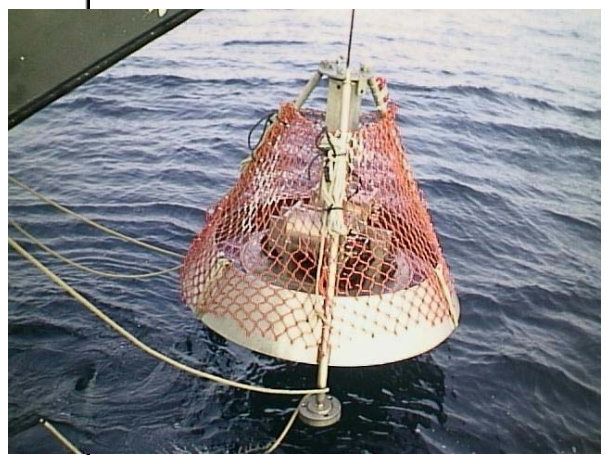
Fractal Dimension: 2

In-situ *Vp* α measurements: NJ shelf



<u>Hypothesis</u>:

95 kHz backscatter correlated with geoacoustic (esp Vp)



Correlation Analysis Results

No strong correlation yet observed between *Vp* - 95 kHz backscatter

- backscatter correlated with coarse fraction
- *Vp* correlated with fine fraction and mean grain size.

Thus, the data samples provide the only measure of spatial variability for surficial *Vp*, α.

	Scale
• Sound speed: 200 - 300 m/sec Attenuation: ~ 1 dB/m/kHz*	10 km
• Sound speed: 100 m/sec Attenuation: ~0.4 dB/m/kHz*	< 1 km
• Sound speed: ~5 m/sec Attenuation: ~0.05 dB/m/kHz*	< 1 m (except where cobbles shells are in path)

* At 65 kHz

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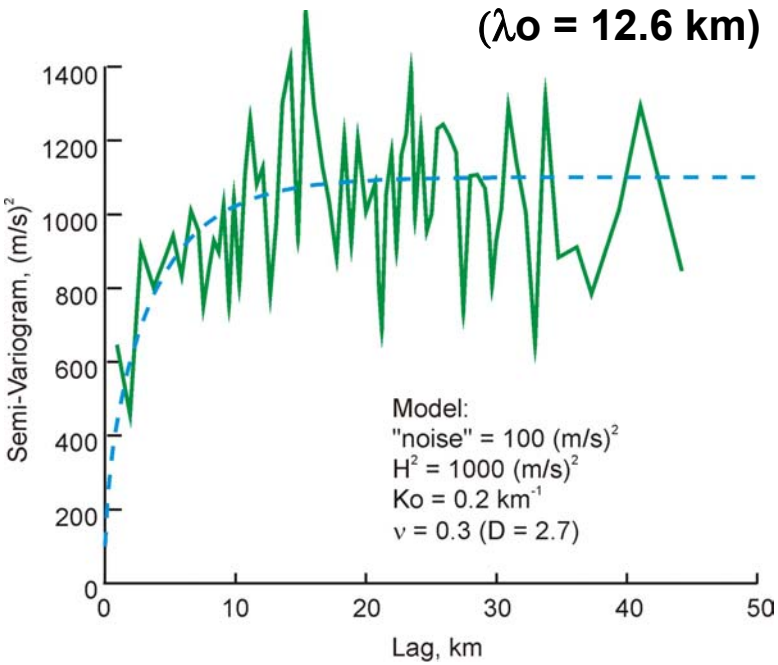
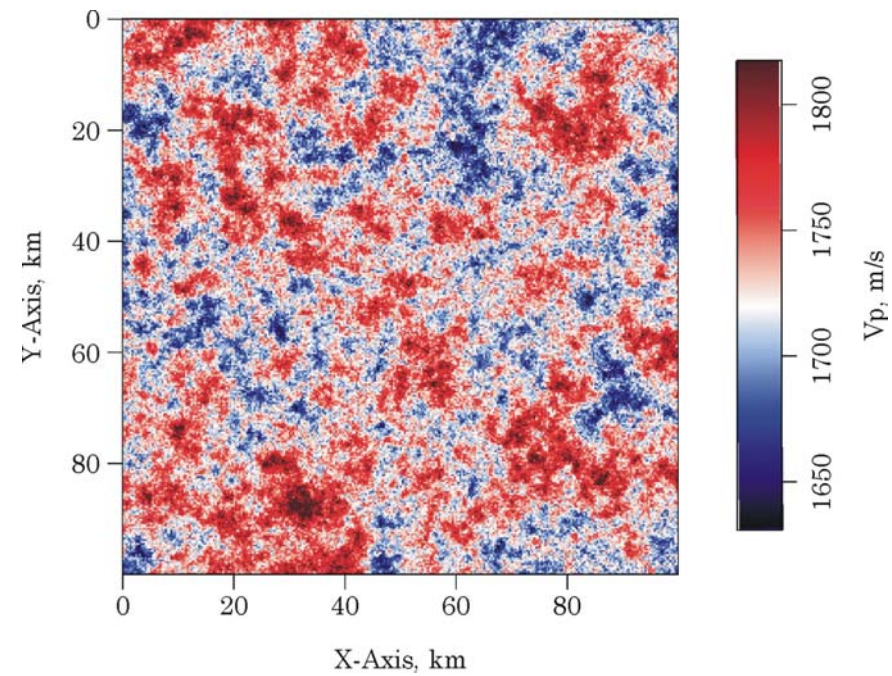
Velocity Semi-Variogram



Realization of Statistical Velocity Model



- A semi-variogram for Vp was constructed from the sample data (excluding Hudson Apron).
- Model allows generating realizations of velocity variability.

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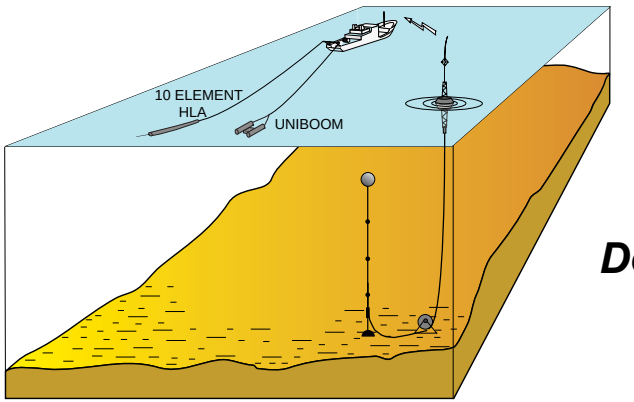
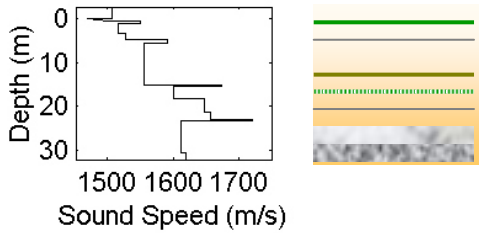
Coupled acoustic measurements

