Using (Ocean) Noise

CARGESE-June,2017

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MOTIVATION:ONE MAN'S NOISE IS ANOTHER MAN'S SIGNAL

- **WHITE NOISE**: "UNCORRELATED" sensor to sensor -NON-PROPAGATING
- **ISOTROPIC NOISE**:PROPAGATING IN ALL DIRECTIONS WITH EQUAL AMPLITUDE
- CONFUSED WITH WHITE NOISE BECAUSE WHEN SENSED AT HALF WAVE LENGTH--same a white noise
- **SEA SURFACE NOISE**: PROPAGATING PARTIALLY CORRELATED-HAS DIRECTIONALITY:
- **SHIPPING NOISE:** PROPAGATING WHEN FAR AWAY-APPEARS TO HAVE SAME PROPERTIES AS SURFACE NOISE
- **BIOLOGICAL NOISE**
- **SEISMIC NOISE**
- **THERMAL NOISE**

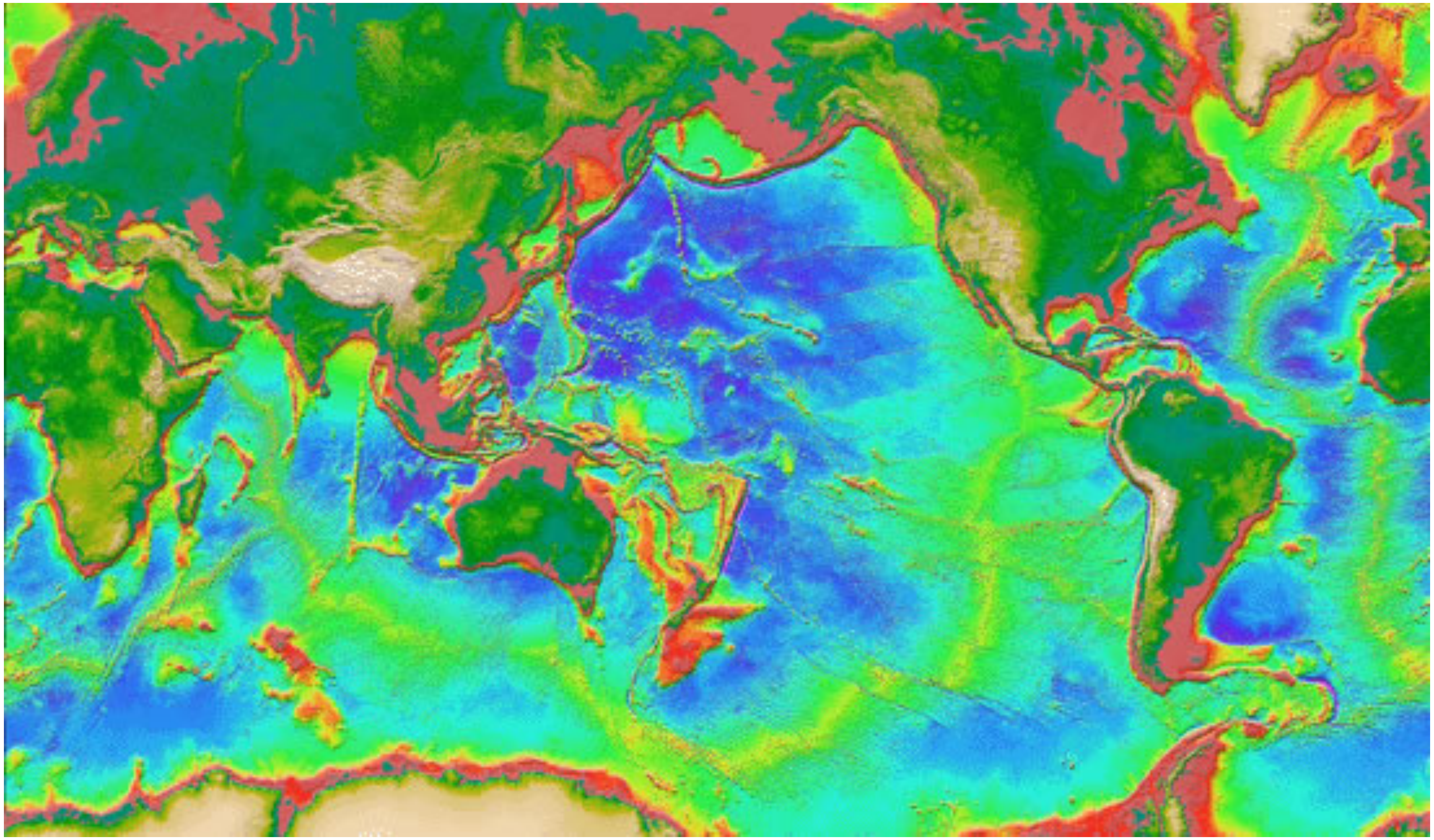
- USUALLY TRY TO DETECT SIGNAL IN NOISE
- USE DIRECTIONALITY/CORRELATION OF NOISE FOR INVERSION
- ACOUSTIC DAYLIGHT,INVERSION
- **THIS TALK WILL END EMPHASIZING UTILITY OF NOISE:**

TREATING NOISE AS THE SIGNAL

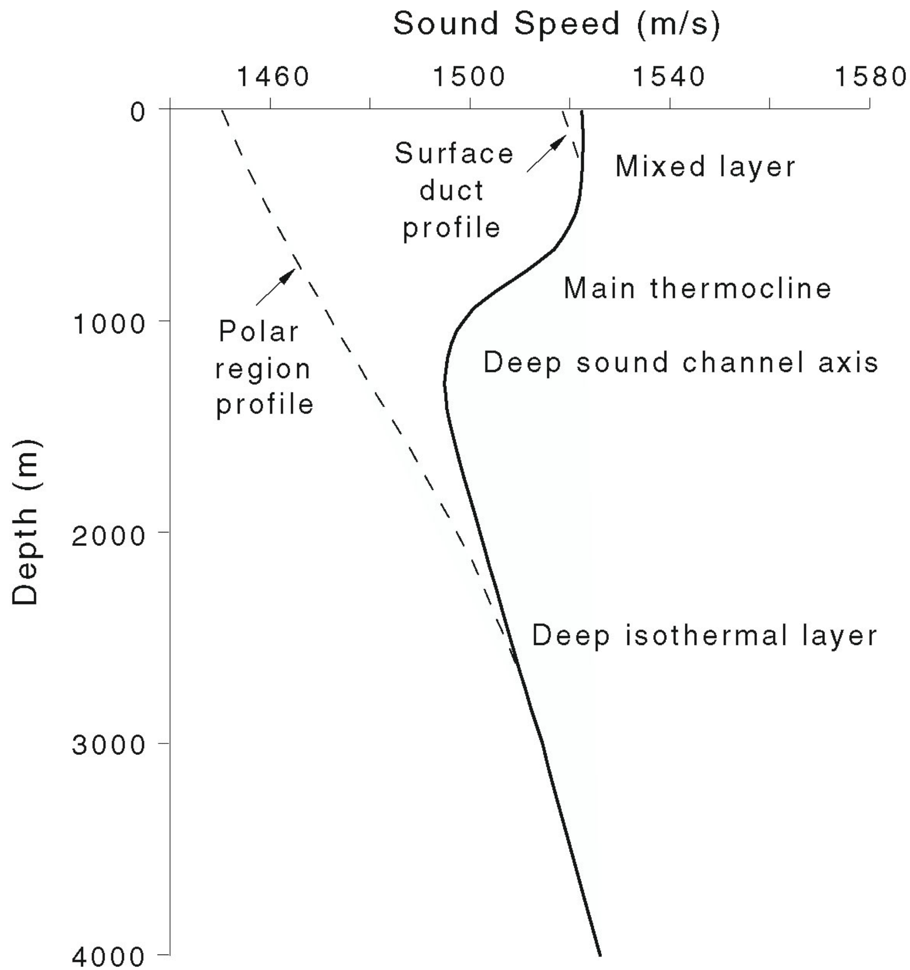
OUTLINE

- **OVERVIEW:OCEAN ACOUSTICS & NOISE**
  - OCEAN ENVIRONMENT
  - PROPAGATION
  - DIFFERENT TYPES OF NOISE
  - SIGNAL PROCESSING: NOISE AS A NUISANCE
  - TOMOGRAPHY
- **EXTRACTING COHERENT INFORMATION FROM NOISE**
  - SENSOR-SENSOR CORRELATION
  - **CHEATING** BEAMFORMING →BEAM-BEAM CORRELATION
  - **MORE CHEATING**
- **WORK IN PROGRESS: SOURCES OF OPPORTUNITY: HIGH RESOLUTION IMAGE FROM MANY LOW RESOLUTION IMAGES**
- **EXTRACTING SCATTERING/STRUCTURE PROPERTIES FROM NOISE**

