Signal Processing for Underwater and Structural Acoustics

CARGESE, September 2019

W. A. Kuperman
MPL, Scripps Institution of Oceanography
University of California, San Diego
wkuperman@ucsd.edu

COMMON PERCEPTIONS (Underwater Acoustics)

- ROBUST ACOUSTICS (MODELING ALWAYS WORKS)
- PASSIVE ACOUSTICS (MATCHED FIELD PROCESSING WORKS)
- VERY LOW SNR SIGNAL PROCESSING CAN BE ATTAINED WITH ”EXOTIC” METHODS
- NOISE IS A NUISSANCE TO BE OVERCOME
- FLUCTUATIONS LIMITS SIGNAL PROCESSING

MY MOTIVATION

- ROBUST ACOUSTICS (MODELING ALWAYS WORKS)

  -AS LONG AS YOU DON'T COMPARE MODEL WITH DATA
- PASSIVE ACOUSTICS (MATCHED FIELD PROCESSING WORKS)- NOT REALLY, – **THE CHALLENGE**
- *VERY LOW SNR SIGNAL PROCESSING* -USUALLY NEVER WORKS -LATEST STUFF BREAKS DOWN AT SAME SNR AS CLASSICAL STUFF – **THE CHALLENGE**
- NOISE A NUISSANCE TO BE OVERCOME – CAN BE USED TO IMAGE OCEAN ENVIRONMENT AND STRUCTURES
- FLUCTUATIONS LIMITS SIGNAL PROCESSING -- BUT MAY BE USABLE - **THE CHALLENGE**

OUTLINE

- **WHAT DOES SIGNAL PROCESSING GIVE YOU?**
- **(Some) UNDERWATER ACOUSTICS (UA)**
- **PASSIVE vs ACTIVE SIGNAL PROCESSING**
- **TYPES OF NOISE in UA**
- **RADIATING TARGETS**
- **AMBIENT NOISE “IMAGING"**
- **SCATTEERING , STRUCTURAL ACOUSTICS and RANDOM ENSONIFATION**

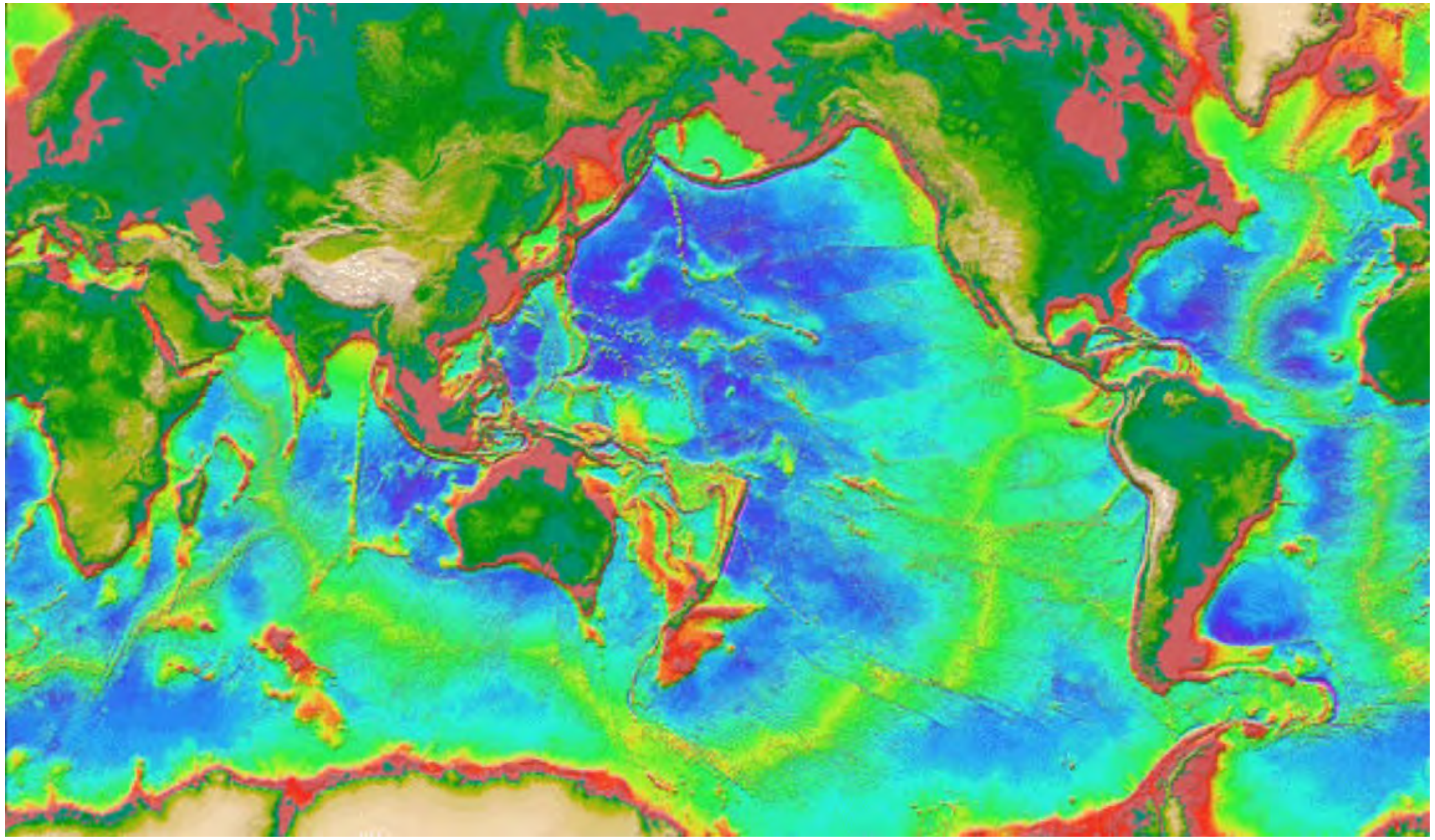
Signal Processing Outcomes

- Information about "target" **[DCLT]**
  - **D**etection
  - **C**lassification
  - **L**ocalization
  - **T**racking

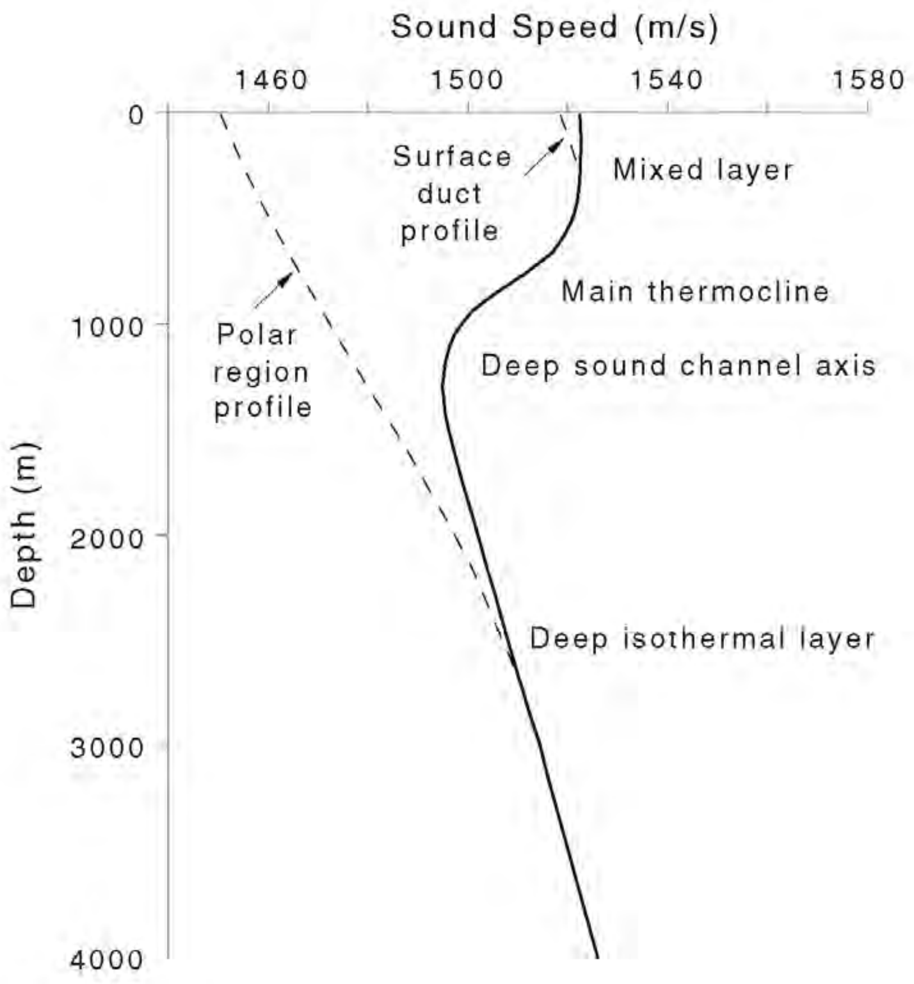
  MOST CRITICAL ISSUE: **LOW SNR**

- Information about medium/object
  - Medium properties [Tomography, Structural Health Monitoring…]

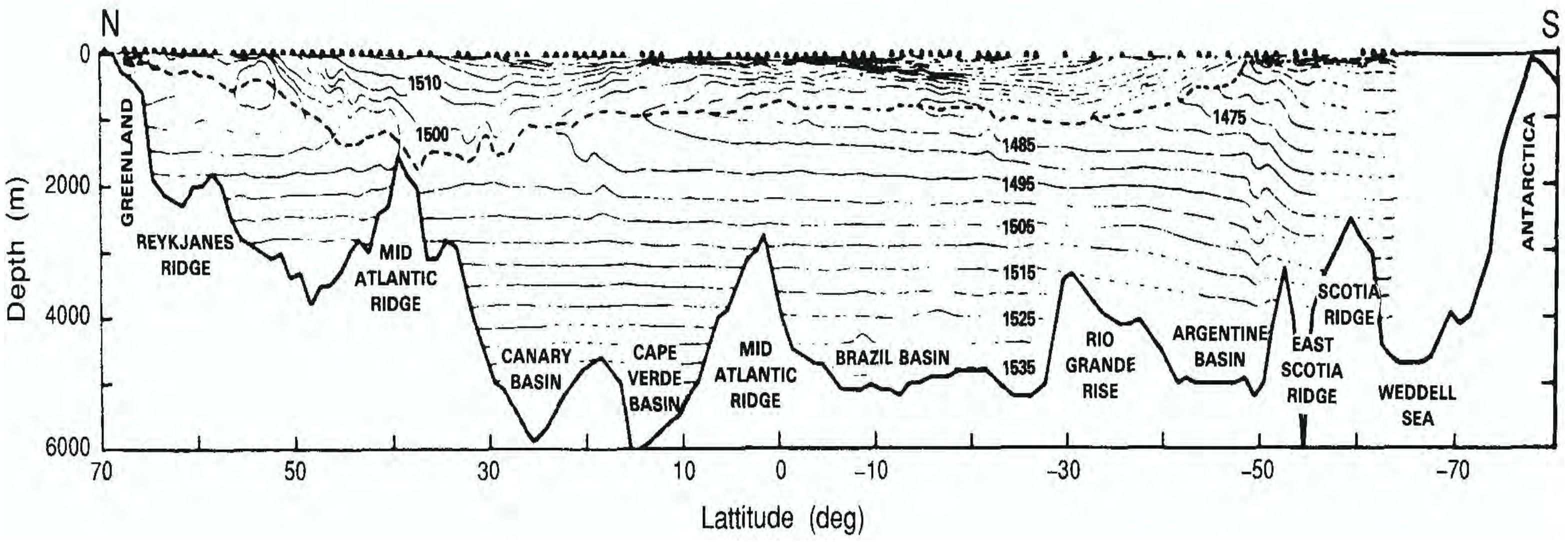
ACOUSTICS IN THE OCEAN



GENERIC SOUND SPEED STRUCTURE



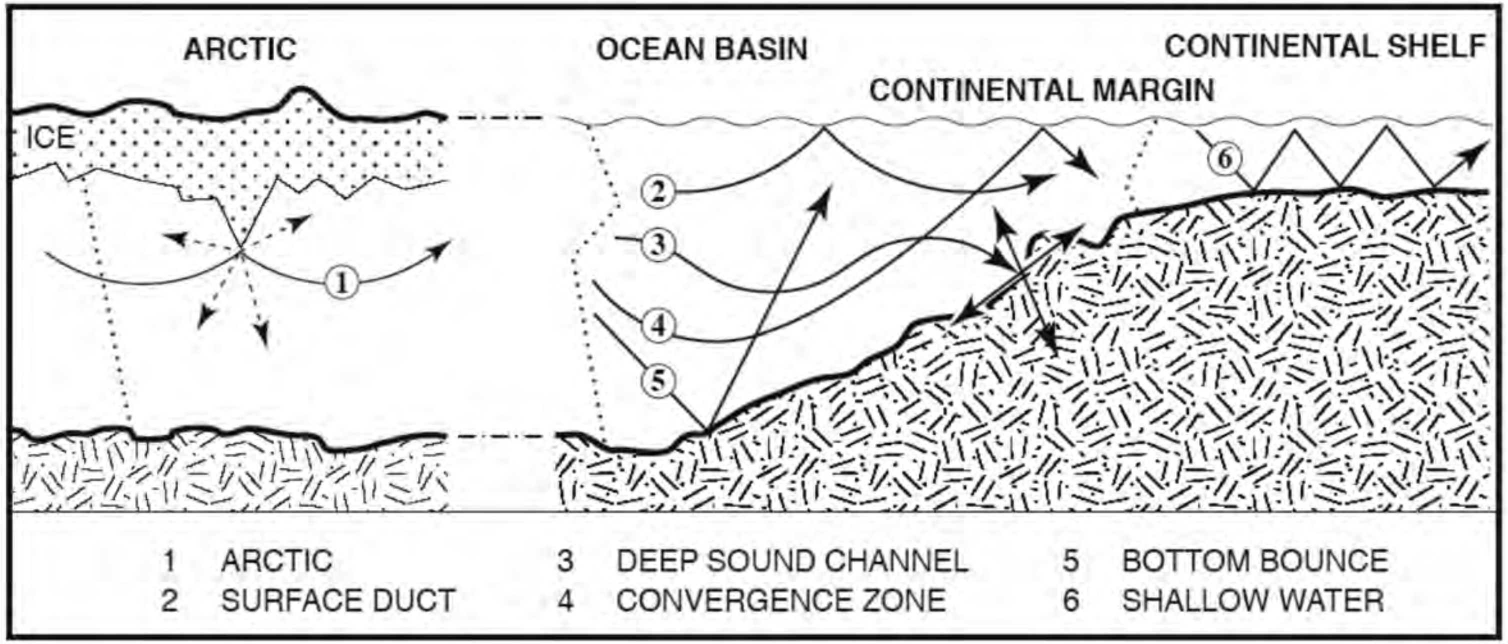
GLOBAL SOUND SPEED STRUCTURE



SNELL'S LAW:

SOUND LIKES LOW SPEEDS

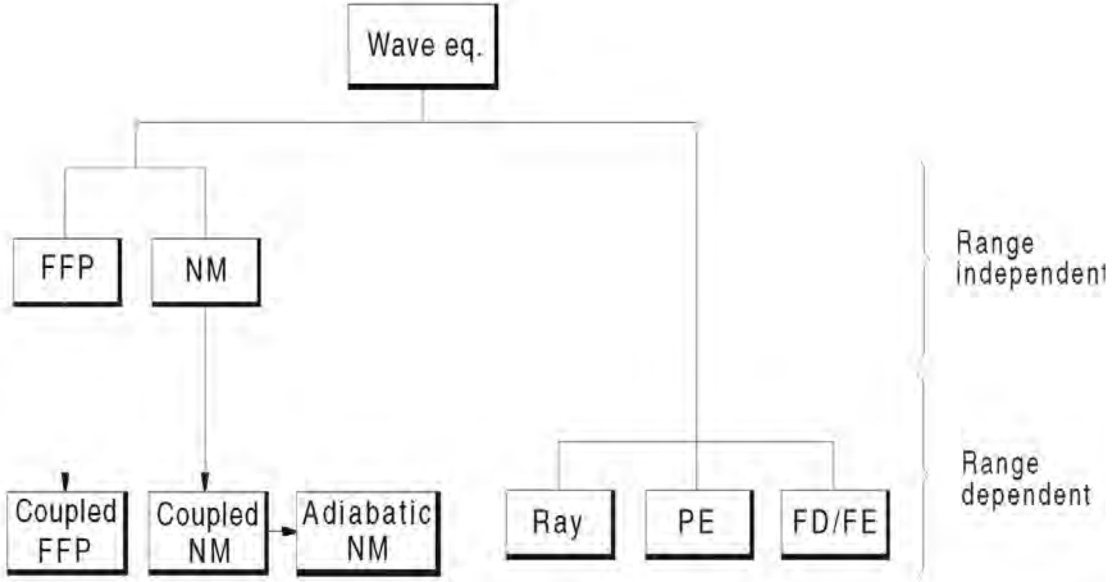
SCHEMATIC OF SOUND PROPAGATION PATHS



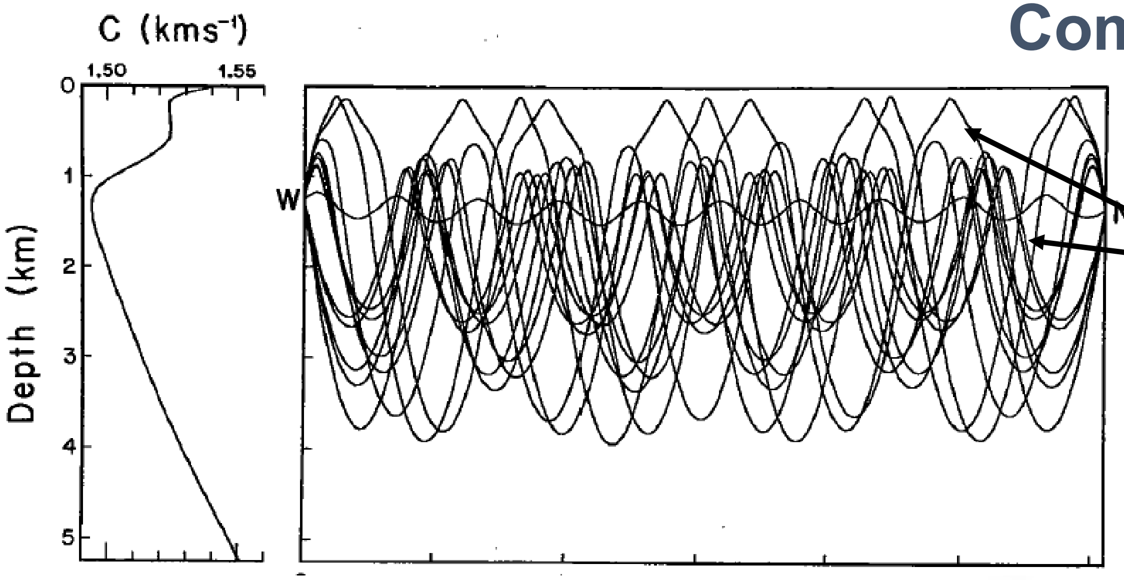
HIERARCHY OF UNDERWATER ACOUSTIC MODELS

Background Theory is in:
Jensen et al: ***Computational Acoustics***

Online Models: https://**oalib**-acoustics.org

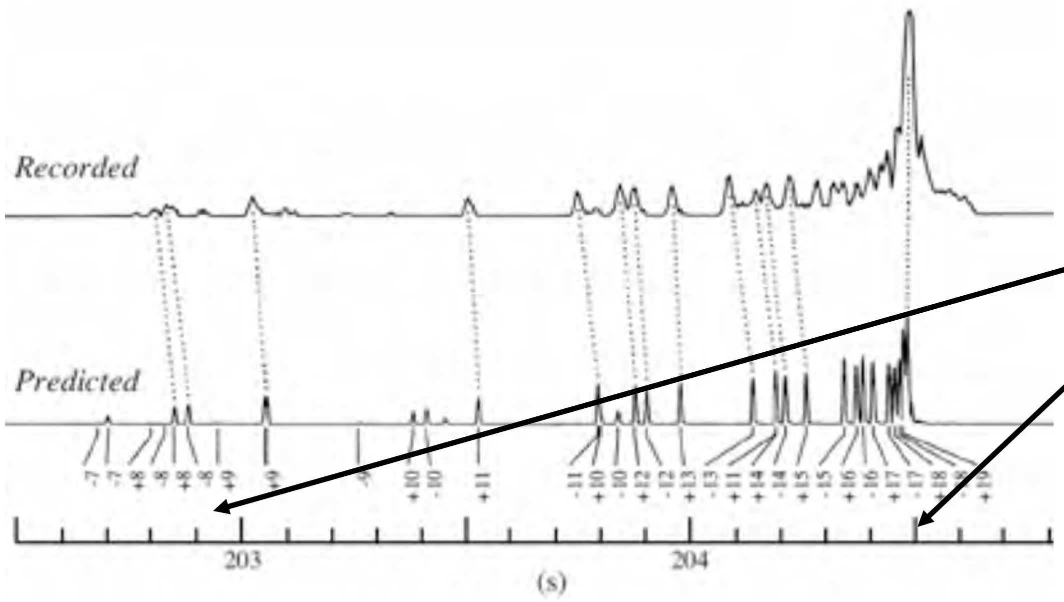


EXAMPLE: Ocean Tomography: Signal Processing using Complexity



Different rays have

Different group speeds



Therefore have different

Arrival times

Which ray corresponds
To which arrival time?

HOW?-for example, use

SENSTIVITY KERNAL/

BORN APPROXIMATION

$$\nabla^2 G(r, r_s; z, z_s) + \frac{\omega^2}{[c + \Delta c(\mathbf{R})]^2} G(r, r_s; z, z_s) = -\delta(R - R_s), \quad (32)$$

which, to lowest order is

$$\nabla^2 G(r, r_s; z, z_s) + k^2(z) G(r, r_s; z, z_s) = -\delta(R - R_s) + \frac{2\omega^2 \Delta c(\mathbf{R})}{c^3} G(r', r_s; z', z_s). \quad (33)$$

The Born approximation then gives

$$G(r, r_s; z, z_s) - G_0(r, r_s; z, z_s) \equiv$$
$$\Delta G = -2\omega^2 \int_V G_0(r, r'; z, z') G_0(r', r_s; z', z_s) \frac{2\Delta c(\mathbf{R}')}{c(\mathbf{R}')^3} dV(\mathbf{R}'), \quad (34)$$

which translates to the sensitivity of the Green's function to a sound speed perturbation,

$$\frac{\partial \Delta G(\mathbf{R}|\mathbf{R}')}{\partial \Delta c(\mathbf{R}')} = -2\omega^2 G(\mathbf{R}|\mathbf{R}') G(\mathbf{R}'|\mathbf{R}_s) \frac{1}{c(\mathbf{R}')^3}, \quad (35)$$

where we have made an obvious change in notation. We will also show below that this result is comparable to the adjoint of the PE model.

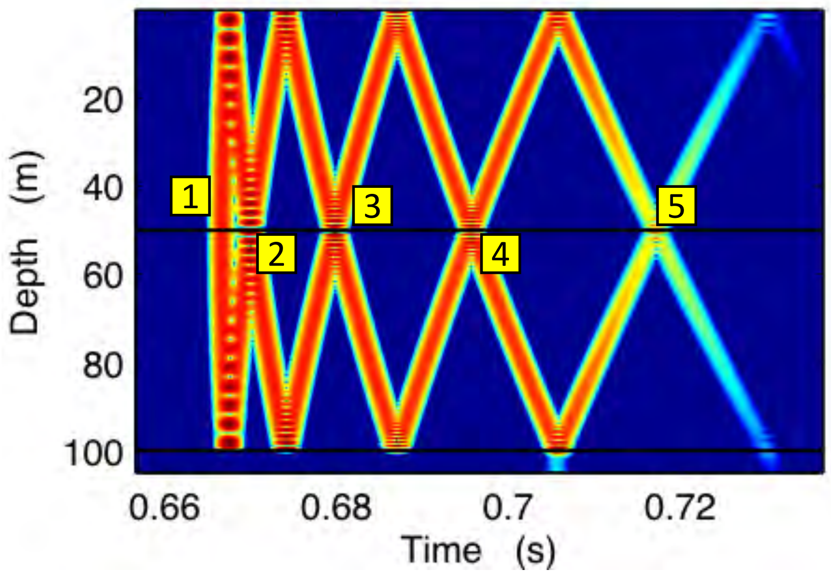
Since the pressure field from a broadband source at receiver r is

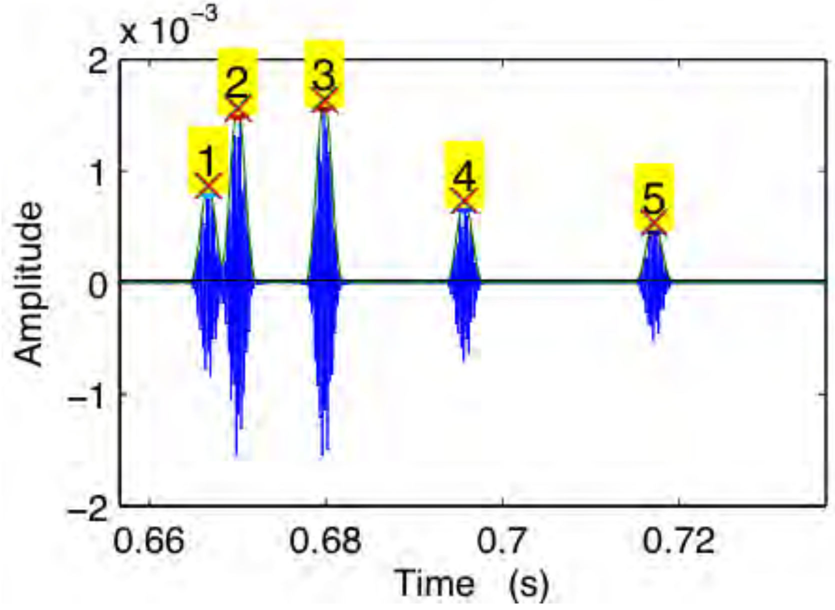
$$p_r(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\mathbf{R}|\mathbf{R}'; \omega; c) P_s(\omega) e^{i\omega t}\, d\omega, \quad (36)$$

and the perturbed pressure is of the same Fourier form, we have

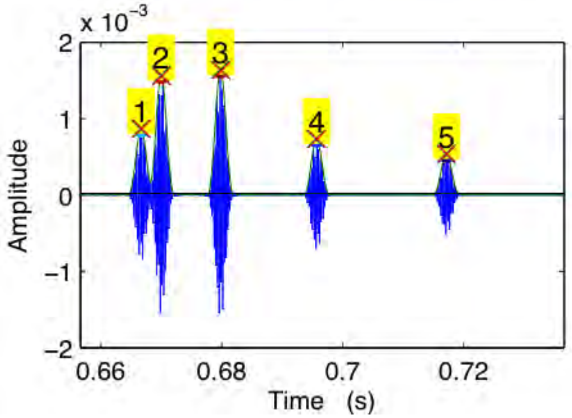
$$\frac{\partial p_r(t)}{\partial c(\mathbf{R}')} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left(-2\omega^2 G(\mathbf{R}|\mathbf{R}') G(\mathbf{R}'|\mathbf{R}_s) \frac{P_s(\omega)}{c(\mathbf{R}')^3} \right) e^{i\omega t}\, d\omega. \quad (37)$$