Reflection

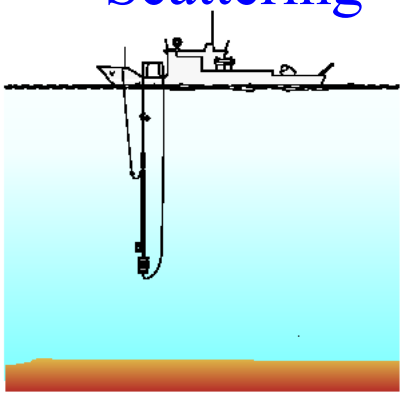




Deterministic Geoacoustics

Sound speed, density, attenuation, gradients ,layers

Scattering



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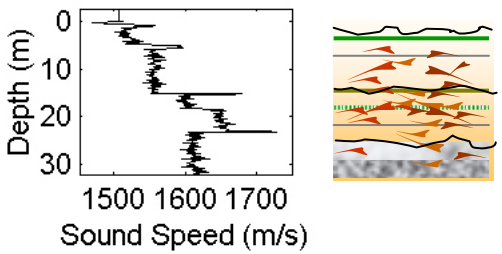
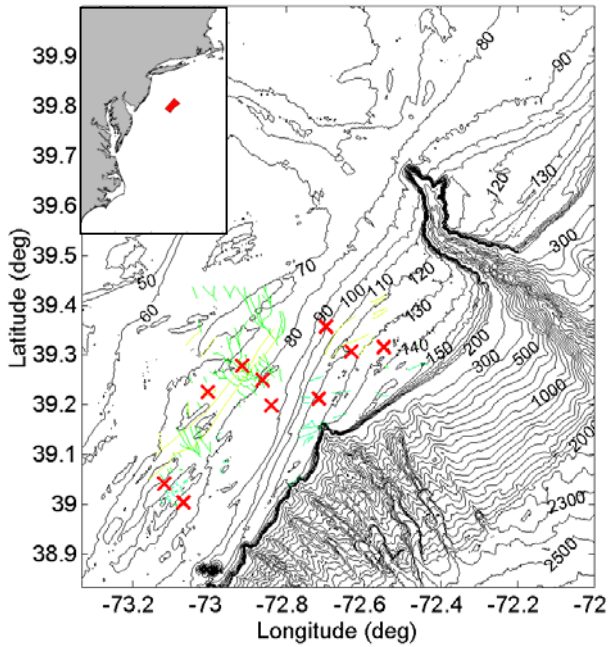
Stochastic Geoacoustics:

roughness, volume, basement parameters

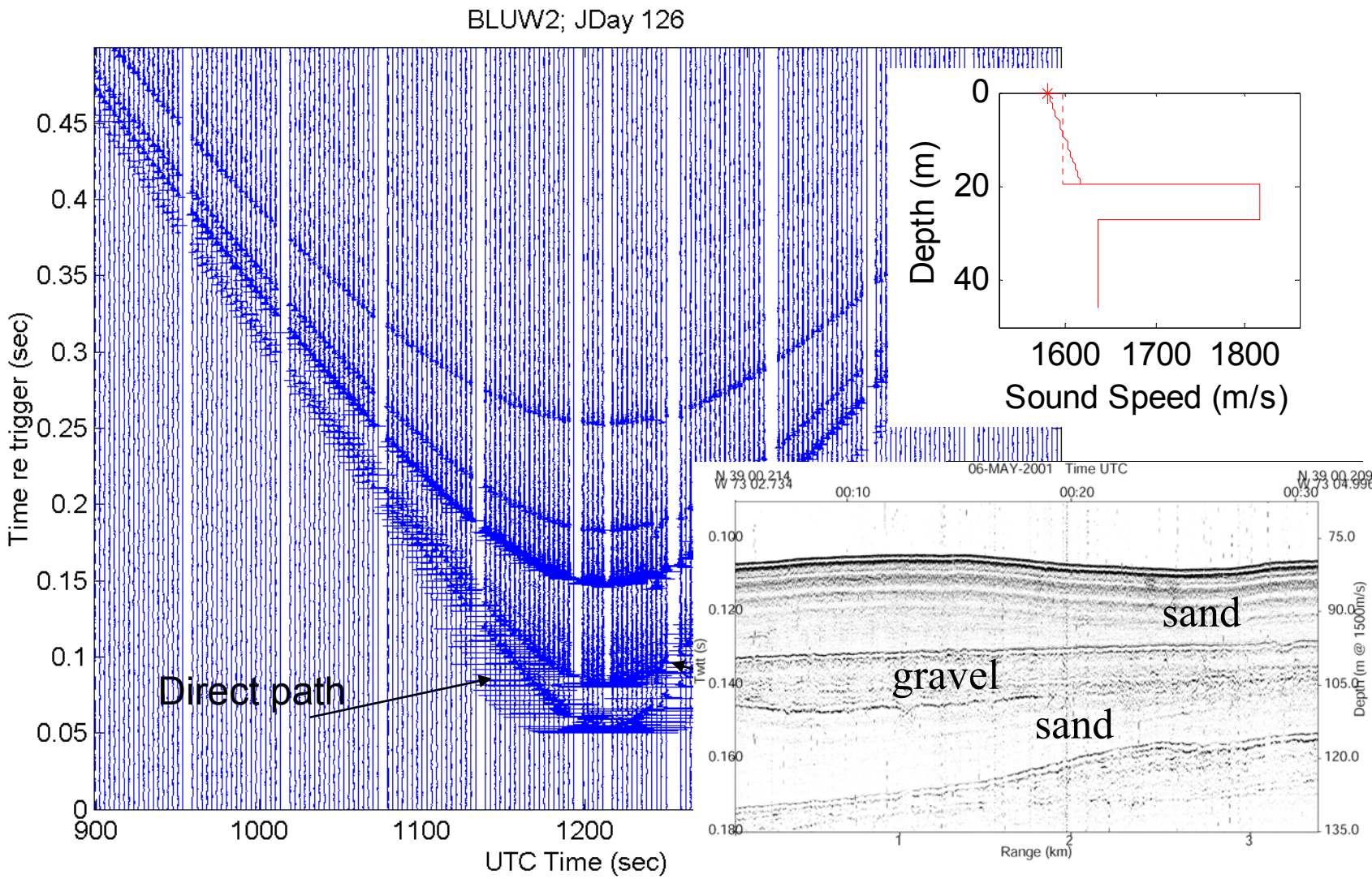


x reflection (200-8000 Hz) and scattering (400-3600 Hz) sites

New Jersey shelf

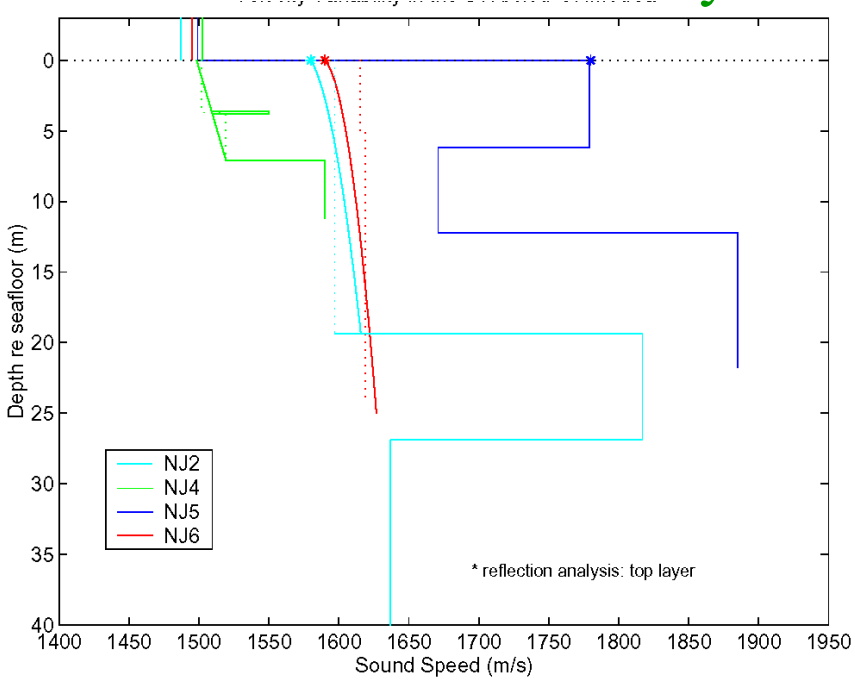


Raw Time series data; Site 2

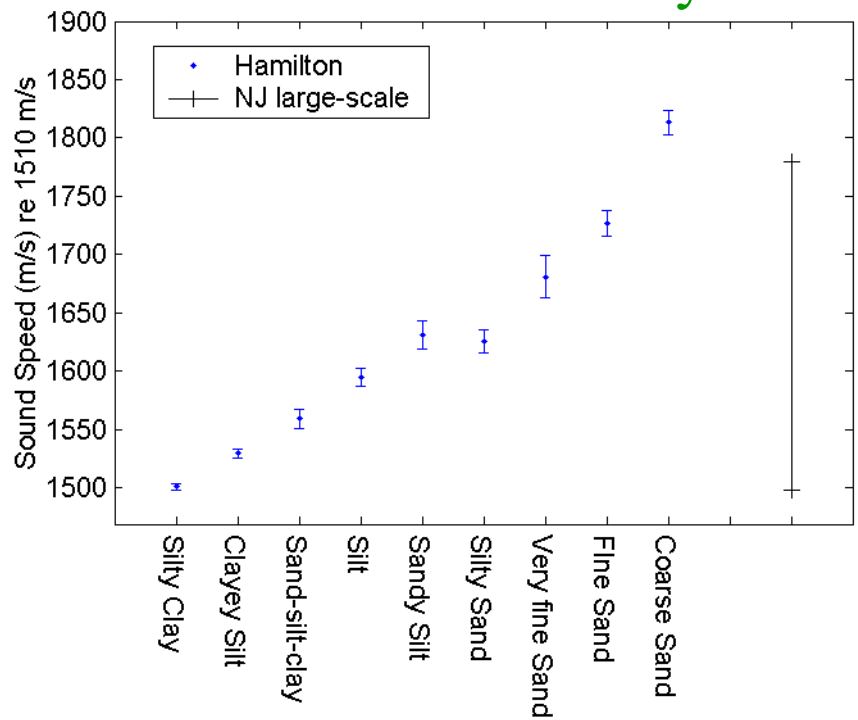


NJ Sediment Velocity

Site to Site Variability



Area Variability



Interim estimates of velocity uncertainty

- ~ ± 4 m/s surficial layer
- ~ ± 15 m/s sub-bottom

NJ observed min/max Vp (4 sites) is 89% Hamilton

NE observed min/max Vp (5 sites) is 65% Hamilton

MP observed min/max Vp (8 sites) is 95% Hamilton

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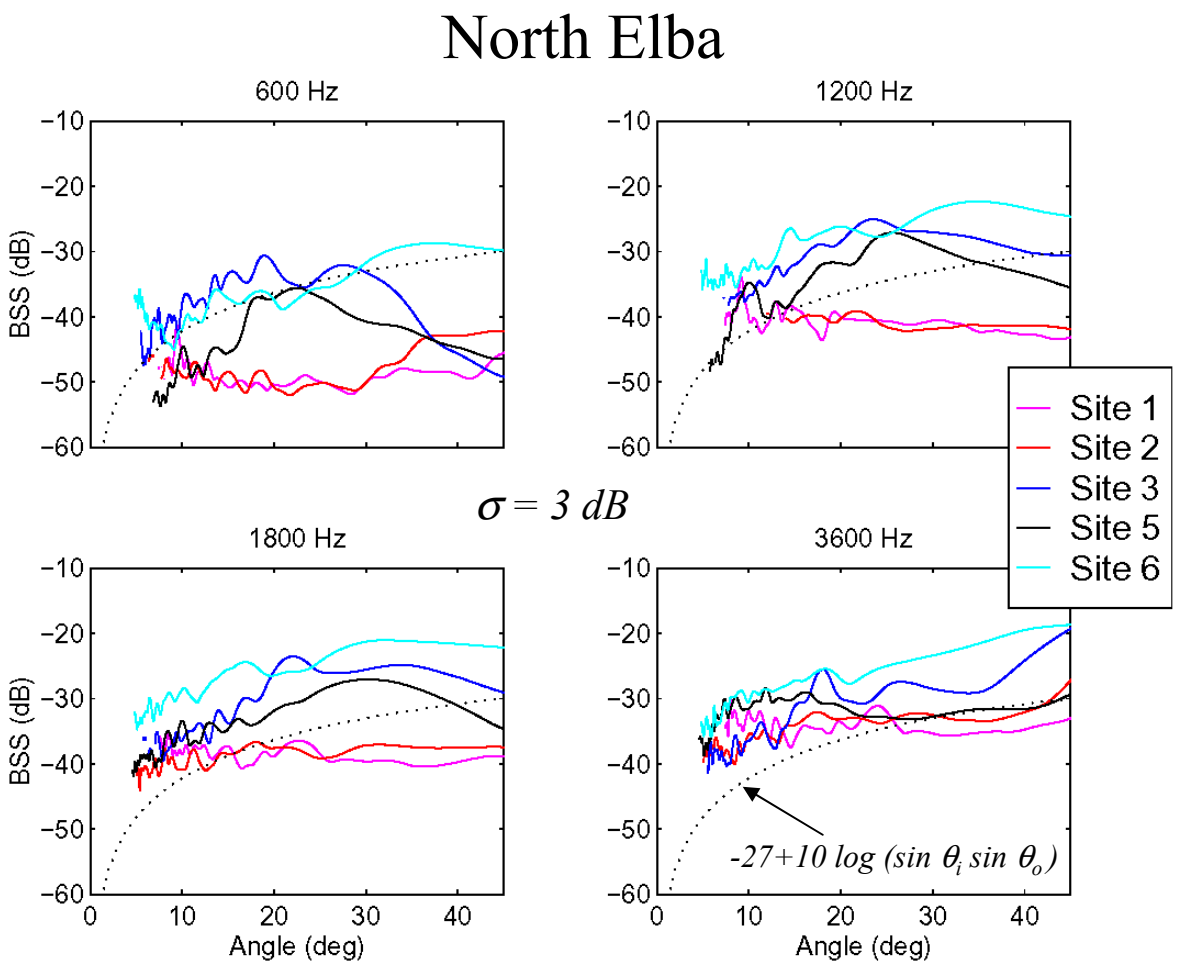
Scattering Strength Variability



