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Comparison of horizontal, vertical, and L-array signal processing: Application to shallow water ocean acoustics

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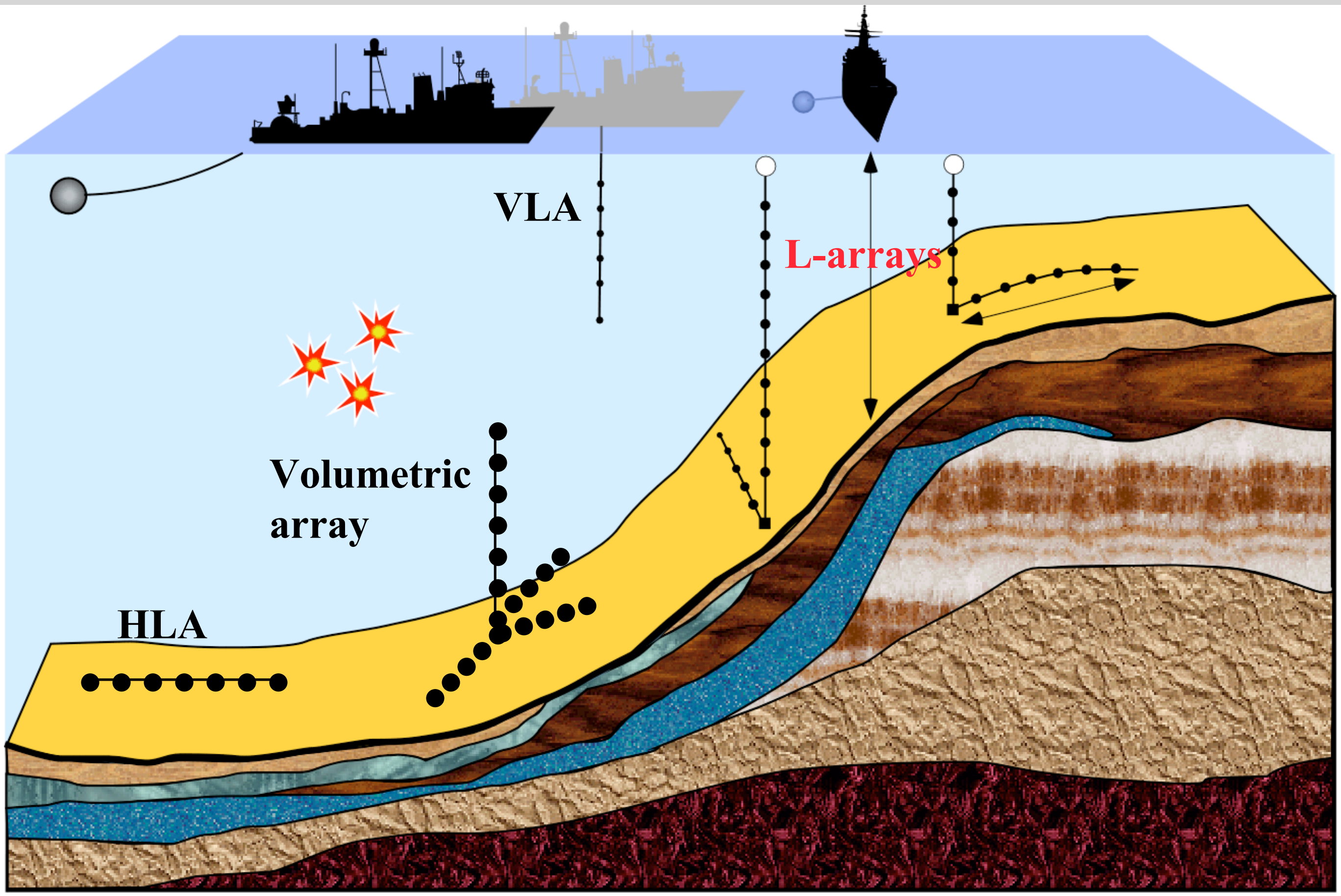
Inference of physical processes and parameter values on continental shelf

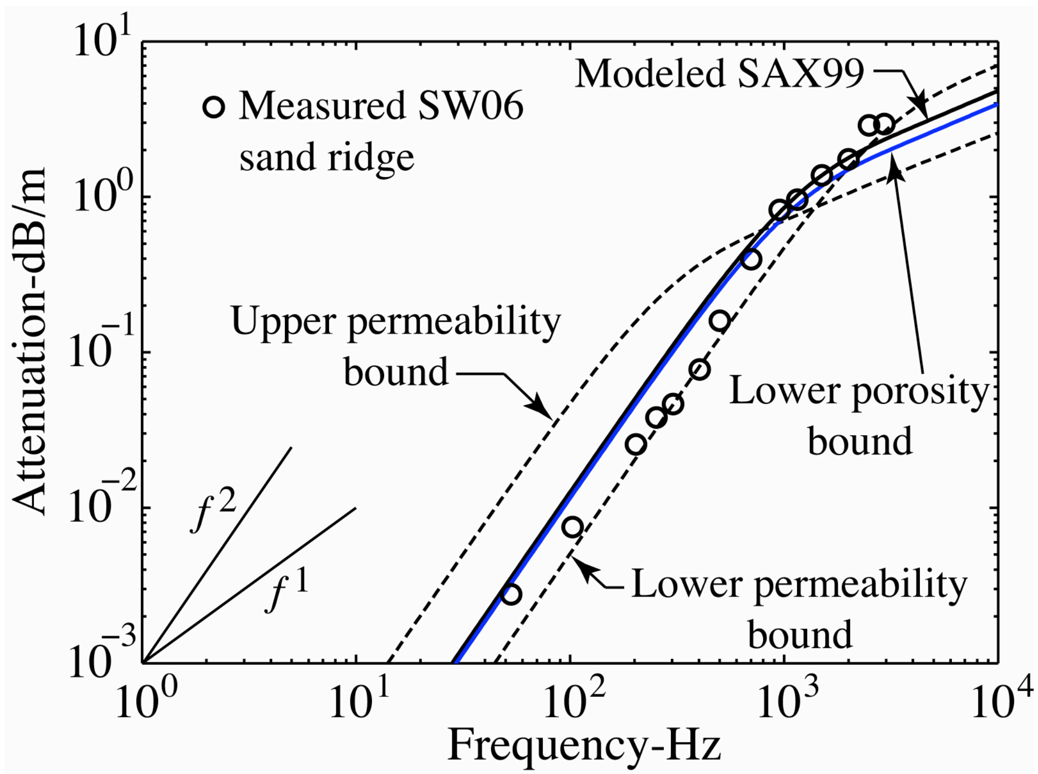
General Question/Issue Addressed: Compared to VLAs and HLAs, what additional **information** about the physical ocean environment can be inferred using 2-D and 3-D arrays?

Discussion today will focus on resolution of L-array relative to HA and VA



Example: sound speed inversions?

If acoustic measurements can **infer information** about the seabed sound speed structure (and dispersion), then long range acoustic data can infer frequency dispersion of attenuation



But, how do we define *infer information*??