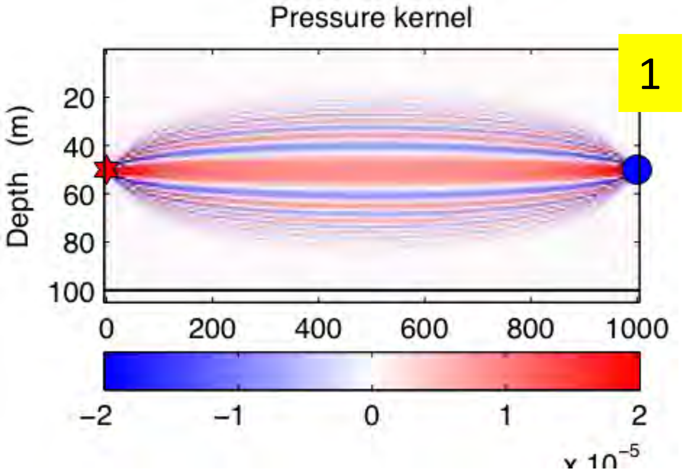
Simulations - pressure record





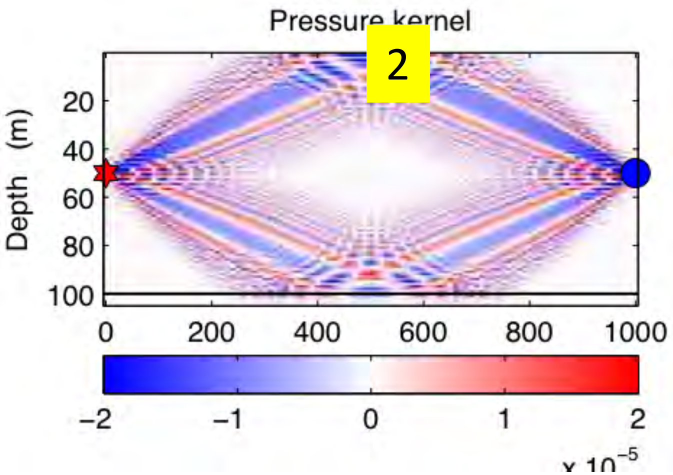
Combine– Kernels for INVERSION

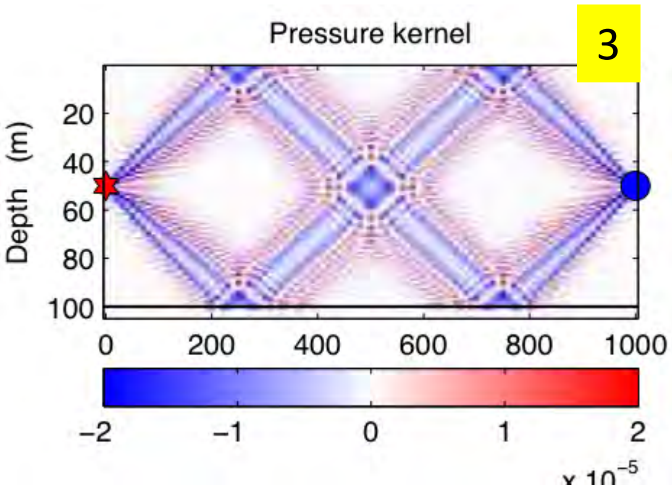




$$\Delta P = H\,\Delta C$$

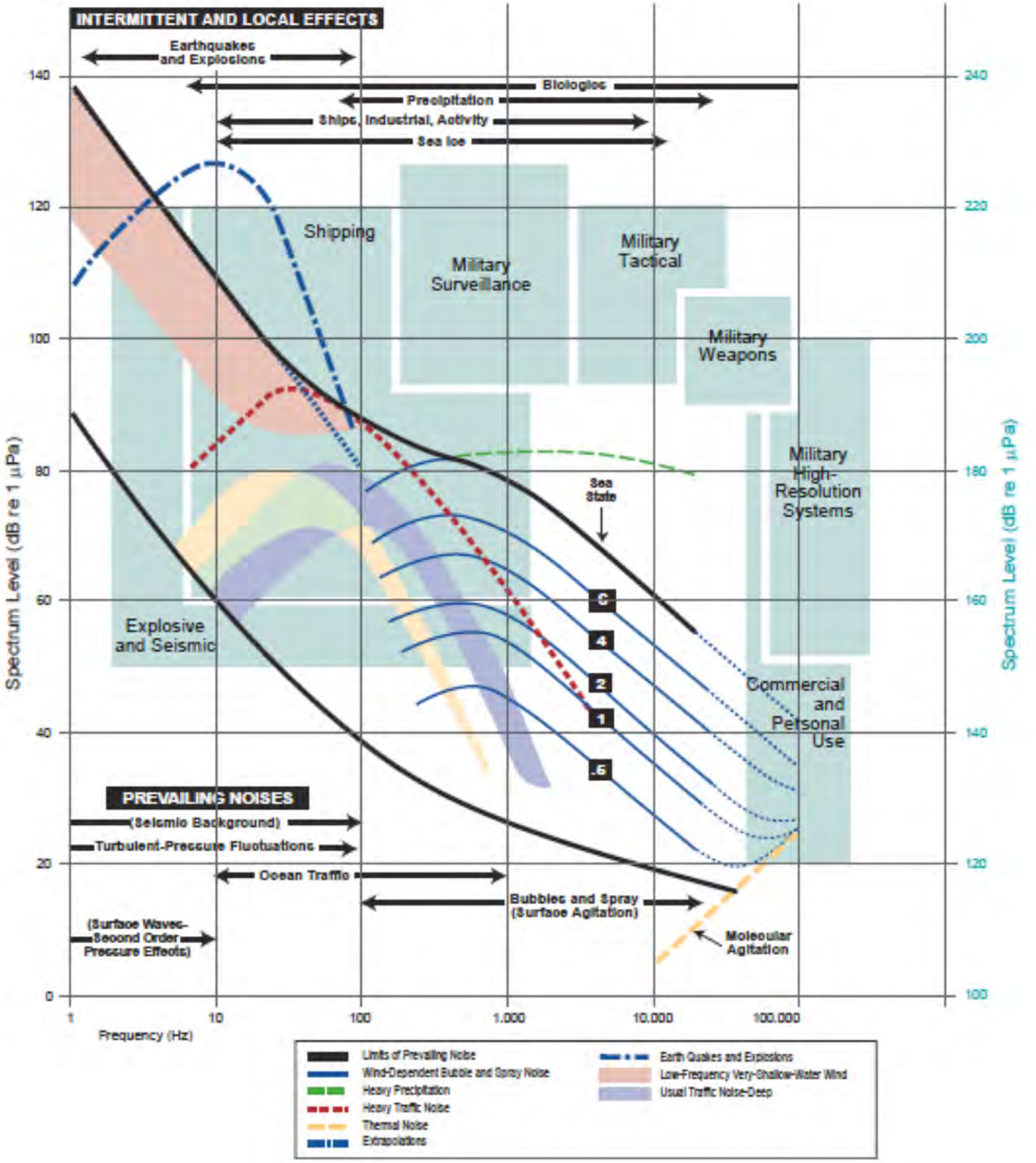
$$\Rightarrow \Delta\hat{C} = \mathrm{Inv}(H)\,\Delta P$$





$$\begin{bmatrix} {}^{1}\Delta p \\ {}^{2}\Delta p \\ {}^{3}\Delta p \\ {}^{4}\Delta p \\ \\ {}^{N}\Delta p \end{bmatrix} = \begin{bmatrix} {}^{1}h_{r_1'} & {}^{1}h_{r_2'} & {}^{1}h_{R'} \\ {}^{2}h_{r_1'} & {}^{2}h_{r_2'} & {}^{2}h_{R'} \\ {}^{3}h_{r_1'} & {}^{3}h_{r_2'} & {}^{3}h_{R'} \\ {}^{4}h_{r_1'} & {}^{4}h_{r_2'} & {}^{4}h_{R'} \\ \\ {}^{N}h_{r_1'} & {}^{N}h_{r_2'} & {}^{N}h_{R'} \end{bmatrix} \begin{bmatrix} \Delta c_{r_1'} \\ \Delta c_{r_2'} \\ \\ \Delta c_{R'} \end{bmatrix}$$

NOISE LEVELS AND SOURCE LEVELS



BRADLEY,STERN
NRC 2008

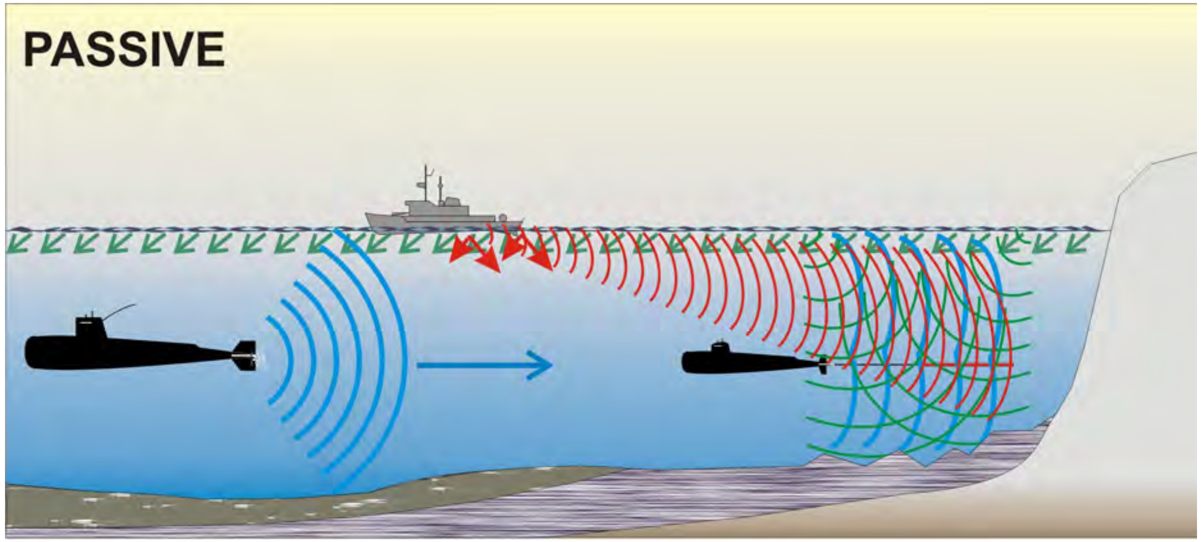
Man Made Sounds

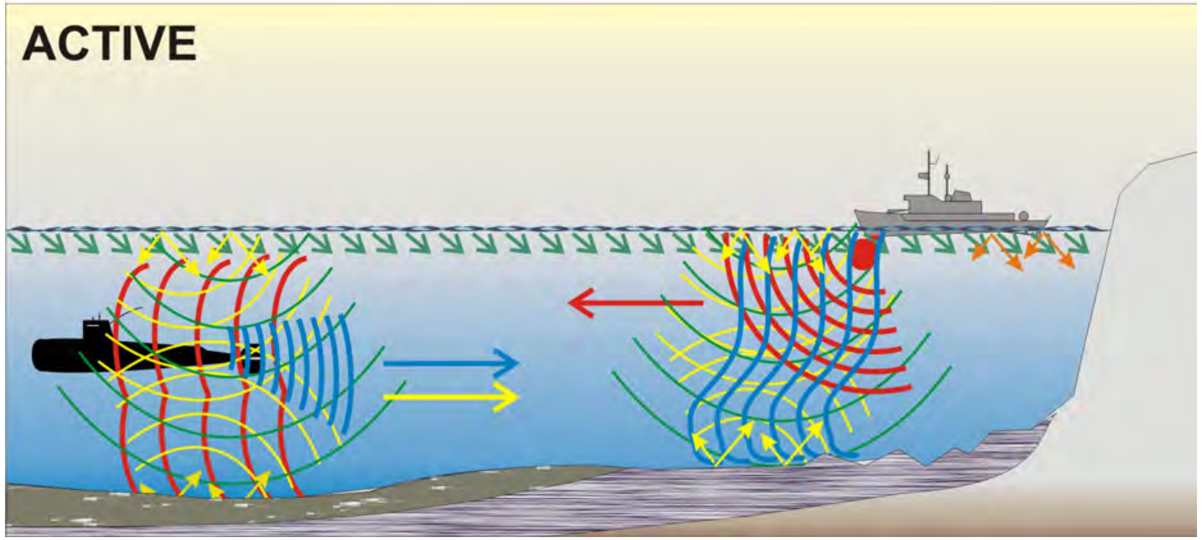
Ships Underway	Broadband Source Level (dB re 1 μPa at 1 m)
Tug and Barge (18 km/hour)	171
Supply Ship (example: Kigoriak)	181
Large Tanker	186
Icebreaking	193
Seismic Survey	**Broadband Source Level (dB re 1 μPa at 1 m)**
Air gun array (32 guns)	259 (peak)
Military Sonars	**Broadband Source Level (dB re 1 μPa at 1 m)**
AN/SQS-53C (U. S. Navy tactical mid-frequency sonar, center frequencies 2.6 and 3.3 kHz)	235
AN/SQS-56 (U. S. Navy tactical mid-frequency sonar, center frequencies 6.8 to 8.2 kHz)	223
SURTASS-LFA (100-500 Hz)	215 dB per projector, with up to 18 projectors in a vertical array operating simultaneously
Ocean Acoustic Studies	**Broadband Source Level (dB re 1 μPa at 1 m)**
Heard Island Feasibility Test (HIFT) (Center frequency 57 Hz	206 dB for a single projector, with up to 5 projectors in a vertical array operating simultaneously
Acoustic Thermometry of Ocean Climate (ATOC)/North Pacific Acoustic Laboratory (NPAL) (Center frequency 75 Hz)	195

Animal Sounds

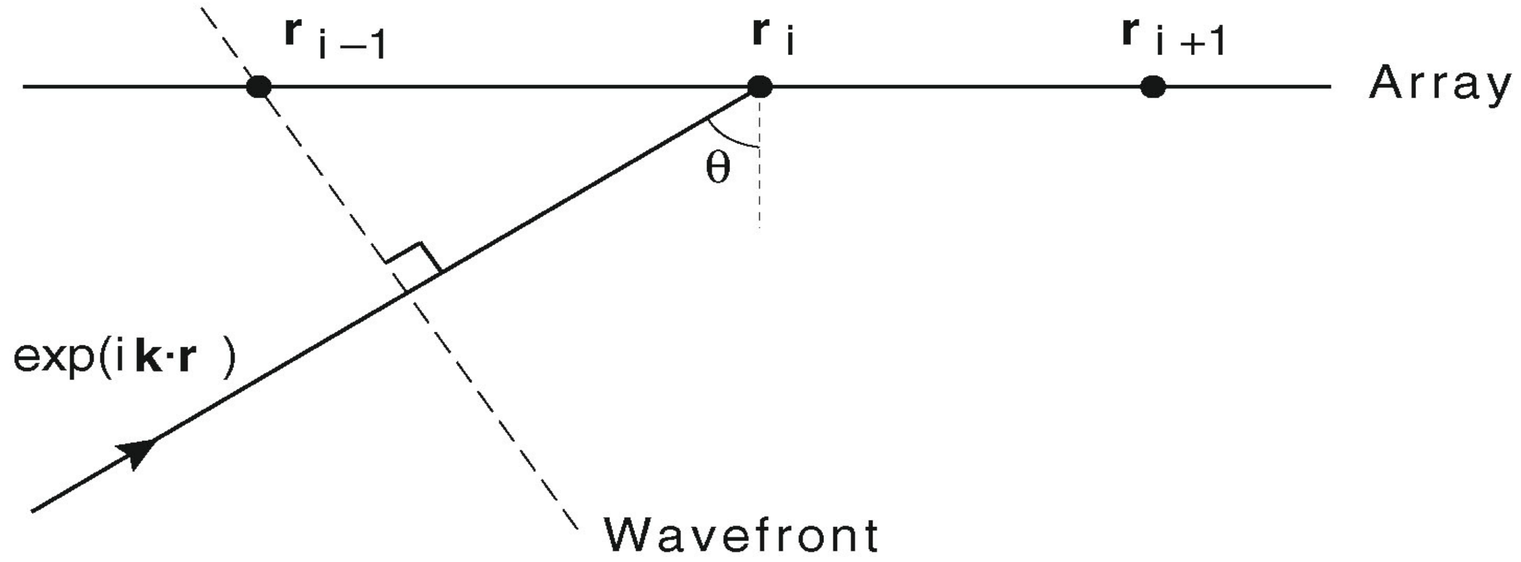
Source	Broadband Source Level (dB re 1 μPa at 1 m)
Sperm Whale Clicks	163-223
Beluga Whale Echolocation Click	206-225 (peak-to-peak)
White-beaked Dolphin Echolocation Clicks	194-219 (peak-to-peak)
Spinner Dolphin Pulse Bursts	108-115
Bottlenose Dolphin Whistles	125-173
Fin Whale Moans	155-186
Blue Whate Moans	155-188
Gray Whale Moans	142-185
Bowhead Whale Tonals, Moans and Song	128-189
Humpback Whale Song	144-174
Humpback Whale Fluke and Flipper Slap	183-192
Southern Right Whale Pulsive Call	172-187
Snapping Shrimp	183-189 (peak-to peak)

TYPICAL SONAR VIEW OF NOISE: NUISANCE





PLANE WAVE BEAMFORMING
gives us
Coherent Gain of Signal over Incoherent Noise and Directionality



s=Signal vector; d=s + noise; K (CSDM) ~ <d d ⁺ > [DATA]

w="replica" vector (usually from a model)

If w=s (or d), then w^+d ⟷ $w^+ Kw$ is maximum

→ At correct angle, each element w_i^* is cc of s_i

PLANE WAVE BEAMFORMING: ADAPTIVE PROCESSORS

Minimum Variance Distortionless Processor

$$F = \mathbf{w}_{MV}^{\dagger}\mathbf{K}\mathbf{w}_{MV} + \alpha(\mathbf{w}_{MV}^{\dagger}\mathbf{w} - 1). \quad (11)$$

(Two independent variables: $\mathbf{w}_{MV}$ and $\mathbf{w}_{MV}^{*}$.)

$$\mathbf{w}_{MV} = \frac{\mathbf{K}^{-1}\mathbf{w}}{\mathbf{w}^{\dagger}\mathbf{K}^{-1}\mathbf{w}}. \quad (12)$$

$$B_{MV}(\theta_s) = [\mathbf{w}^{\dagger}(\theta_s)\mathbf{K}^{-1}(\theta_{true})\mathbf{w}(\theta_s)]^{-1}. \quad (13)$$

Eigenvector Beamformers

$$\mathbf{K} = \sum_{i=1}^{M} \lambda_i \mathbf{v_i}\mathbf{v_i}^{\dagger}, \quad (14)$$

$$\mathbf{K}\mathbf{v_i} = \lambda_i \mathbf{v_i}, \quad i = 1, \ldots, M. \quad (15)$$

$$\mathbf{K} = \sum_{i=1}^{p} \sigma_i \mathbf{s_i}\mathbf{s_i}^{\dagger} + \mathbf{K}_n. \quad (16)$$

$$\mathbf{K} = \sum_{i=1}^{p} \sigma_i \mathbf{s_i}\mathbf{s_i}^{\dagger} + \sigma_n \mathbf{I} = \sum_{i=1}^{p} (\sigma_i + \sigma_n)\mathbf{v_i}\mathbf{v_i}^{\dagger}. \quad (17)$$

$$\mathbf{K}' = \sum_{i=1}^{p} \lambda_i \mathbf{v_i}\mathbf{v_i}^{\dagger}. \quad (18)$$

$$\mathbf{K}_{\perp sig}^{-1} = \sum_{i=M-p}^{M} \lambda_i^{-1} \mathbf{v_i}\mathbf{v_i}^{\dagger}. \quad (19)$$

Conventional and MVDR ("ADAPTIVE") Beamforming

For each hypothetical source position (r_i,z_i), a replica vector d is implemented as:

d = $p_{zs\,=\,zi}$(distance source array, depth of elemts)

d is then normalized to unity.

- Conventional BF:

$$W_c = d$$

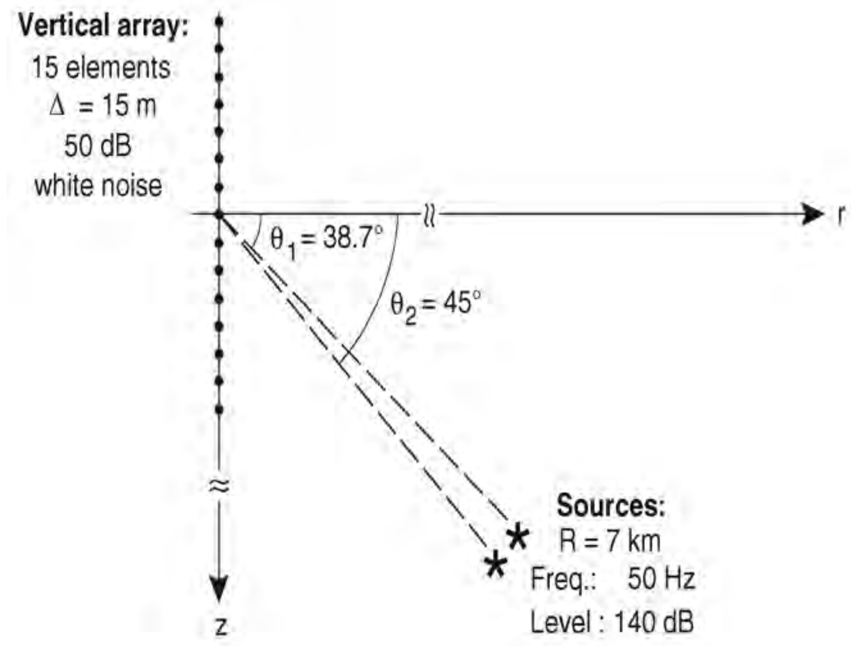
- MVDR BF:

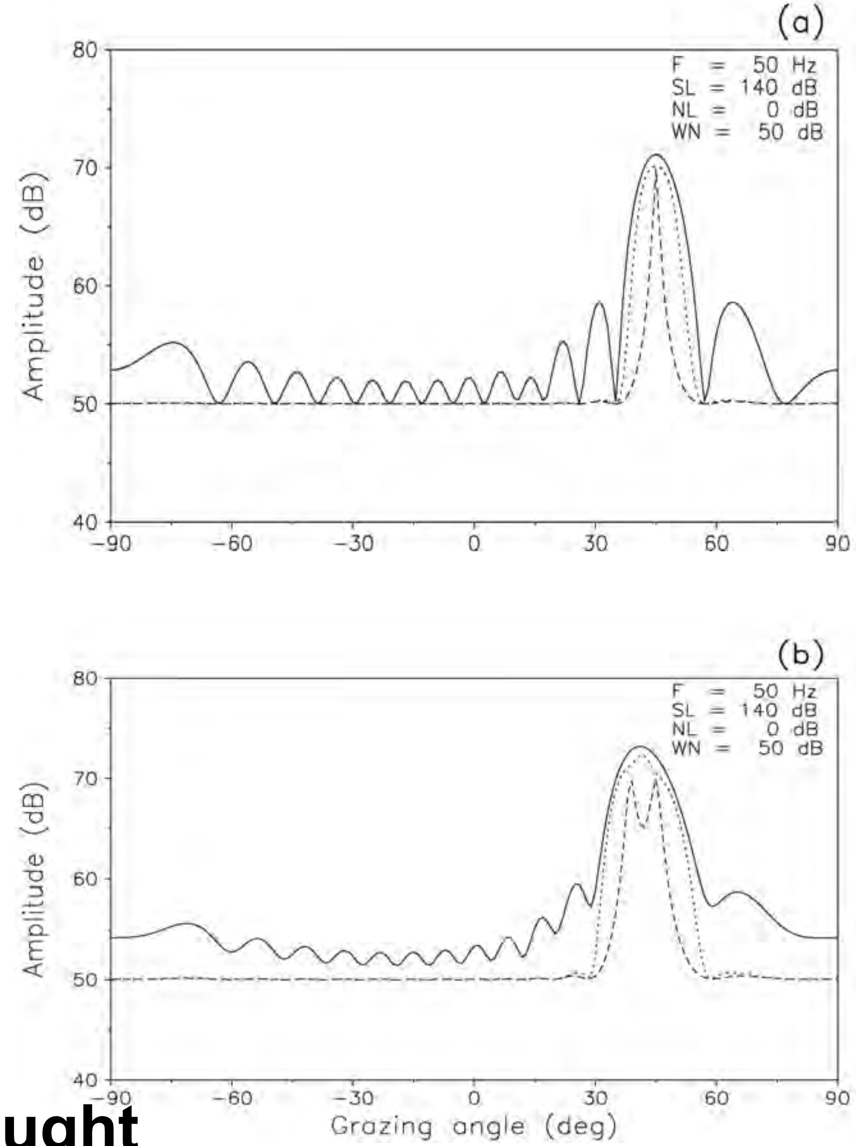
$$W_{MV} = \frac{K^{-1}d}{d^H K^{-1} d}$$