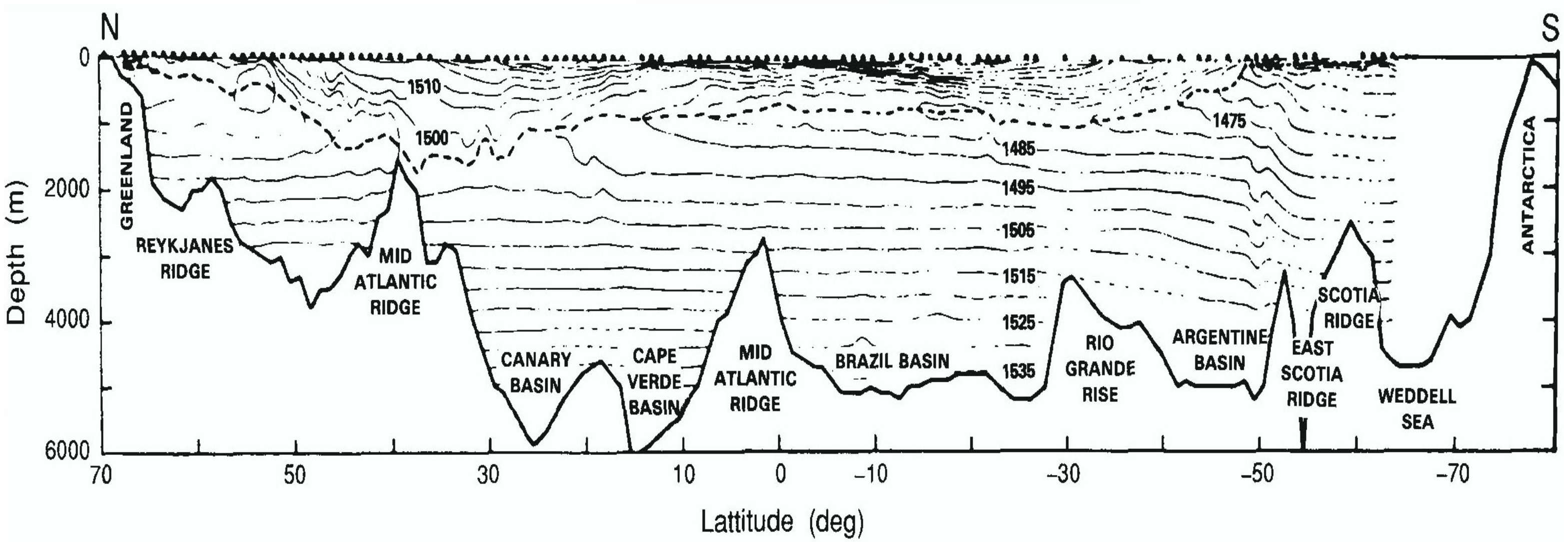
ACOUSTICS IN THE OCEAN



GENERIC SOUND SPEED STRUCTURE



GLOBAL SOUND SPEED STRUCTURE

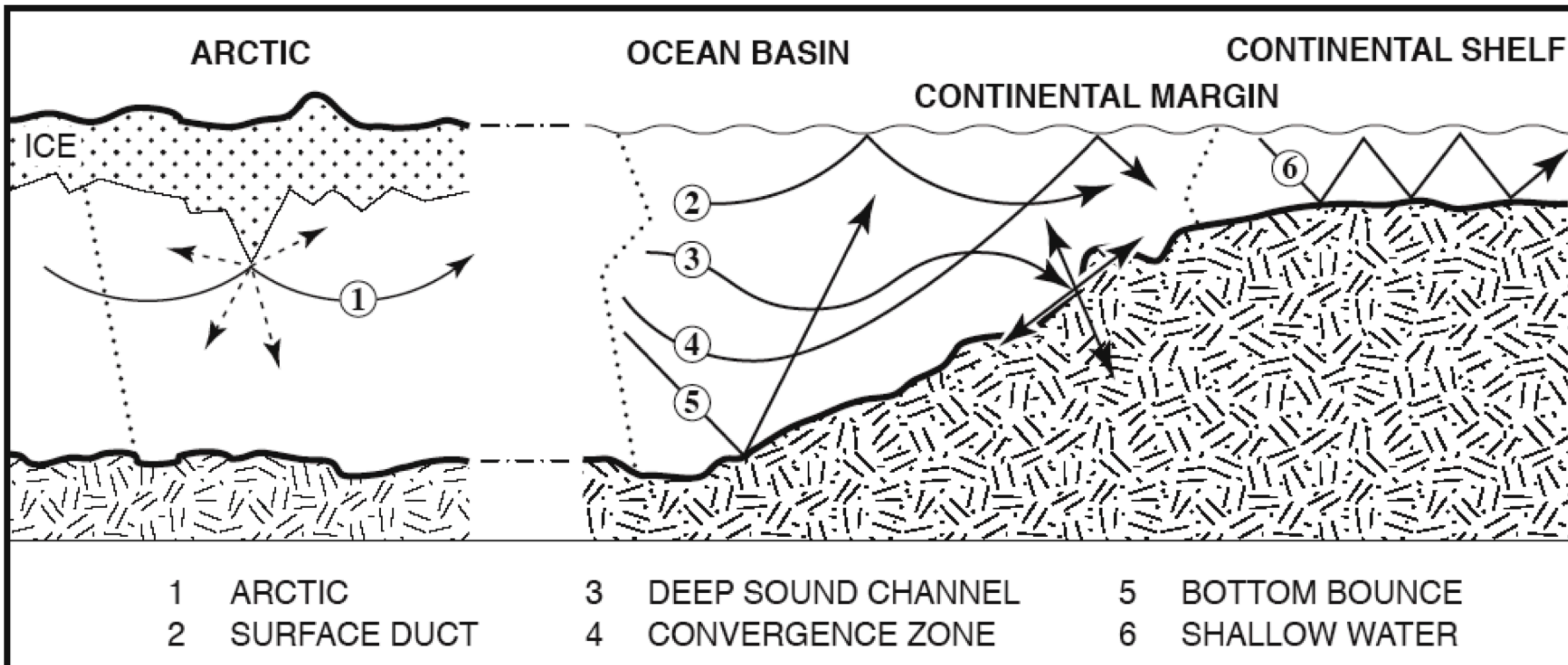


- OCEAN ENVIRONMENT
- PROPAGATION
- DIFFERENT TYPES OF NOISE
- SIGNAL PROCESSING: NOISE AS A NUISANCE

SNELL'S LAW:

SOUND LIKES LOW SPEEDS

SCHEMATIC OF SOUND PROPAGATION PATHS



- OCEAN ENVIRONMENT
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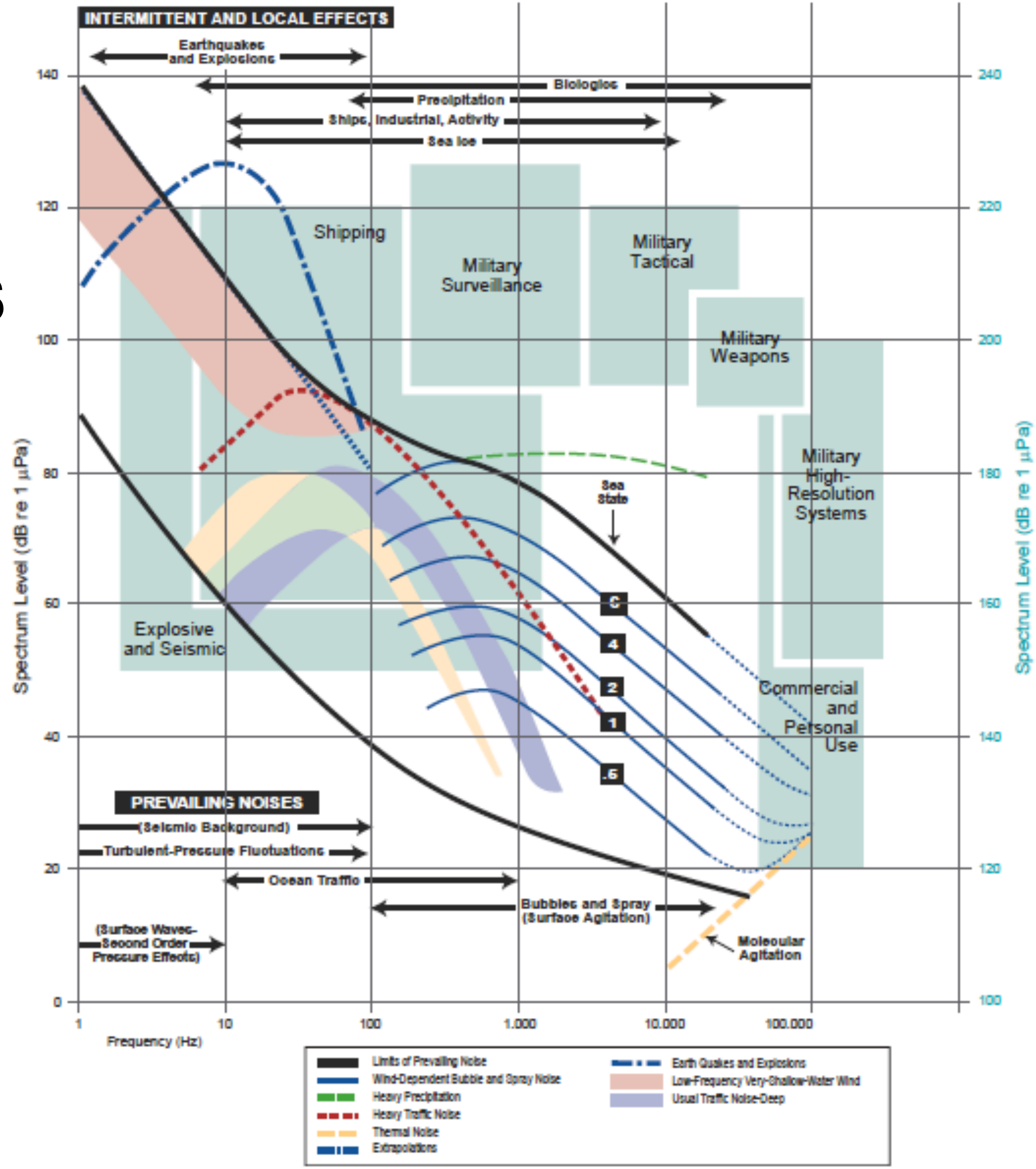
NOISE LEVELS AND SOURCE LEVELS



BRADLEY,STERN
NRC 2008

Man Made Sounds

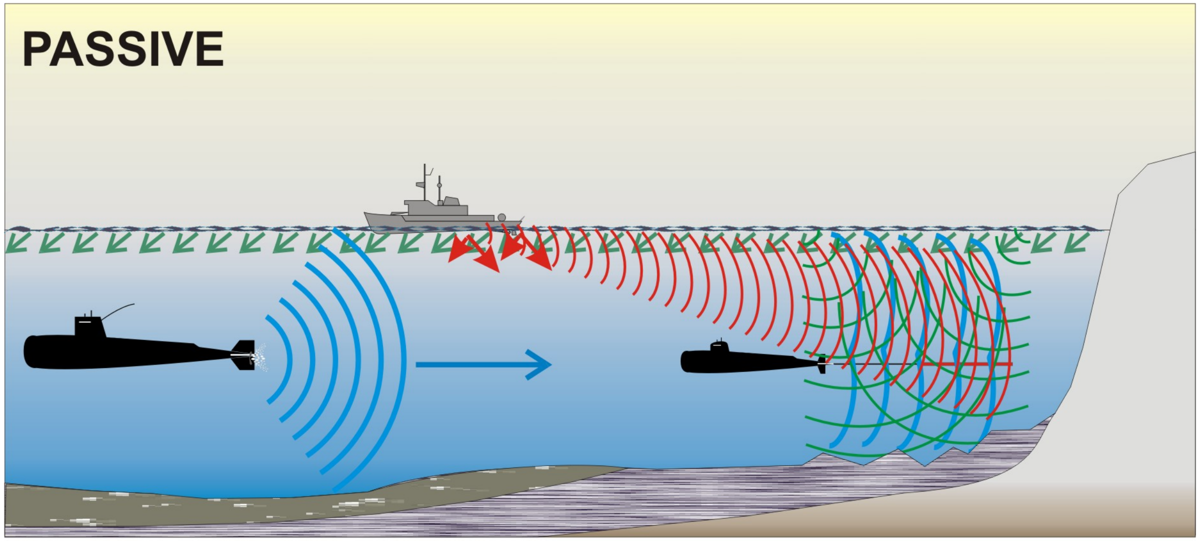
Ships Underway	Broadband Source Level (dB re 1 μPa at 1 m)
Tug and Barge (18 km/hour)	171
Supply Ship (example: Kigoriak)	181
Large Tanker	186
Icebreaking	193
Seismic Survey	**Broadband Source Level (dB re 1 μPa at 1 m)**
Air gun array (32 guns)	259 (peak)
Military Sonars	**Broadband Source Level (dB 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

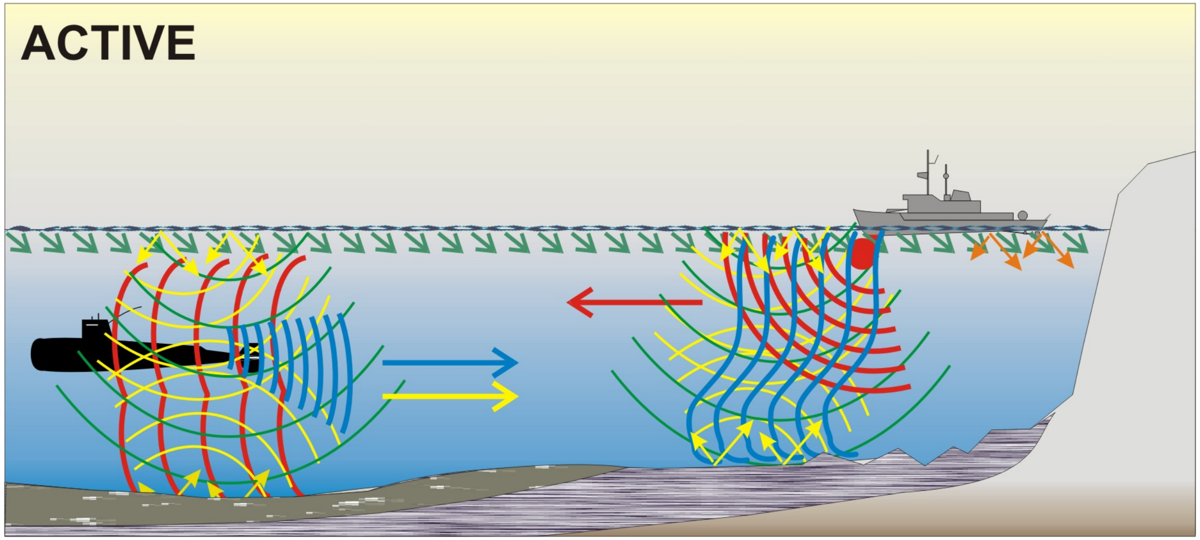
Animal Sounds

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)

- OCEAN ENVIRONMENT
- PROPAGATION
- DIFFERENT TYPES OF NOISE
- SIGNAL PROCESSING: From NOISE AS A NUISANCE

TYPICAL SONAR VIEW OF NOISE: NUISANCE





ARRAY GAIN: Signal adds up faster than noise

$$\frac{S^2}{N^2} = \frac{\overline{\left[\sum_{i=1}^{m} s_i(t)\right]^2}}{\overline{\left[\sum_{i=1}^{m} n_i(t)\right]^2}}, \longrightarrow \frac{S^2}{N^2} \equiv \frac{\sum_{i,j=1}^{m} s_{ij}}{\sum_{i,j=1}^{m} n_{ij}}, \longrightarrow \frac{S^2}{N^2} = \frac{s^2}{n^2} \frac{\sum_{i,j=1}^{m} \hat{s}_{ij}}{\sum_{i,j=1}^{m} \hat{n}_{ij}}.$$

$$AG = 10 \log \frac{S^2/N^2}{s^2/n^2} = 10 \log \frac{\sum_{i,j=1}^{m} \hat{s}_{ij}}{\sum_{i,j=1}^{m} \hat{n}_{ij}},$$