Claude Shannon

Edwin Jaynes

Maximum Entropy in a Nutshell

Shannon or Gibbs Entropy

$$S = -\int_{\Omega} dW\, \rho(W|D) \ln [\rho(W|D)/ \rho(W)]$$

$\delta S = 0$ subject to stated constraints

Constraints $\int_{\Omega} dW\, \rho(W|D) = 1 \quad \int_{\Omega} dW\, C(W)\, \rho(W|D) = \langle C \rangle$

$$\rho(W|D) = \frac{\rho(W) \exp(-C(W, D)/T)}{Z}$$

Canonical Distribution

$$Z = \int_{\Omega} dW\, \rho(W) \exp(-C(W, D)/T)$$

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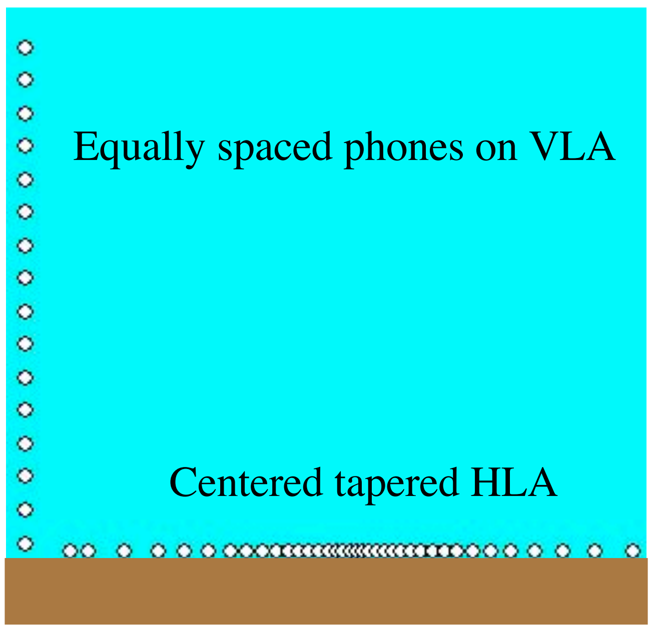
Methodology

- Compare resolution of value of seabed sound speed ratio R_1 inferred from simultaneous signal processing of both HA and VA to separate processing of HA and VA of bottom mounted L-array recordings during Shallow Water 2006 experiment
- σ_{R1} inferred from a MaxEnt approach
  - Coupling versus decoupling of first sediment layer with deeper layers
    - More layers than needed leads to better fits to data but greater uncertainty; compliments Occam's Razor
  - Various values for <C> (how much importance do we attach to global minimum solution?)
  - If resolution with L-array is higher relative to HA only, what portion of VA contributes the most?

L-Array Geometry

52-element L-array deployed during Shallow Water 2006 on New Jersey continental shelf in ~ 70 m of water



Signal Processing

HLA - complex beam spectra
VLA - complex omni spectra

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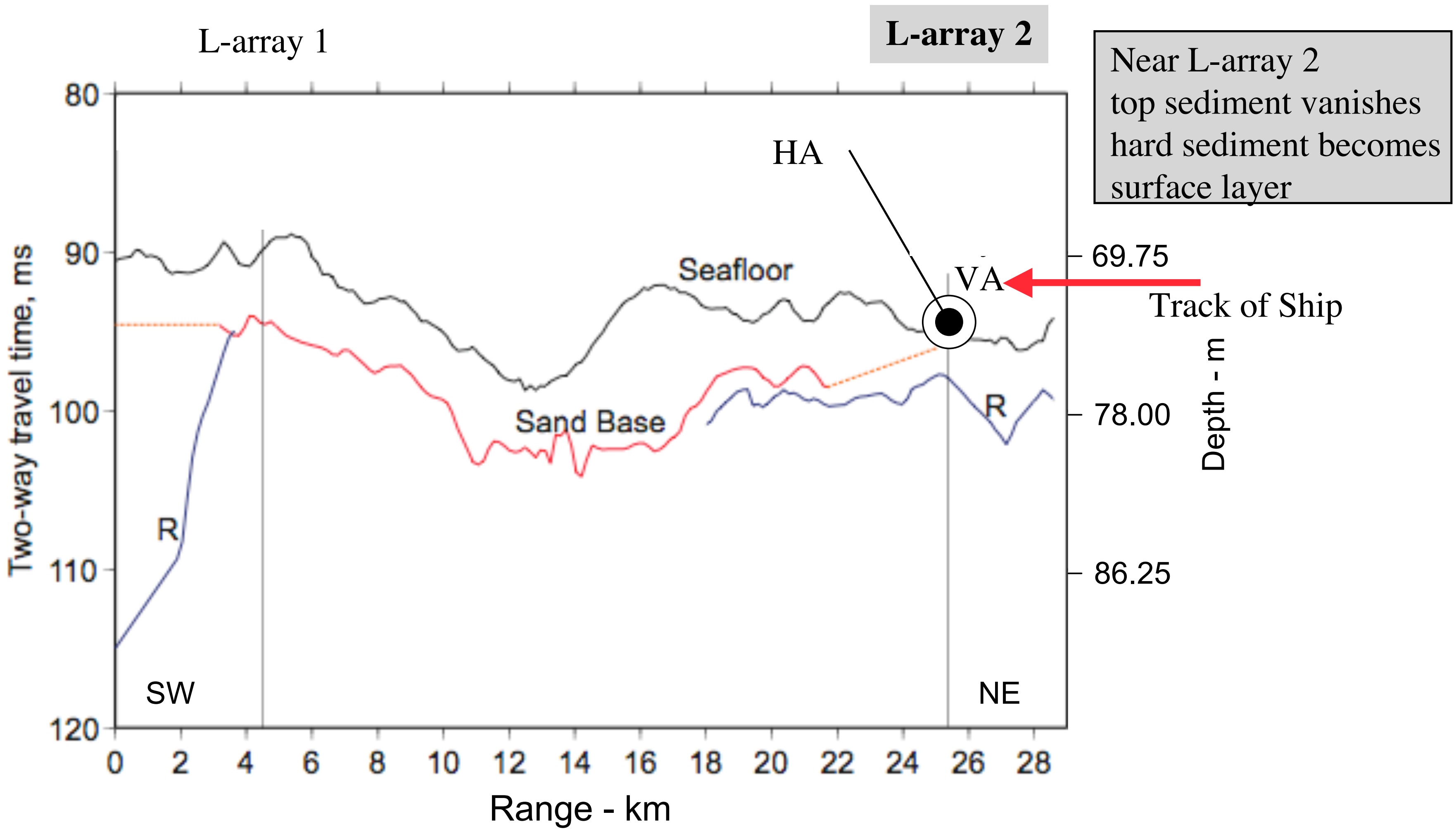
Experimental set up for portion of SW06



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Representation, Assumptions, and Unknowns = 15

RV KNOOR

Uniform motion ~ 4 km track

52-element L-array

f_1=59.8 Hz, f_2=80.6 Hz, f_3= 136 Hz, f_4=150 Hz

SL(f_1), SL(f_2), SL(f_3), SL(f_4)

VA offset

Range at t_0

Bearing at t_0

Speed

Course

Water depth

Single Sound Speed Profile
from measurement (potential
large source of uncertainty)

HA

Upper and lower bounds
of ratio vary between silty sand
and very course sand

Ratio (1)
Thickness (1)

ρ_1 = 1.8 g/cc α_1 = 0.55 dB/m@ 1 kHz ε = 1.8

Ratio (2)
Thickness (2)

ρ_2 = 1.8 g/cc α_2 = 0.15 dB/m@ 1 kHz ε = 1.0

Ratio (substrate)

ρ_2 = 1.9 g/cc α_2 = 0.10 dB/m@ 1 kHz ε = 1.0

Signal Processing

Center Frequency Averaged Source Level

Center Frequency Model Cross Spectrum

$$C = \sum_{\substack{\text{center}\\\text{frequencies}}} \frac{\sum_{\substack{\text{element pairs,}\\\text{sequences}}} \left| \langle D_i D_j^* \rangle - |S_f| M_i^* M_j \right|^2}{N_{CEN} \sum_{\substack{\text{element pairs,}\\\text{sequences}}} \left| \langle D_i D_j^* \rangle \right|^2}$$