Power output:

$$B = W^H K W$$

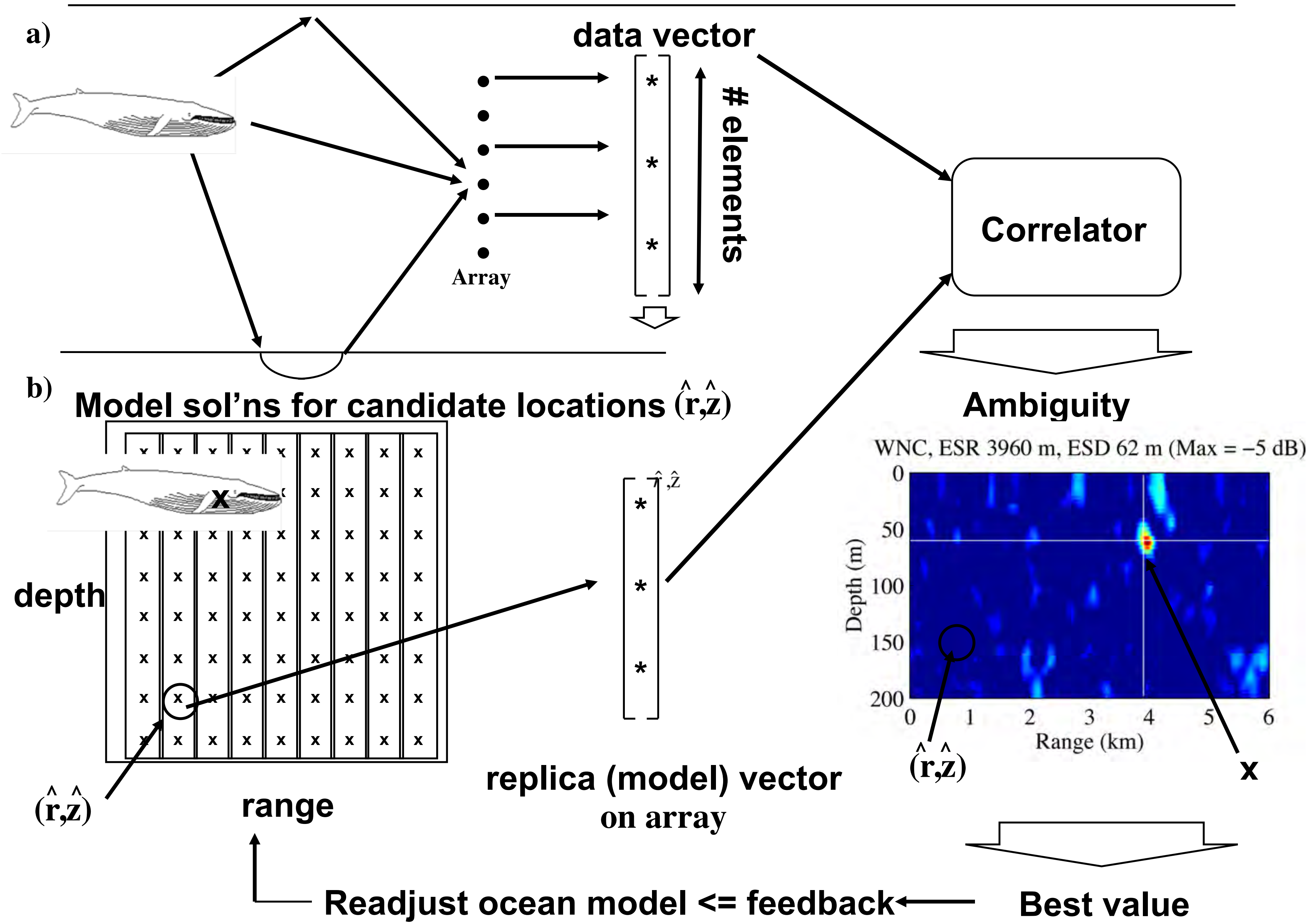
LINEAR AND ADAPTIVE
BEAMFORMING



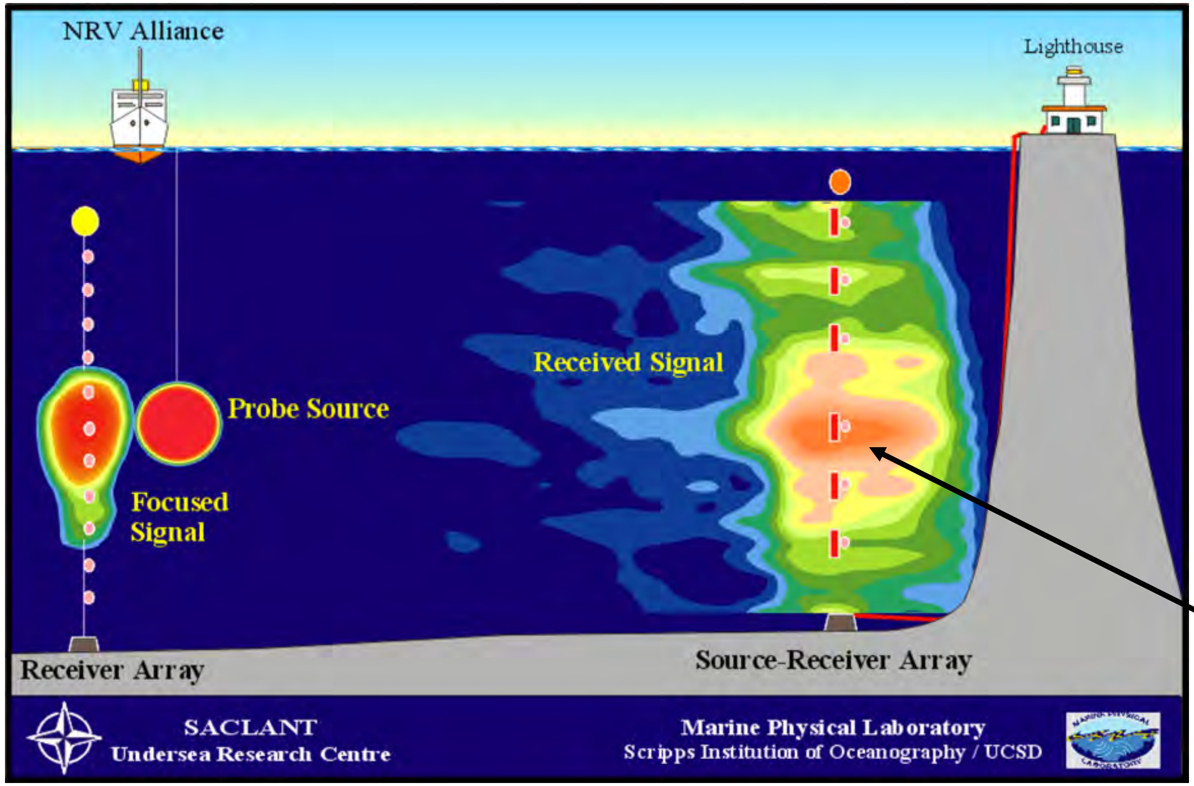


One of sources could be thought of a *coherent* interferor (eigenvector decomposition)

Matched Field (Model Based) Processing (MFP)



COMPARE TO: Time Reversal Process in the Ocean



data

Frequency Domain

$$P_{pc}(r,z;\omega) = \sum_{j=1}^{J} G_{\omega}(r;z,z_j)\,G^{*}_{\omega}(R;z_j,z_{ps})$$

Time Domain

$$P_{pc}(r,z;t) = \frac{1}{(2\pi)^2}\int \sum_{j=1}^{J}\left[\int G_{t'+t''}(R,z_j,z_{ps})\,G_{t'}(R,z_j,z_{ps})\,dt'\right] S(t''-t+T)\,dt''$$

Time Reversal vs Matched Field Processing

$$\mathbf{B}_{\mathbf{TRP}} = \left|\mathbf{P}^{+}\mathbf{W}\right|^{2}$$

W : Time Reverse Data and retransmit using ACTIVE SOURCES

$$\mathbf{B}_{\mathbf{MFP}} = \mathbf{W}^{+}(\mathbf{P}\mathbf{P}^{+})\mathbf{W}$$

W : computer generated replica fields

$$B = W^{H} K W$$

SO: TR EXISTENCE THEOREM THAT MFP SHOULD WORK

WHEN DOES ALL THIS (TR=MFP) TYPICALLY WORK?

- STABLE ENVIRONMENT
- LOWER FREQUENCIES
- GOOD SNR

STABLE, LOWER FREQ. MFP: (450 Hz)

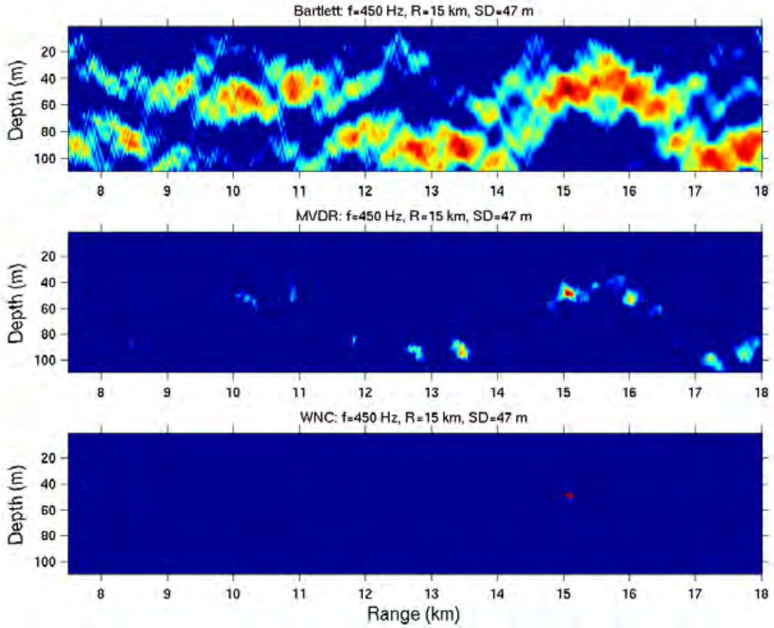
SD: 47 m, R = 15 km

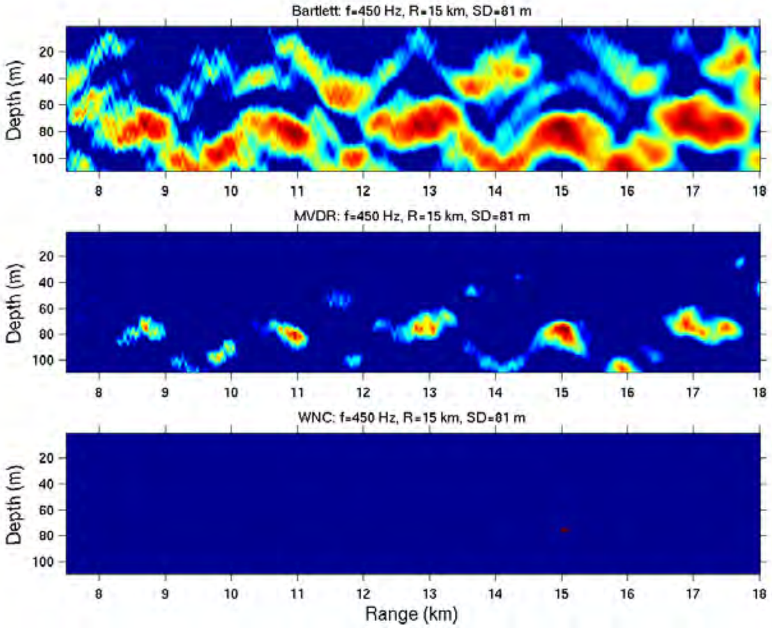
SD: 81 m, R=15km 15km km

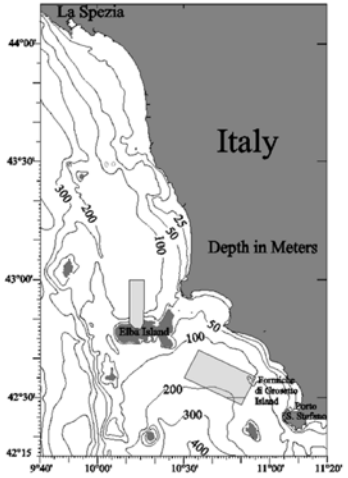
BT

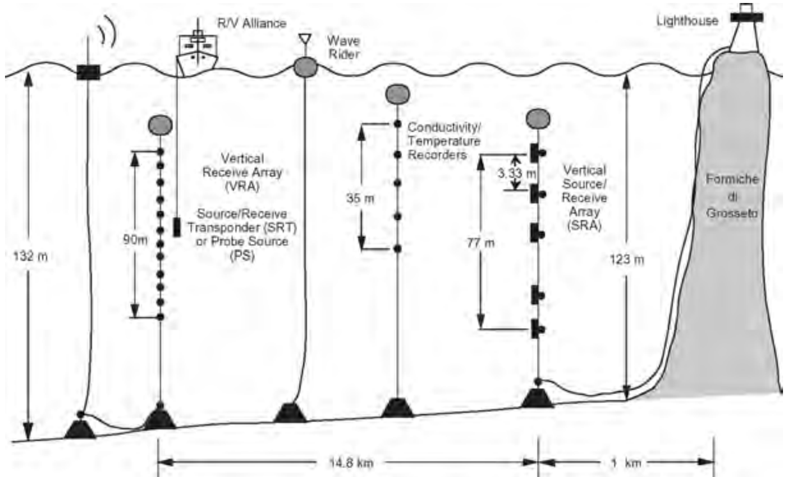
MVDR

WNC



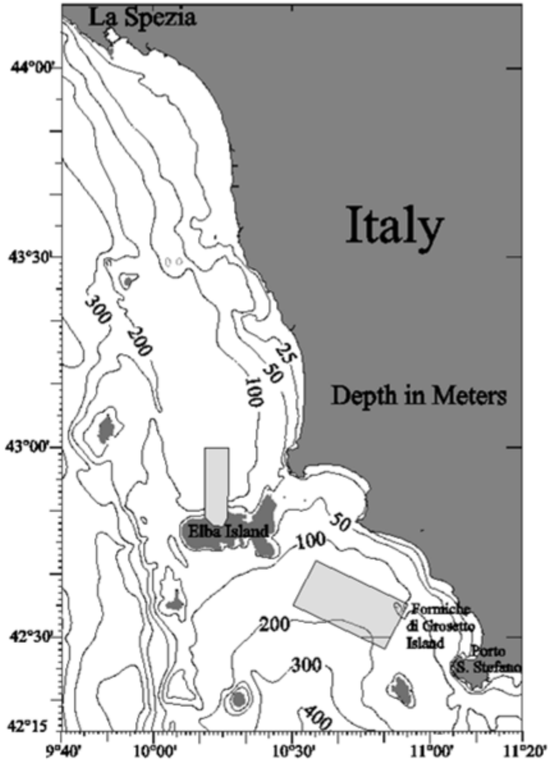


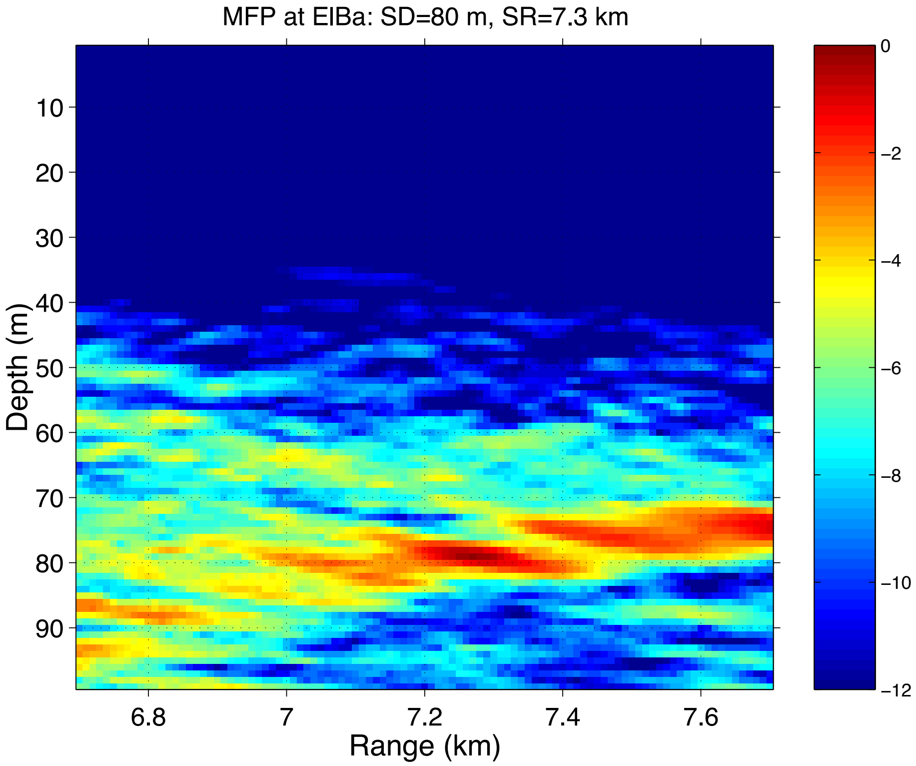


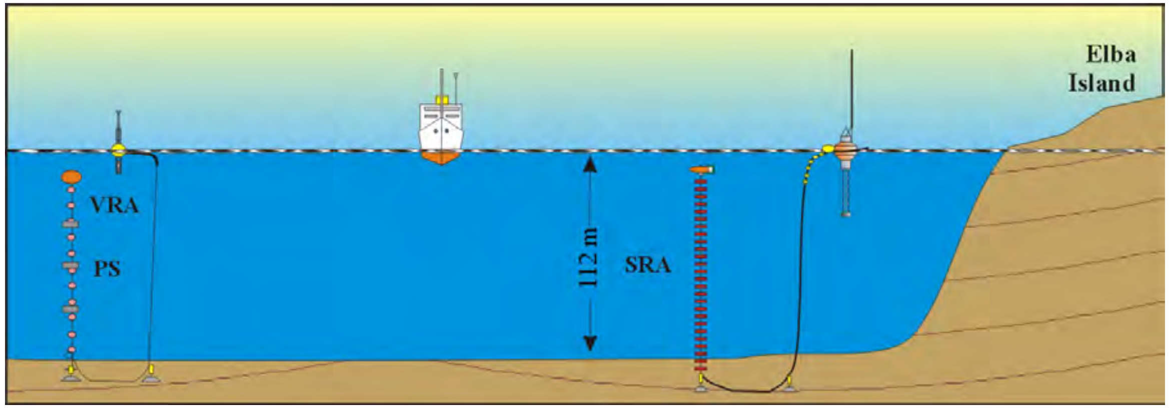


SRA: 23 elements
3.33-m spacing
(77-m aperture)

BUT AT HIGHER FREQUENCY(3.5 kHz)



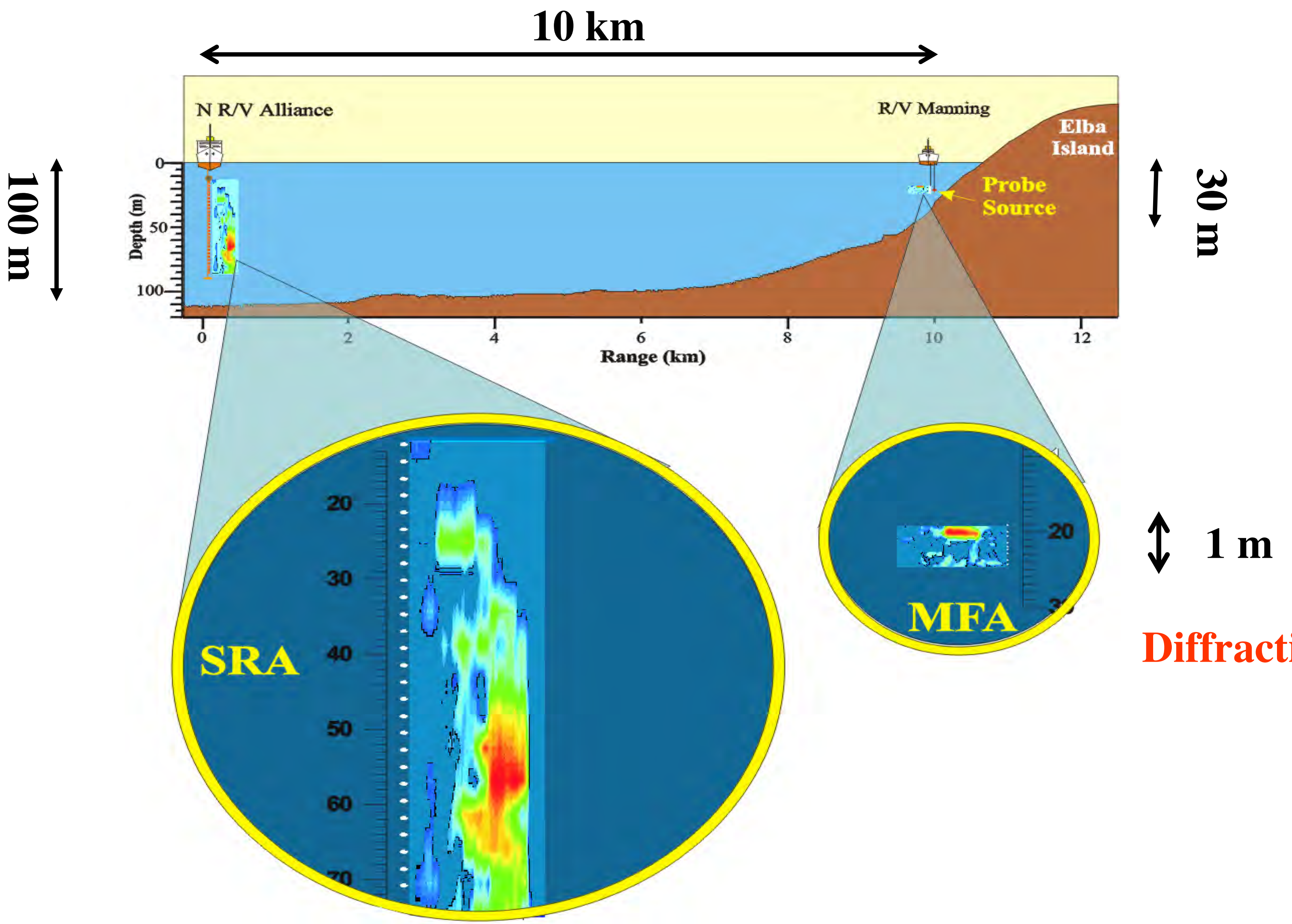




SRA: 29 elements
3.33-m spacing
(78-m aperture)

Time Reversal Mirror Experiment: Elba

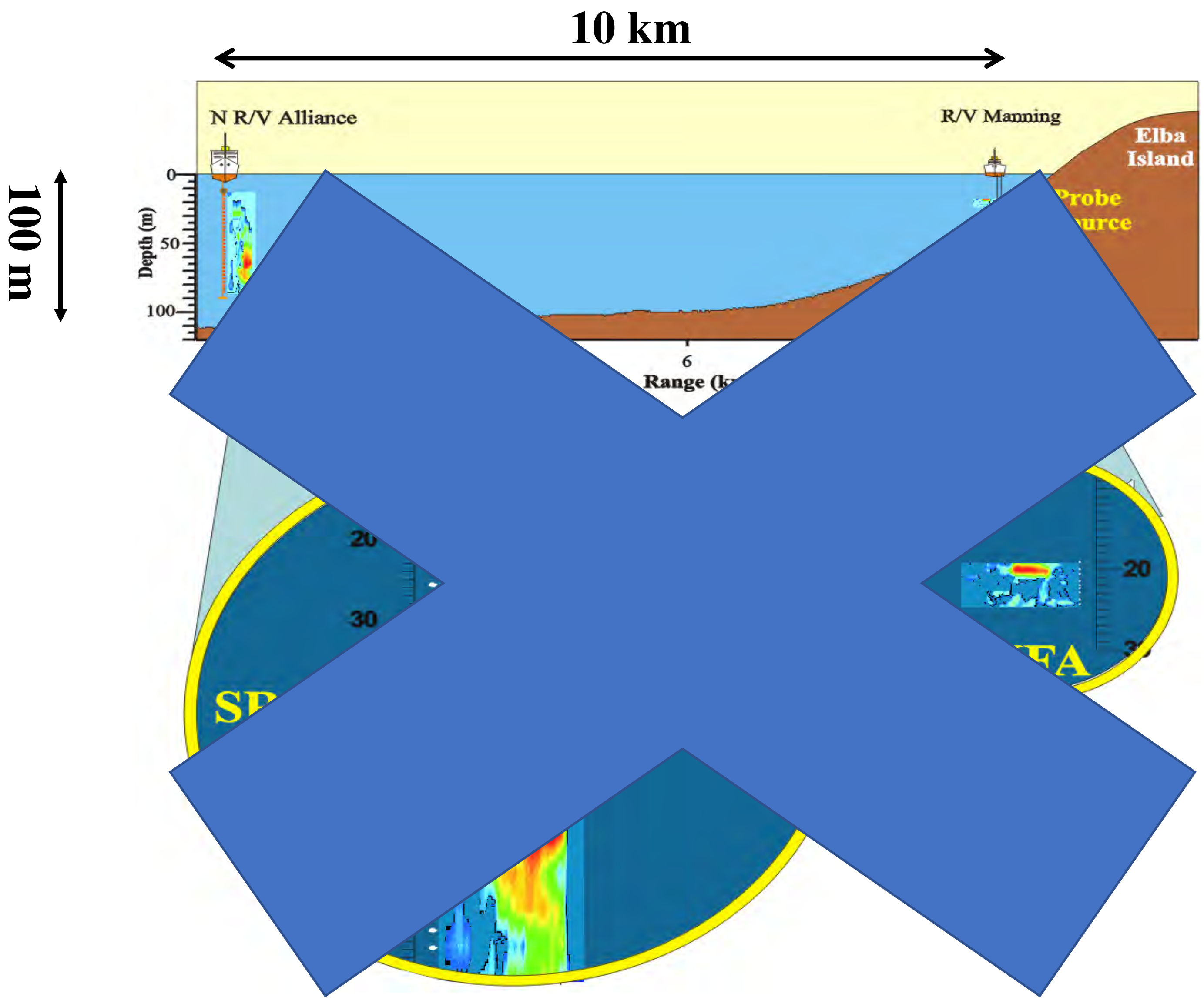
SUPER EXISTENCE THM for MFP



Diffraction limit

Time Reversal Mirror Experiment: Elba

SUPER EXISTENCE THM for MFP



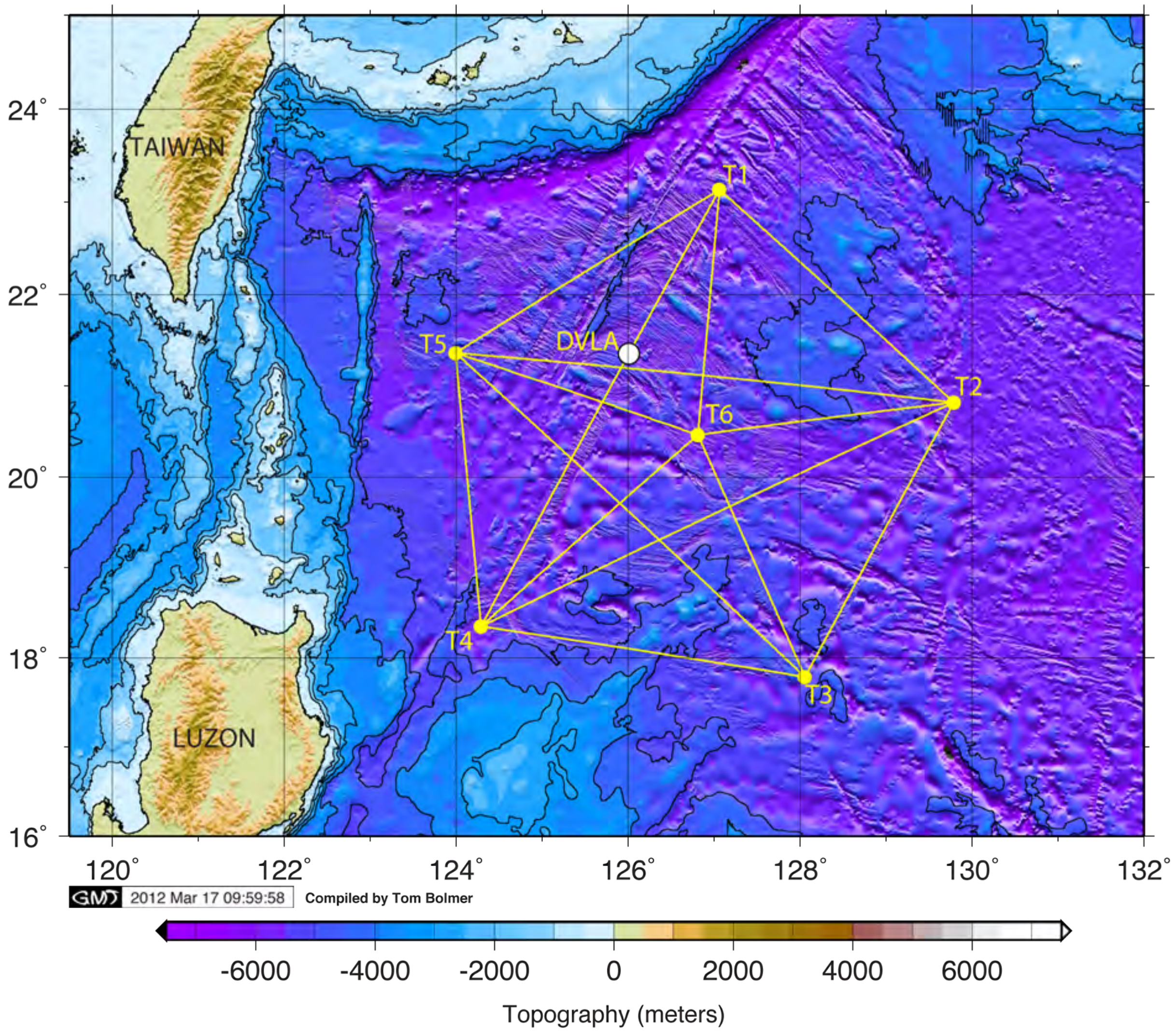
MFP HAS NOT WORKED

Because Environment NOT Known Well Enough

CAN TOMOGRAPHY HELP?