Incoherent: no correlation between sensors: no X-terms in sum->m terms Vs m^2 for coherent

Isotropic noise $\hat{n}_{ij} = \frac{\sin(kd)}{kd}, \quad i \neq j$ is uncorrelated at $\lambda / 2$

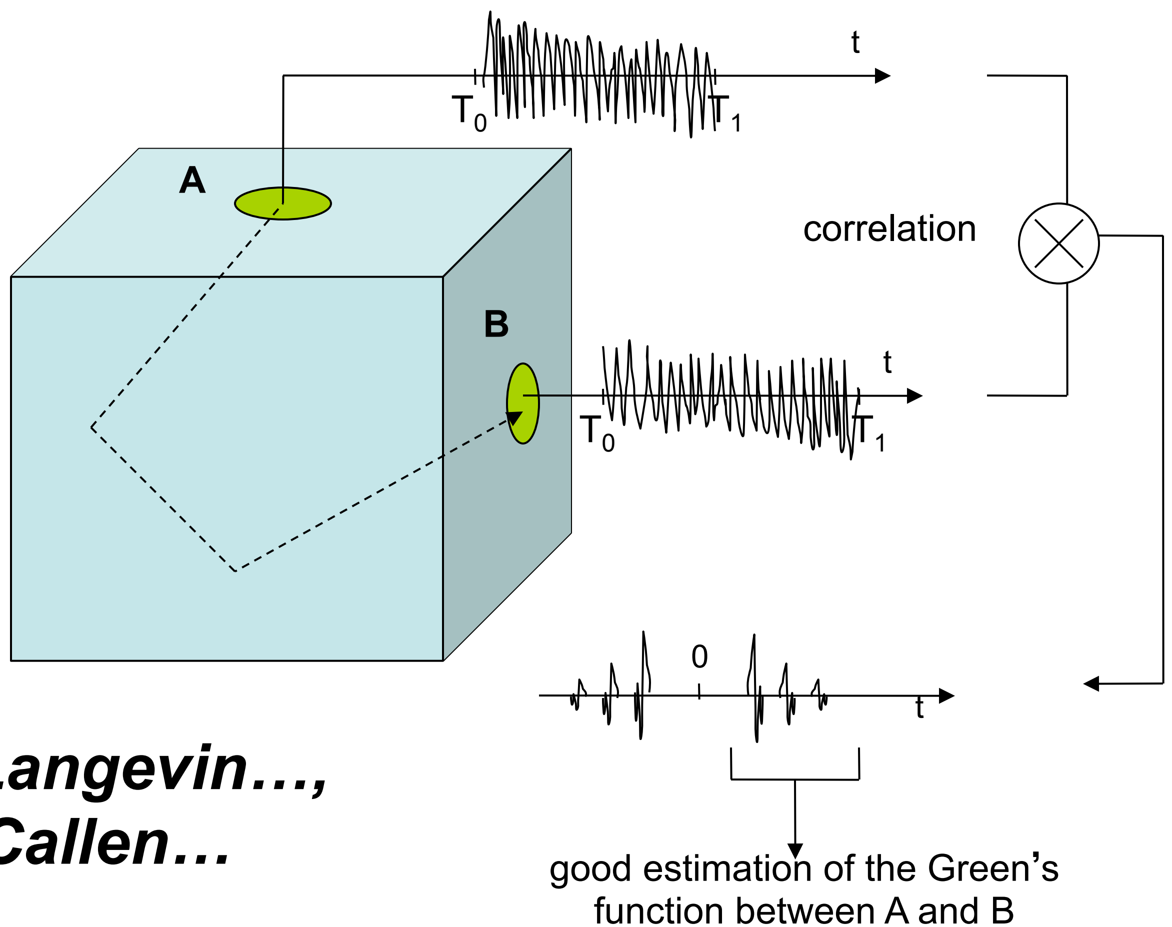
$\longrightarrow$ AG = 10 *log* m

- **EXTRACTING COHERENT INFORMATION FROM NOISE**

Coherent signals from thermal noise

First experimental demonstration in ultrasonics (0.1 – 0.9 MHz)

R.L. Weaver & O.I. Lobkis, Phys. Rev. Lett., 2001



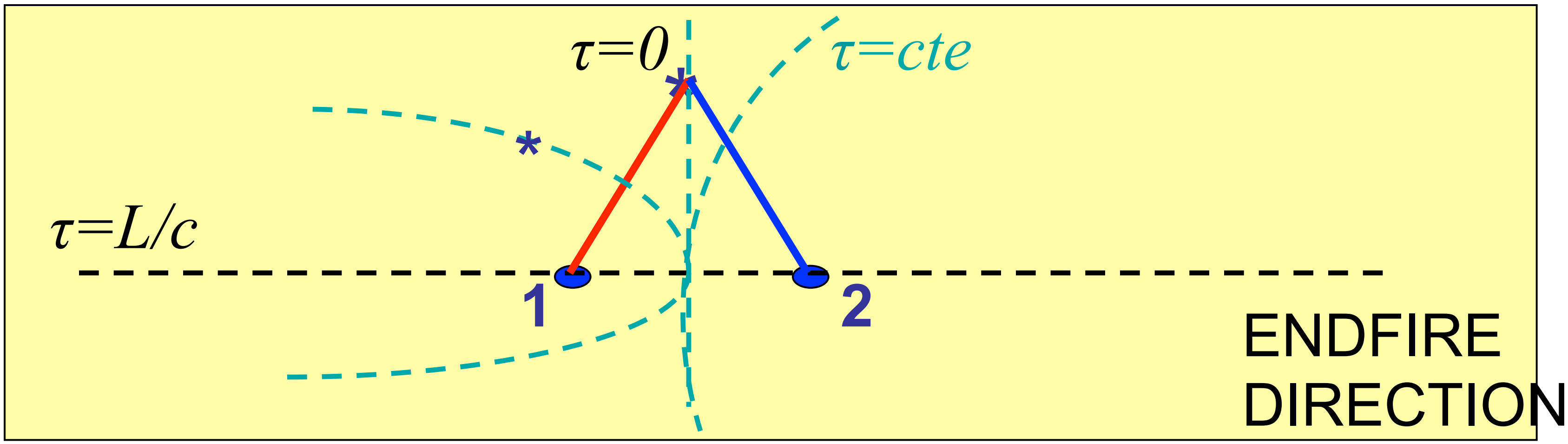
History: Einstein, Langevin…, Johnson,Nyquist, Callen…

NOISE CORRELATIONS IN OCEAN ACOUSTICS
VIA

- FREE SPACE
- WAVEGUIDE
- BEAM FORMING

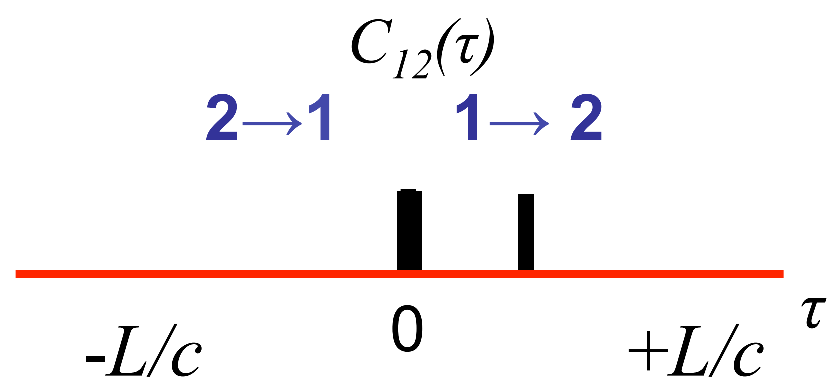
Noise cross-correlation: Free space

$$C_{12}(\tau) = \int_{-\infty}^{\infty} P(\mathbf{r}_1, t)\, P(\mathbf{r}_2, t+\tau)\, \mathrm{d}\, t.$$



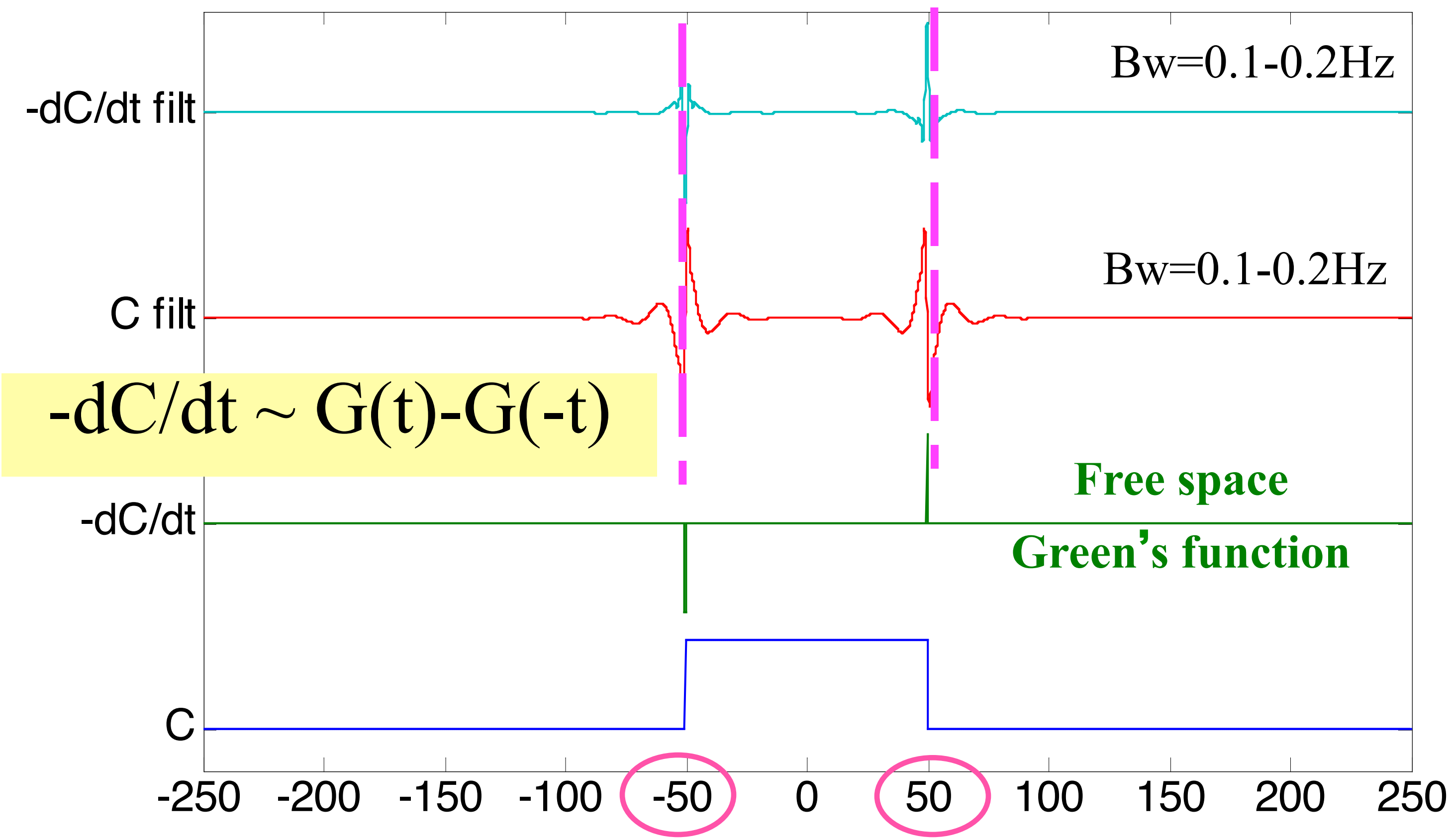
Noise sources yielding constant time-delay τ, lay on same Hyperbola

$$\tau = \frac{|r_2 - r_s| - |r_1 - r_s|}{c} \leq \frac{L}{c}$$



Isotropic distribution of uncorrelated random noise sources

C, dC/dt, band-limited signal



•With cross-correlation process the phase of the source signal is removed,

→Arrival time is given by the center of the pulse (envelope maximum)