Center Frequency Averaged Cross–Spectral Data

$$\langle D_i D_j^* \rangle = |D_{RL}|^2 \sum_{\text{bins}} D_i D_j^* / |D_{REF}|^2$$

Cross Spectrum Normalization for Center Frequency Averaging

$$|D_{REF}|^2 = N_{BINS} \sum_{\text{elts}} |D_i|^2 / N_{ELTS}$$

Cross Spectrum Normalization for Center Frequency Average RL

$$|D_{RL}|^2 = \sum_{\text{bins,elts}} |D_i|^2 / (N_{ELTS} N_{BINS})$$

Minimization of Cost Gives SLs

$$|S_f| = \frac{\sum_{\substack{\text{element pairs,}\\\text{sequences}}} \langle D_i D_j^* \rangle M_i^* M_j + \text{C.C.}}{2 \sum_{\substack{\text{element pairs,}\\\text{sequences}}} |M_i^* M_j|^2}$$

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Signal Processing (cont)

Substituting for $|s_f|$ gives correlation form of cost function: $0 \leq C \leq 1$

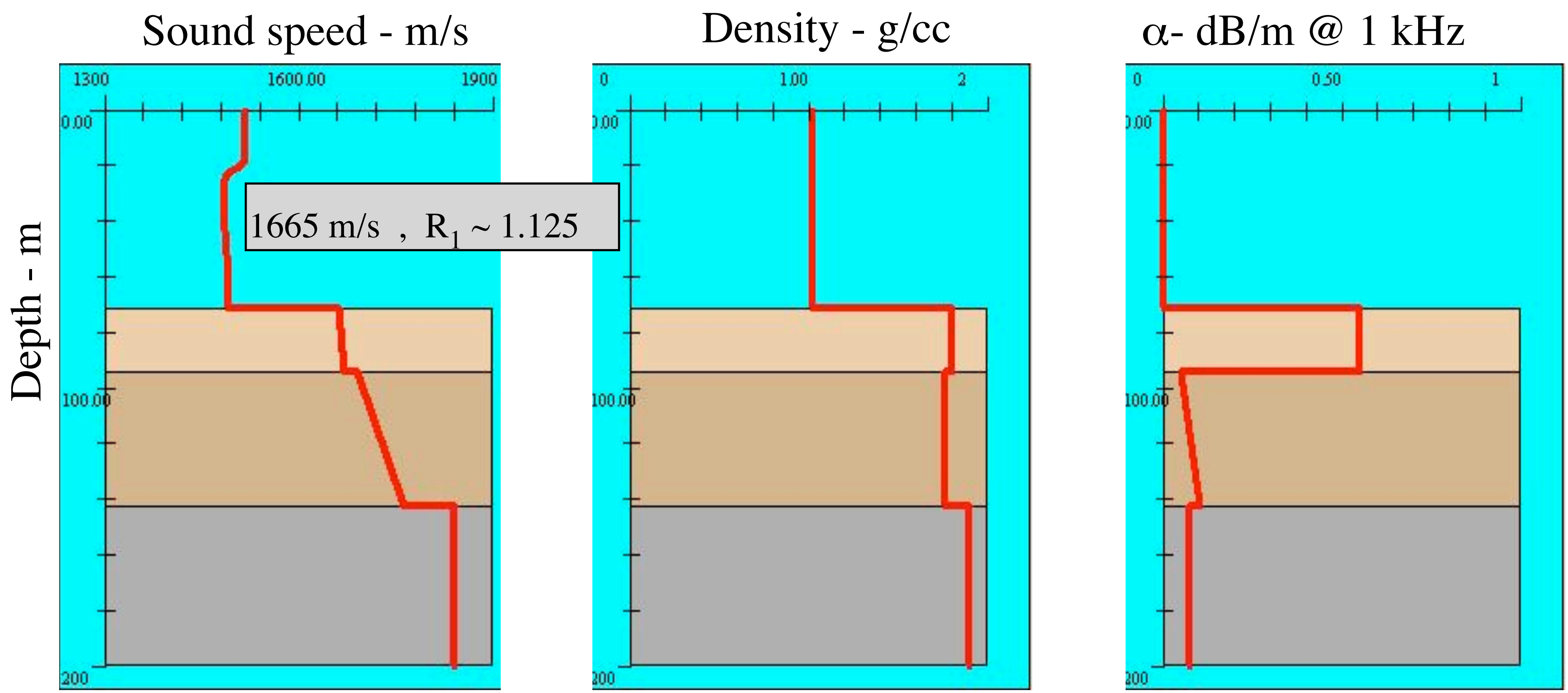
incoherent sum over center frequency

coherent sum over pairs and sequences

$$C = 1 - \sum_{\substack{\text{center}\\ \text{frequencies}}} \frac{\left| \displaystyle\sum_{\substack{\text{element pairs,}\\ \text{sequences}}} \frac{\langle D_i D_j^* \rangle M_i^* M_j + \text{C.C.}}{2} \right|^2}{N_{CEN} \displaystyle\sum_{\substack{\text{element pairs,}\\ \text{sequences}}} \left| \langle D_i D_j^* \rangle \right|^2 \sum_{\substack{\text{element pairs,}\\ \text{sequences}}} \left| M_i^* M_j \right|^2}$$

Includes gain in the coherent sum over pairs and sequences to fit multipath arrivals and source track dependence.
Includes amplitude information to fit TL shape.