Large variability in scattering strength within a shallow water area

- intrinsic
- geometric

Site-to-site variability in frequency dependence

Significant variability in angular dependence; low angles

$BSS \propto \sin\theta_i \sin\theta_o$

$BSS \propto \sin\theta_i$

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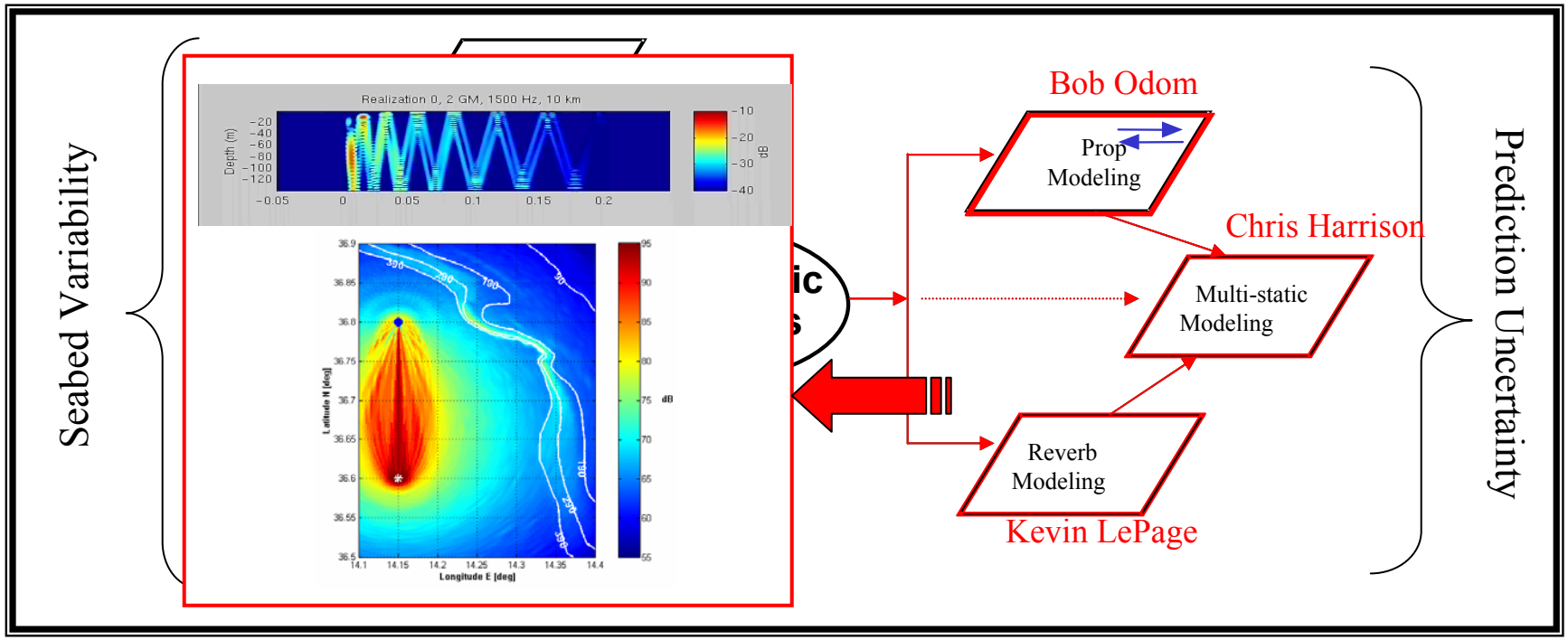
Seabed Variability Team Approach



Environmental Variability * Measurement Error * Model/Inversion Error/uncertainty ⇒ Acoustic Prediction Uncertainty

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SUPREMO
Multistatic Sonar Performance Model

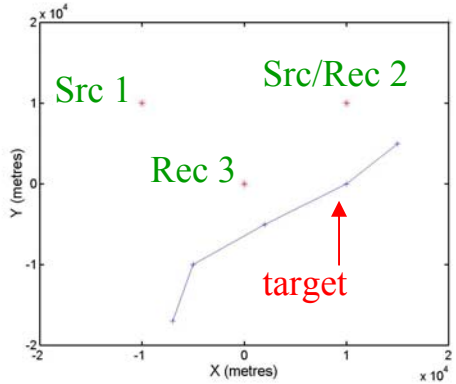
Phenomena of Interest:

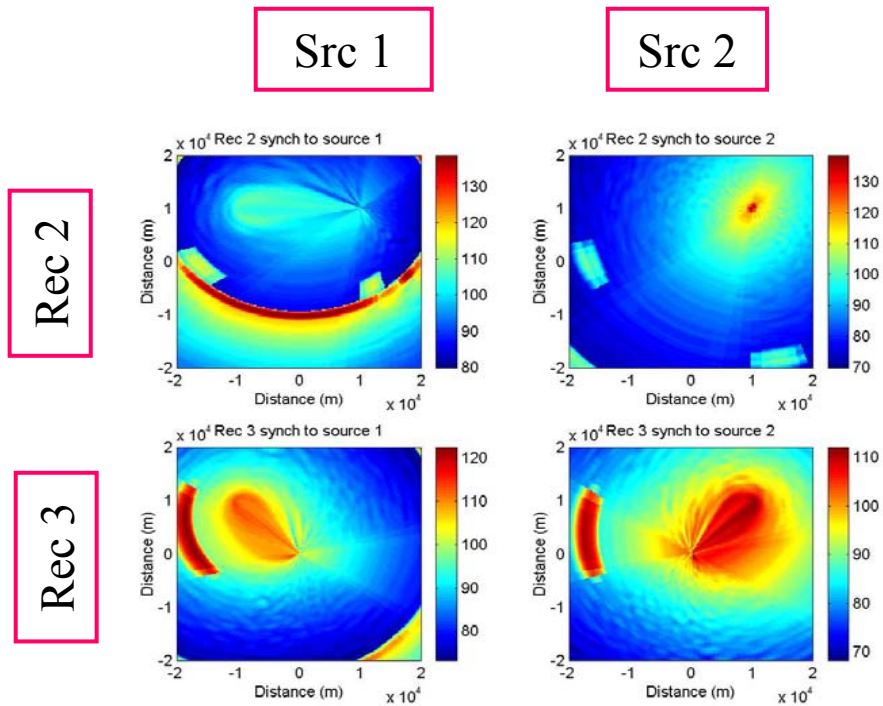
- Benefits of Multistatics
  - Many target aspects - ‘glint’ (mirror reflection)
  - Choice of reverb. background - ‘geo-clutter’ (eg ridges)

- Problems of Multistatics
  - Interference from other sources
  - Simultaneous geometries - complicated
  - Possible mismatch of source and receiver

- How to combine ‘extra information’

- Effect of environmental uncertainty





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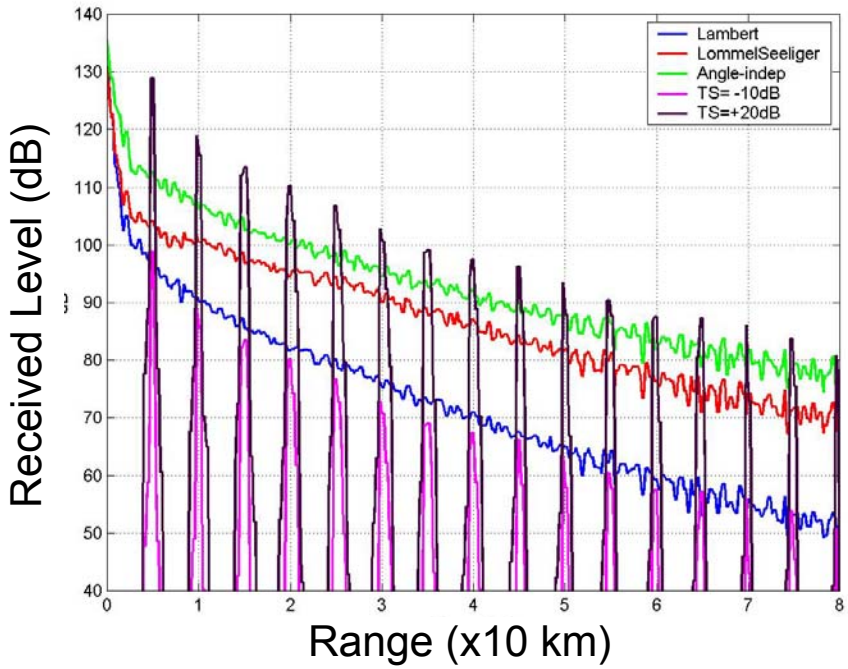
Environmental Variability

- Determine uncertainty in SE/Area coverage associated with uncertainty/variability in
  - scat law; spatial variation of scat strength/law, tilted facets; ray angle on slope; bottom loss (geoacoustics);...
- Investigate 'scattering patch' statistics



Variability of bottom scattering strength angular dependence has a large impact on Signal Excess, 10 dB @ 10 km.