→**SIGNAL PROCESSING?**

2010–2011 NPAL Philippine Sea Experiment
(MOST ACCURATE TOMOGRAPHY EXP TO DATE)



- T1–T6: WRC transceivers
- 660 km diameter
- DVLA
- Moored oceanographic sensors
- CTD
- Acoustic Seagliders

WORCESTER ET AL

SUMMARY OF SELECTED RESULTS

- Model with Climatology 150 ms
- Assimilate Oceanography 80 ms
- Assimilate Acoustics <20ms

- 20 ms →30 meters
- 300 Hz→Wavelength 5 m

No enhancement for Array Processing (need ~$\lambda/8$)

{Accuracy off by a factor of ~ 30)

Mismatch shows up as NOISE

Some Thoughts on UW (Passive) Signal Processing

- Classical plane wave array processing well understood and limited by rigorous statistically derived bounds (on variances) and SNR
- Matched field Processing works only for lower frequencies where environment can be described with sufficient accuracy.
- Some focalization methods have been shown to be promising but still very SNR limited
- No new methods have reliably gone beyond above limitations.
- Random Fluctuation Theory so far applied to just quantifying limitations
- Machine Learning has not *yet* provided additional capabilities or insight

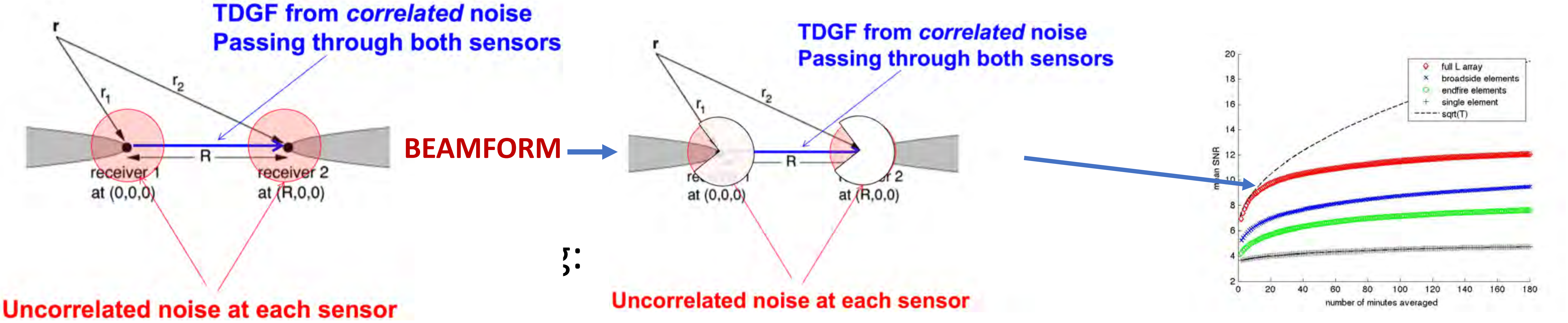
HAVE NOT YET TAKEN (PASSIVE) ADVANTAGE OF COMPLEXITY!!!

……………….MOVING ON to NOISE CORRELATION METHODS in UW ….

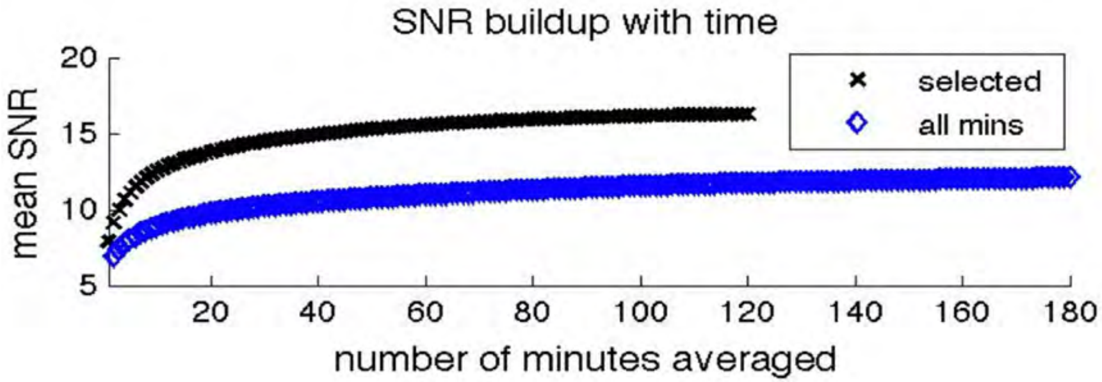
NOISE CORRELATIONS IN OCEAN ACOUSTICS

<u>Is now very mature</u>: FREE SPACE; WAVEGUIDE; BEAMFORMING—

ISSUE: CORRELATION TIME vs Medium Fluctuation Time: **SPEEDUP Process:**

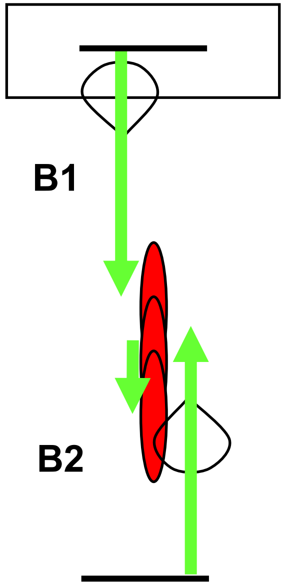


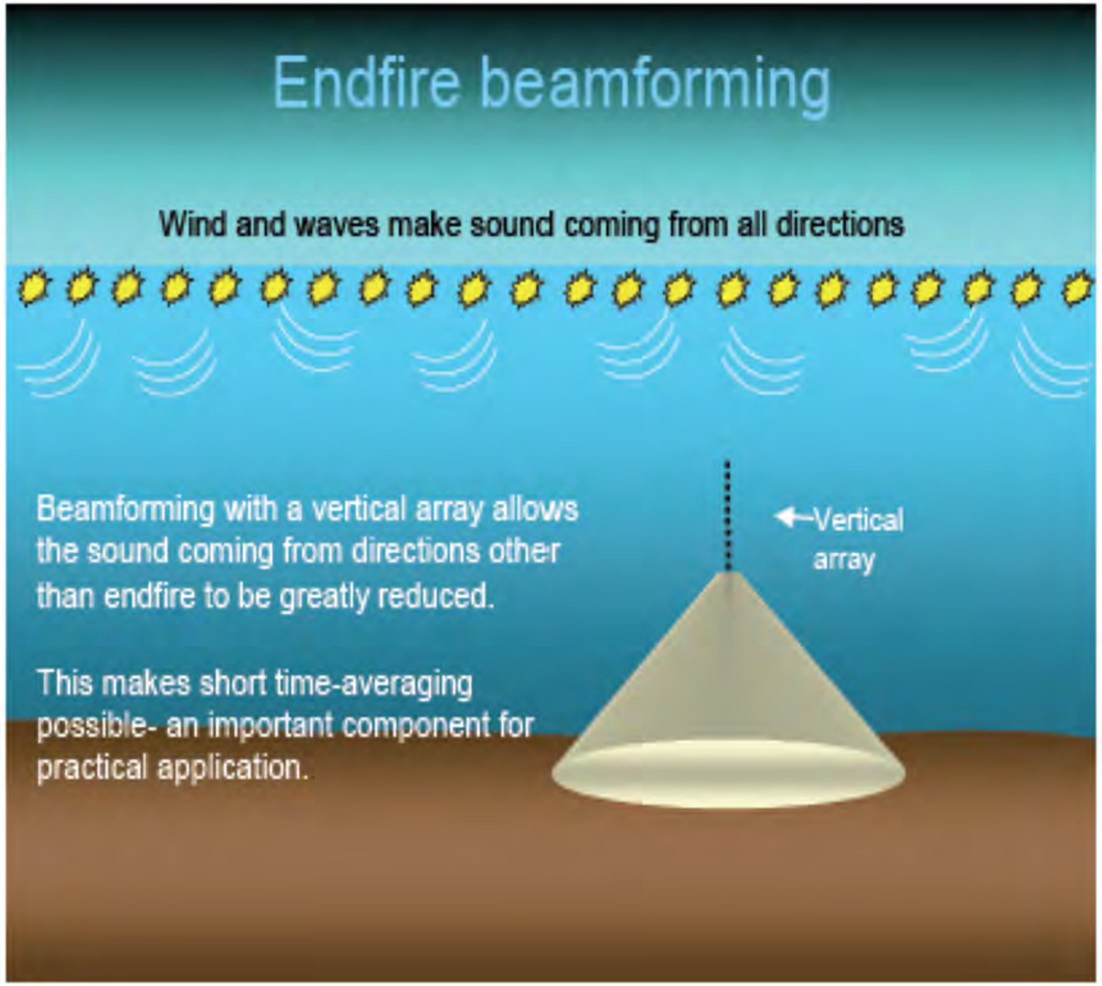
Pick endfire levels only above
A threshold **and throw data Away!!!**



Passive fathometer:
(Horizontal Array used as Vertical Array)

Using ambient noise on a drifting array we can map the bottom properties

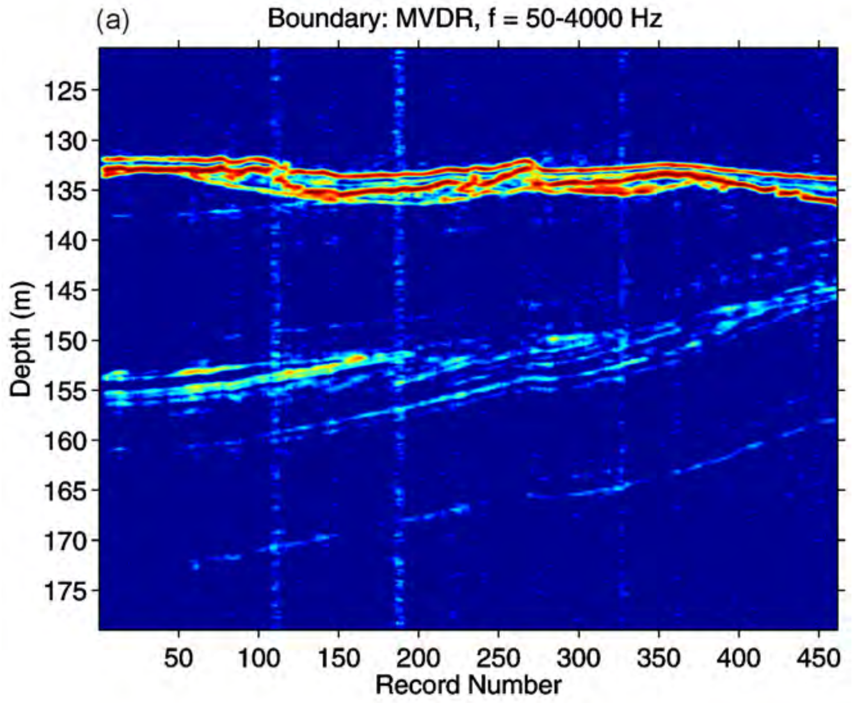


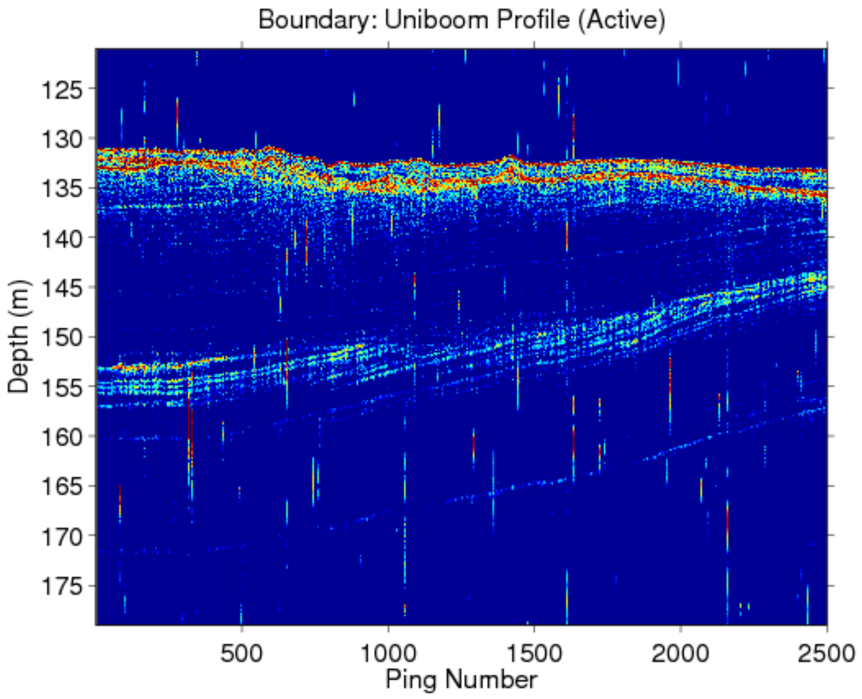


Siderius et al., JASA 2006,
Gerstoft et al., JASA 2008,
Harrison, JASA 2009,
Traer et al., JASA 2009,
Siderius et al., JASA 2010

Passive fathometer (drifting array)

Ambient noise 50-4000 Hz **Boomer**

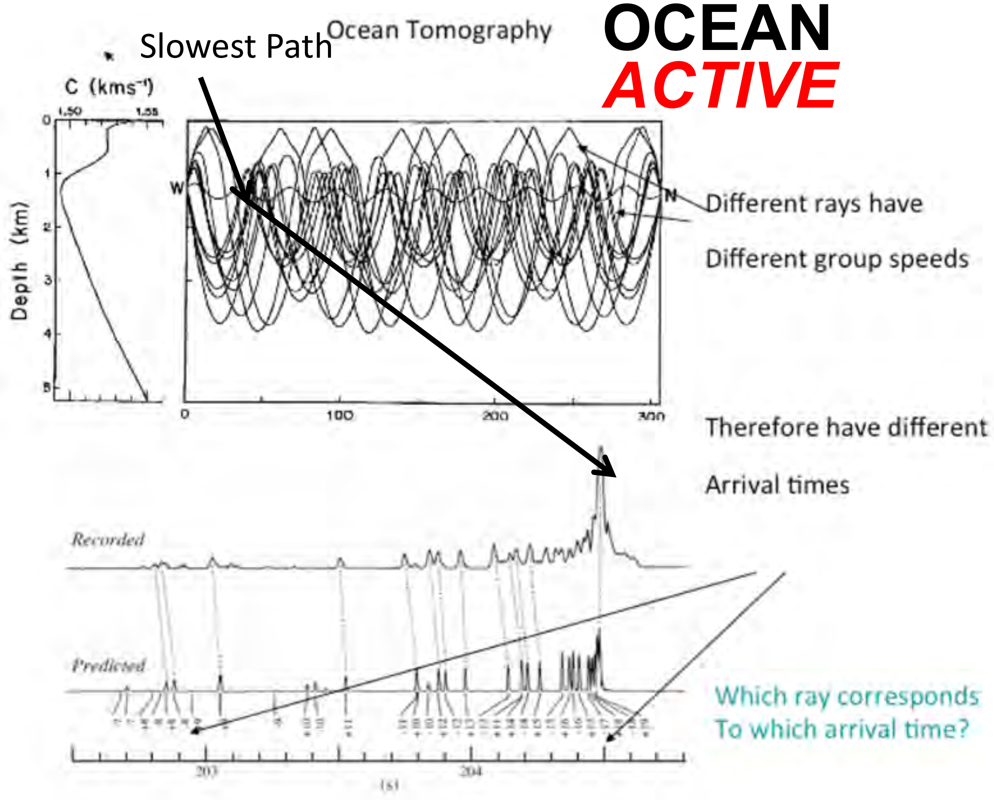




Adaptive processing gives better resolution of reflections

Siderius, Gerstoft et al., 2009 NURC data

BACKGROUND IIA: IMAGING OCEAN *ACTIVE*



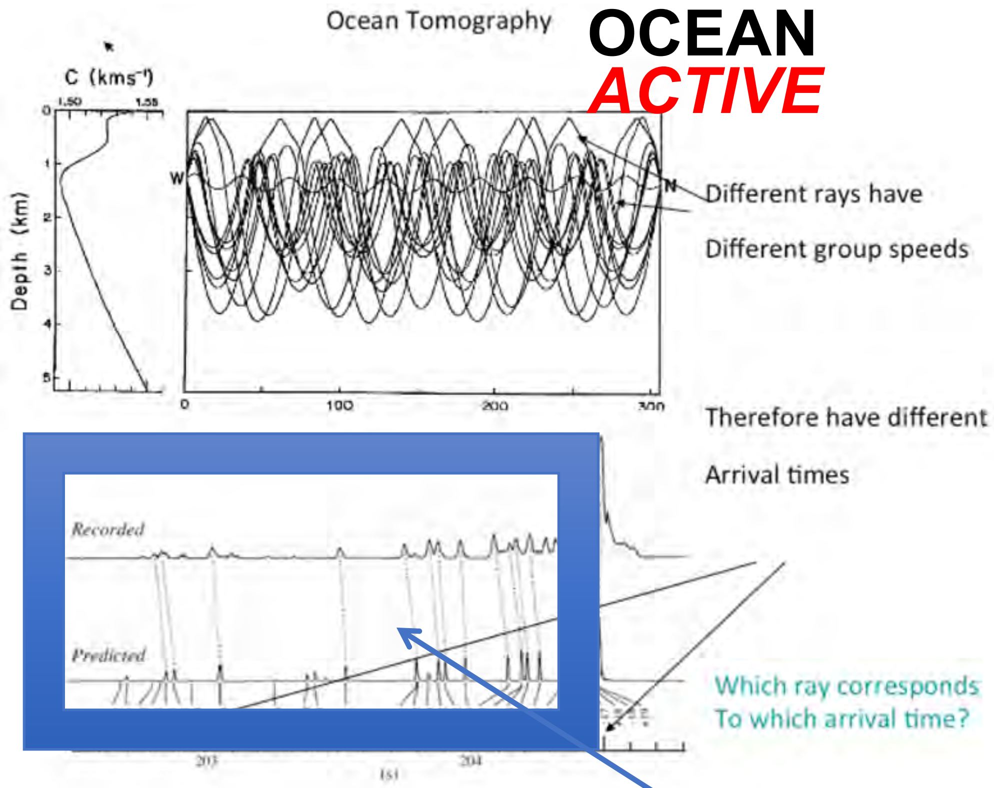
REQUIRES ACTIVE SOURCE THAT IS:

1) PERFECTLY KNOWN WRT TIME SIGNAL AND SYNCRONIZATION
2) PERFECTLY KNOWN WRT SOURCE/RECEIVER GE0METRY

BIG OCEAN TOMOGRAPHY and NOISE

Fried et al

BACKGROUND IA: IMAGING OCEAN
ACTIVE



WITHOUT ACTIVE SOURCE THAT IS:

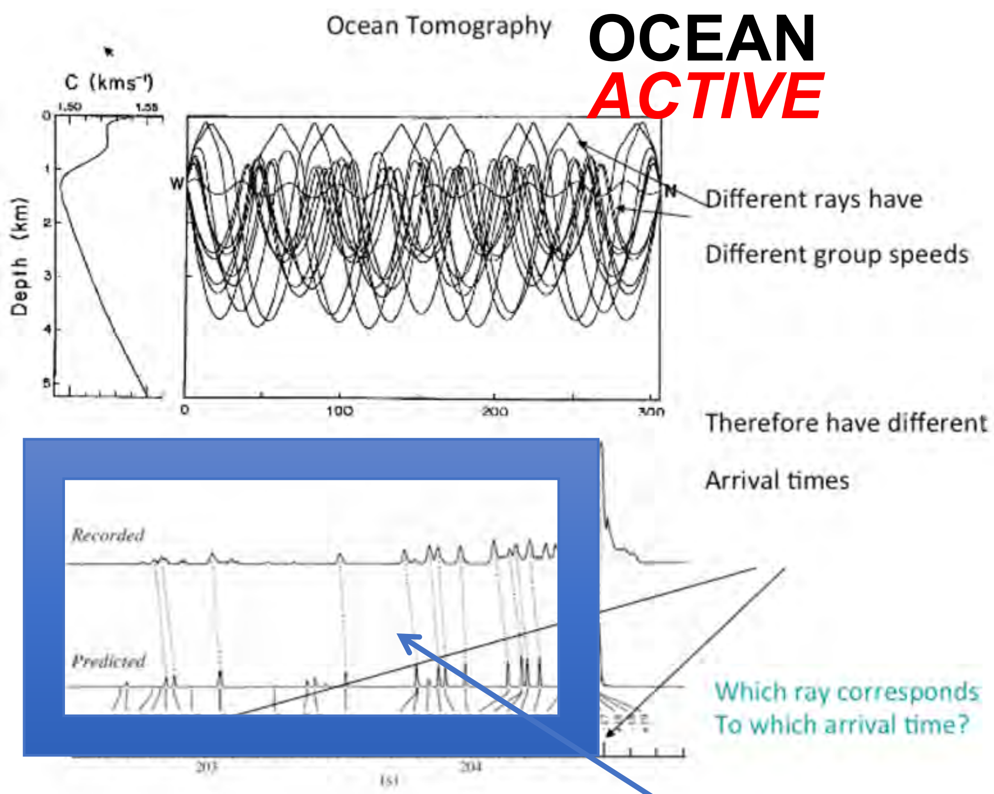
1) PERFECTLY KNOWN WRT TIME SIGNAL AND SYNCRONIZATION
2) PERFECTLY KNOWN WRT SOURCE/RECEIVER GE0METRY

GOAL:
IMAGE WITH ONLY RANDOM AMBIENT SOURCES OF OPPORTUNITY

Fried et al

BACKGROUND IIB: IMAGING OCEAN

ACTIVE



WITHOUT ACTIVE SOURCE THAT IS:

1) PERFECTLY KNOWN WRT TIME SIGNAL AND SYNCRONIZATION
2) PERFECTLY KNOWN WRT SOURCE/RECEIVER GE0METRY

VERY HARD

GOAL:

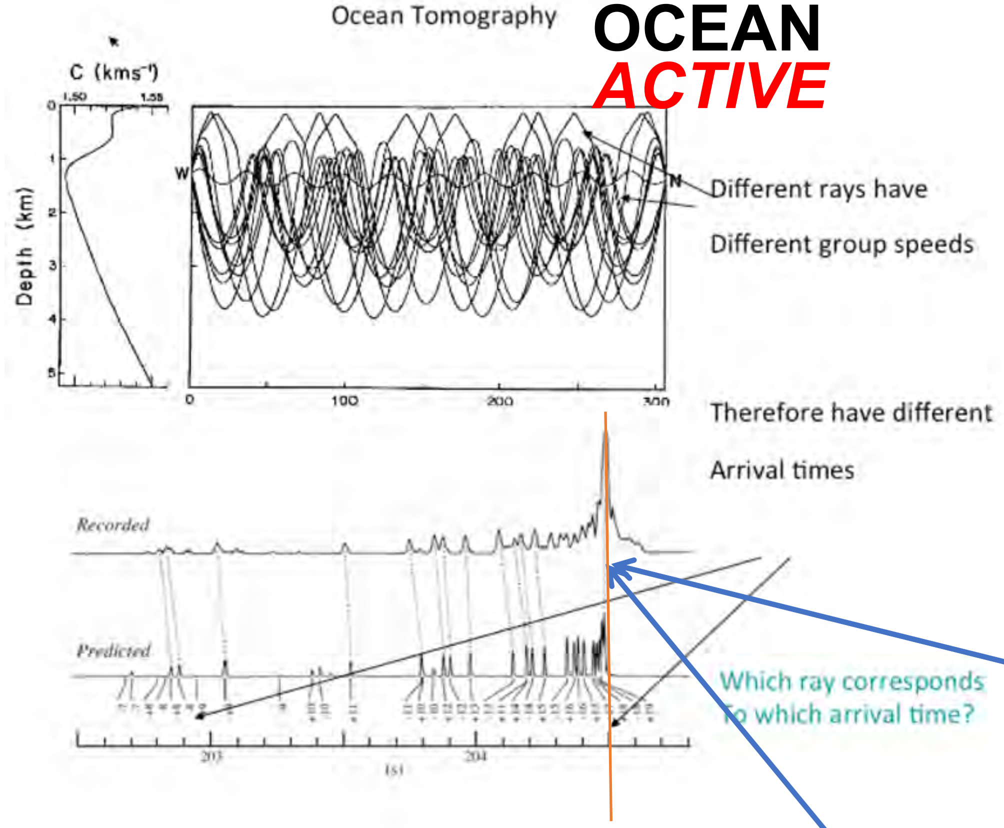
IMAGE WITH ONLY RANDOM AMBIENT SOURCES OF OPPORTUNITY

WITHOUT SOURCE INFO

Fried et al

BACKGROUND IIC: IMAGING OCEAN

ACTIVE



WITHOUT ACTIVE SOURCE THAT IS:

1) PERFECTLY KNOWN WRT TIME SIGNAL AND SYNCRONIZATION
2) PERFECTLY KNOWN WRT SOURCE/RECEIVER GE0METRY

LAST ARRIVAL

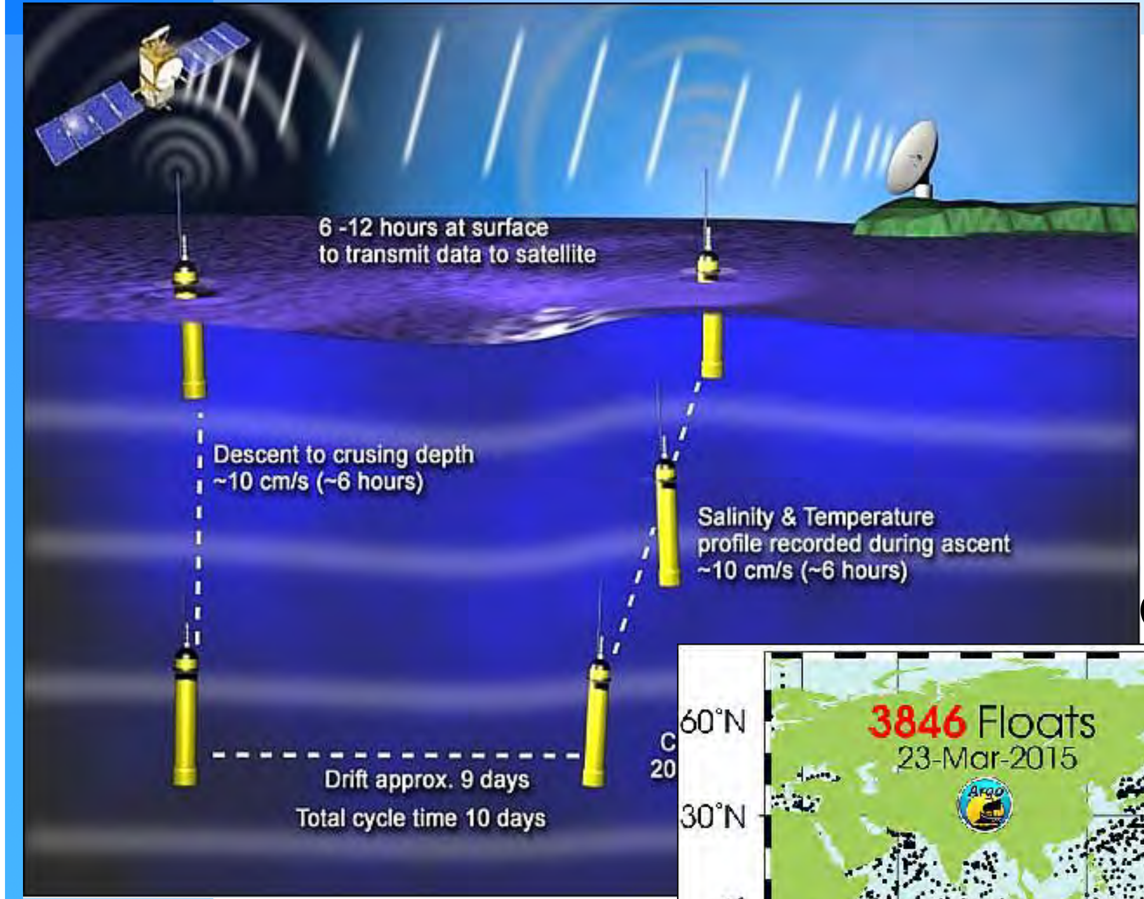
LESS HARD WITHOUT SOURCE INFO

GOAL:

IMAGE WITH ONLY RANDOM AMBIENT SOURCES OF OPPORTUNITY

Fried et al

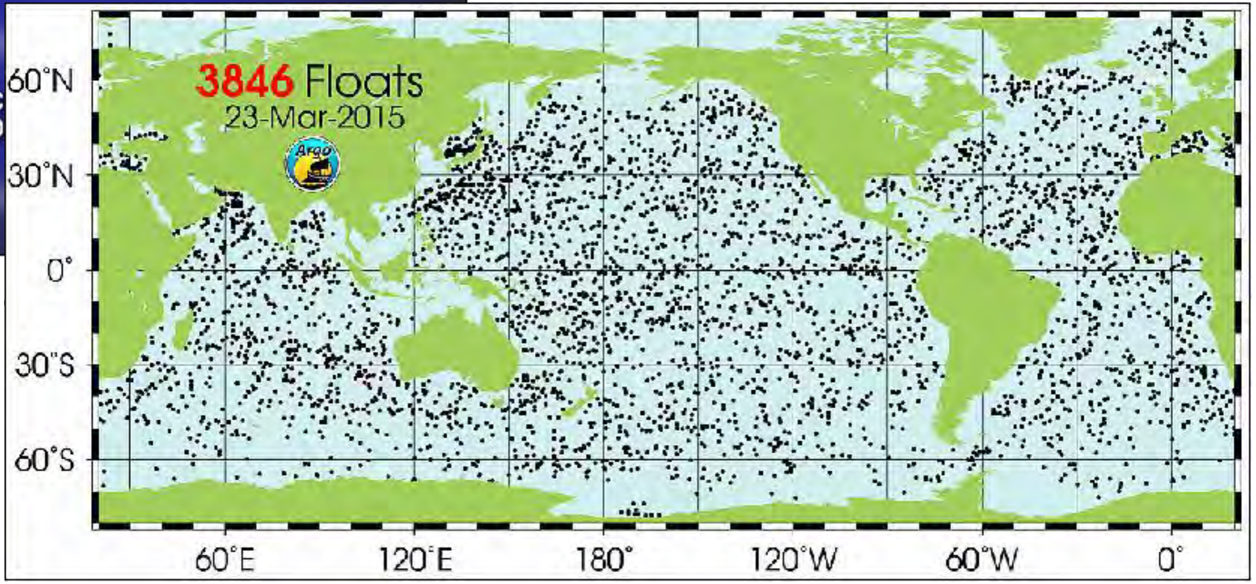
Measuring deep ocean temperatures



Schematic view of the SOLO fl
(image credit: UCSD)

- Satellite observations are most suited for sensing ocean temperature "close" to surface
- Deep oceans most commonly sense with profiling floats.

[image credit: AIC (Argo Information Center), USCD]



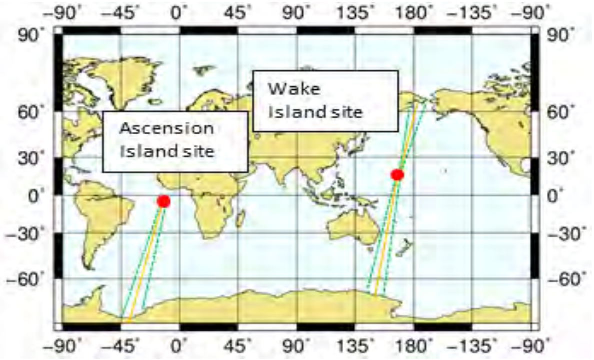
NOISE

Passive thermometry of the deep ocean

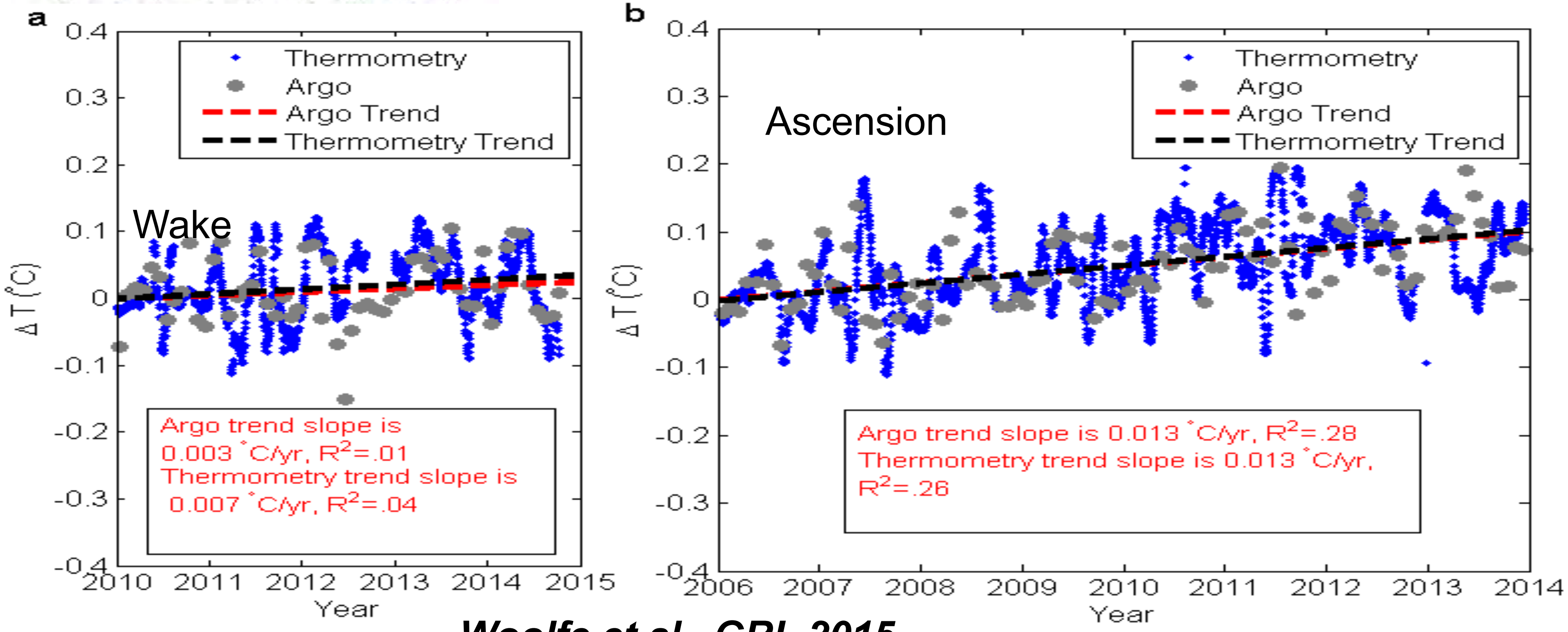
Comparison with ARGO temperature data (*Roemmich, D. and J. Gilson, 2009*)

Estimating Temperature changes: $\frac{\Delta t}{t_0} = -\frac{\Delta c}{c_0} = \alpha \Delta T (1 + \frac{\mu\beta}{\alpha})$ (Munk et al. 2009)

From baseline sound speed profile



Good match between Passive thermometry vs. Argo for linear trend & fluctuations (mesoscale variability ?)-1 week correlation intervals



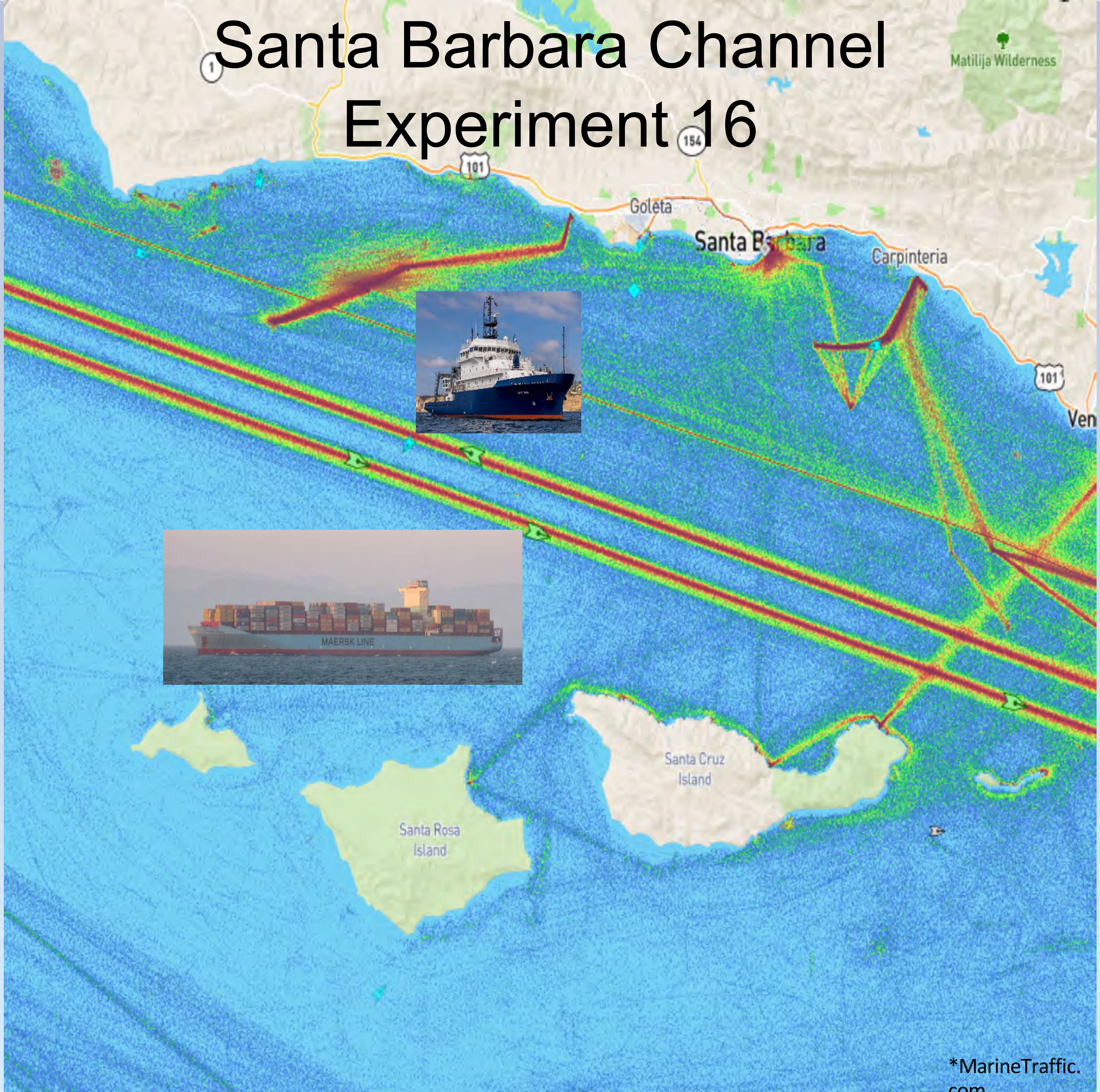
Woolfe et al., GRL 2015

Add Peak Tracking Optimization-Factor of 10 Reduction in Correlation Time

Woolfe et al., JASA-EL, 2015

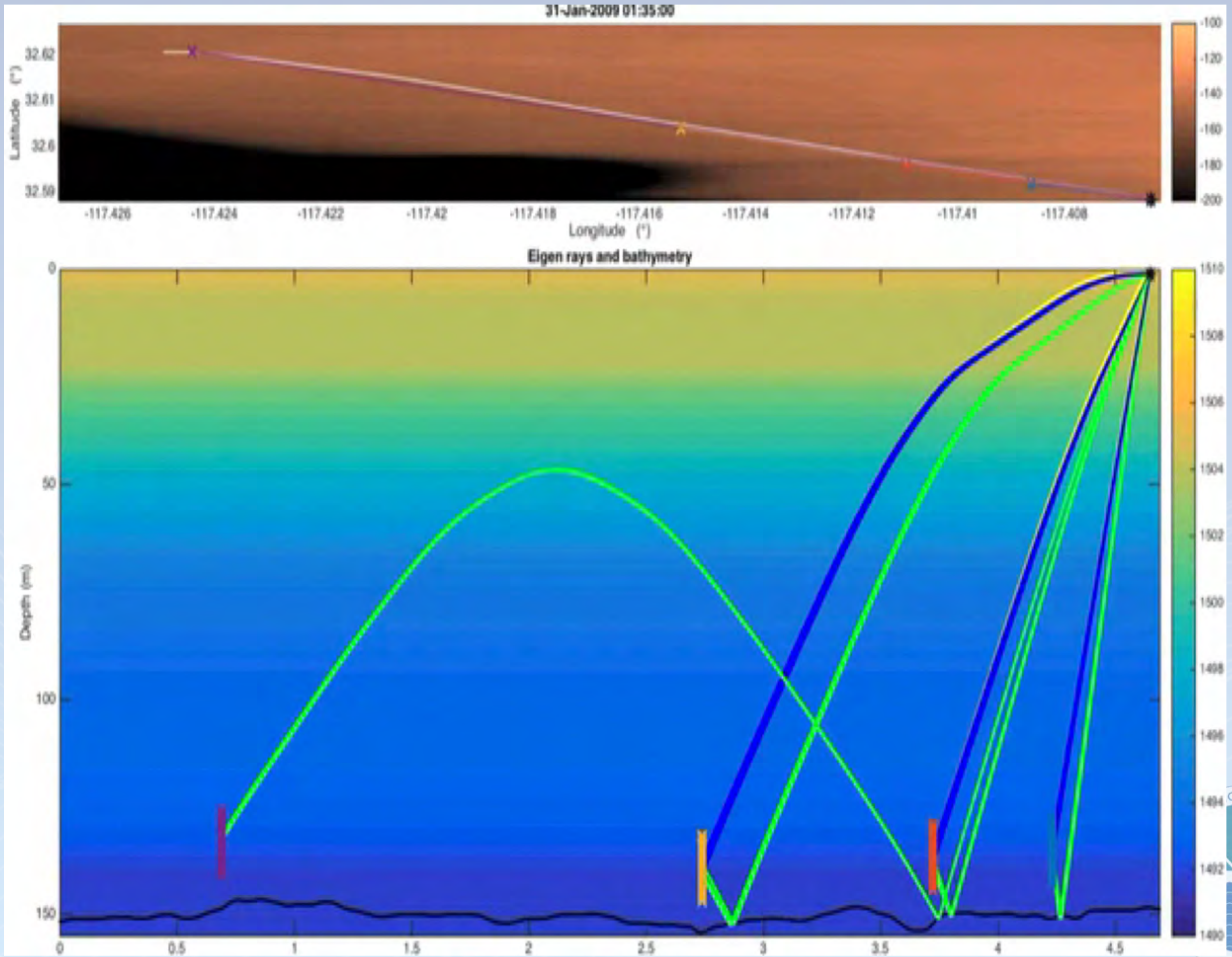
STAY TUNED

Santa Barbara Channel Experiment 16

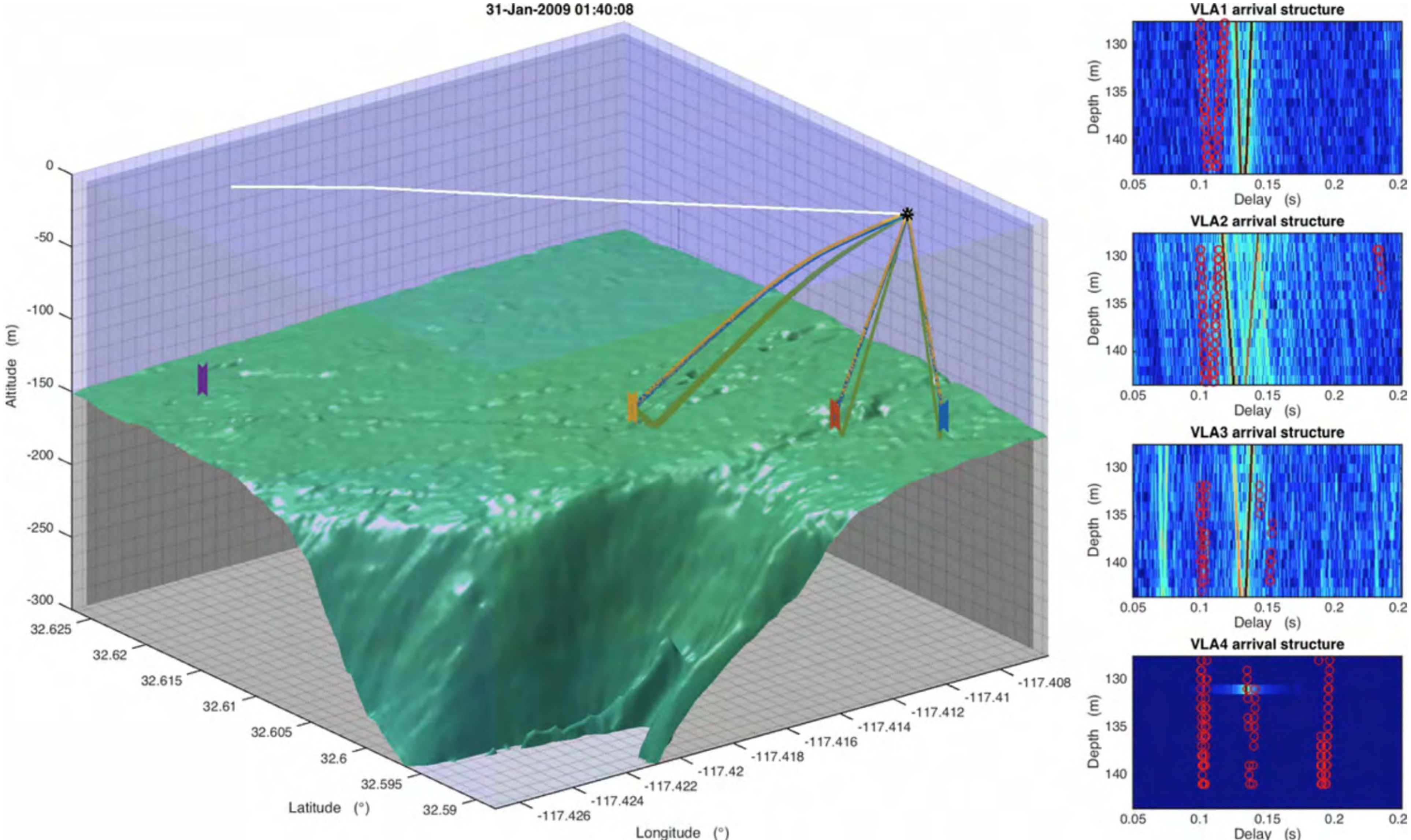


*MarineTraffic.com

Eigenrays and Bathymetry (active)



DATA+DECONVOLUTION+MODEL+AIS



AEL~cm

Preliminary Moving Tomograpy Results

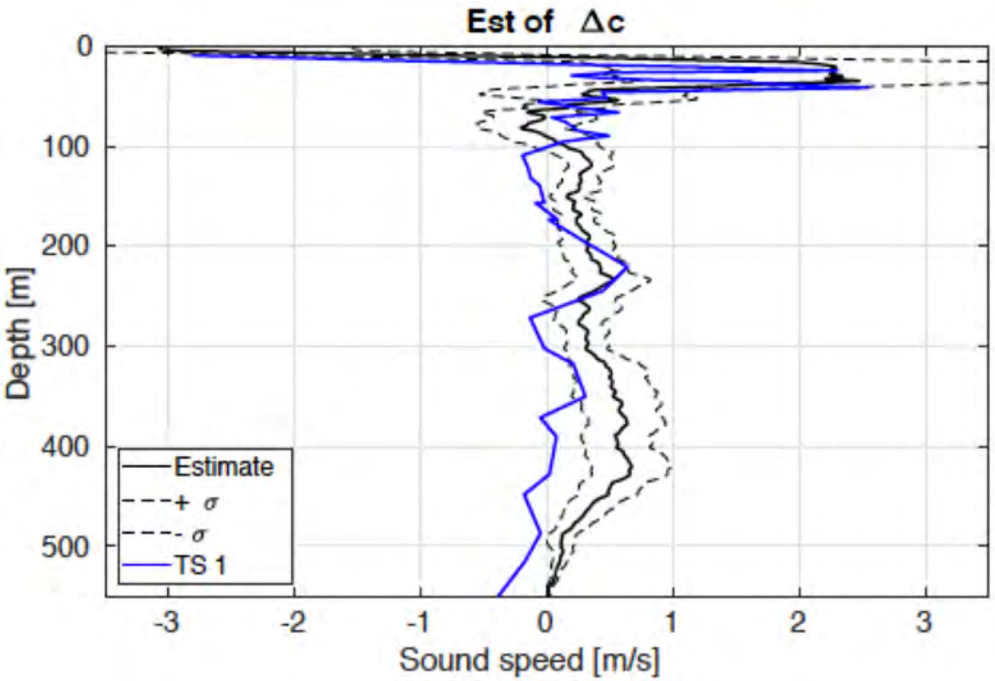


FIG. 4. Inversion results corresponding to the location of thermistor string (TS) 1 showing sound speed perturbation estimate and its standard deviation (calculated from estimated horizontal decorrelation scales).

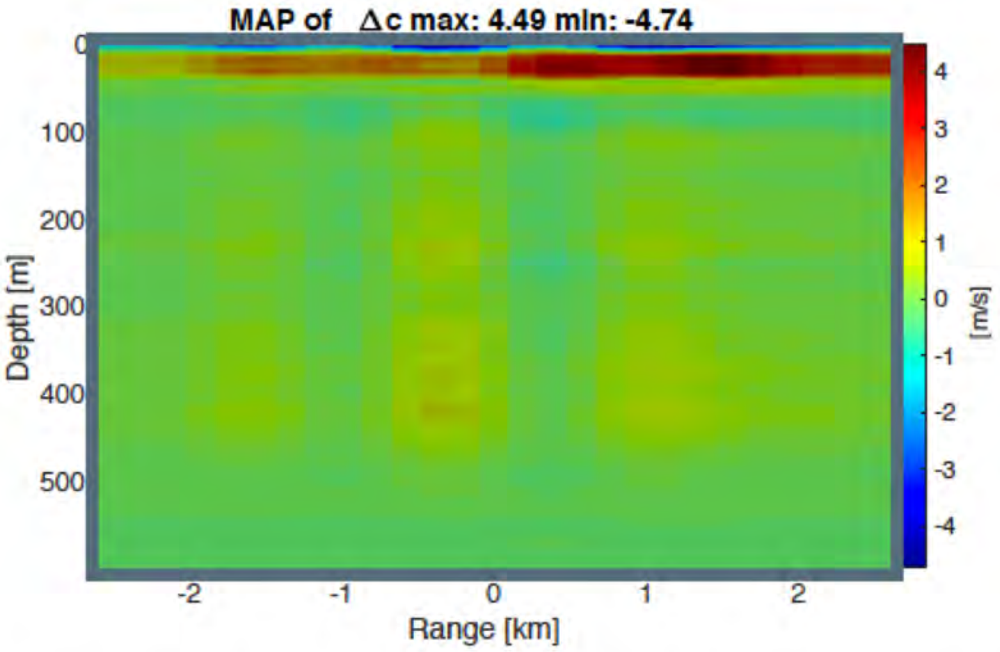


FIG. 5. Sound speed perturbation estimate corresponding to the blue slice shown in Fig. 10.

Gemba et al…in prep.

MOVING ON:

NOISE and STRUCTURAL ACOUSTICS:

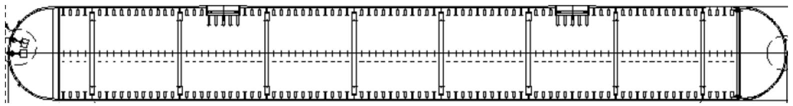
Holographic array for determining structural acoustic properties

With: Jit Sarkar, Sandrine T. Rakotonarivo, Simone Sternini, Alexis Bottero, Earl G. Williams, J.D. Tippmann, P. Roux

OBJECTIVES

- Construct a laboratory to measure the structural Green's function of an elastic object (structural impedance matrix) excited by an external random noise field, by using measurements of surface velocity & pressure.
- With this information predict the scattered field for any coherent incident field condition, **in any medium**.