Maximum likelihood seabed structure



Atten (dB/m) = $(f/1000)^{1.8}$

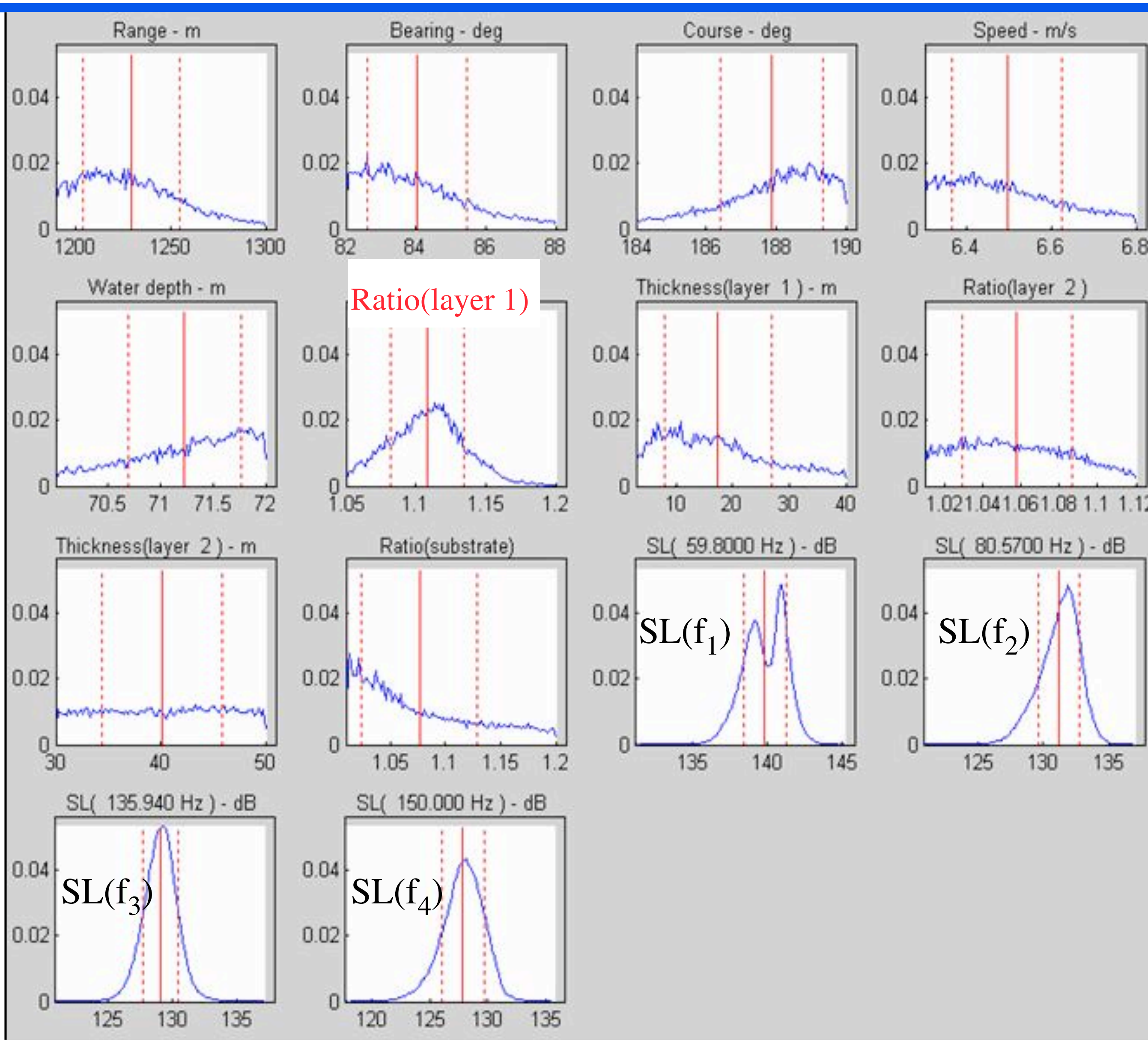
with f in Hz

Uncertainty arises from small fluctuations about average seabed structure

HA only 3 m sediment lower limit, n=1

$2\sigma_{R1} = 0.053$

~ (1637-1715 m/s)



$\langle C \rangle = 1/2(C_{min} + \overline{C}_u)$

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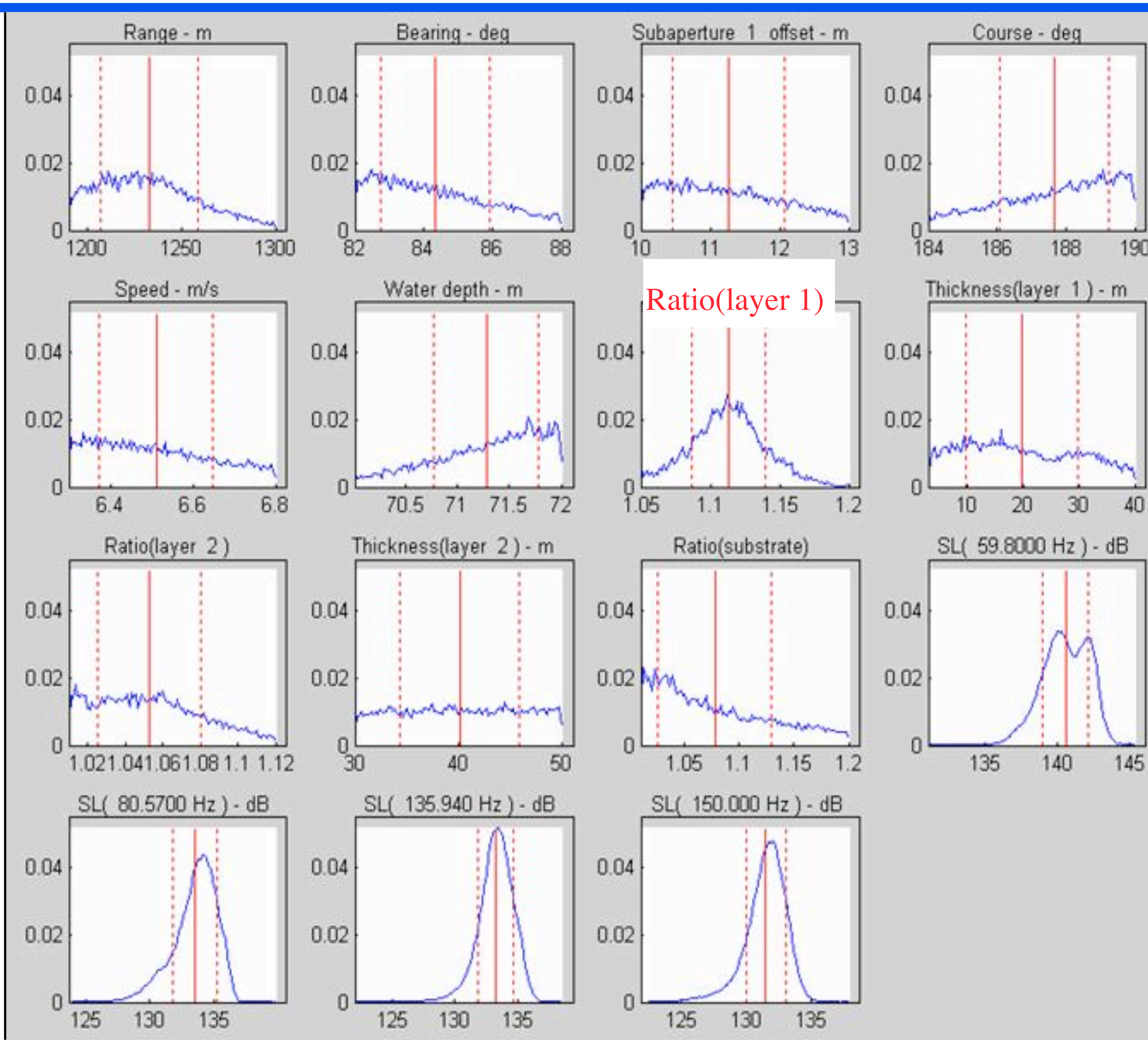
VA only 3 m sediment lower limit, n=1



$2\sigma_{R1} = 0.054$

~ (1637-1715 m/s)