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Bottom Property Parameter Sensitivity

- Model-data sensitivities are required to construct an accurate picture of effect of variability on acoustic prediction uncertainty
  - Required quantities are the functional or Gateaux derivatives

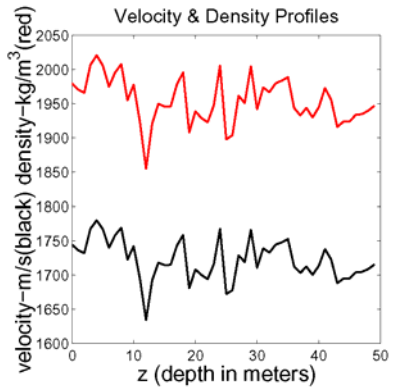
$$\left(\frac{\partial P}{\partial \kappa}, \frac{\partial P}{\partial \rho}\right)$$

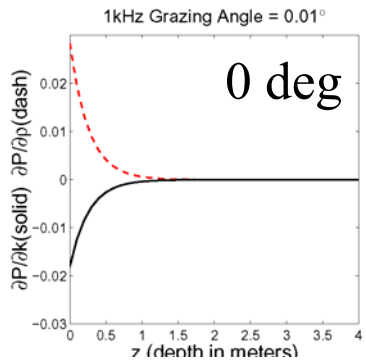
  - Other quantities of interest are obtained from the derivative chain rule
- Linearize about a global model minimum

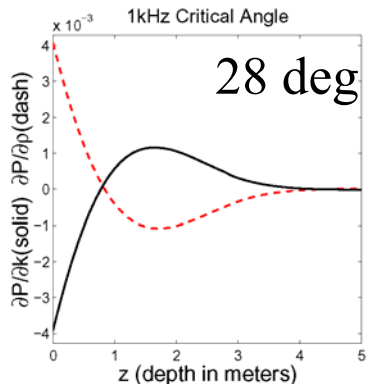
Gateaux Derivatives

Goff NJ variability

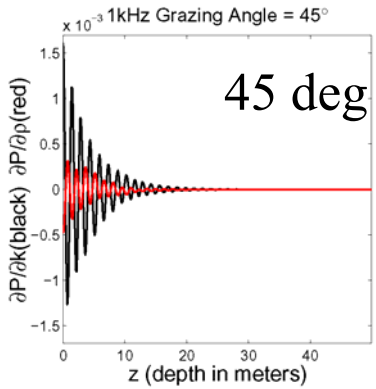
- The Frechet derivatives are the sensitivity functions for the model and data.
  - Large derivatives - data sensitive to model
  - Small derivatives - data insensitive to model







- Fast efficient implementation permits:
  - Rapid characterization of model/data sensitivities
  - Efficient inversions
  - First step towards model resolution matrix



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Modeling Uncertainty of Prop through Oceanography

Closed form

» Krolik, J. Acoust. Soc. Am. **92** 1408-19

» LePage, J. Comp. Acoust. **9** 1455-74

$$\left\langle p_{STA}^2(t,r,z)\right\rangle \approx 2\pi \sum_{n=1}^{N}\sum_{m=1}^{N} \frac{e^{i\int k_n^o(r')-k_m^o(r')dr'}}{\sqrt{\int k_n^o(r')dr' \int k_m^o(r')dr'}} \phi_n(z_s)\phi_m(z_s)\phi_n(z)\phi_m(z)$$

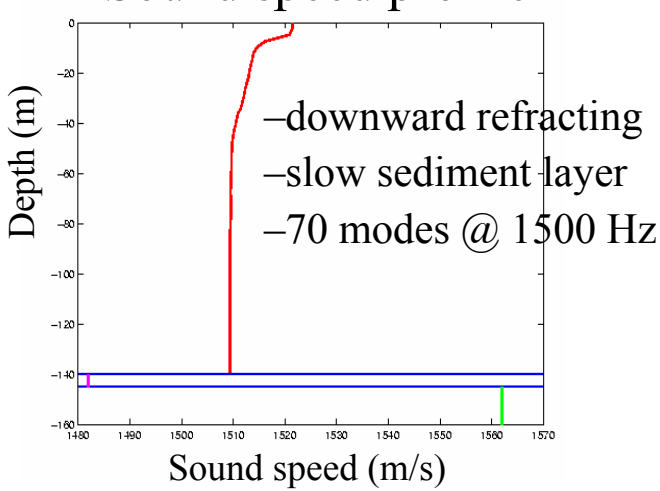
$$\times \int_{-\Delta\omega}^{\Delta\omega}\int_{-\Delta\omega}^{\Delta\omega} e^{-i\omega_1\left(t-\int S_n(r')dr'\right)} e^{i\omega_2\left(t-\int S_m(r')dr'\right)} e^{-\omega_1^2/2\Delta\omega^2} e^{-\omega_2^2/2\Delta\omega^2} d\omega_1 d\omega_2$$

$$\times \prod_{e=1}^{E} e^{-\left(\Delta k_{en}-\Delta k_{em}+\omega_1\Delta S_{en}-\omega_2\Delta S_{em}\right)^2 \sigma_{g_e}^2 r\ell_e/2}$$

Product over EOFs (uncorrelated)