Ribbed cylindrical shell (C50)



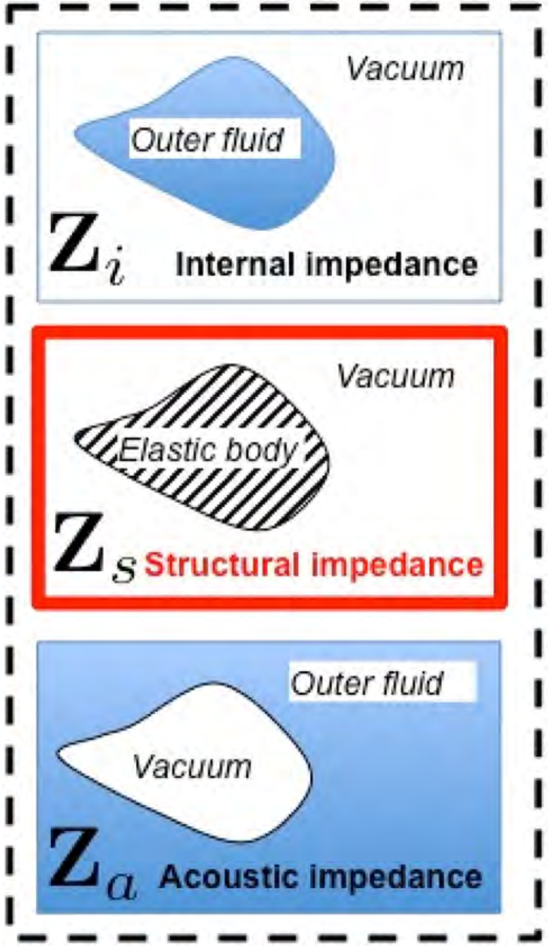
Rakotonarivo, Kuperman, Williams (2013), *Prediction of a body's structural impedance and scattering properties using correlation of random noise* , JASA (2013)

OUTLINE

- THEORY BEHIND MEASUREMENTS
- LABORATORY COMPONENTS
- MEASUREMENTS AND COMPARISON WITH FEM

INTRODUCTION-1

We need three *surface* impedances to characterize the scattering from an elastic body given the incident pressure field:



$$\mathbf{p} = \mathbf{p_i} + \mathbf{p_s} \text{ and } \mathbf{v} = \mathbf{v_i} + \mathbf{v_s}$$

→ $\mathbf{p_i} = -\mathbf{Z_i}\mathbf{v_i}$ Incident Fields

(i.e. Interior Neumann Green fcn.)

→ $\mathbf{p} = -\mathbf{Z_s}\mathbf{v}$ Total Fields

$\mathbf{Z_s}$ is the Structural Impedance

→ $\mathbf{p_s} = \mathbf{Z_a}\mathbf{v_s}$ Scattered Fields

(i.e. Exterior Neumann Green fcn.)

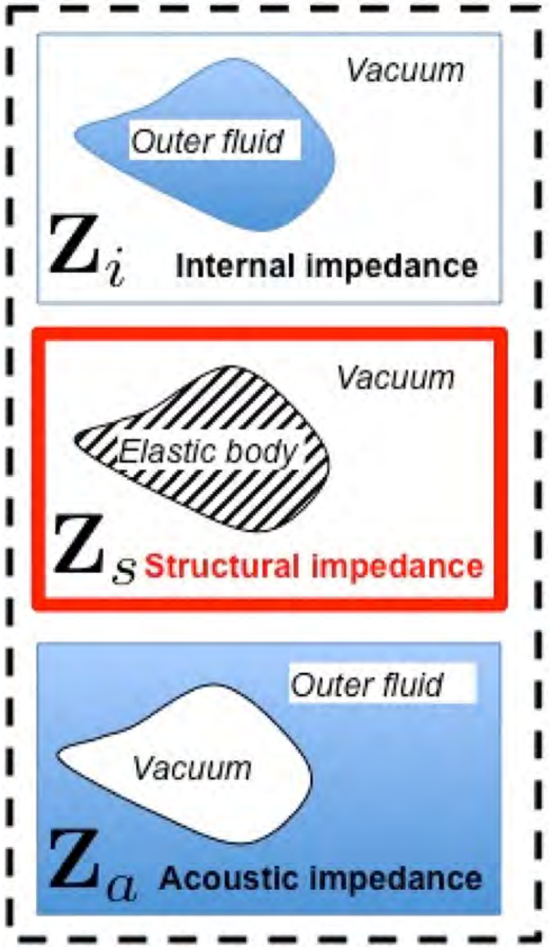
Borgiotti (1990); Gaumond et Yoder (1995); Lucifredi and Schmidt (2004); Bobrovnitskii (2006)

INTRODUCTION-2

Simple manipulation of the impedances yields[1],

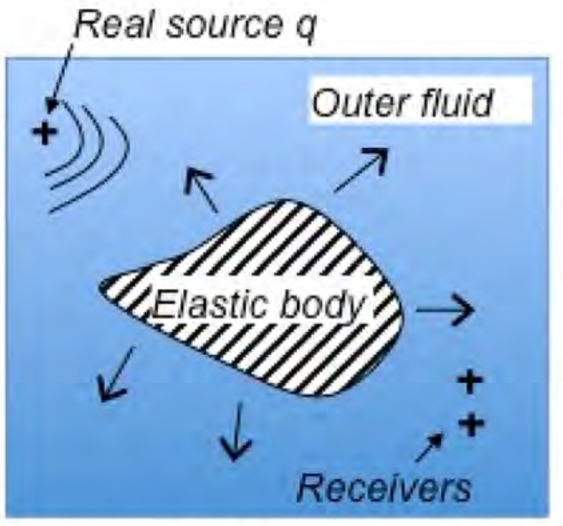
where $\mathbf{p}_s$ is the scattered field **on the surface:**

$$\mathbf{p}_s = \underbrace{\left(\frac{1}{\mathbf{Z}_a} + \frac{1}{\mathbf{Z}_s}\right)^{-1} \left(\frac{1}{\mathbf{Z}_i} - \frac{1}{\mathbf{Z}_s}\right)}_{Q = \text{Scattering Matrix}} \mathbf{p}_i$$



$\mathbf{Z}_s$ contains the physics of the elastic body *when placed in a vacuum*

NOTE: $Y=Z^{-1}$



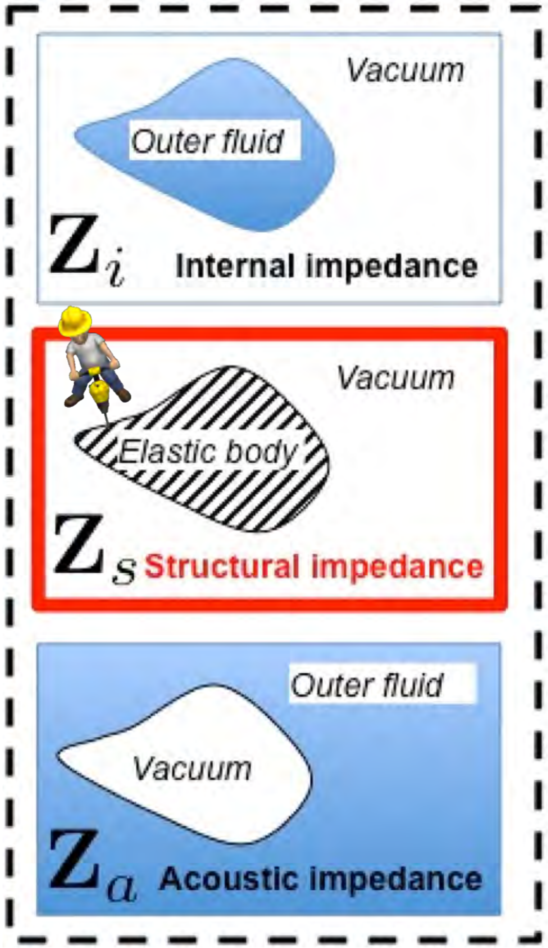
Scattered field at the receivers

[1]Bobrovntiskii (2006), *A new impedance-based approach to analysis and control of sound scattering*

Borgiotti (1990); Gaumond et Yoder (1995); Lucifredi and Schmidt (2004); Bobrovnitskii (2006)

INTRODUCTION-2

Simple manipulation of the impedances yields[1],

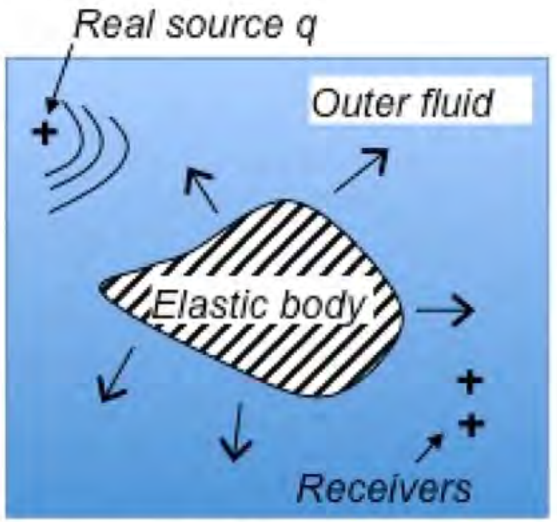


where $\mathbf{p}_s$ is the scattered field **on the surface:**

$$\mathbf{p}_s = \underbrace{\left(\frac{1}{\mathbf{Z}_a} + \frac{1}{\mathbf{Z}_s}\right)^{-1} \left(\frac{1}{\mathbf{Z}_i} - \frac{1}{\mathbf{Z}_s}\right)}_{Q=\text{Scattering Matrix}} \mathbf{p}_i$$

$\mathbf{Z}_s$ contains the physics of the elastic body *when placed in a vacuum*

NOTE: $Y=Z^{-1}$



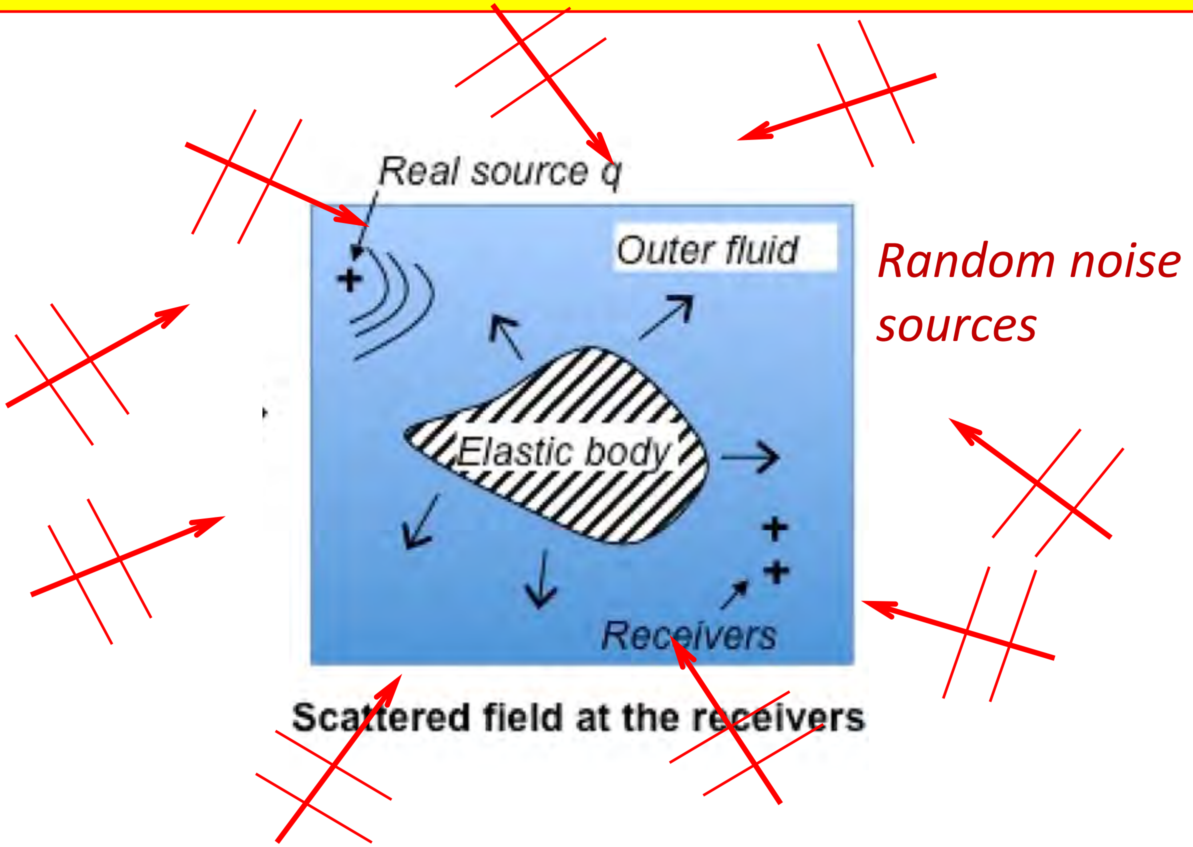
Scattered field at the receivers

[1]Bobrovntiskii (2006), *A new impedance-based approach to analysis and control of sound scattering*

Borgiotti (1990); Gaumond et Yoder (1995); Lucifredi and Schmidt (2004); Bobrovnitskii (2006)

SO, WE NEED TO MEASURE $\mathbf{Z_s}$

- Measure : $\mathbf{Z_s}$ the elastic object's structural impedance matrix by placing it in a random noise field and measuring surface normal velocity and pressure. (Scattered field ”loaded object then easily determined*)
- * Bobrovntiskii (2006), *Rakotonarivo, Williams, Kuperman (2013)*



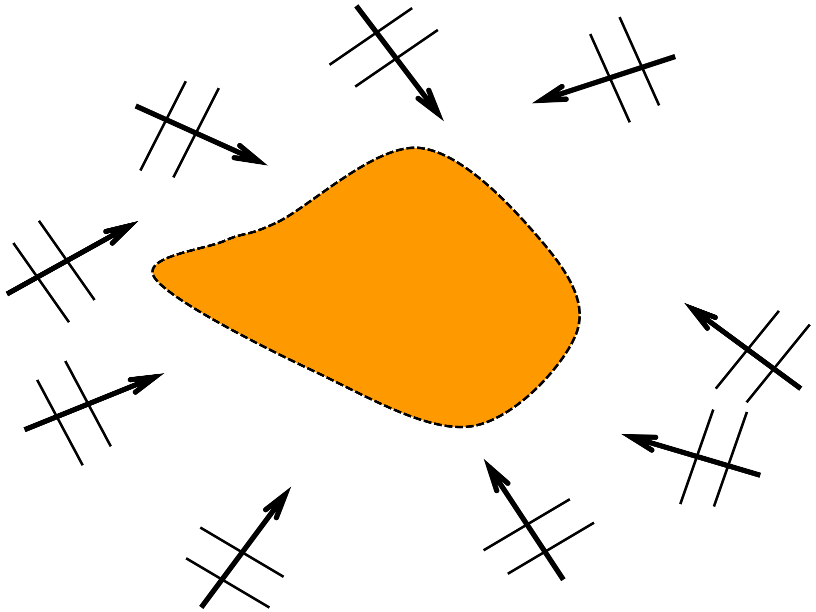
MEASUREMENT of the STRUCTURAL IMPEDANCE

Cross-Correlation method to predict Z_s from the noise

$$\mathbf{p} = -\mathbf{Z_s}\mathbf{v}$$

Multiply both sides by $\mathbf{p}^H$

L realizations (random noise sources)



Outer Products, cross-correlations of all sensor pairs, are averaged over *L* realizations

$$\langle \mathbf{p}\mathbf{p}^H \rangle = -\mathbf{Z_s} \langle \mathbf{v}\mathbf{p}^H \rangle$$

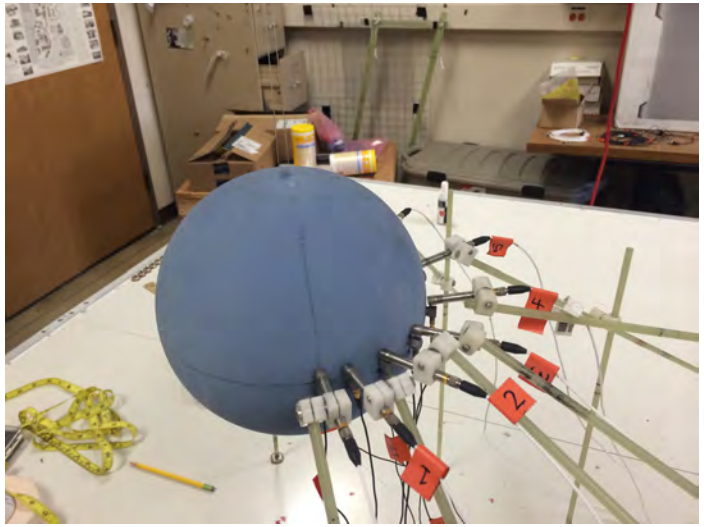
Pressure field at *N* surface nodes

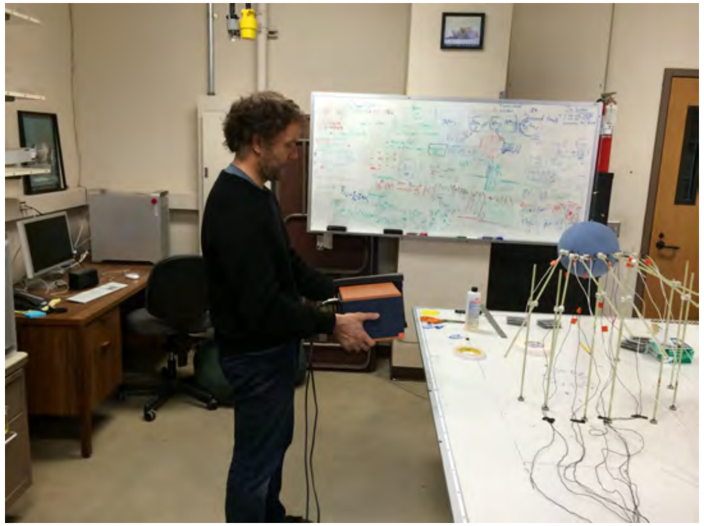
Normal velocity at *N* surface nodes

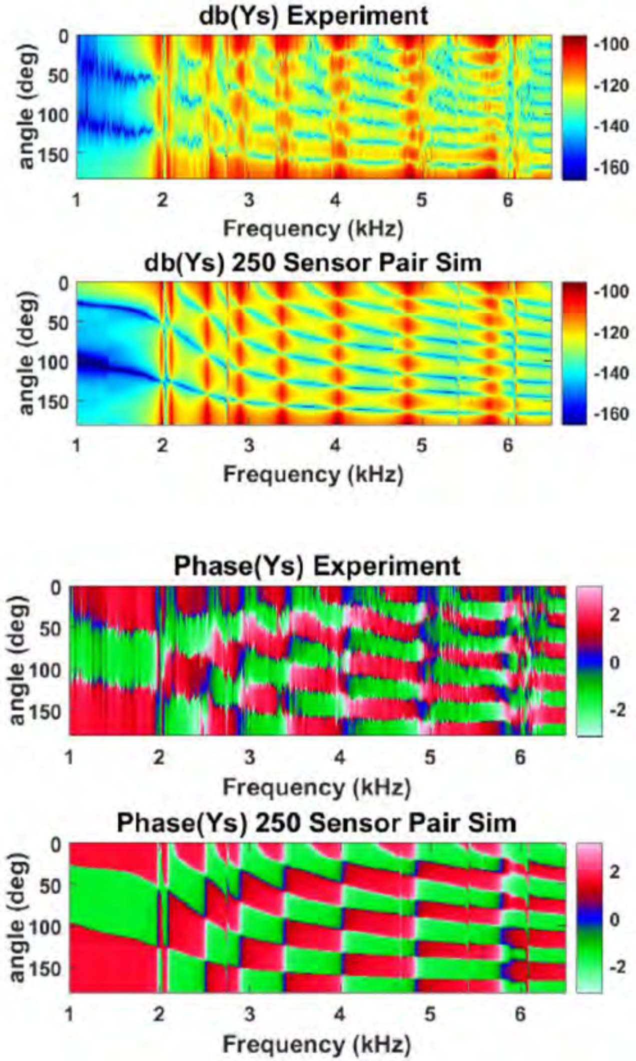
Rakotonarivo, Williams, Kuperman… (2013,2017)

LAST TIME: Proof of Concept: Initial on-the-object measurements

- Measurements with only 8+8 sensors on the surface of spherical shell placed in noise
- Symmetry(not possible for arbitrary object) used for data analysis







- Successful construction of Ys
- Insufficient accuracy to get S-matrix in water

→

- **FOR ARBITRARY SCATTERER NEED ABOUT 250 ACCELS AND MIKES**

CONSTRUCT A Dual Surface Array

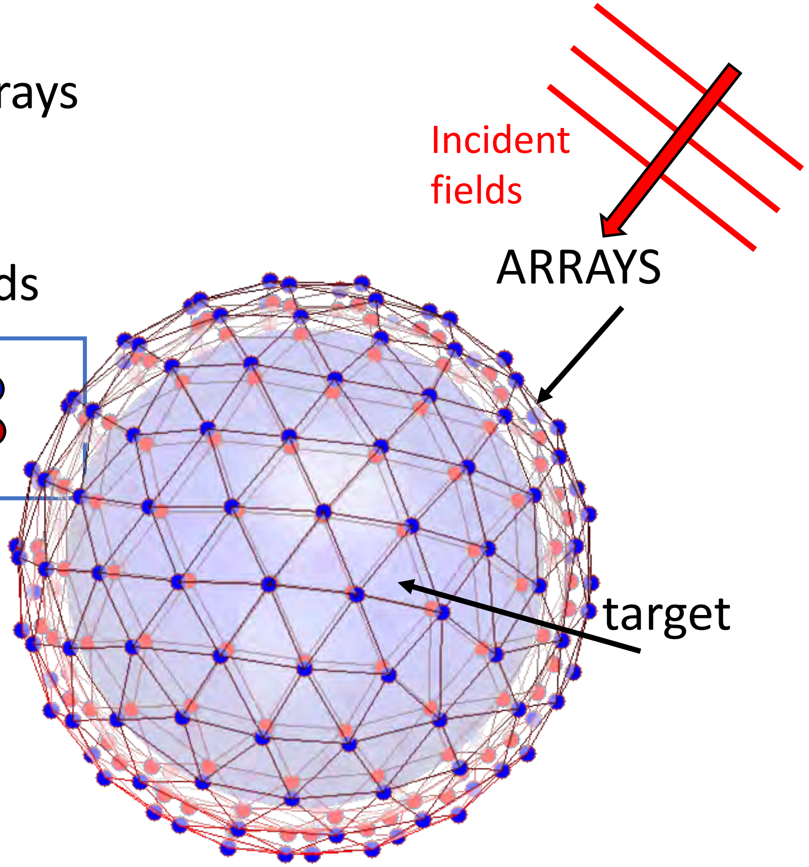
We require a measurement of the total pressure and normal velocity on the surface of a Target

1. Use two conformal (~250-element) arrays "Holographic Surfaces"

2. (FST) Separate Incident/Scattered Fields

3. Compute Pressure and Velocity on object surface

4. Compute Ys…

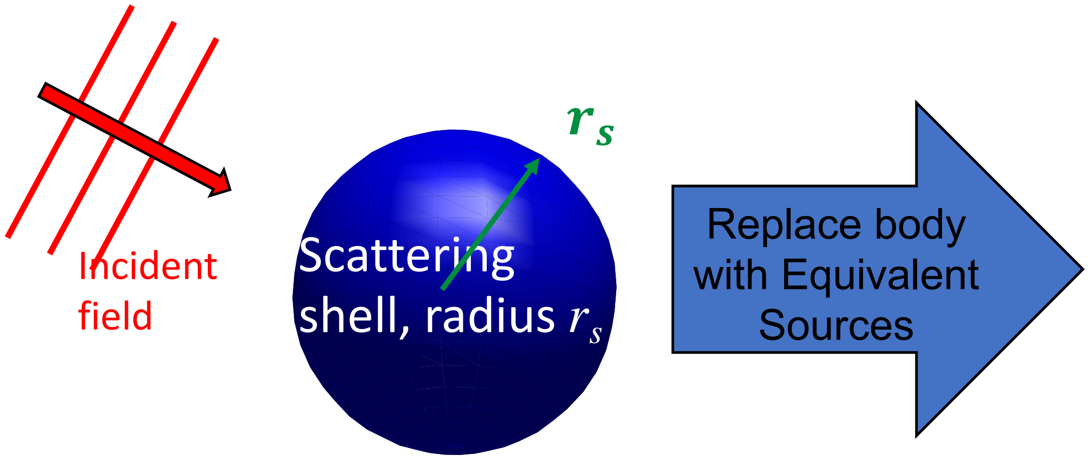


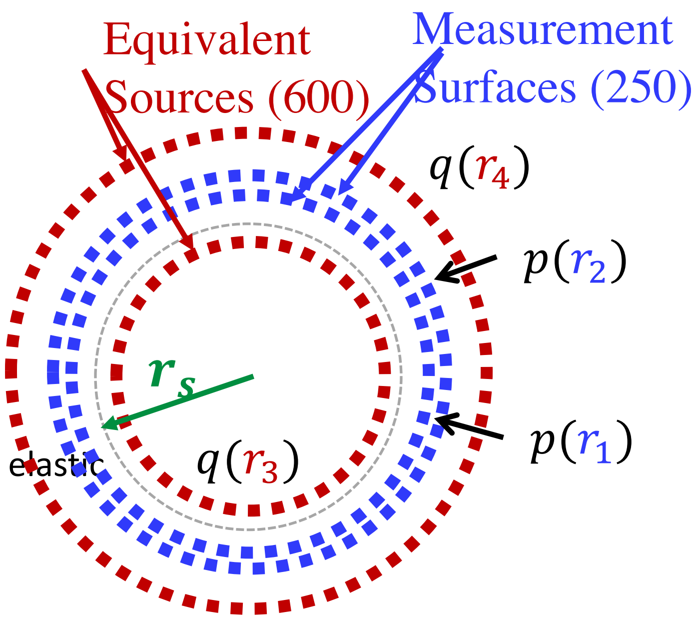
Dual conformal mic surfaces

HOW?