Note that

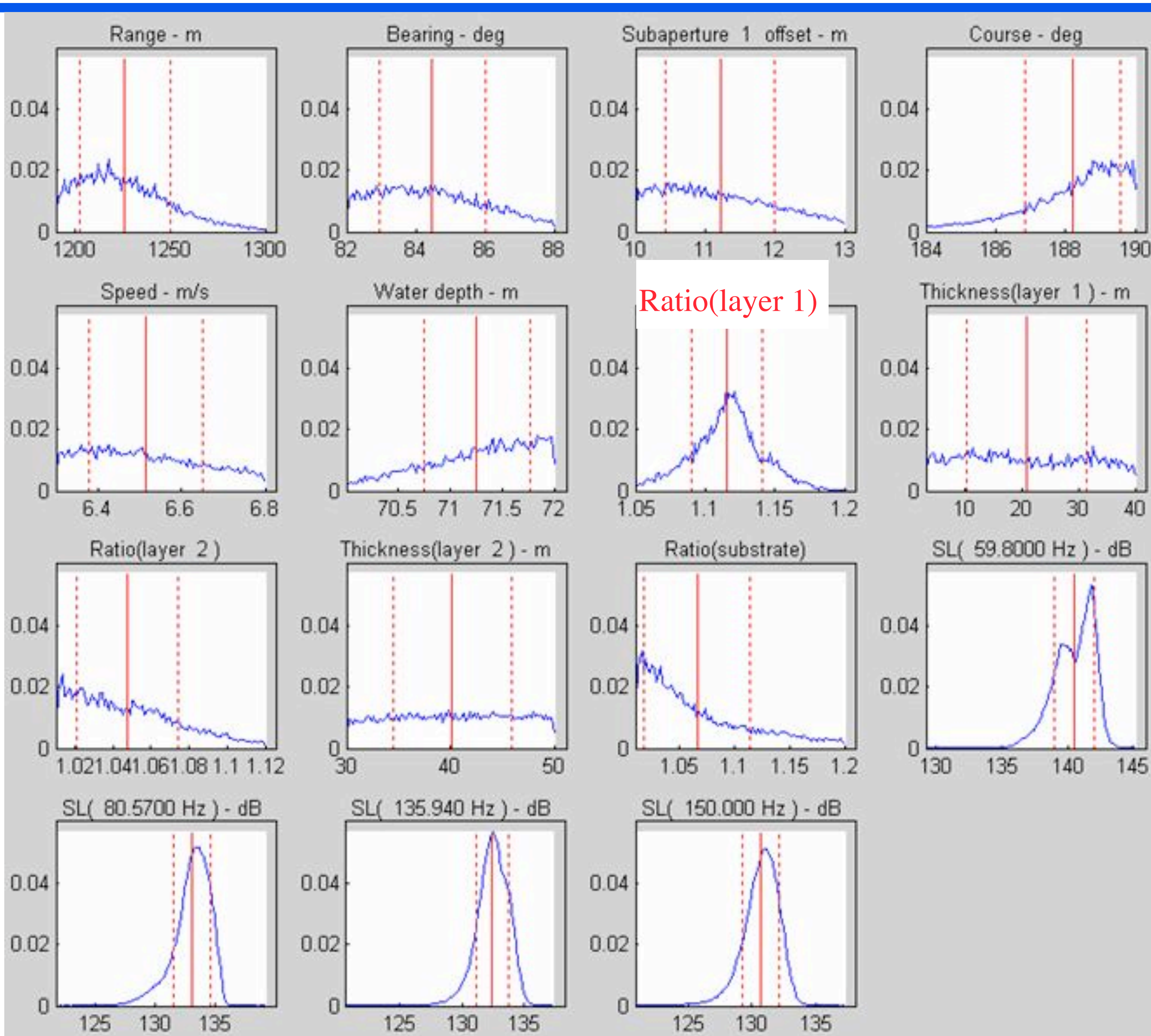
$\langle R1 \rangle$ and $2\sigma_{R1}$

remain

approximately

unchanged

L-Array only 3 m sediment lower limit, n=1



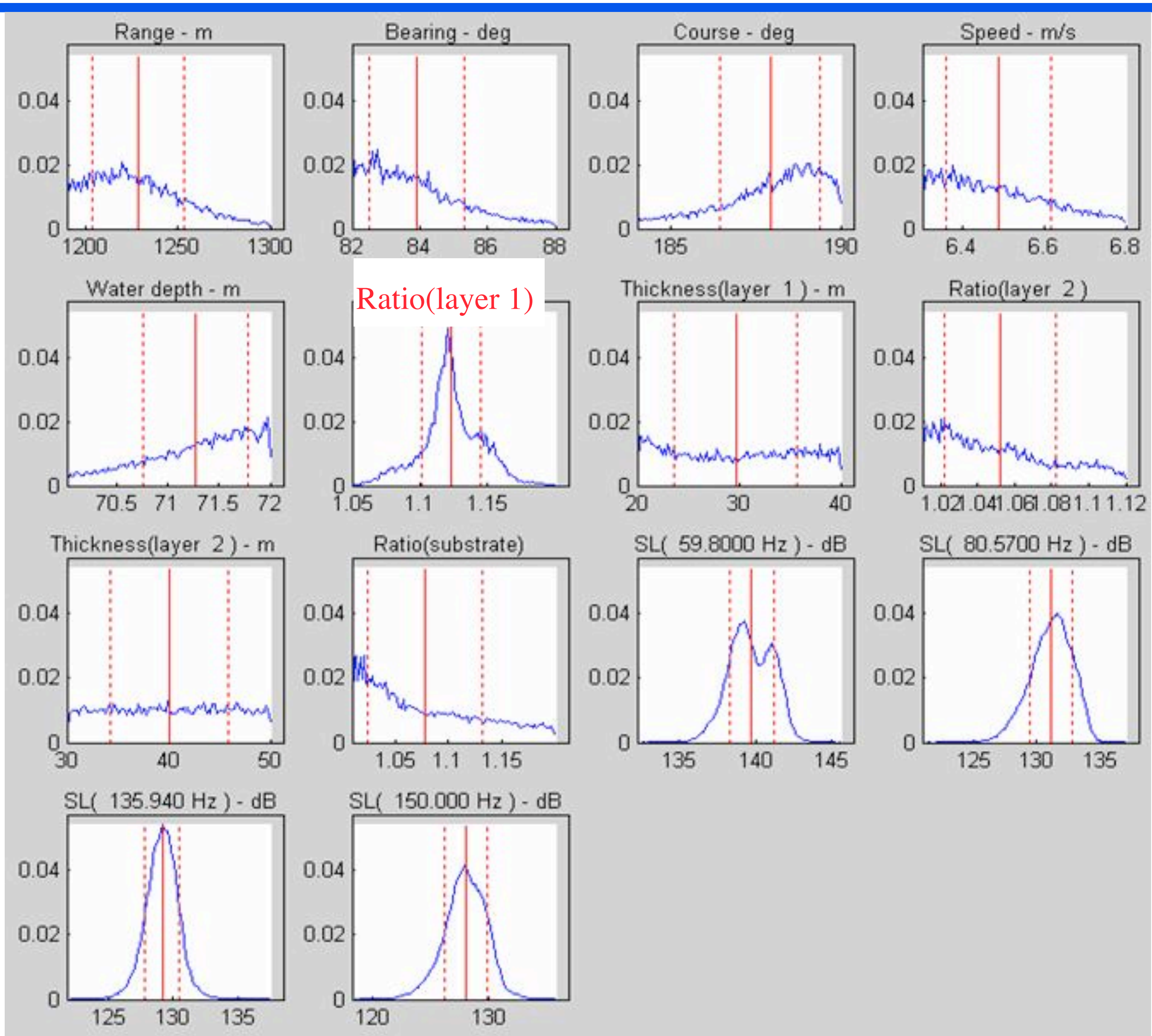
$2\sigma_{R1} = 0.050$

~ (1628-1702 m/s)