Decorrelation of modal cross terms caused by uncertainty of phase integral

Sound speed profile



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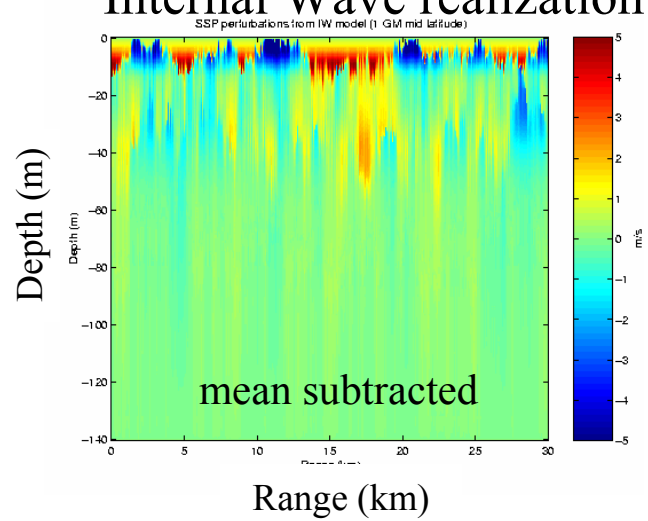
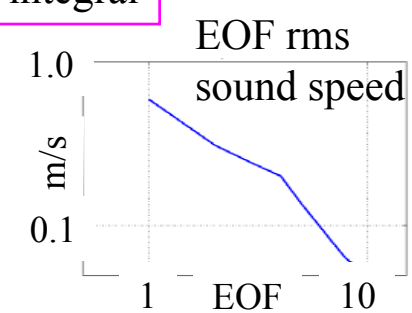
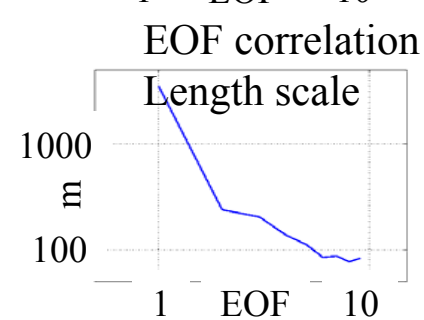
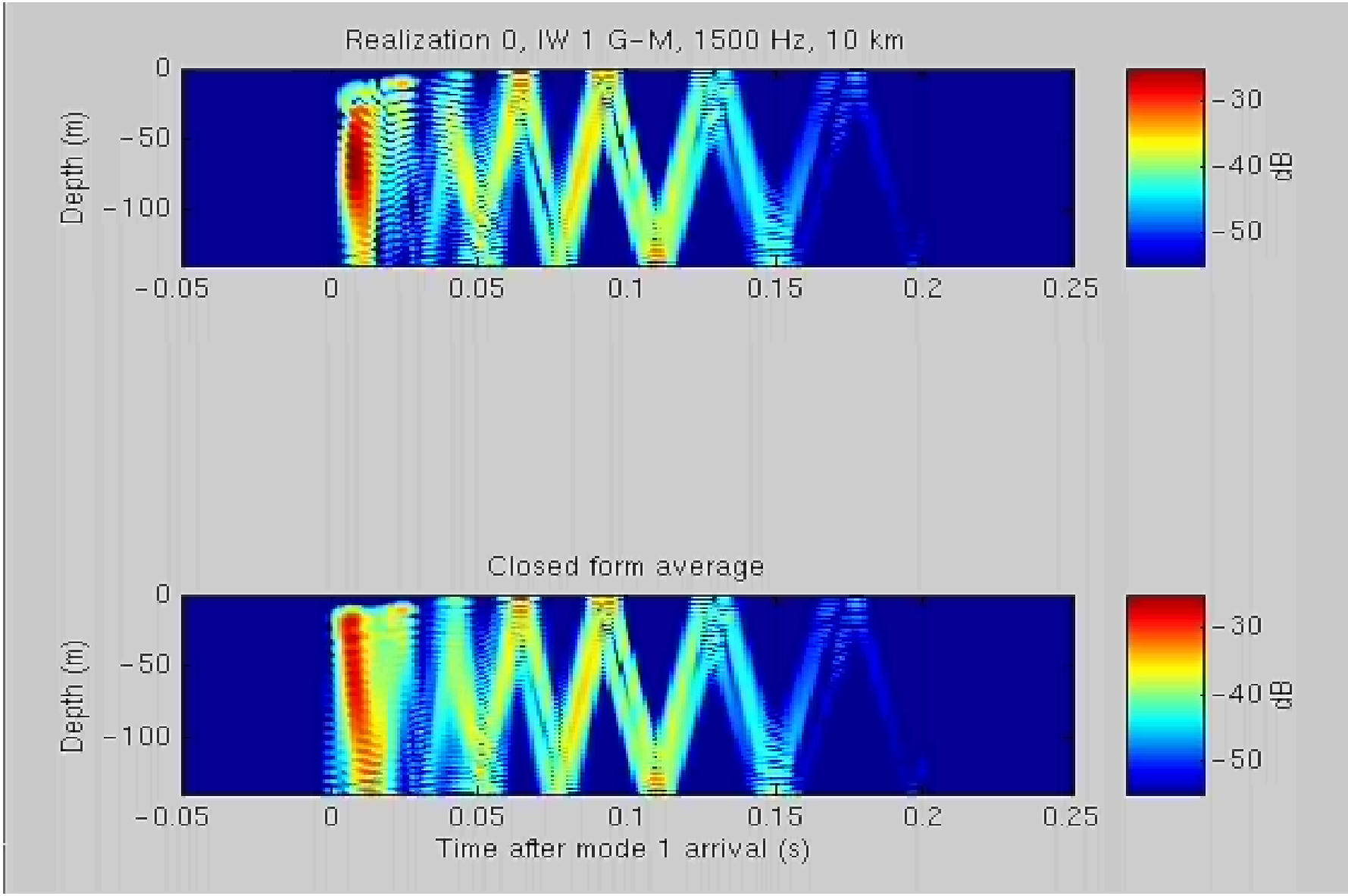
Internal Wave realization





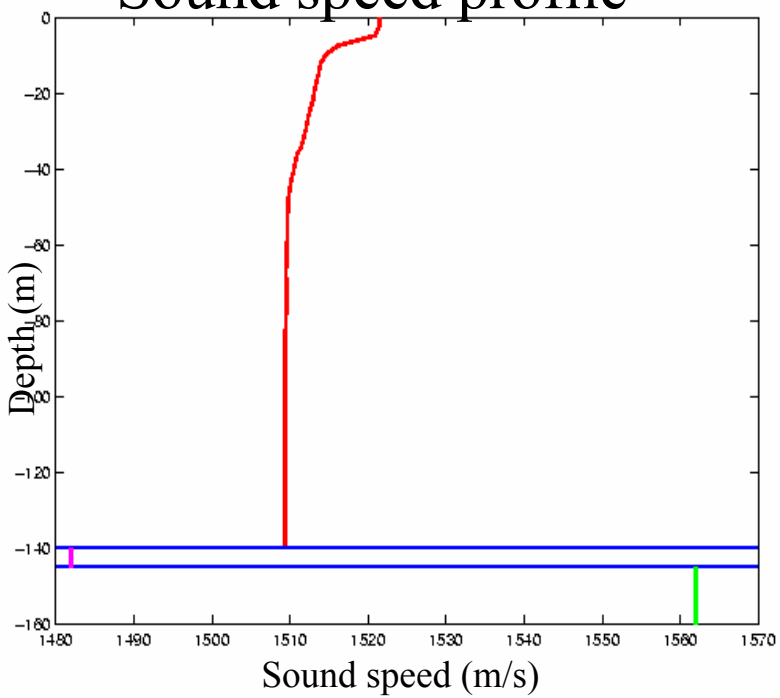


Fluctuations of Intensity Averaged over IW Realizations



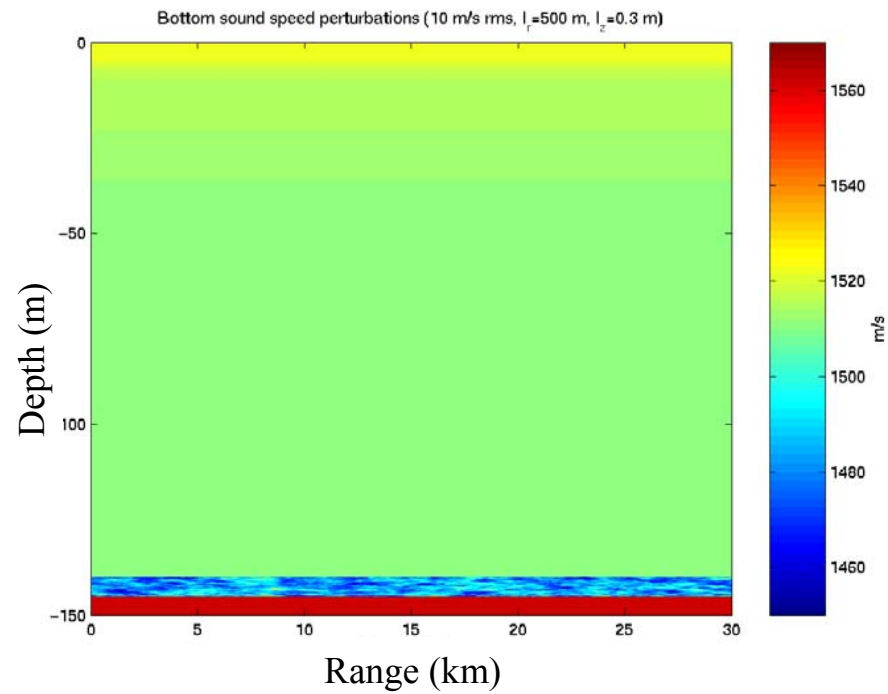
Modeling Uncertainty of Prop/ Reverb over Uncertain Bottom