Field Separation (FST) using Equivalent Source Method:

We need to find p and v on surface of object





- NAH SURFACES: Two conformal measurement arrays ($p(r_1), p(r_2)$) close to elastic target
- Two equivalent source surfaces of unknown strengths,
  - $q(r_3)$ inside for scattered field
  - $q(r_4)$ outside for incident field
- ($p(r_1), p(r_2)$) are sums of incident and radiated fields so we can invert for q's using free field Green's functions

$$\begin{bmatrix} G_{31} & G_{41} \\ G_{32} & G_{42} \end{bmatrix} \begin{bmatrix} q(r_3) \\ q(r_4) \end{bmatrix} = \begin{bmatrix} p(r_1) \\ p(r_2) \end{bmatrix}$$

$$\begin{bmatrix} q(r_3) \\ q(r_4) \end{bmatrix} = \begin{bmatrix} G_{31} & G_{41} \\ G_{32} & G_{42} \end{bmatrix}^{-1} \begin{bmatrix} p(r_1) \\ p(r_2) \end{bmatrix}$$

- Knowing q's we propagate both fields to surface to get total **p(r$_s$)** and **v(r$_s$)**

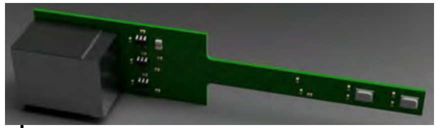
$$p_i(\mathbf{r}_s) = \sum_{\mathbf{r}_4} G(\mathbf{r}_s, \mathbf{r}_4) q(\mathbf{r}_4) \qquad v_i(\mathbf{r}_s) = \frac{1}{i\omega\rho} \frac{\partial}{\partial n(\mathbf{r}_s)} \sum_{\mathbf{r}_4} G(\mathbf{r}_s, \mathbf{r}_4) q(\mathbf{r}_4)$$

$$p_s(\mathbf{r}_s) = \sum_{\mathbf{r}_3} G(\mathbf{r}_s, \mathbf{r}_3) q(\mathbf{r}_3) \qquad v_s(\mathbf{r}_s) = \frac{1}{i\omega\rho} \frac{\partial}{\partial n(\mathbf{r}_s)} \sum_{\mathbf{r}_3} G(\mathbf{r}_s, \mathbf{r}_3) q(\mathbf{r}_3)$$

- ***ISSUE: TOTAL VELOCITY on SURFACE is VERY SMALL. So Use:*** Elastic Component of Velocity (Blocked Pressure Subtraction)

WHAT WE'RE USING: Laboratory Equipment

- Custom Dual Digital MEMS Microphone sensors

- Custom Data Aggregator Boards

- Digital only DAQ – No amplifier/conditioners/ADC required



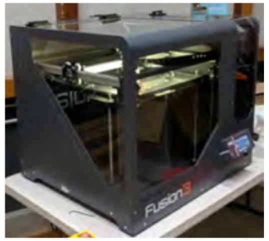

NI myRIO (small FPGA)

Digilent Digital Discovery (small FPGA)

NI PXIe system (+4x large FPGAs)

- NVIDIA DGX-Station GPU processing system


- 3x 3D Printers


- 2x 3D Scanners


- Scanning Laser Doppler Vibrometer

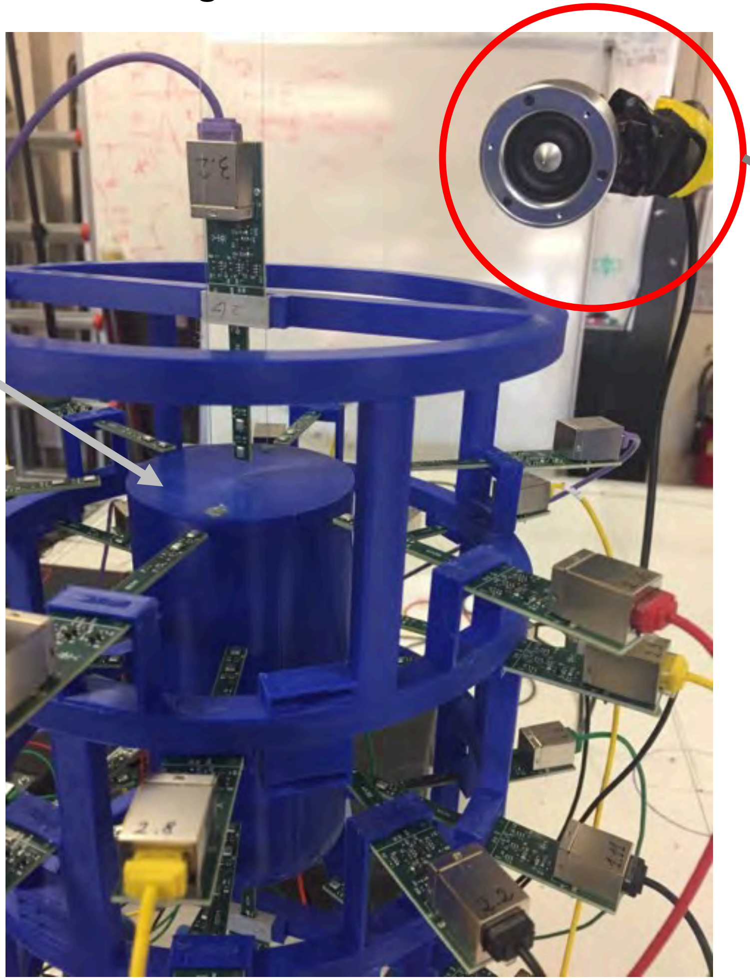

- Robotic manipulator

Measurements with capped cylindrical target

- Measurements with 32 sensors mounted on the scaffold, at 5mm and 15mm from the cylindrical target

- A white noise source (0.5-24 kHz bandwidth) at 340 different locations was used to generate the incident acoustic field around the target

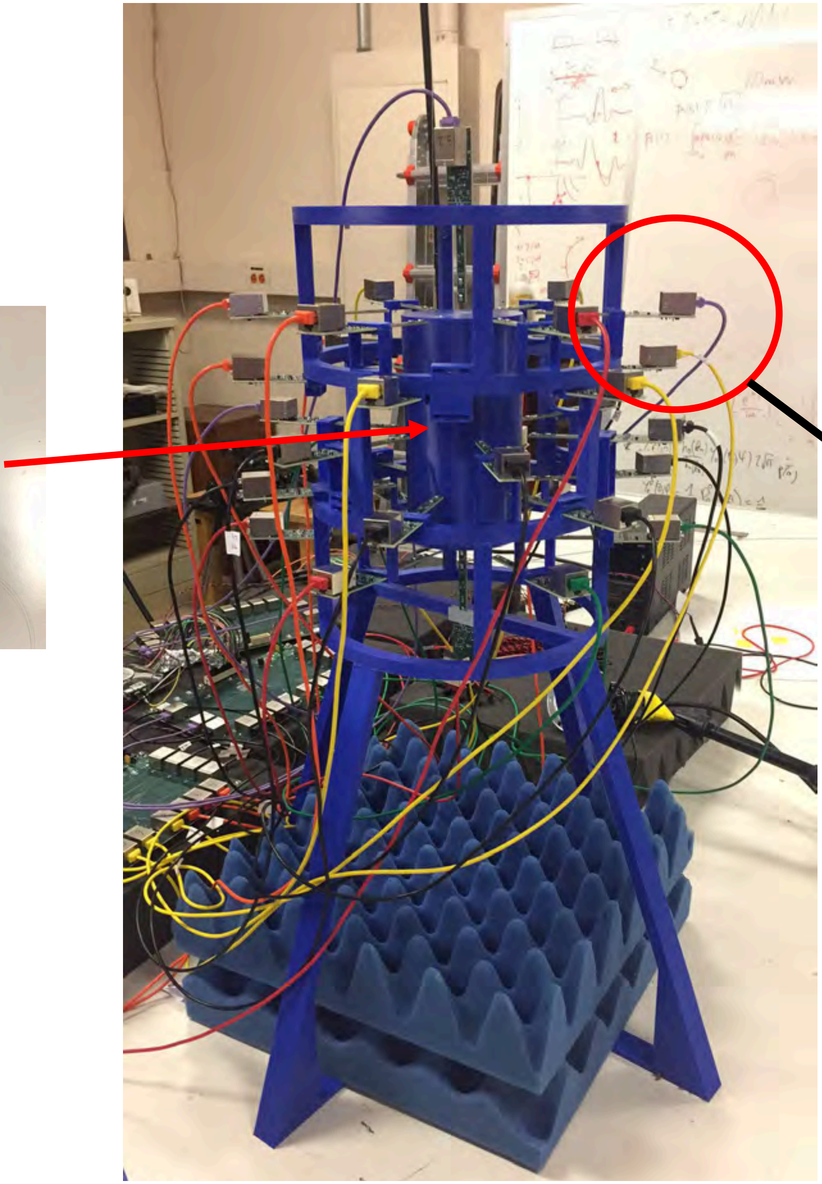
- Capped Cylindrical Target:
  Height: 0.15 m
  Thickness: 0.0025 m
  Outer radius: 0.04 m
  Material: PLA



Speaker (source)

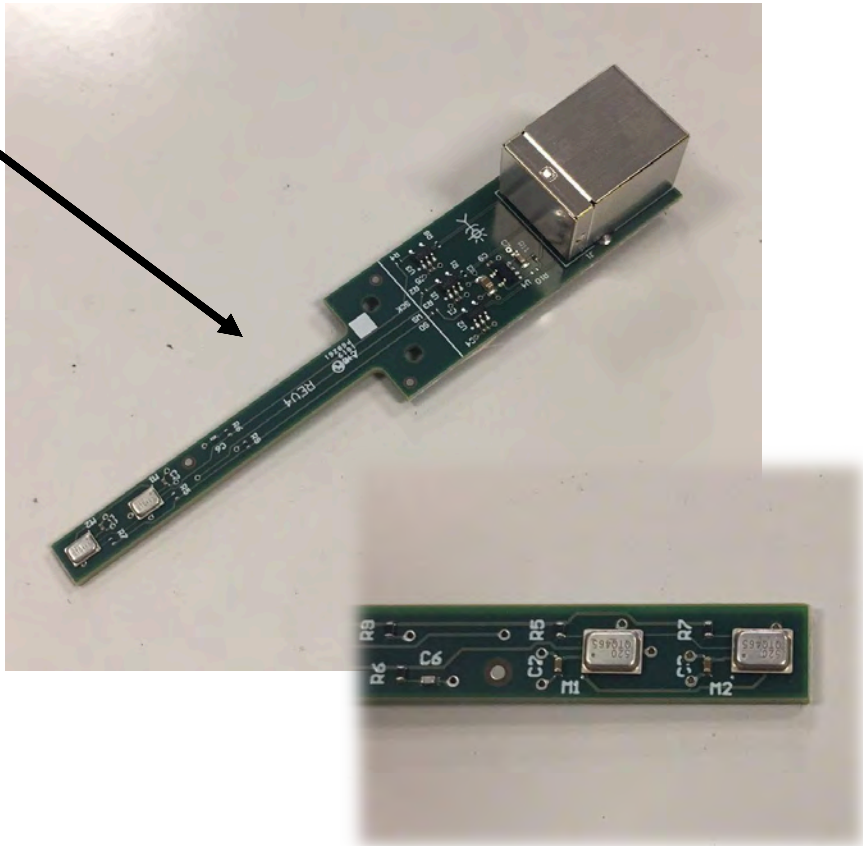
Experimental Setup

- Measurements with 10 or 32 sensors mounted on the scaffold, at 5mm and 15mm from the cylindrical target

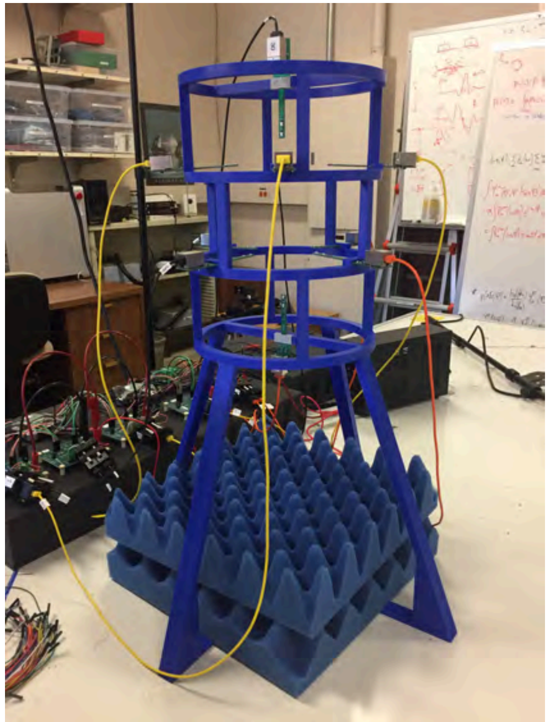


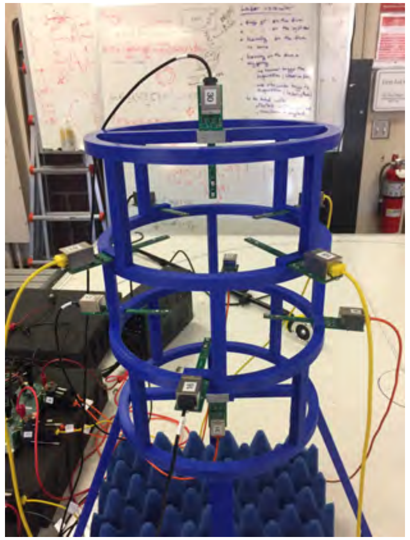
- Tests performed with and without target using a white noise source at different locations around the scaffold

- Pairs of MEMS sensors were used to record the acoustic signals (hologram surfaces)

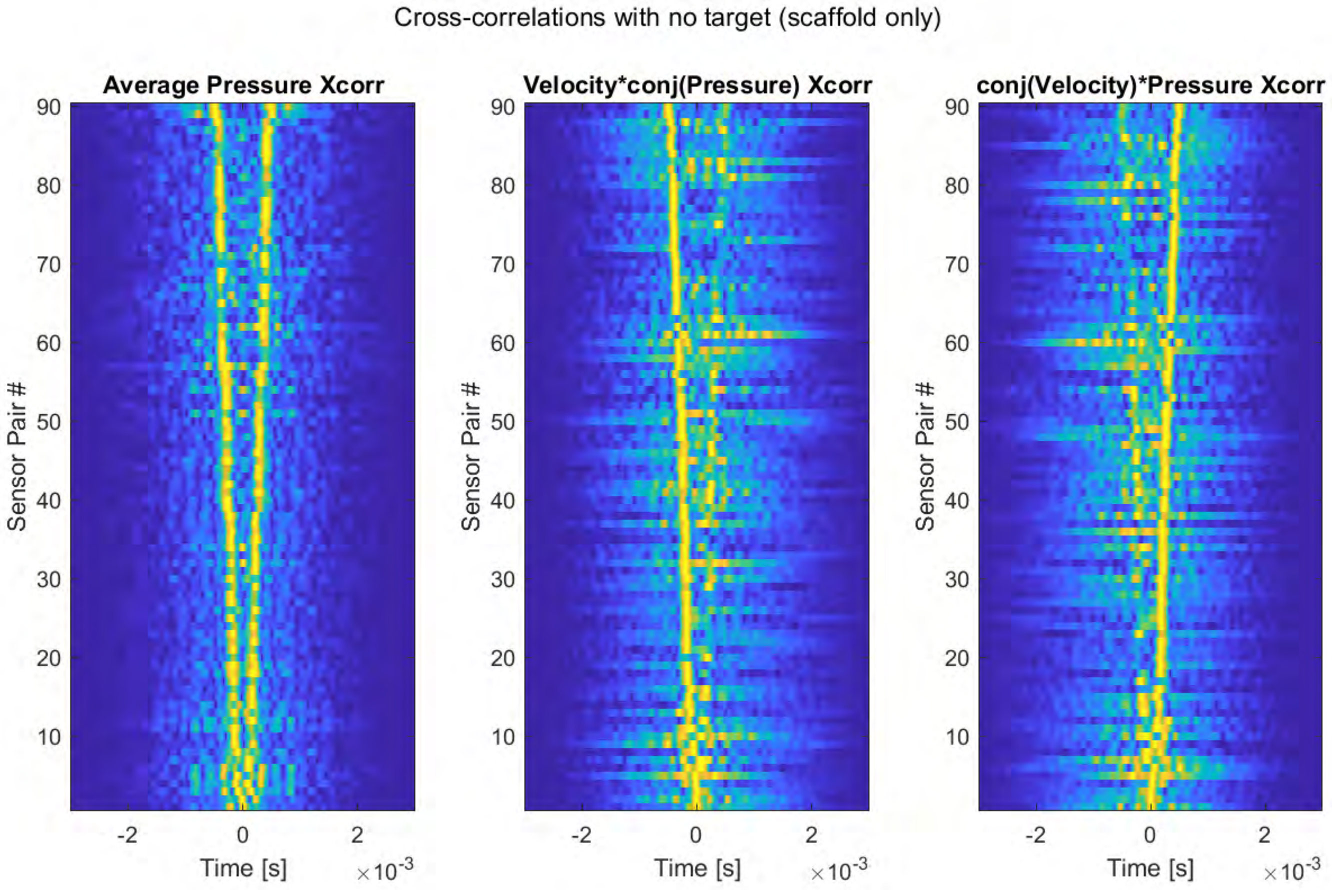


Measurements with no target (scaffold only)





- Measurements with only 10 sensors mounted on the scaffold and no cylindrical target (305 source positions, white noise 0.5-24 kHz bandwidth)
- Reconstruction of the Green's function between all sensor pairs does not seem to be affected by the presence of the scaffold

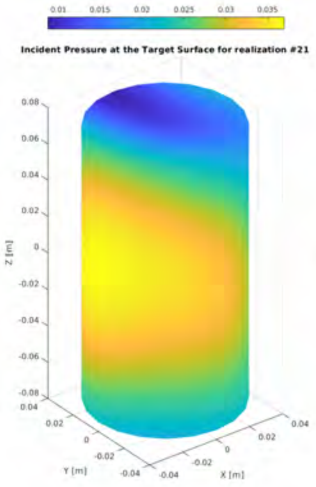


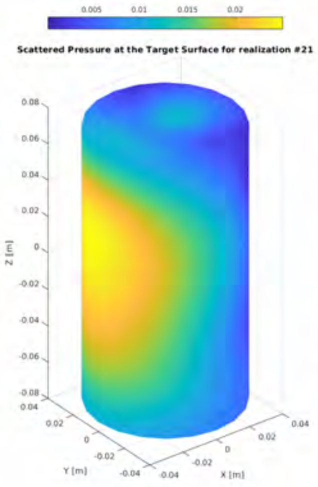
Reconstructed Pressure and Velocity at the Target Surface

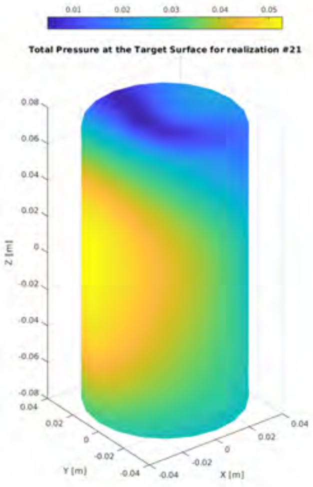
f = 950 Hz

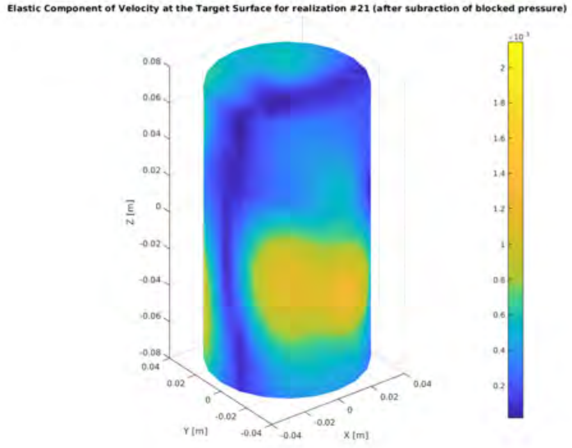
Incident Pressure | Scattered Pressure | Total Pressure | Elastic Velocity

Source Position # 21

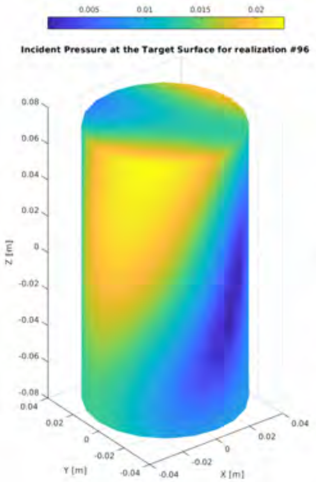


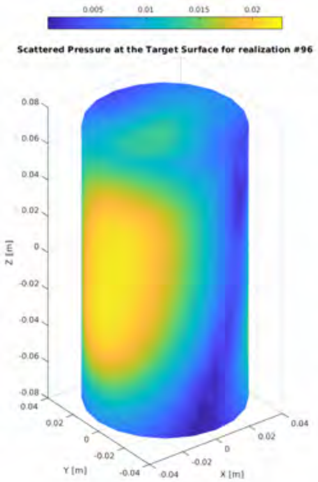


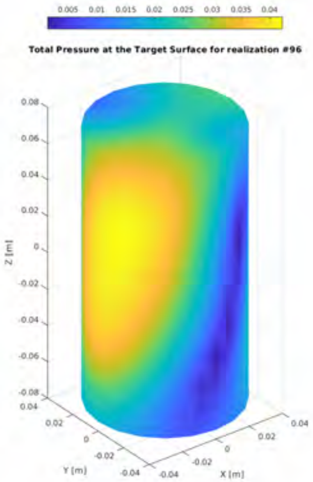


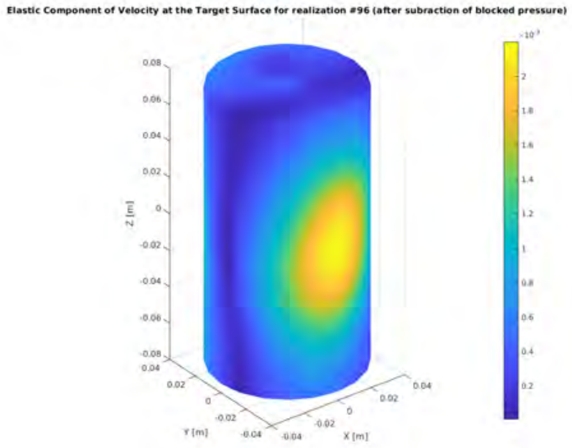


Source Position # 96









FEM Simulation of the Capped Cylindrical Target

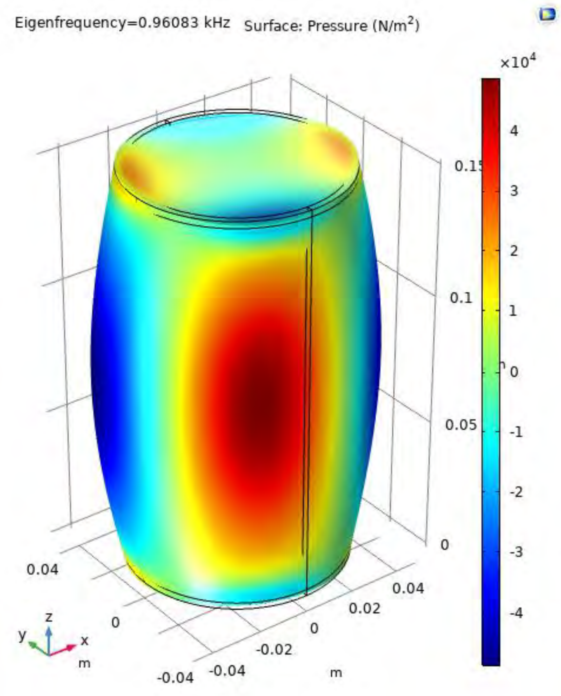
- Cylinder Properties:
  - Height: 0.15 m
  - Thickness: 0.0025 m
  - Outer radius: 0.04 m

Inner medium: Air
ρ = 1.225 kg/m^3
c = 340 m/s

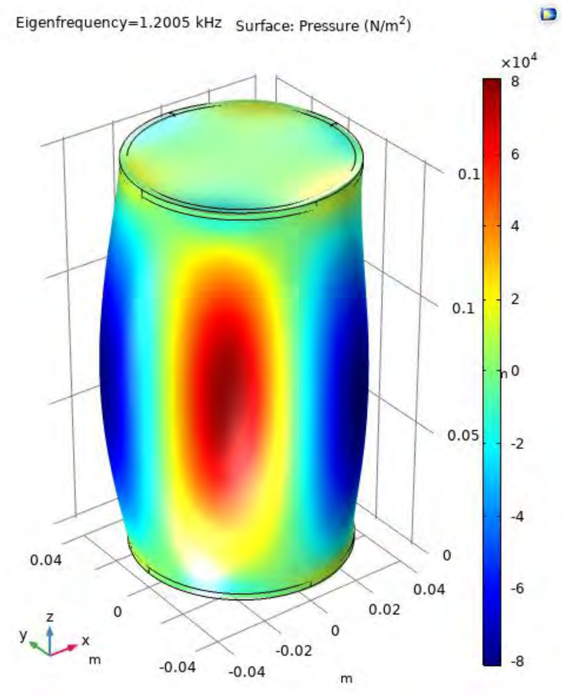
Cylinder Material: PLA
Young's modulus E = 3.5 Gpa
Poisson ratio $\nu = 0.33$
Density ρ = 1250 kg/m^3
Lossless shell

Eigenfrequency Analysis

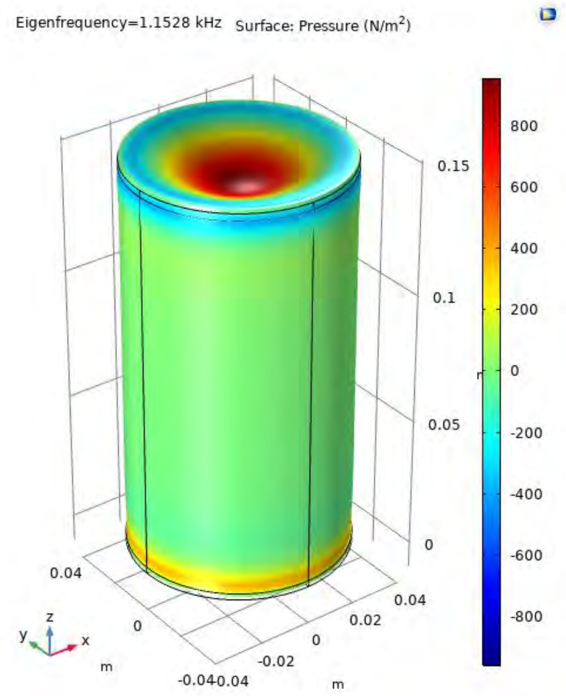
N = 2 at 960 Hz



N = 3 at 1200 Hz



Cap Mode at 1150 Hz

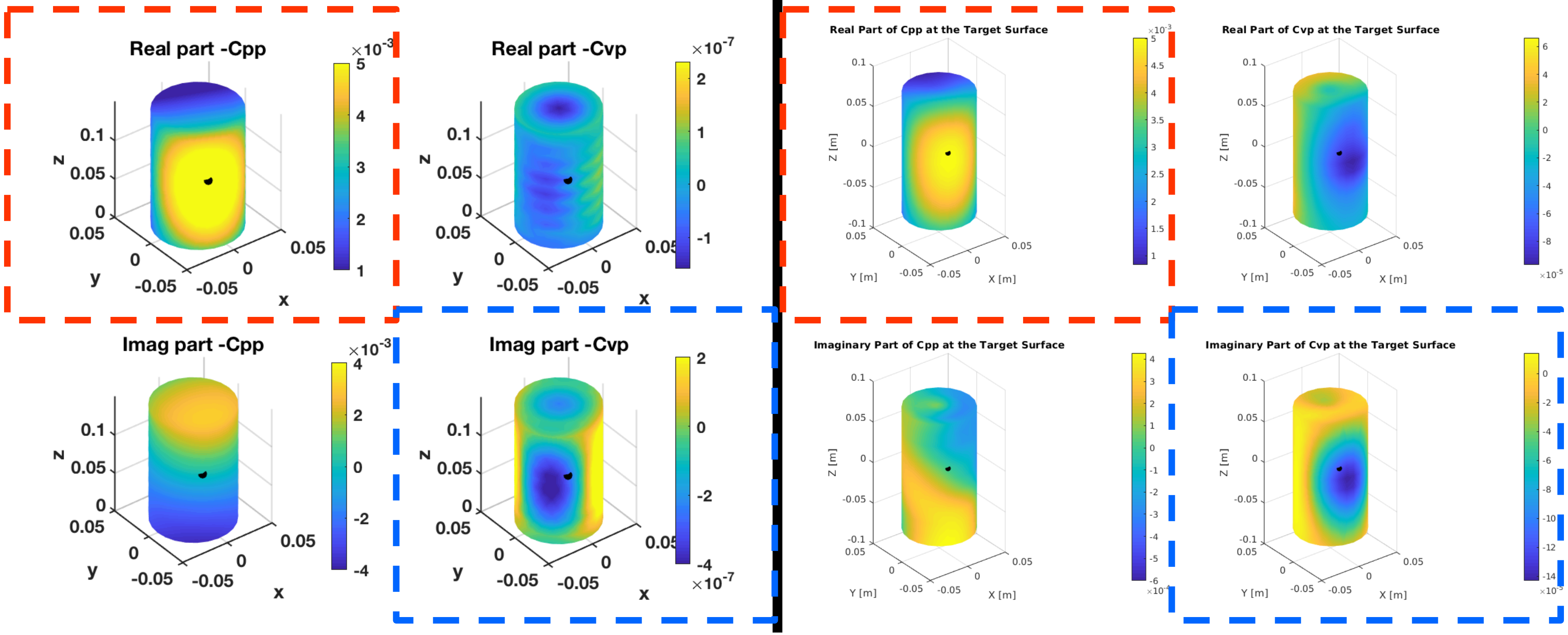


Correlation Matrices at the Target Surface

- Comparison of real and imaginary parts of the correlation matrices (pressure-pressure and velocity-pressure) at 950 Hz for simulated and experimental data (black dot = excitation point)