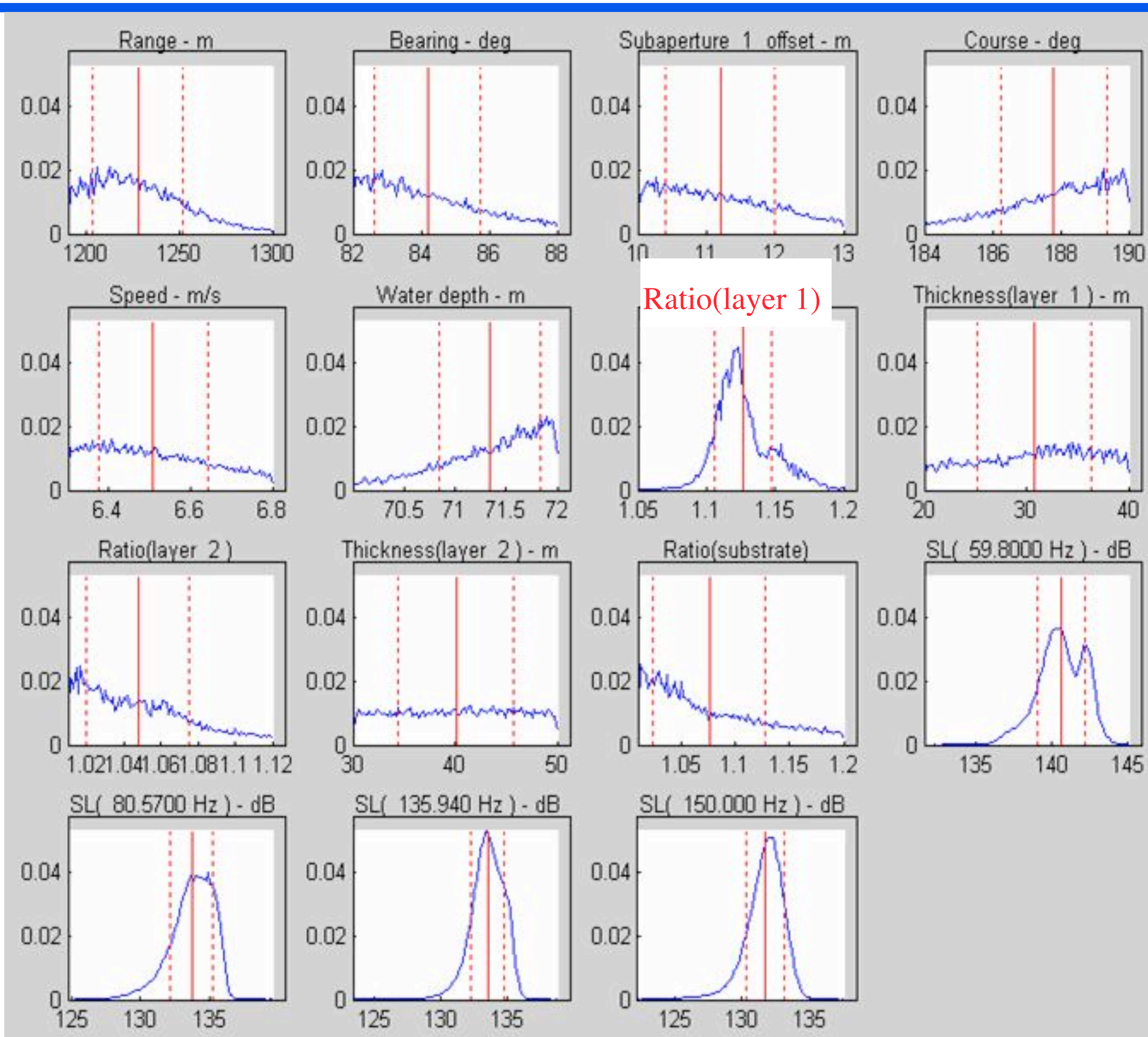
HA only 20 m sediment lower limit, n=1

$2\sigma_{R1} = 0.045$

~ (1632-1698 m/s)



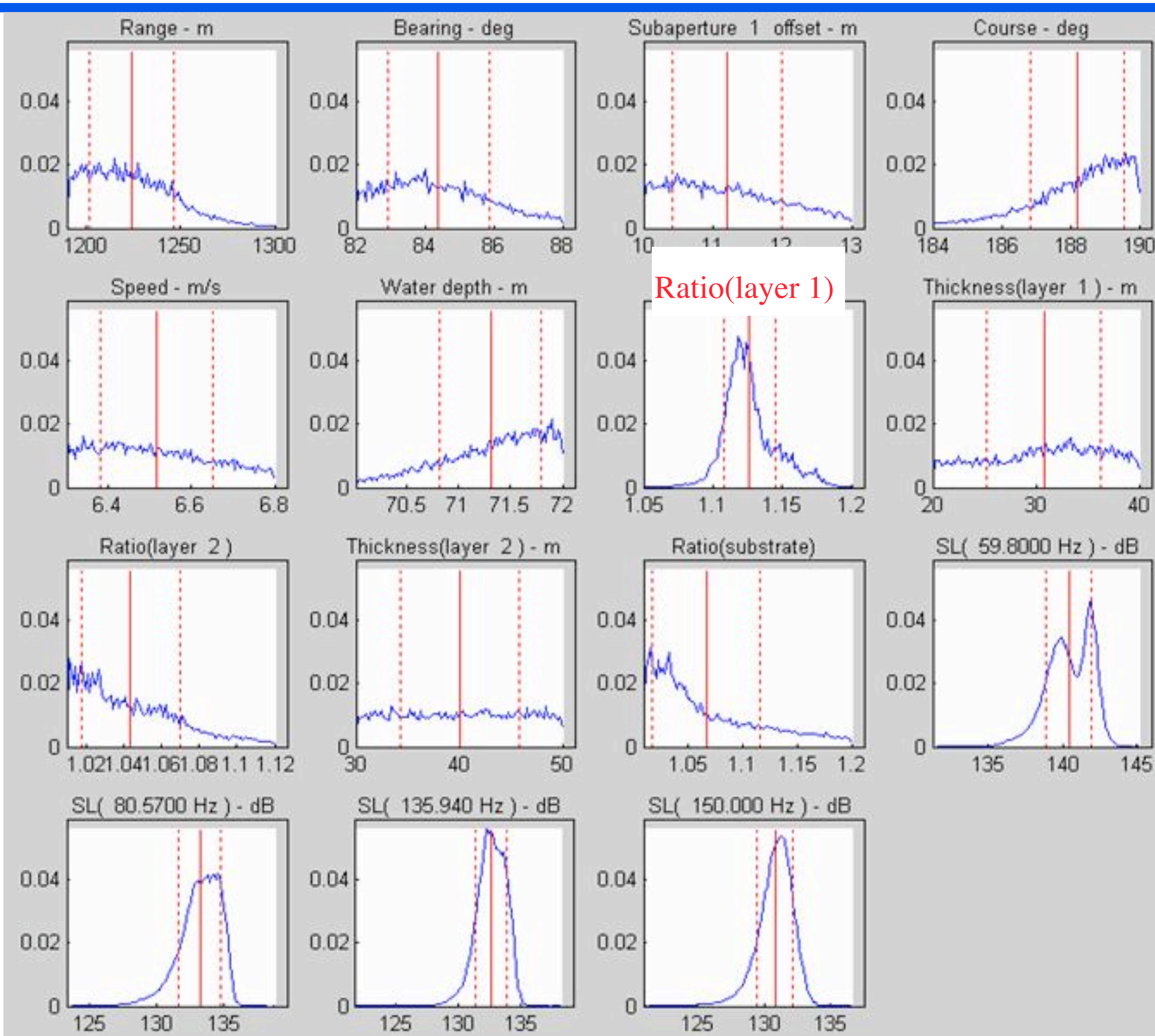
VA only 20 m sediment lower limit, n=1



$2\sigma_{R1} = 0.041$

~ (1635-1695 m/s)