Sound speed profile



- downward refracting
- slow sediment layer
- 70 modes @ 1500 Hz

- Bottom realization



- l_x=500 m
- l_y=0.3 m

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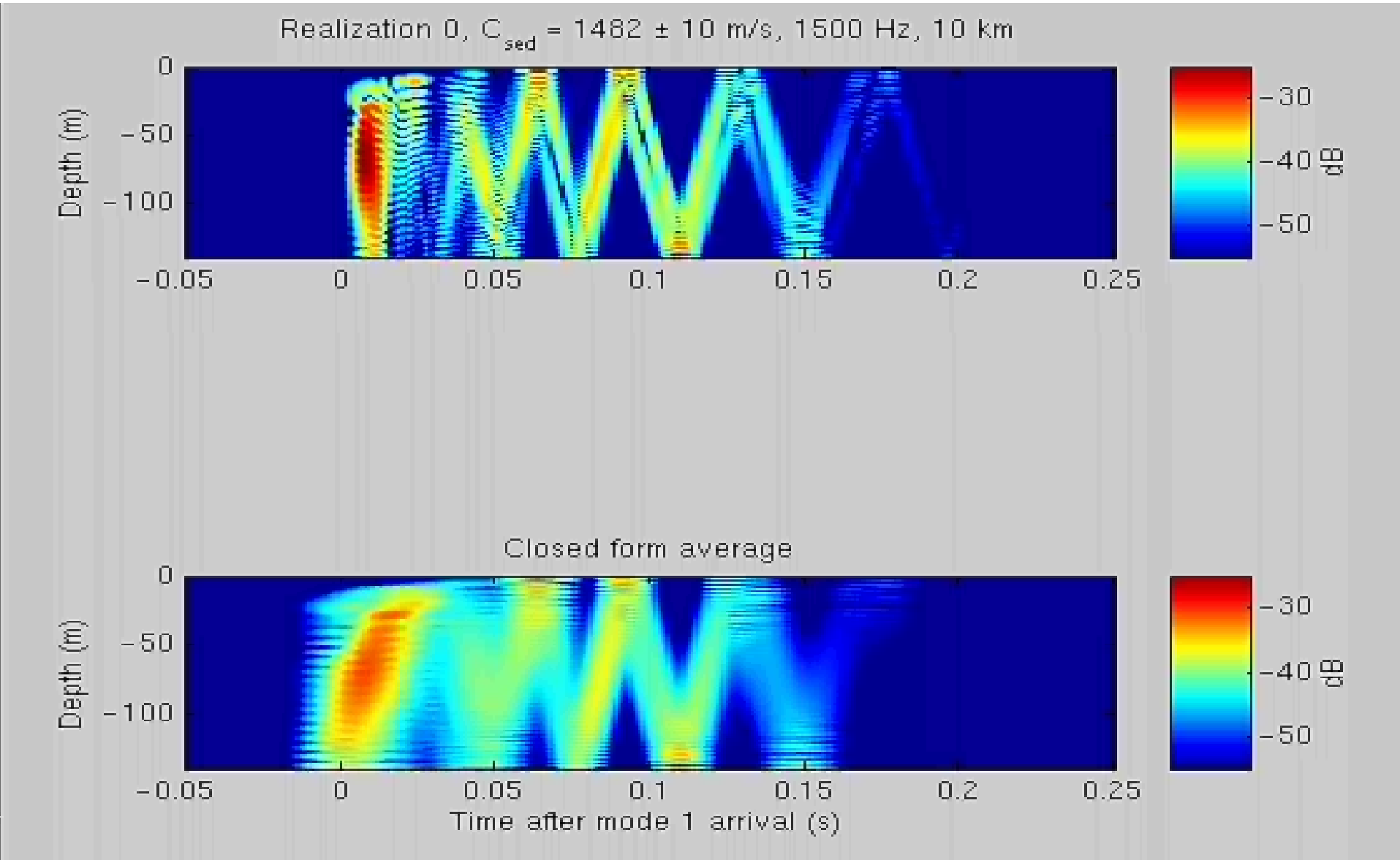
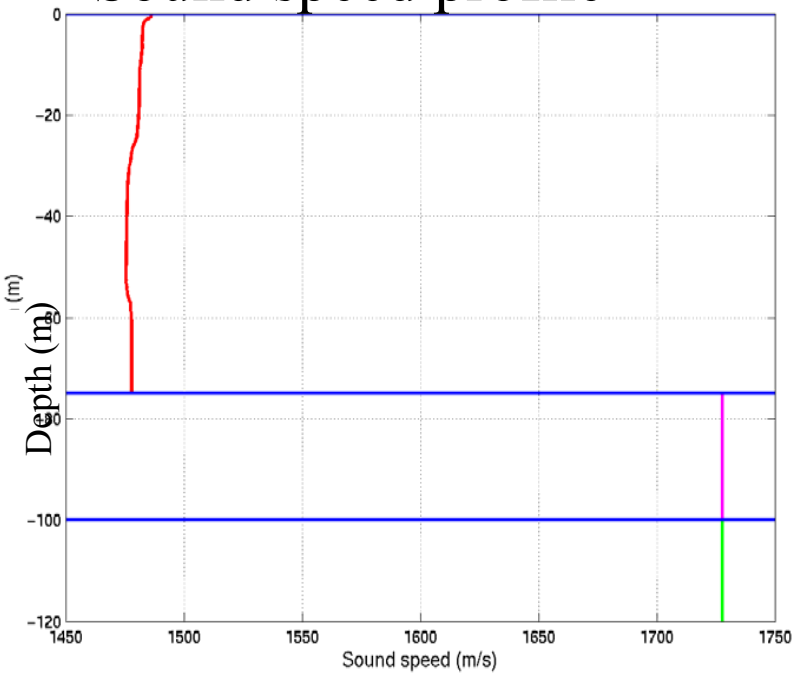
Fluctuations of Intensity for Perturbations in Slow Bottom



Modeling Uncertainty of Prop over NJ Shelf (Goff model)

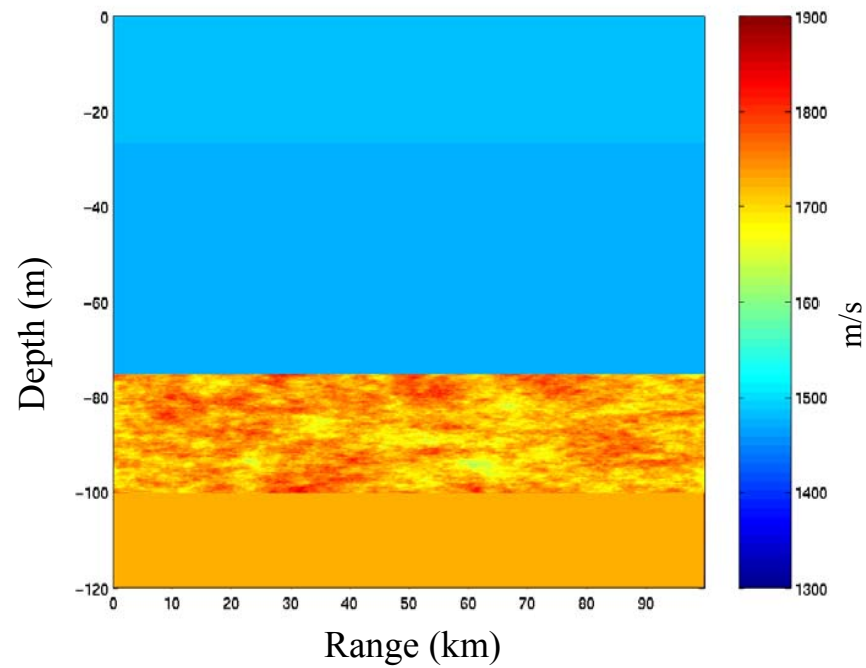
- Sound speed profile



Sound speed (m/s)