COMSOL SIMULATION | EXPERIMENTAL DATA

$\langle \mathbf{pp}^H \rangle$ $\langle \mathbf{vp}^H \rangle$ | $\langle \mathbf{pp}^H \rangle$ $\langle \mathbf{vp}^H \rangle$

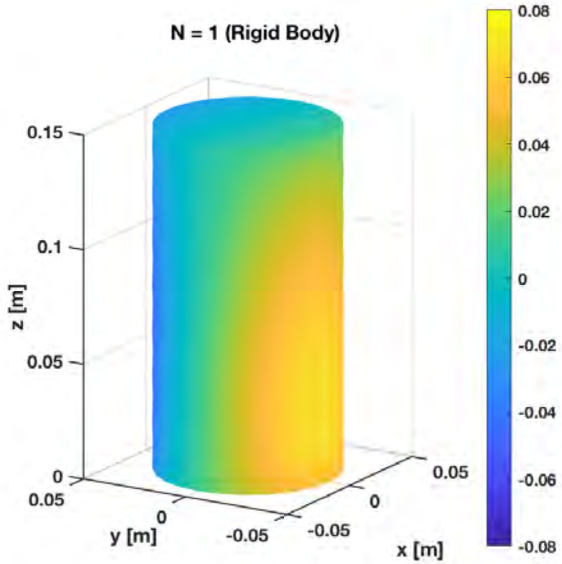


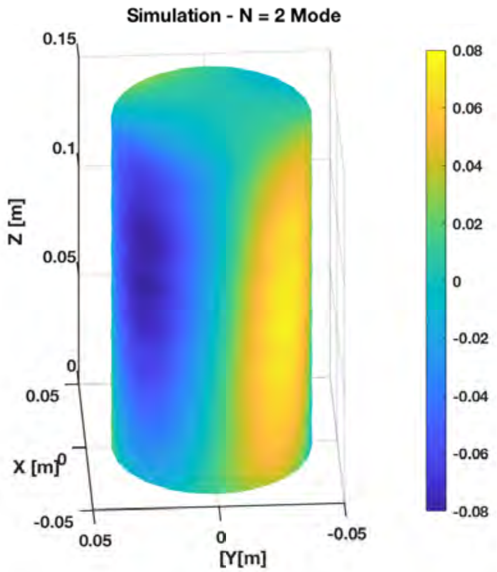
- Good match for the real part of Cpp and the imaginary part of Cvp
- Imaginary part of Cpp and real part of Cvp not relevant as they are mainly related to medium losses

Comparison of Eigenmodes between FEM and Experiments

- SVD of <pp*> = U S V* ➡ Columns of U and V are related to the eigenmodes of the target

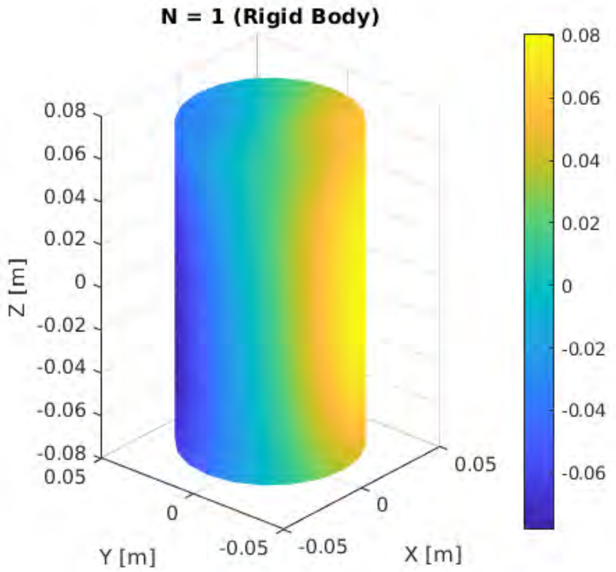
COMSOL SIMULATION

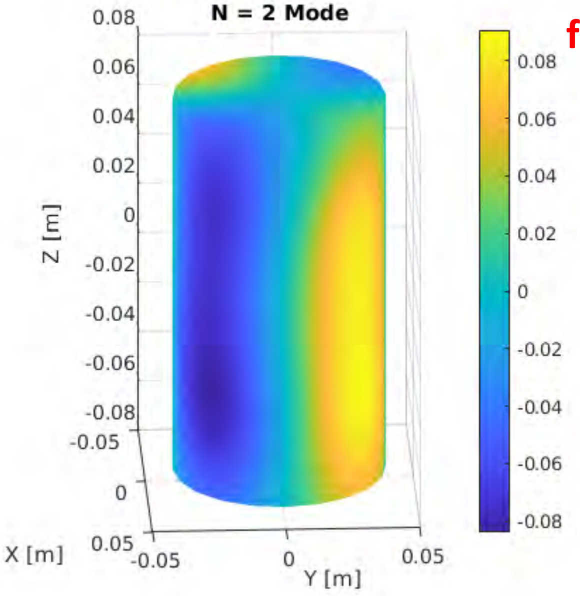




EXPERIMENTAL DATA

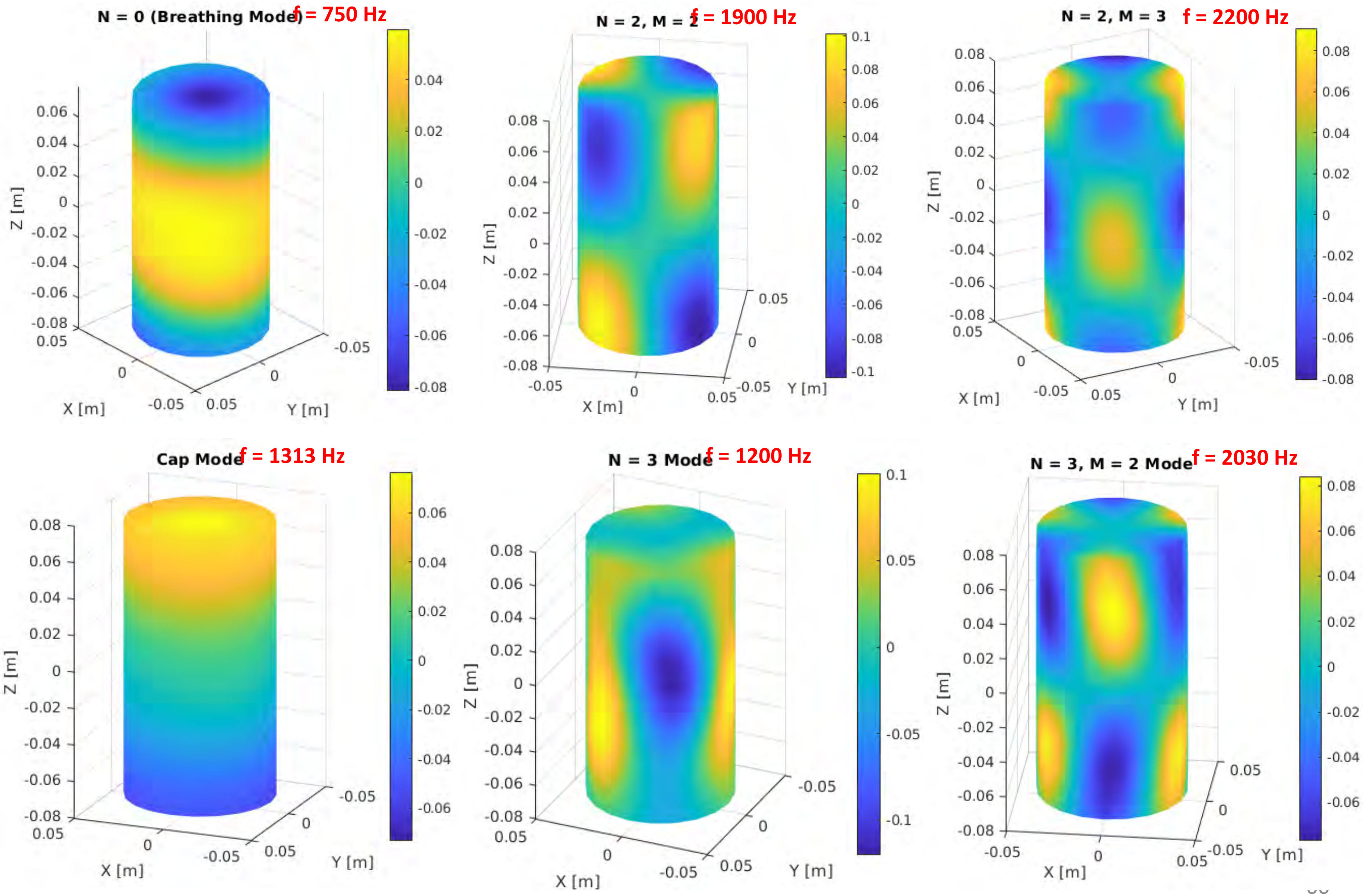
f = 700 Hz





f = 960 Hz

Additional Eigenmodes reconstructed from Experiments

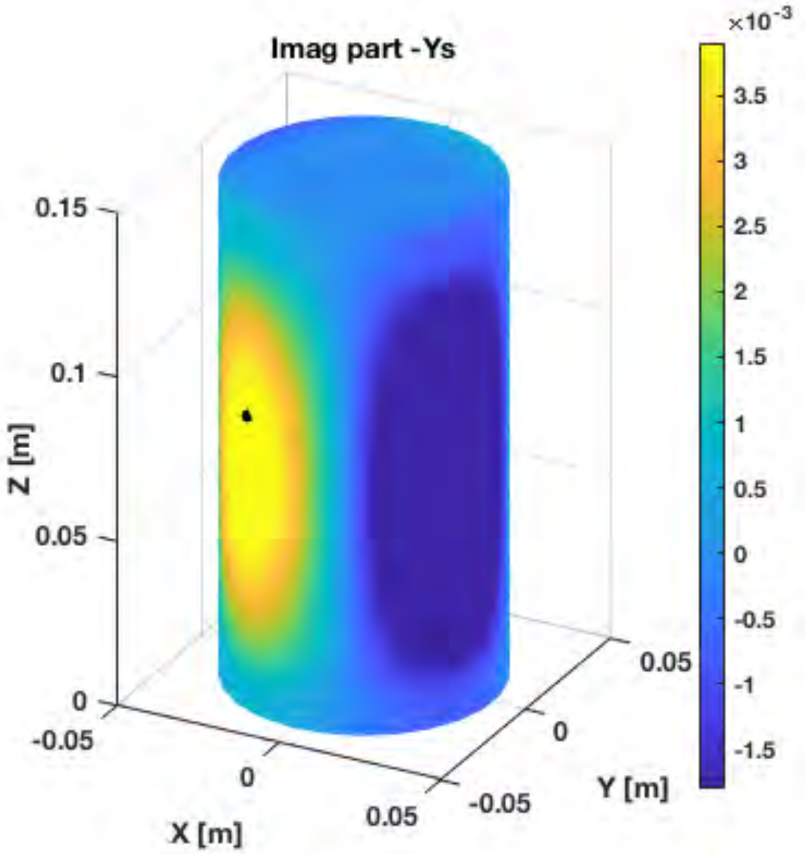


Structural Admittance

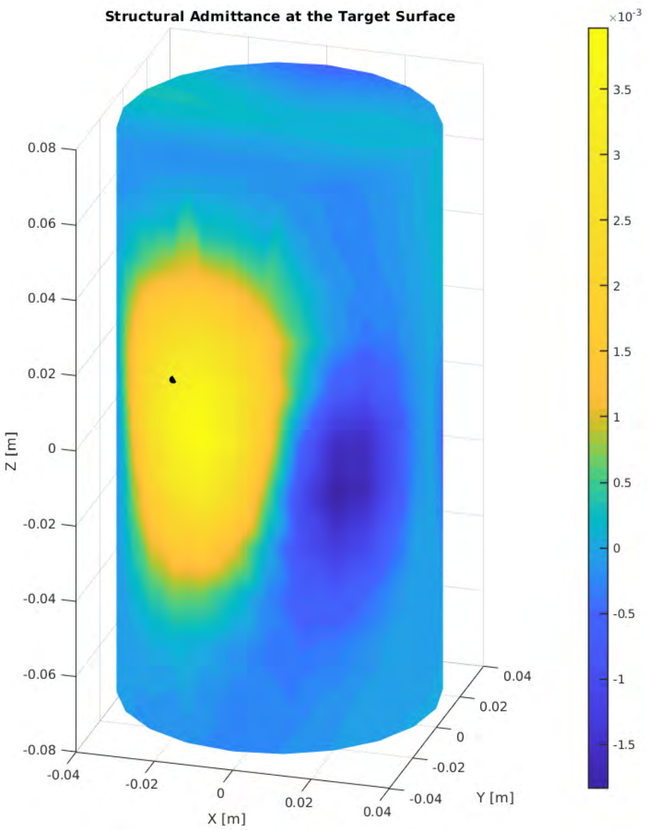
➢ Comparison of the structural admittance of the cylindrical target at 950 Hz for simulated and experimental data (black dot = excitation point) using the first 20 singular values

$$Y_S = \langle vp^* \rangle \langle pp^* \rangle^{-1}$$

COMSOL SIMULATION



EXPERIMENTAL DATA

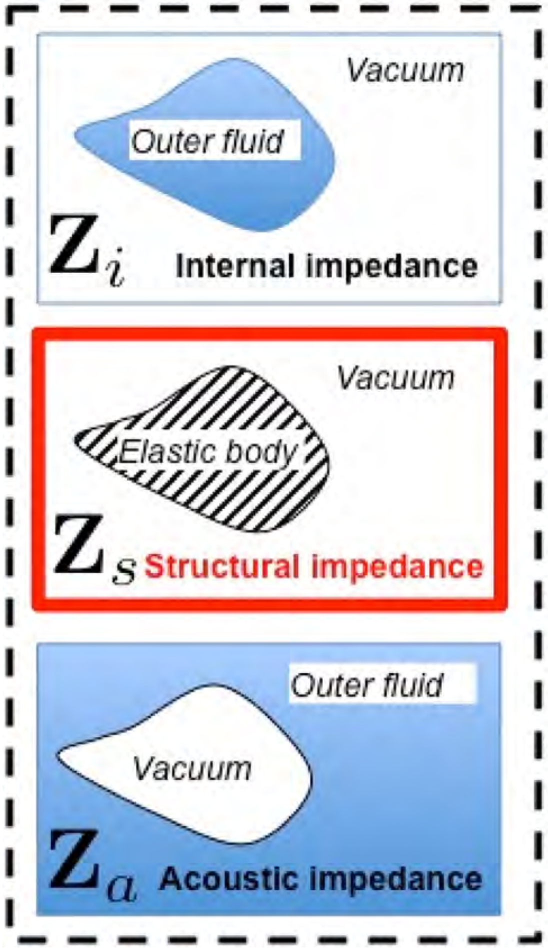


WHERE WE ARE GOING:

SCATTERING FROM "LOADED" TARGET: INCLUDE EXTERNAL MEDIUM

Simple manipulation of the impedances yields[1],

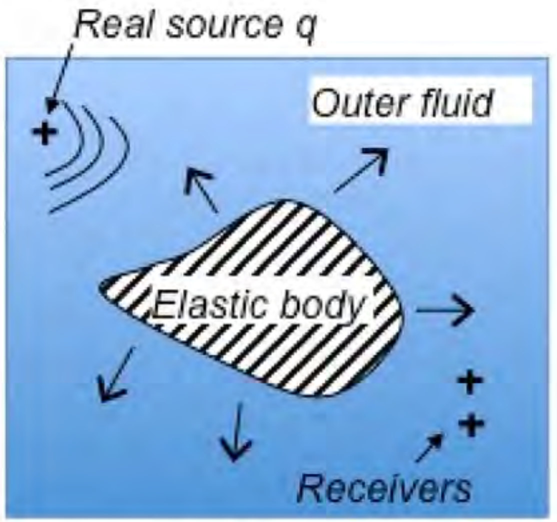
where $\mathbf{p}_s$ is the scattered field **on the surface:**



$$\mathbf{p}_s = \underbrace{\left(\frac{1}{\mathbf{Z}_a} + \frac{1}{\mathbf{Z}_s}\right)^{-1}\left(\frac{1}{\mathbf{Z}_i} - \frac{1}{\mathbf{Z}_s}\right)}_{\mathbf{S}=\text{Scattering Matrix}} \mathbf{p}_i$$

$\mathbf{Z}_s$ contains the physics of the elastic body *when placed in a vacuum*

NOTE: $Y=Z^{-1}$

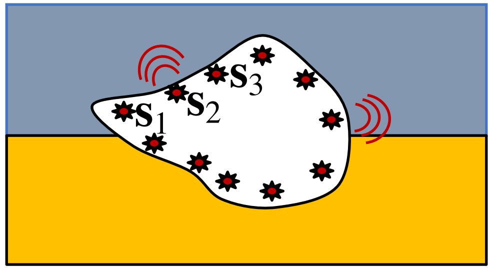


Scattered field at the receivers

[1]Bobrovntiskii (2006), *A new impedance-based approach to analysis and control of sound scattering*

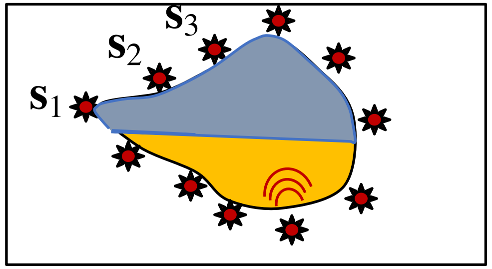
Borgiotti (1990); Gaumond et Yoder (1995); Lucifredi and Schmidt (2004); Bobrovnitskii (2006)

“Insertion” into the medium
Example: a partially buried mine

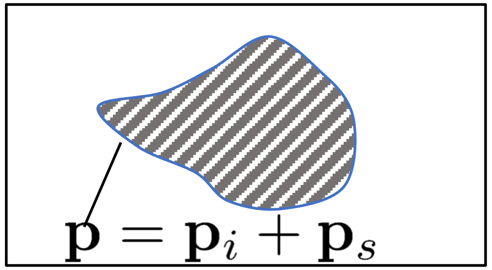


$$\mathbf{Z}_a = \mathcal{G}\mathcal{G}_v^{-1}$$

key
in vacuo region
sand
water
mine



$$\mathbf{Z}_i = \mathcal{G}_i\mathcal{G}_{iv}^{-1}$$

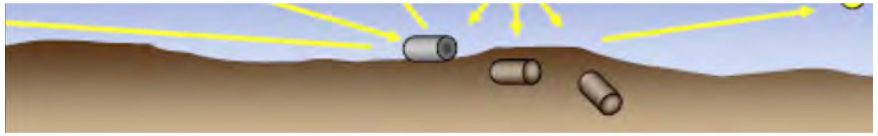


$$\mathbf{Z}_s$$

$$\mathbf{p}_s = \mathcal{G}\mathbf{s}$$

Any propagation code (e.g. RAM by Collins) that accommodates point sources in layered media can be used to provide the medium Green functions,

$$\mathcal{G}, \mathcal{G}_v, \mathcal{G}_i, \mathcal{G}_{iv}$$

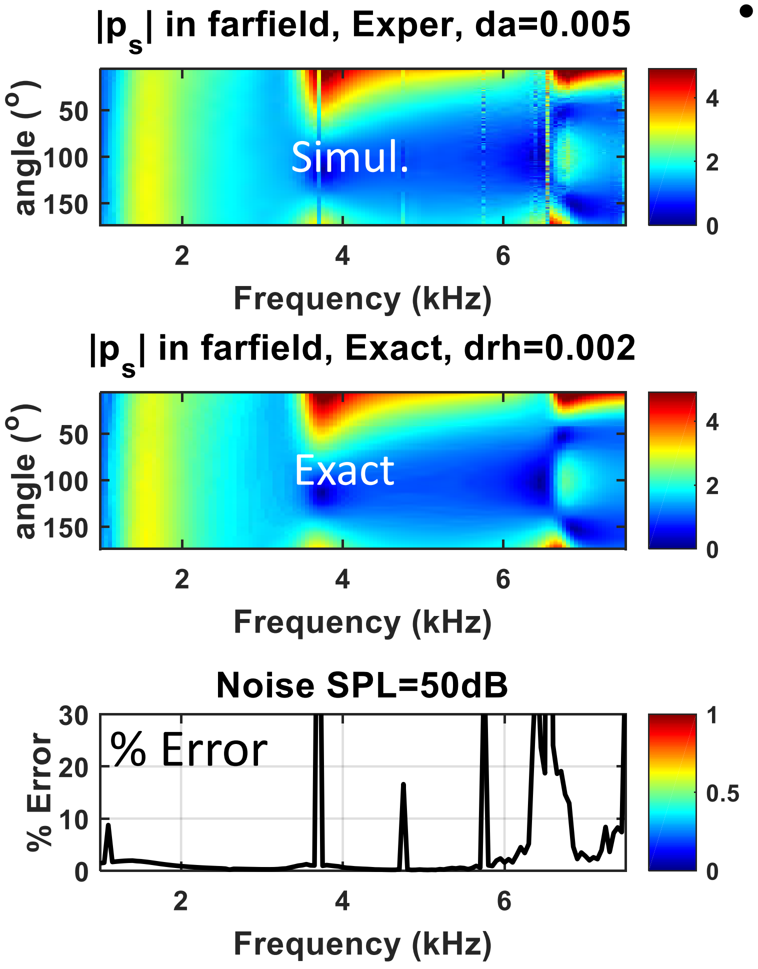


$$\mathbf{p}_s = \underbrace{\left(\frac{1}{\mathbf{Z}_a} + \frac{1}{\mathbf{Z}_s}\right)^{-1}\left(\frac{1}{\mathbf{Z}_i} - \frac{1}{\mathbf{Z}_s}\right)}_{\mathbf{S}=\text{Scattering Matrix}}\mathbf{p}_i$$

Simulated Experiment: Target Echo Strength in Water

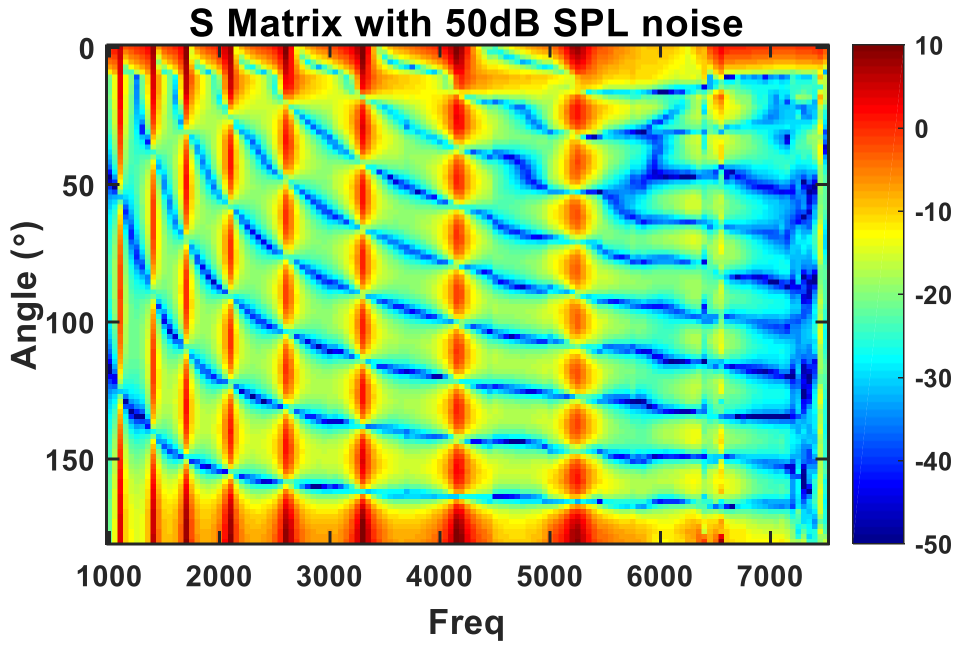
$$\mathbf{p}_s = \mathbf{S}\,\mathbf{p}_i$$

$$\mathbf{p}_{s\,ff} = \mathbf{H}\mathbf{p}_s$$



- Two 250 mike arrays (separated by 5 mm)
- Two 600 point equivalent sources arrays
- 300 incident plane waves (isotropic)
- SNR ~ 44dB (traveling wave noise)

$$\mathbf{S} = (\mathbf{Y}_a + \mathbf{Y}_s)^{-1}(\mathbf{Y}_i - \mathbf{Y}_s)$$



Structural Acoustics

- INITIAL DEMO: EVEN WITH LIMITED NUMBER OF SENSORS, DETAILED STUCTURAL PROPERTIES DETERMINED
- NOT SHOWN: LOCALIZATION OF DEFECTS*
- NEXT:
  - REFINE ACCURACY
  - DETERMINE SCATTERED FIELD OF MEDIUM -“LOADED” TARGET AND CONFIRM
  - EXTEND MEASUREMENTS TO MORE COMPLEX OBJECT USING 500 SENSORS
  - STRUCTURAL TOMOGRAPHY

*Lubeigt et al (JASA EL 2019), Metwally et al:Poster

SUMMARY

- OCEAN IS A *DYNAMIC* COMPLEX MEDIUM; GOAL IS TO EXTEND PROCESSING TO COMPLEX, LOW SNR SCENARIOS.
  - SUFFICIENT *A PRIORI* MEDIUM KNOWLEDGE NOT POSSIBLE
  - USE THROUGH THE SENSOR DATA AND PHYSICS OF COMPLEX MEDIA
  - NOISE FOR TOMOGRAPHY AND ….

- STRUCTURAL ACOUSTICS: STRUCTURE IS COMPLETELY DESCRIBED BY ITS SURFACE IMPEDANCE, Z (or ADMITTANCE, Y)
  - NOISE (AND HOLOGRAPHY) CAN PROVIDE Z
  - NOISE CAN PROBE FOR STRUCTURAL DEFECTS (SHM)