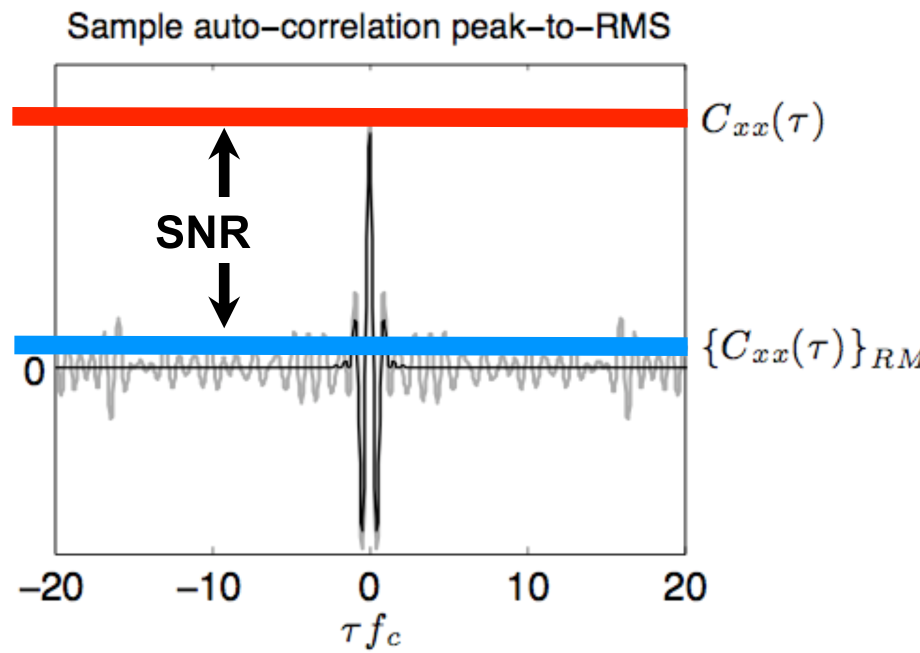
•Isotropic noise distribution → Symmetric Correlation function.

SNR

coherent energy
at time τ

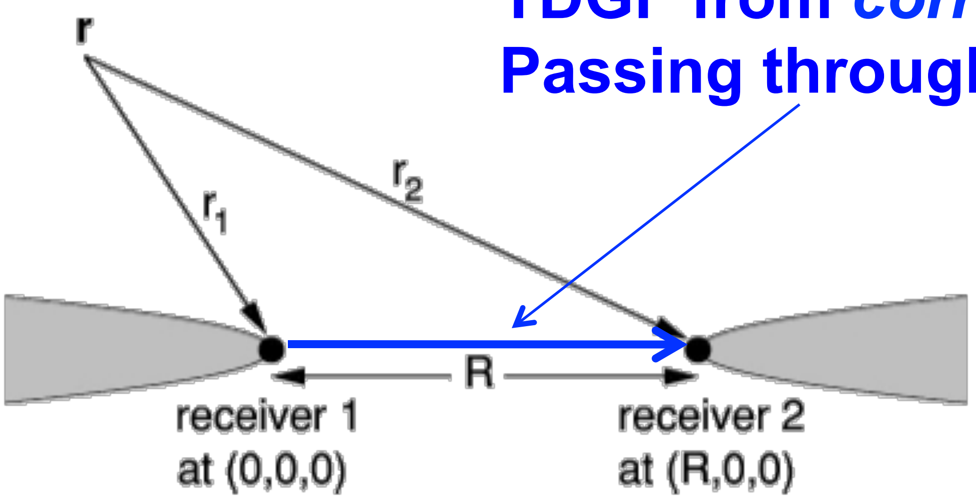
$$SNR = \frac{C_{ab}(\tau)}{\sqrt{\frac{1}{\Delta t}\int_0^{\Delta t} d\tau C_{ab}^2(\tau)}}$$

RMS = total energy
incident on sensors



Physics of Correlation Process

TDGF from *correlated* noise
Passing through both sensors



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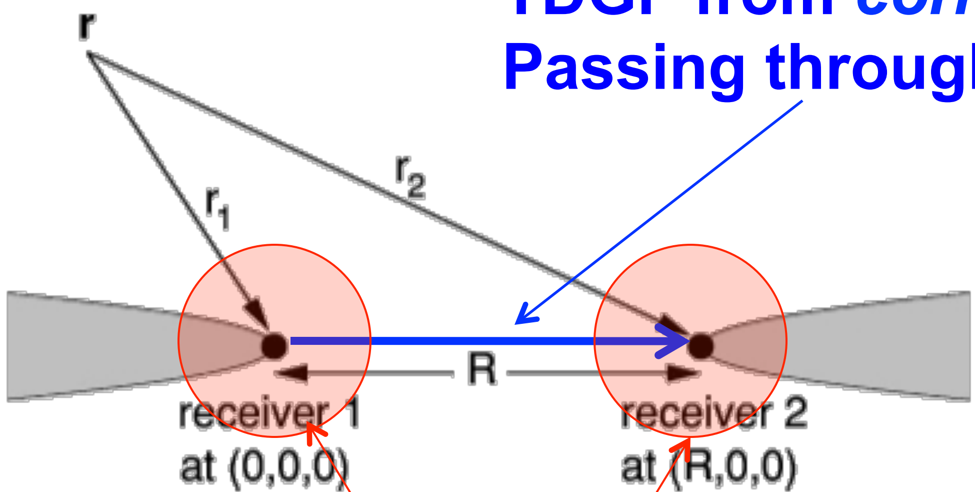
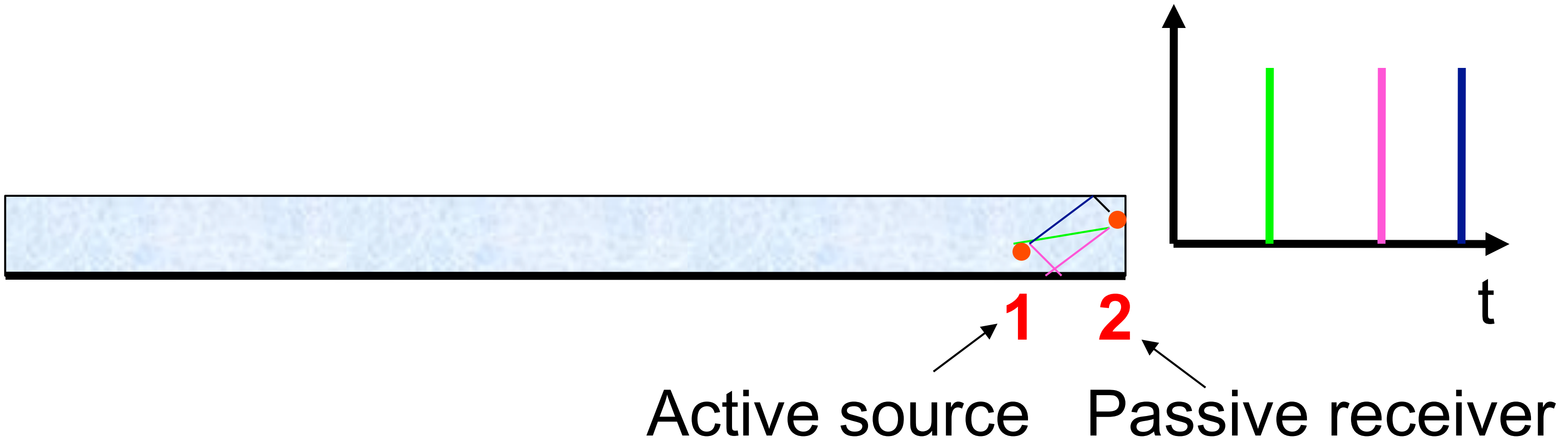
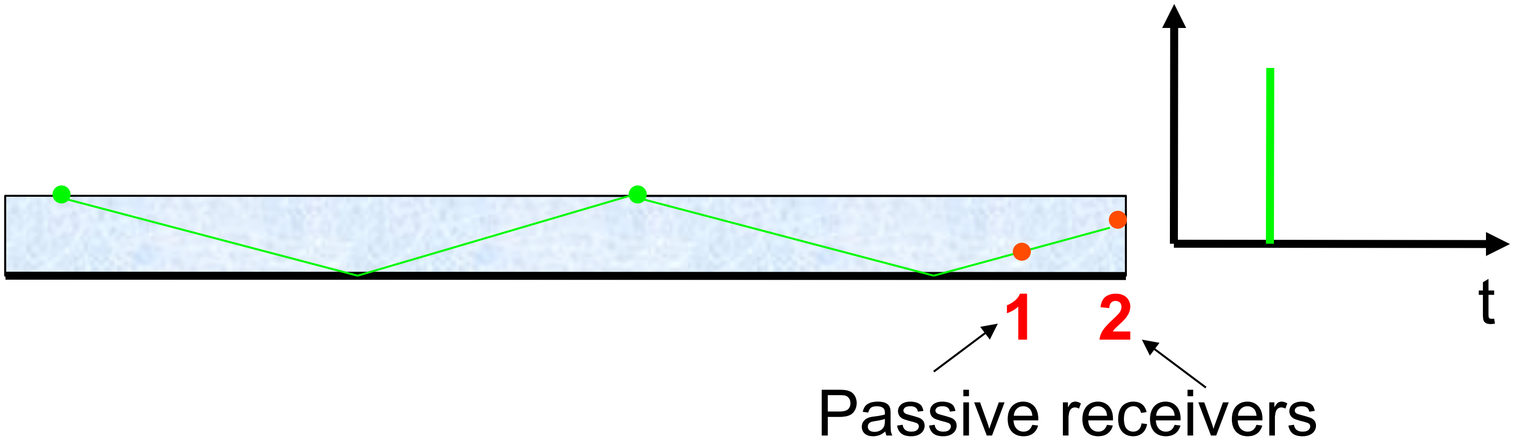