  - downward refracting
  - 1728 m/s sand
  - 84 modes @ 1600 Hz

- Bottom realization



  - 30 m/s rms variability
  - $l_x \approx 10$ km
  - $l_y = 5$ m

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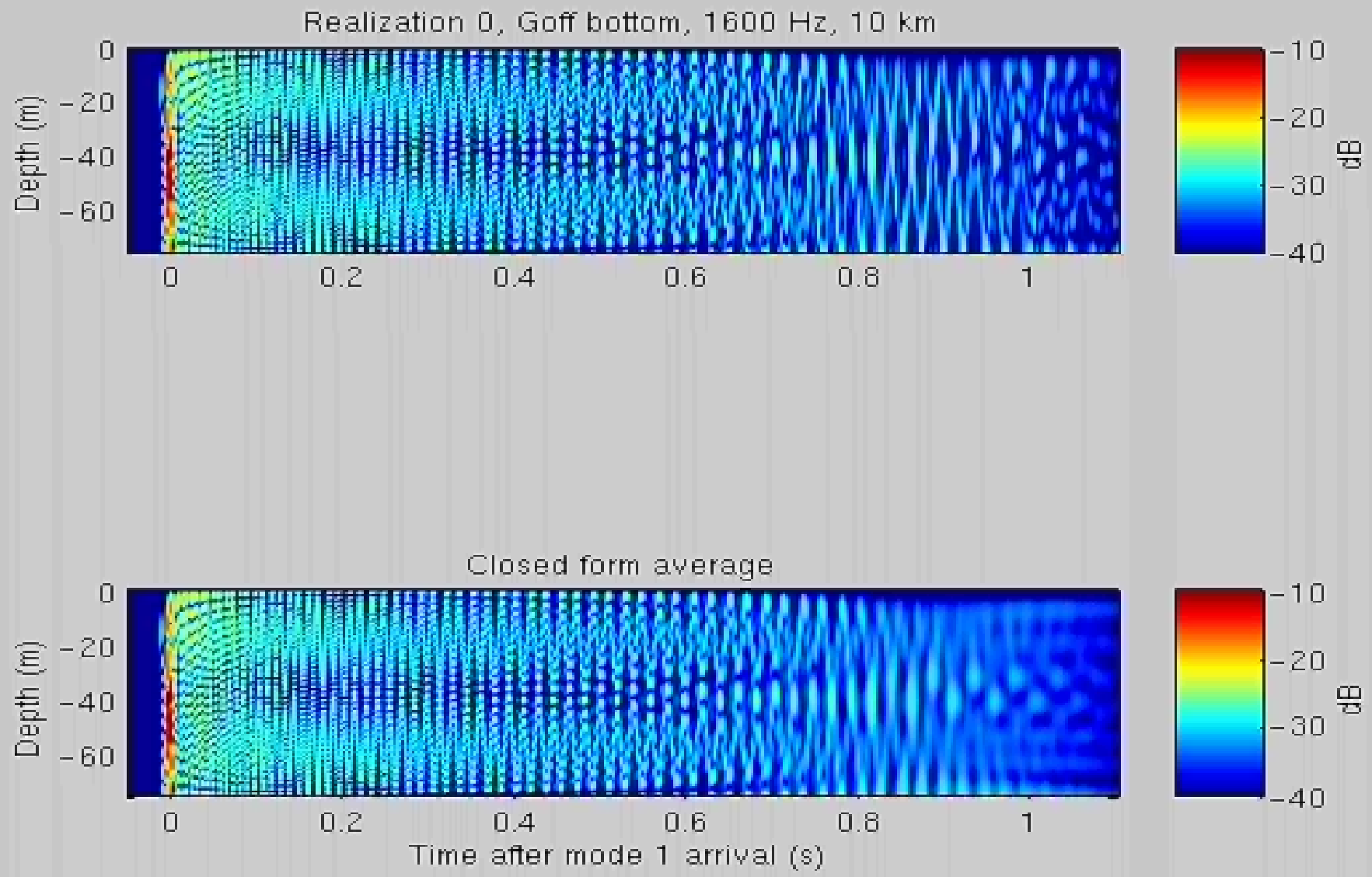
Fluctuations of Intensity for New Jersey Shelf Bottom 1.6 kHz



Summary

<u>Significant Progress in:</u>

- Developing statistical models of geoacoustic variability on NJ shelf
- Developing measures of uncertainty in geoacoustic models/measurements/inversions
- Developing tools for modeling impact of geoacoustic uncertainty on TL/RL/SE

Important Findings

No strong correlation yet observed between Vp and 95 kHz backscatter

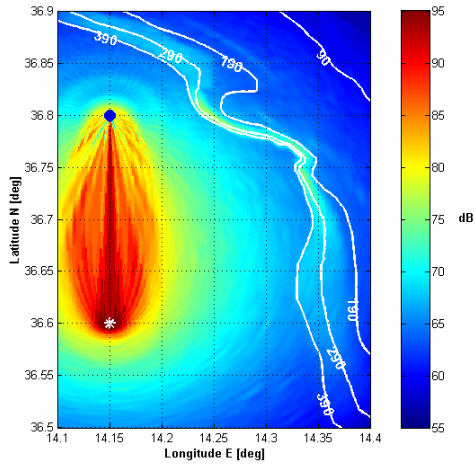
For propagation uncertainty:

- geoacoustic variability affects the latest arrivals ($V_p/V_w>1$)
- geoacoustic variability affects the whole signal ($V_p/V_w<1$);
- oceanographic variability always affects the earliest arrivals

Geoacoustic variability, though large, may be consistent from region to region certain cases and thus enable extrapolation

Seabed Team interim Products

for dissemination



Please contact us for models/data:

Bathymetric uncertainty – Larry Mayer

Statistical bathymetry model NJ shelf - J. Goff

Statistical model of near-surface velocity variability NJ shelf – J. Goff

2D realizations of ρ, β, ϕ,κ NJ shelf & passive margin – J. Syvitski/I. Overeem
http://instaar.colorado.edu/deltaforce/projects/dri.html

2D realizations of V_p, V_s, α_p,α_s, ρ NJ shelf & passive margin – L. Pratson

3D geoacoustic model (lab gen strata) – L. Pratson

Multistatic modeling – Chris Harrison

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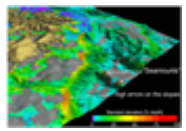
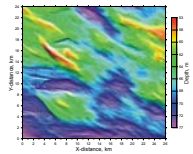
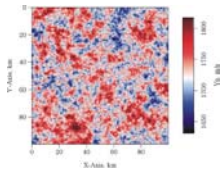


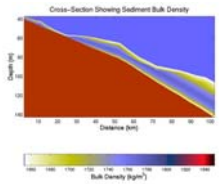
Statistical bathymetry model NJ shelf - J. Goff



Statistical model of near-surface velocity variability NJ shelf – J. Goff



2D realizations of ρ, β, ϕ,κ NJ shelf & passive margin – J. Syvitski/I. Overeem



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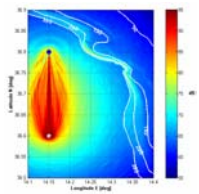

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Seabed Variability Team

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John Goff	Statistical characterization of geoacoustics/morphology	UTIG goff@ig.utexas.edu
Chris Harrison	Multi-static modeling	SACLANTCEN harrison@saclantc.nato.int
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Kevin LePage	Reverberation modeling	SACLANTCEN lepage@saclantc.nato.int
Larry Mayer	Geoacoustic/morphology measurements	U. New Hampshire larry.mayer@unh.edu
Bob Odom	Propagation modeling (forward/inverse)	APL/UW odom@apl.washington.edu
Irina Overeem	Predictive geophysical modeling	INSTAAR, U. Colorado Irina.Overeem@Colorado.EDU
Lincoln Pratson	Predictive geoacoustic modeling; 3D lab strata	Duke U. lincoln.pratson@duke.edu
James Syvitski	Predictive geophysical modeling	INSTAAR, U. Colorado James.Syvitski@Colorado.EDU