L-Array only 20 m sediment lower limit, n=1



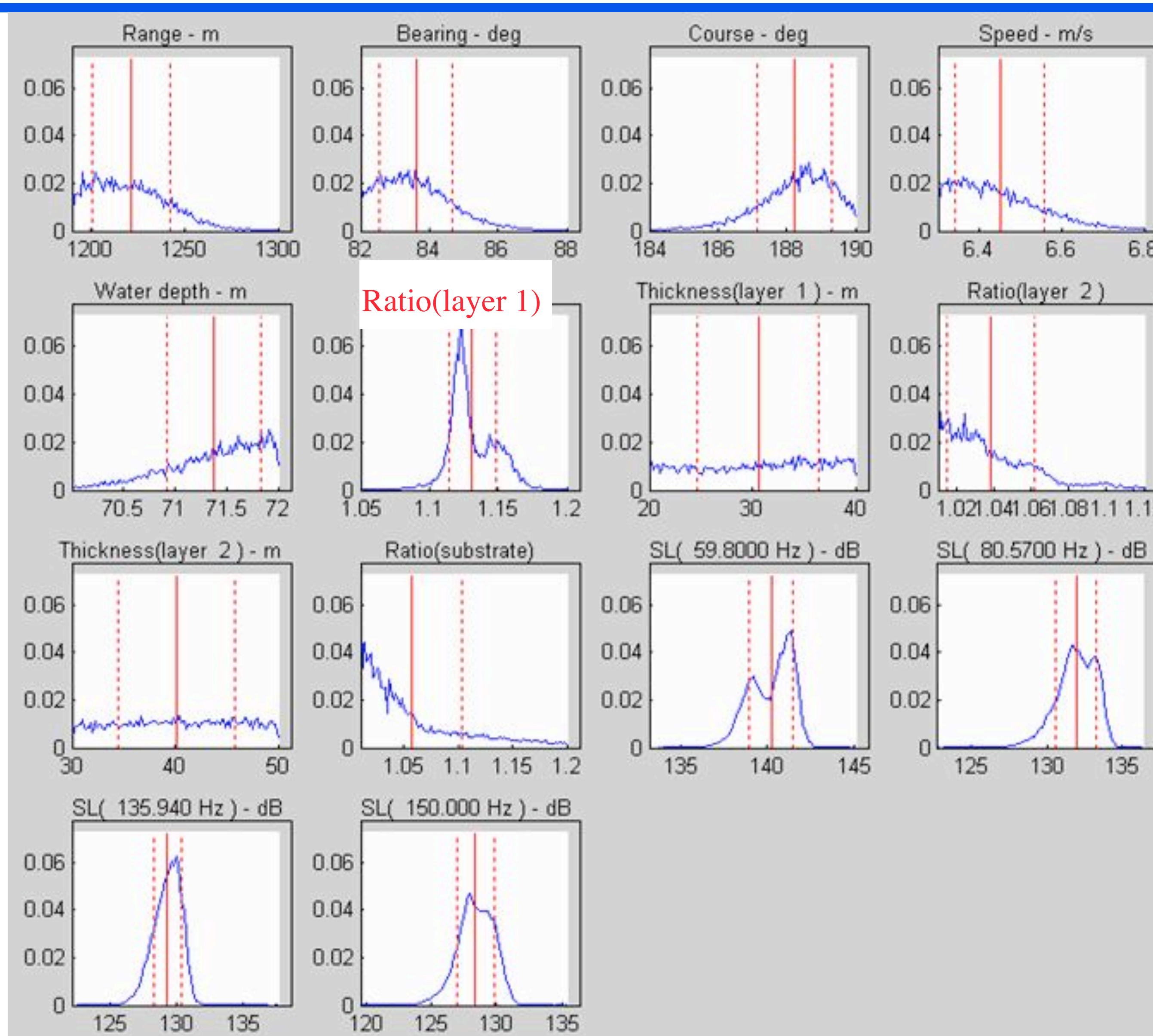
$2\sigma_{R1} = 0.039$

~ (1636-1694 m/s)

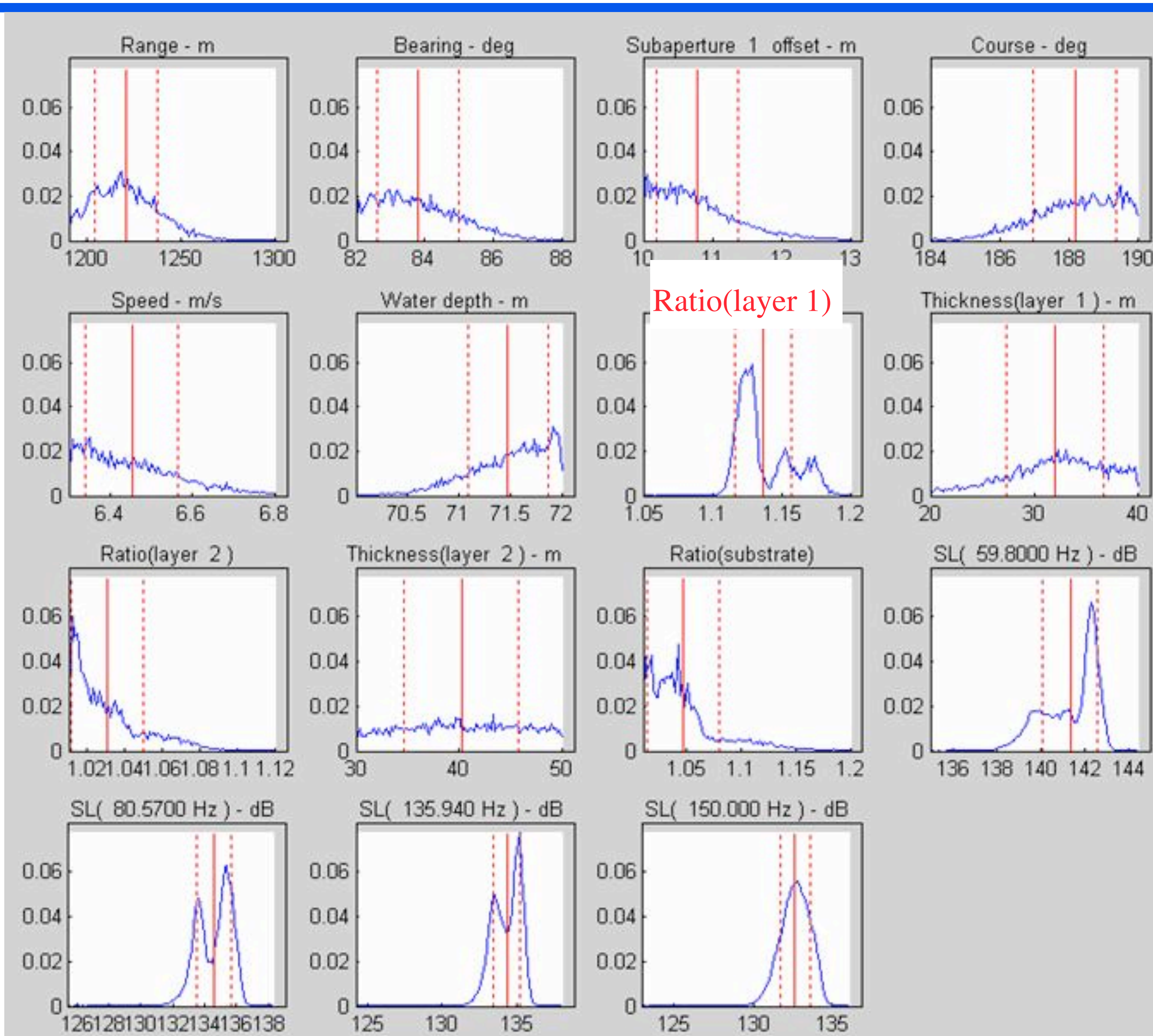
HA only 20 m sediment lower limit, n=.9

$2\sigma_{R1} = 0.034$

~ (1640-1691 m/s)