Uncorrelated noise at each sensor

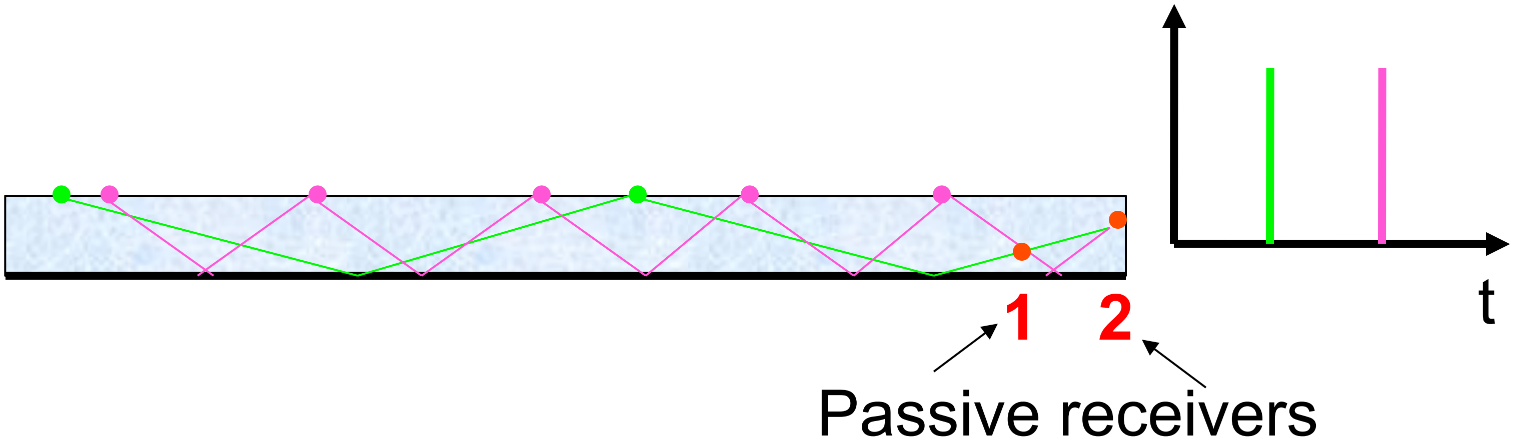
Waveguide:Arrival times



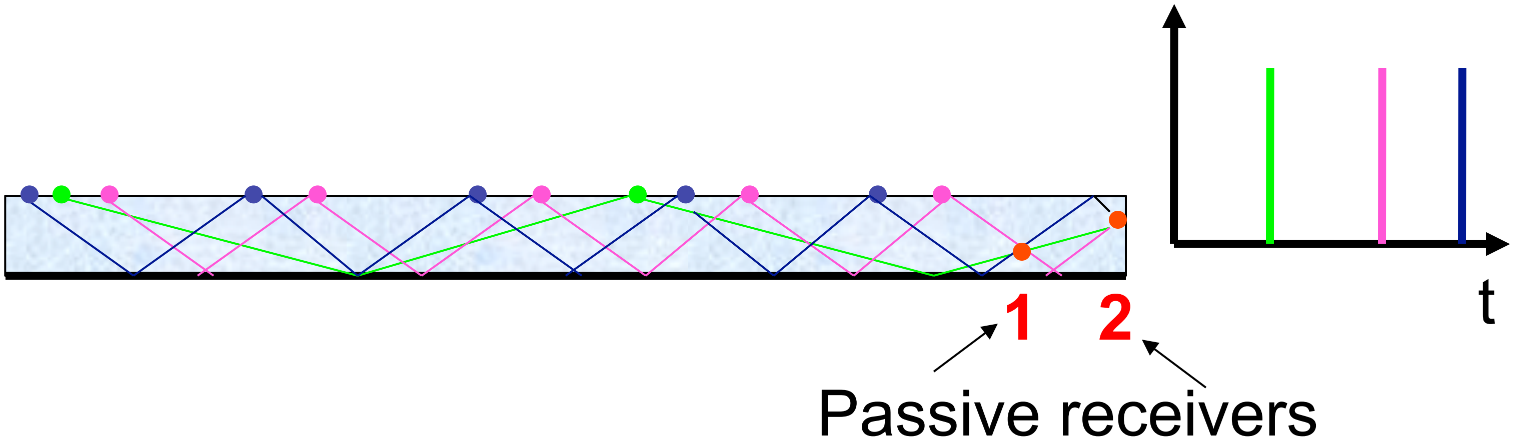
Correlation times with noise sources



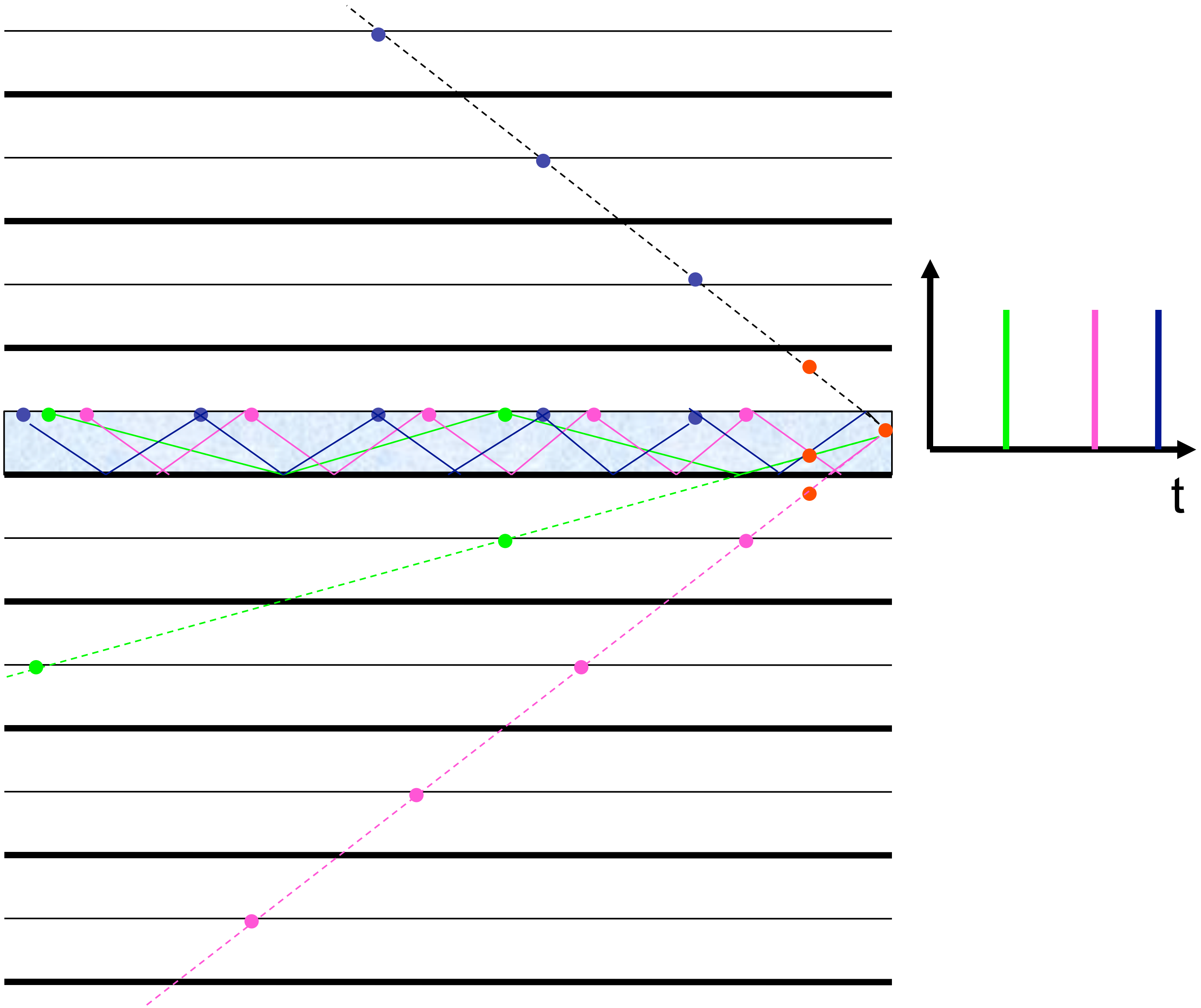
Correlation times with noise sources



Correlation times with noise sources

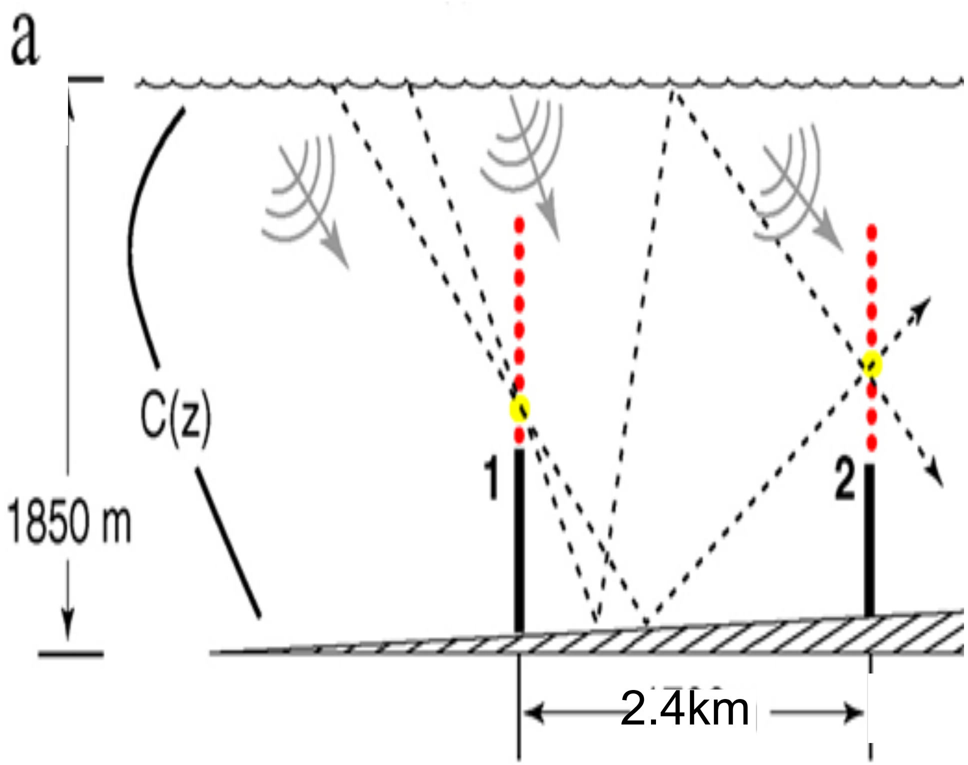


Correlation times-Noise Source Images



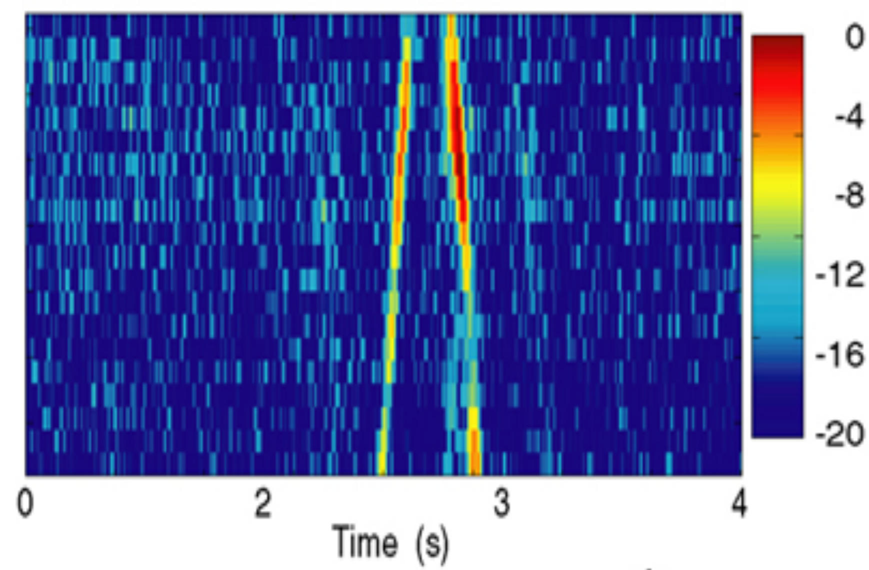
Underwater Acoustics

(non-free space)



NPAL data

Experimental results (70 – 130 Hz)

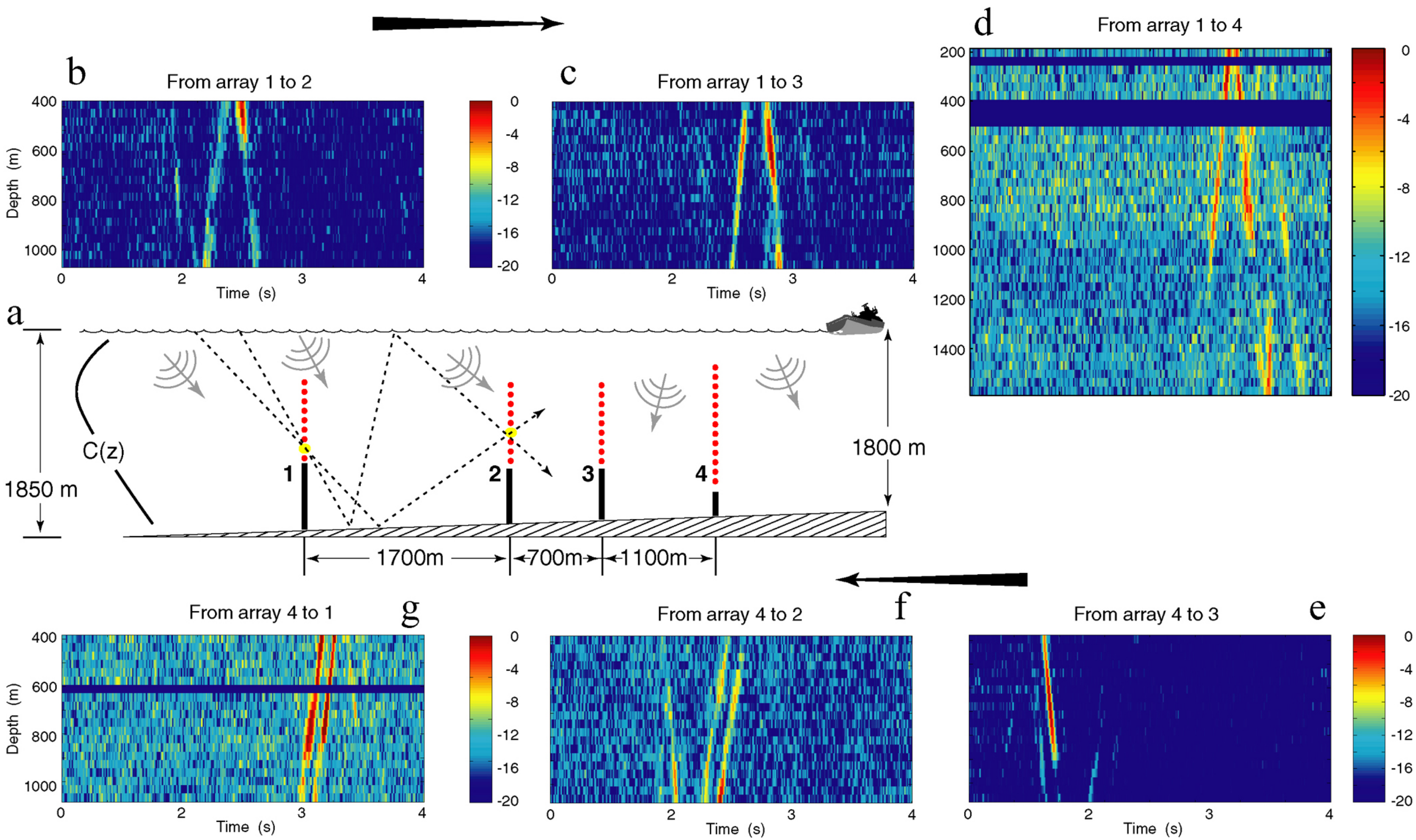


Noise events propagating through receivers 1 and 2 average-up coherently over the long-time in the cross-correlation function.