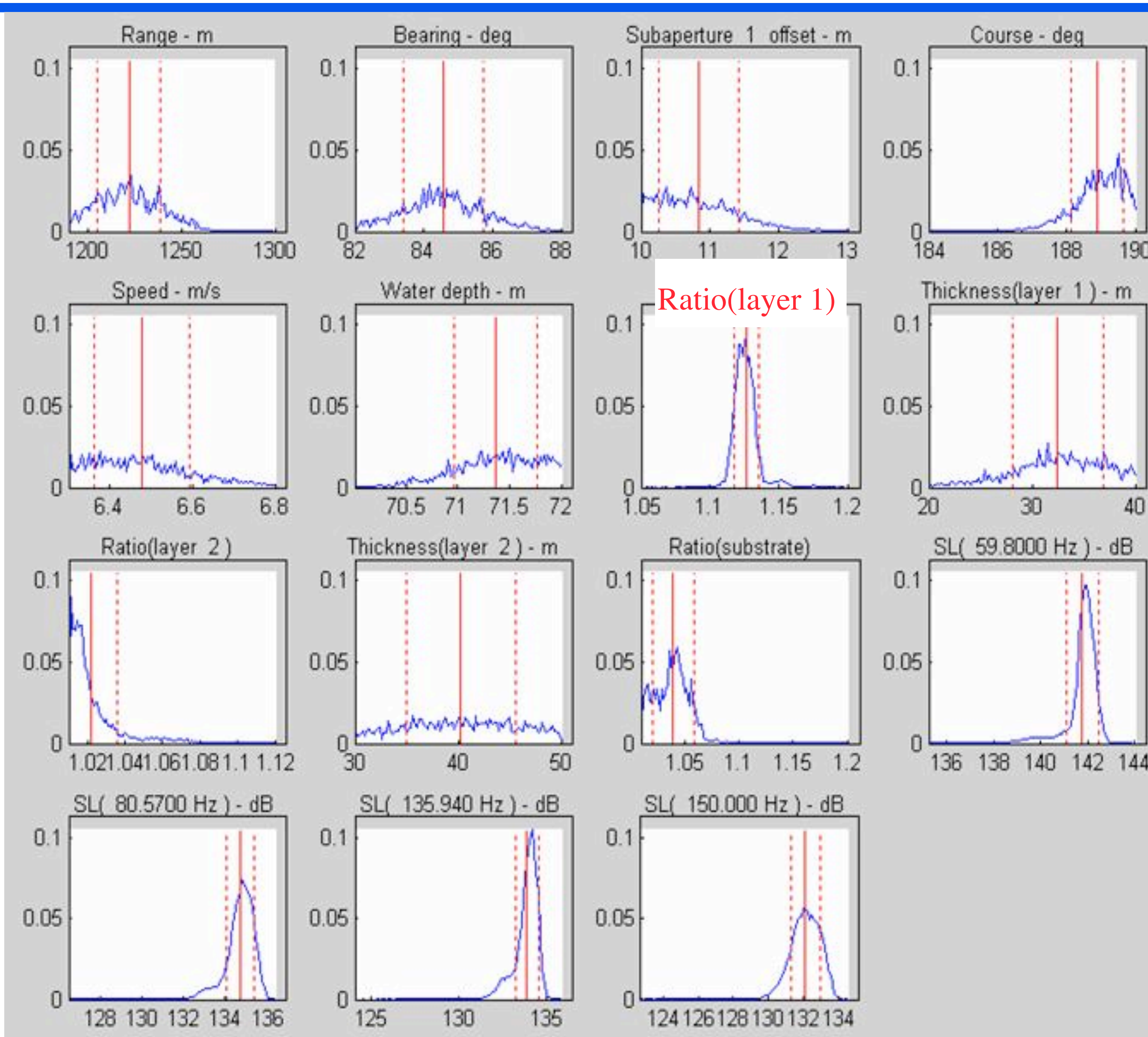
VA only 20 m sediment lower limit, n=.9



$2\sigma_{R1} = 0.040$

~ (1635-1695 m/s)

L-Array only 20 m sediment lower limit, n=.9



$2\sigma_{R1} = 0.028$

~ (1644-1686 m/s)

Summary of ratio resolution with L-array for Ship of Opportunity Data in SW06

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Resolution of sound speed ratio 2 σ

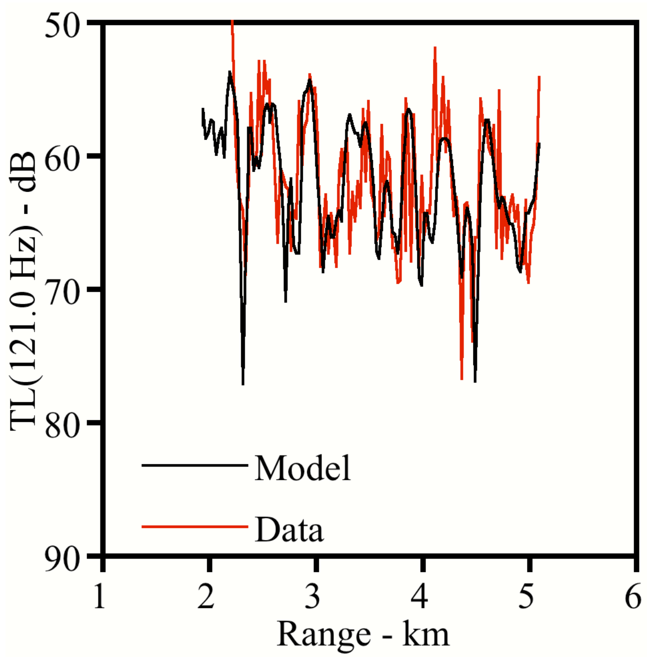
Signal processing and lower bound on sediment thickness	HL processing only	VL processing only	HL+VL processing
3-m lower limit of 1st sediment layer 2 HL subapertures, n=1	0.053	0.054	0.050
20-m lower limit of 1st sediment layer 2 HL subapertures, n=1	0.045	0.048	0.039
20-m lower limit of 1st sediment layer 4 HL subapertures, n=1	0.048	0.048	0.040
3-m lower limit of 1st sediment layer 2 HL subapertures, n=0.9	0.052	0.057	0.040
20-m lower limit of 1st sediment layer 2 HL subapertures, n=0.9	0.034	0.040	0.028

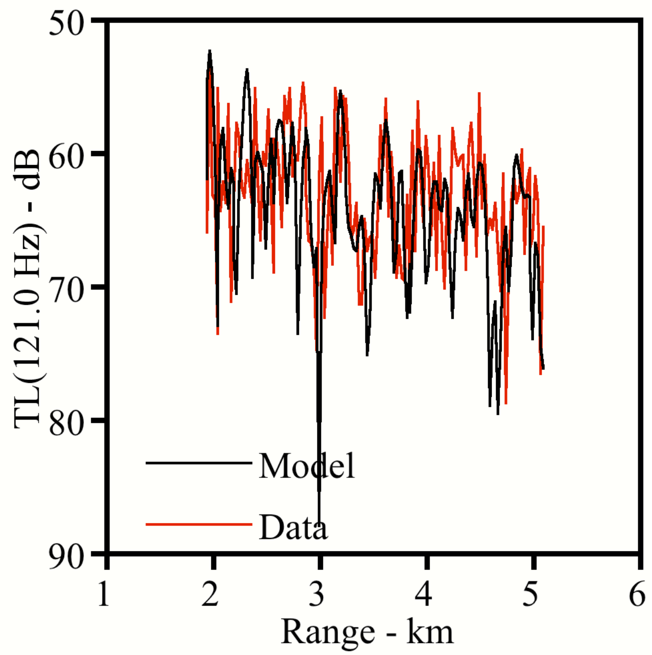
In all cases resolution increased using L-array

Summary

- Current work
  - Quantified **increase in resolution** of sound speed ratio of seabed by doing simultaneous processing in vertical and horizontal dimension
  - Increase in resolution depends on assumptions
    - Representation of seabed
    - Proximity of importance sampling near global minimum; <C>
- Future and ongoing work
  - Estimation of <C>
  - New estimates of sound speed and attenuation dispersion and uncertainty from SW06
  - Apply to range-dependent cases
  - Design of future arrays (3-D) and experiments

Phones 1 and 10





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Phones 14 and H