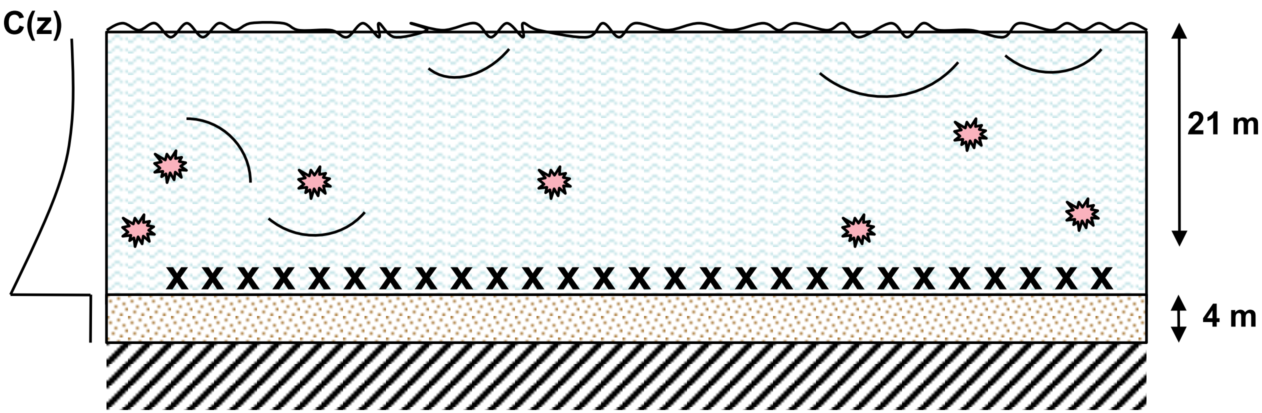
Coherent wavefronts yield an estimate of the Green's function between 1 and 2.

Roux & Kuperman (JASA, 2004), Sabra et al. (JASA, 2005), (IEEE. J. Ocean. Eng. 2005)

Experimental results (70 – 130 Hz)



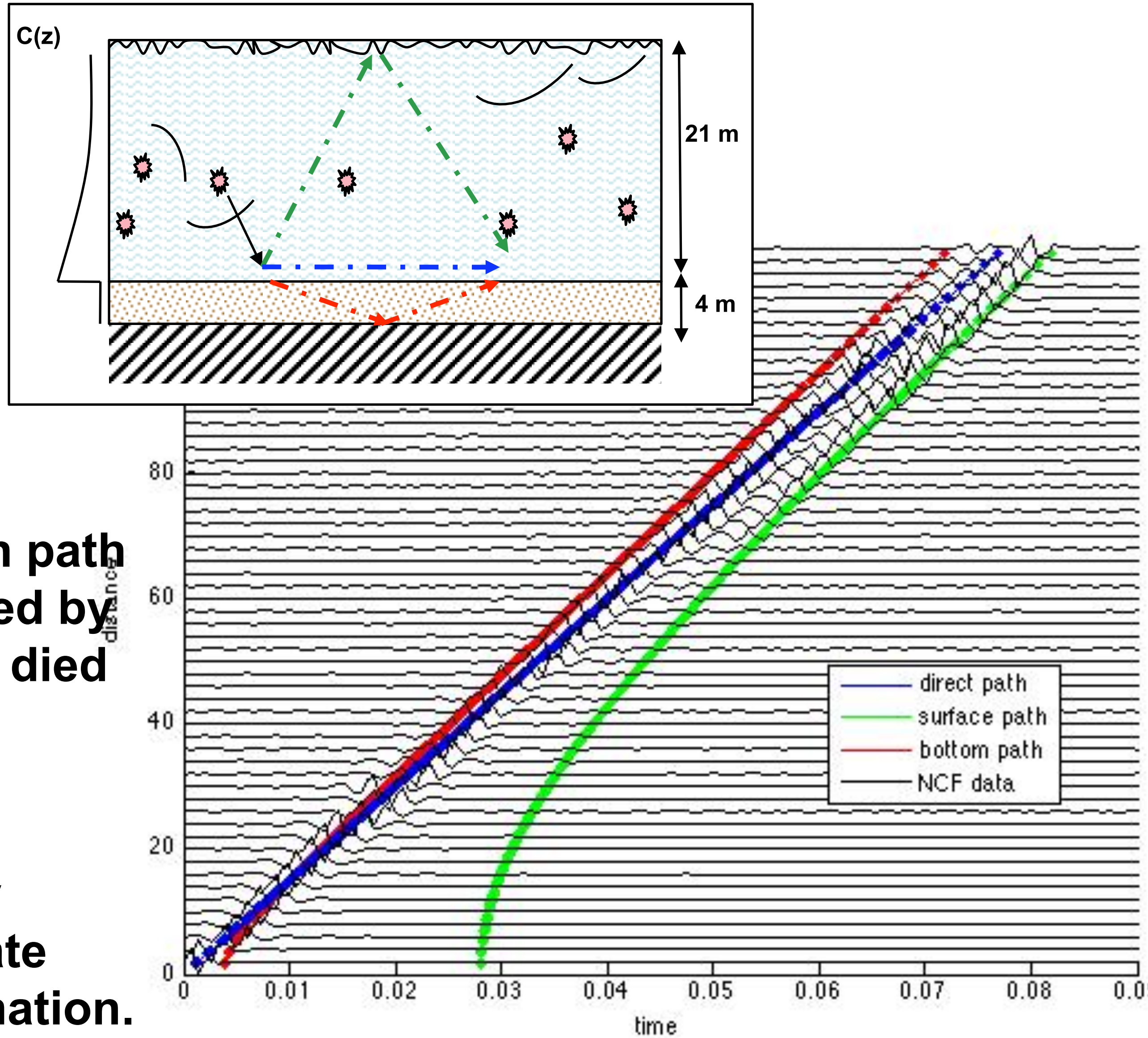
"Croaker" Fish



Fish Noise in Very Shallow Water

D'Spain et al

Looking for the sediments



Sediment reflection path but it was dominated by the direct path and died out over longer distances

---working on array processing to isolate bottom path/information.

Fried et al 2008

THE PROBLEM

TIME OF ARRIVAL PEAKS FROM SENSOR-SENSOR CORRELATION PROCESSING TAKES TOO LONG TO BUILD UP

ISSUE: CORRELATION TIME *vs* OCEAN TIME SCALES

THE PROBLEM

TIME OF ARRIVAL PEAKS
FROM
SENSOR-SENSOR
CORRELATION PROCESSING
TAKES TOO LONG TO BUILD UP

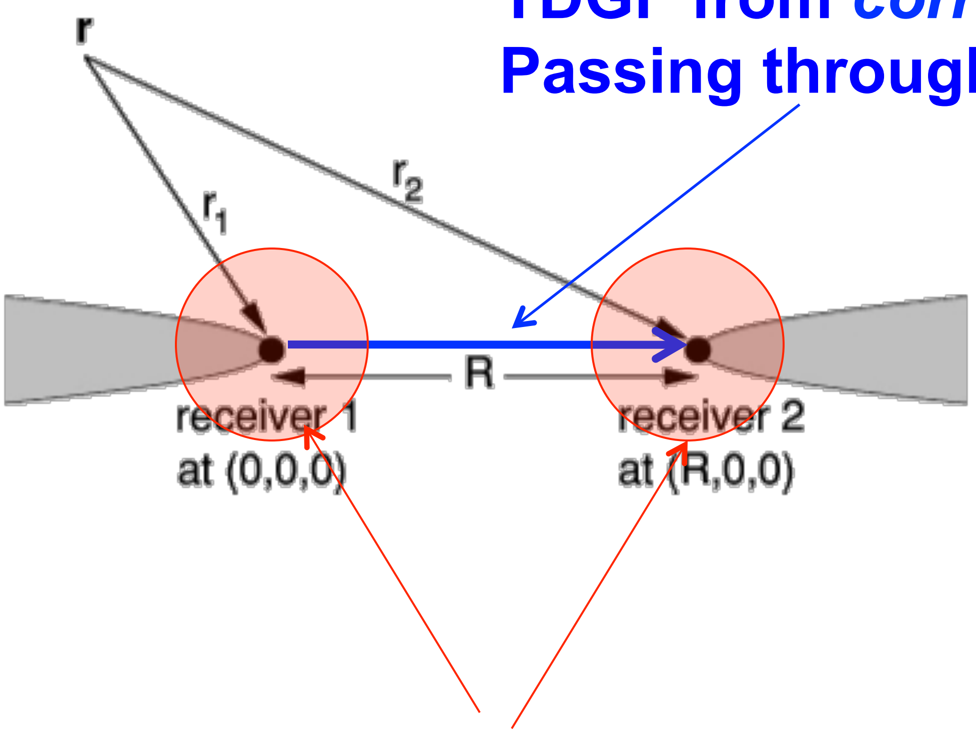
SO→CHEAT

ISSUE: CORRELATION TIME *vs* OCEAN TIME SCALES

NOISE CORRELATION PROCESSING USING SPATIAL ARRAYS

- BECAUSE: TAKE ADVANTAGE OF PHYSICS
- RESULT: ENHANCES EXTRACTION OF TIME OF ARRIVAL STRUCTURE OF TDGF

Physics of Correlation Process



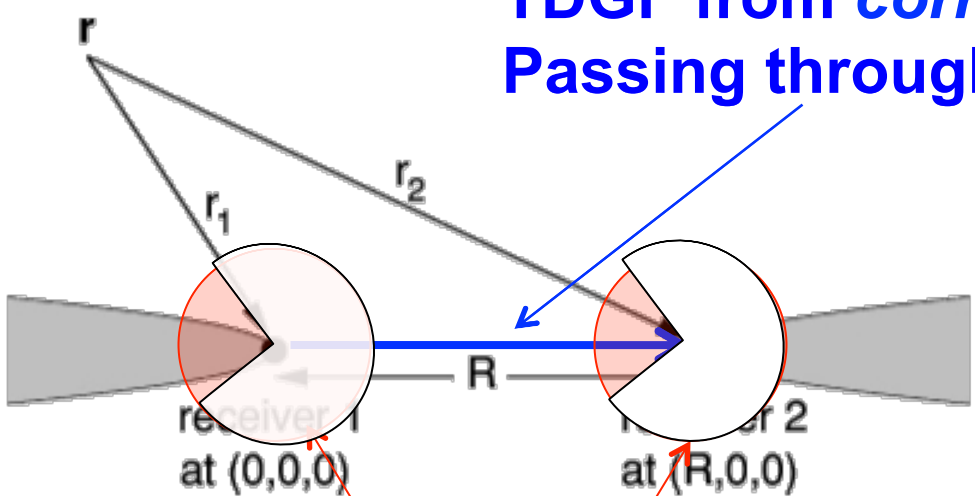
TDGF from *correlated* noise Passing through both sensors

Uncorrelated noise at each sensor

Even a Vertical Array w/ Azimuthal Symmetry does not discriminate in horizontal

BEAMFORM!

TDGF from *correlated* noise
Passing through both sensors



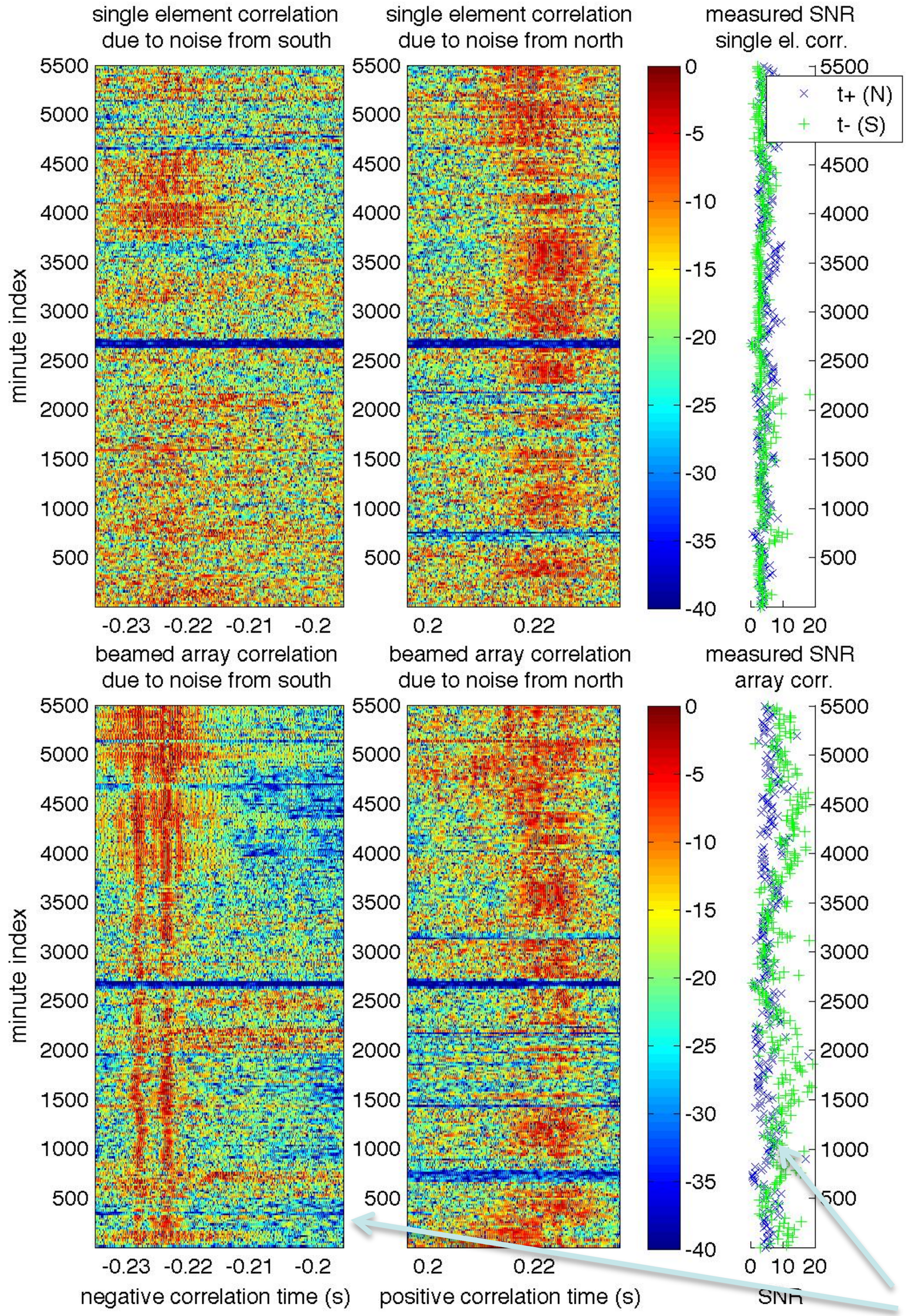
Uncorrelated noise at each sensor

Array can reduce incoherent noise→Shorten Corr. Time

GOAL OF ARRAYS OR ANTENNAS:

1. ADD UP MORE “SIGNAL” THAN “NOISE”
2. LOOK IN A CERTAIN DIRECTION
   - TOWARD A SIGNAL OF INTEREST
   - LOW SIDELOBES
3. ADAPTIVE PROCESSING: USE DATA FOR HIGH RESOLUTION AND MINIMIZE SIDELOBES

1-2 kHz Noise

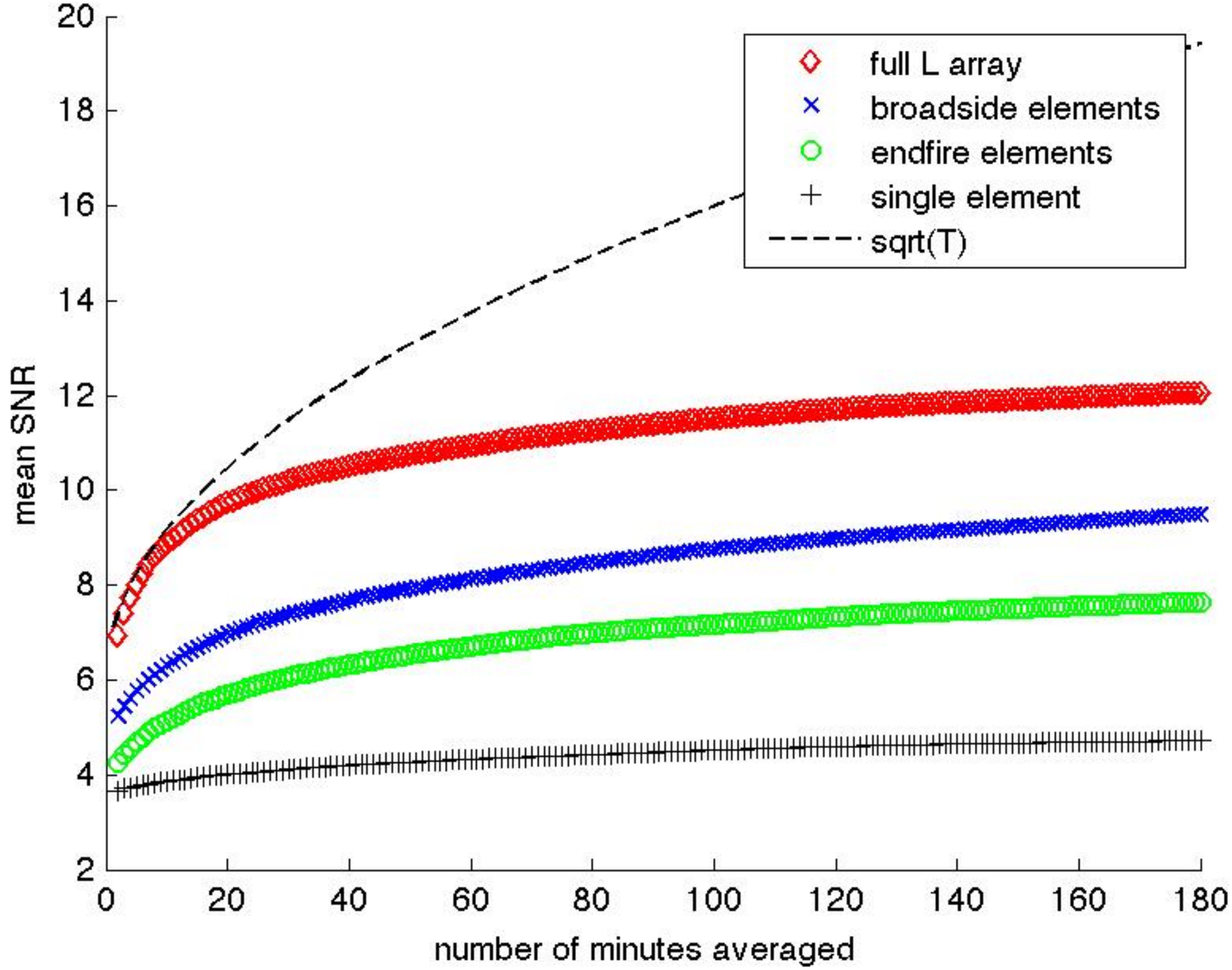


Single Sensor Correlations

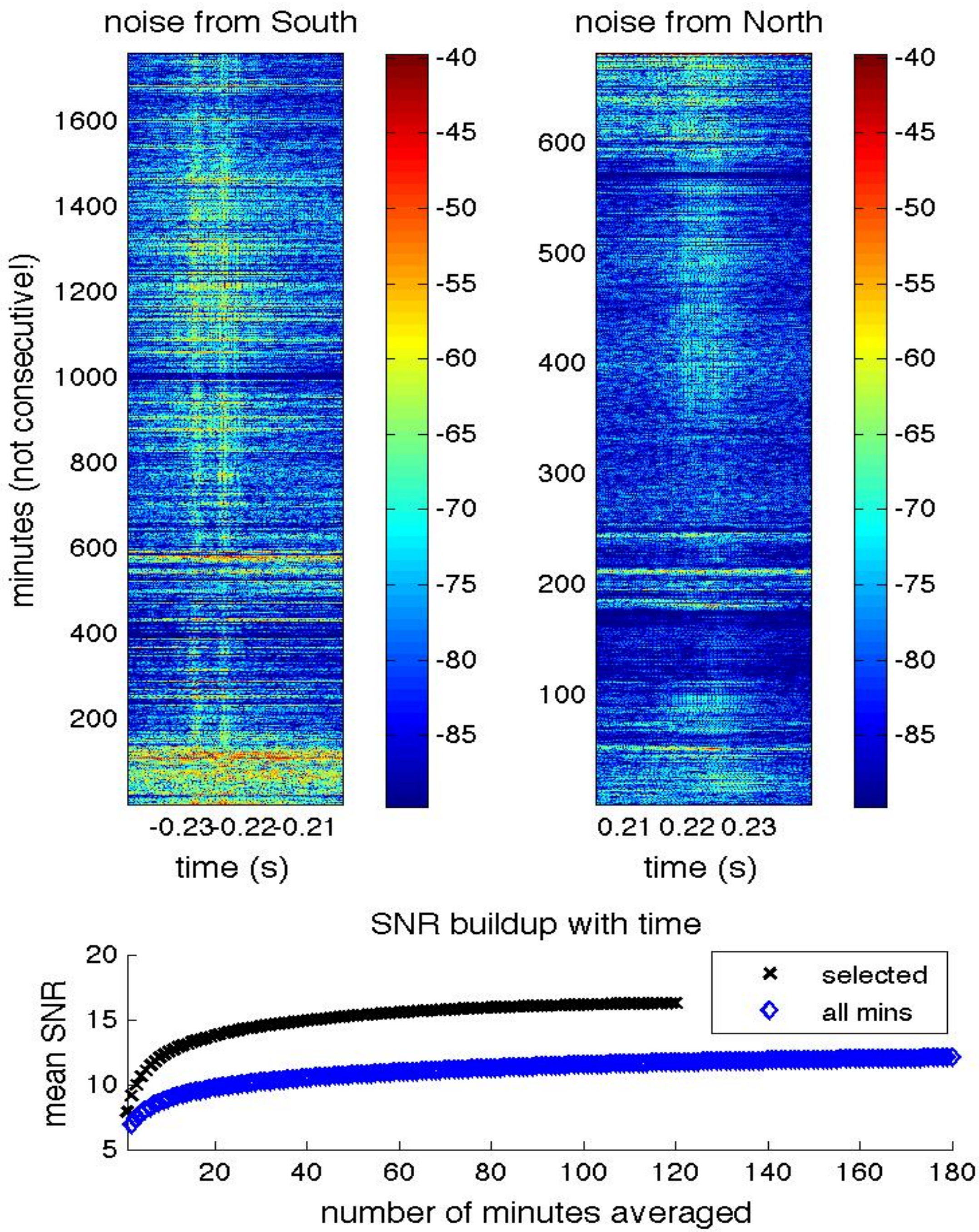
Beam Correlations between L-Shaped Arrrays

Green is noise from south

SUMMARY OF ARRAY RESULTS



Selective Or "a priori" Correlation processing

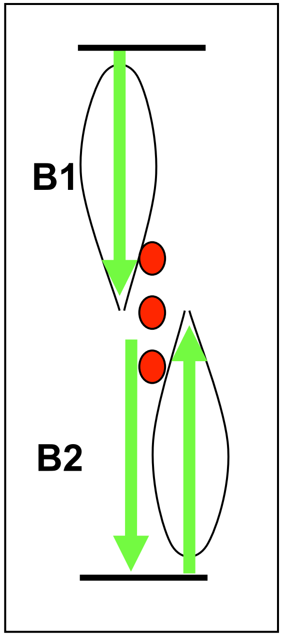


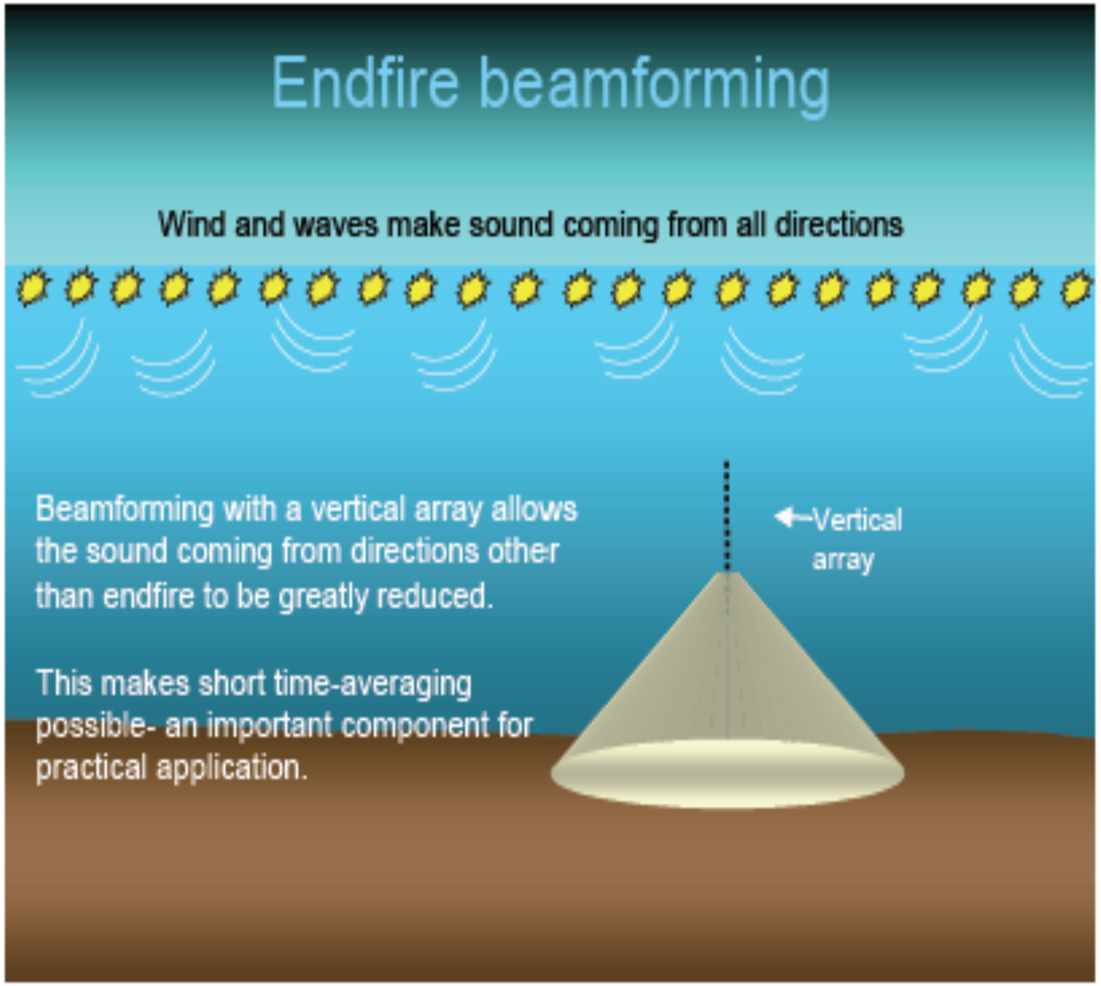
MORE "CHEATING"

Passive fathometer:

(Horizontal Array used as Vertical Array)

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

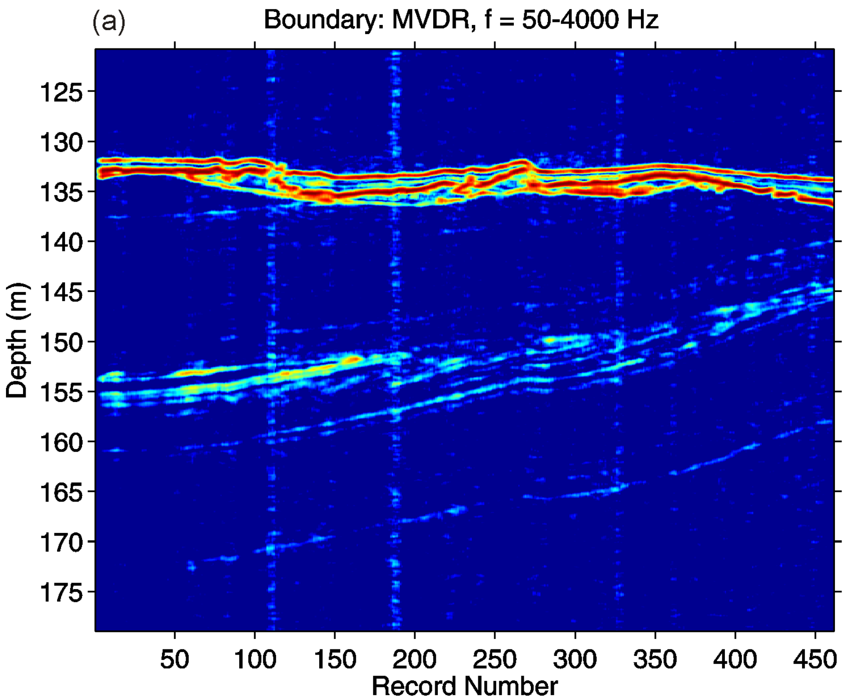




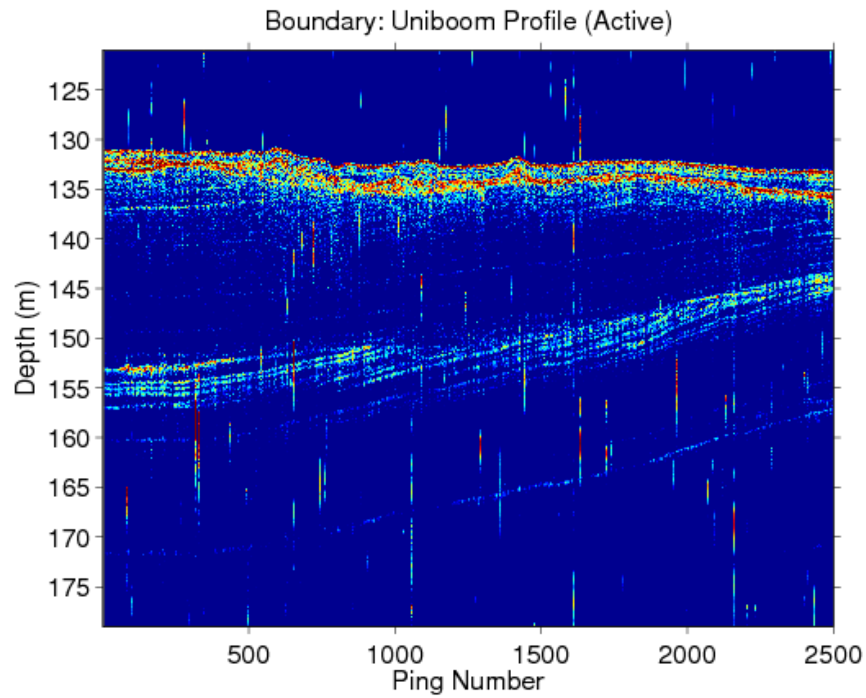
Siderius et al., JASA 2006,
Gerstoft et al., JASA 2008,
Harrison, JASA 2009,
Traer et al., JASA 2009,
Siderius et al., JASA 2010

Passive fathometer (drifting array)

Ambient noise 50-4000 Hz



Boomer



Adaptive processing gives better resolution of reflections

Siderius, Gerstoft et al., 2009 NURC data

LESSONS LEARNED: Noise correlation between two Horizontal arrays

- Beam-Beam Correlation Processing enhances extraction of arrival times
- The processing is based on
  - Beams along endfire
  - Reduction of uncorrelated noise (vs sensors that receive all noise) since the correlation peaks must ("overcome") emerge from this noise
- The emergence time is (still) less than √T because ocean is not stationary over correlation time interval
- **Selective ('a priori") correlation processing** reduces the total build up of uncorrelated noise so that emergence time AND SNR of correlation peaks are enhanced.

A Conclusion: Noise Correlation Processing Appears Promising for Geophysical Inversion

BUT NOT YET

for “Ocean Tomography” [why?->

Noise Correlation Processing has become a tool for Geophysical Inversion

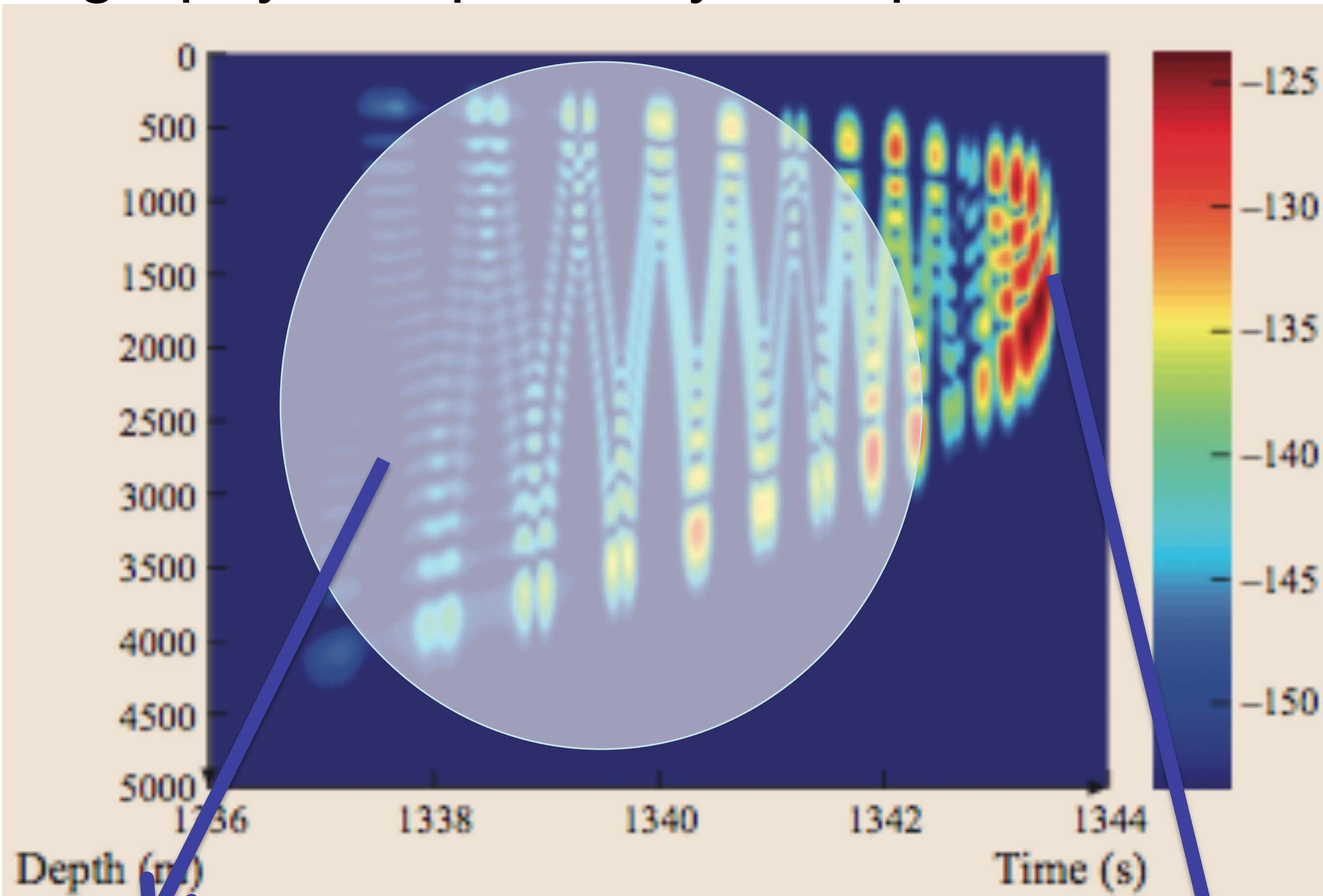
BUT NOT YET

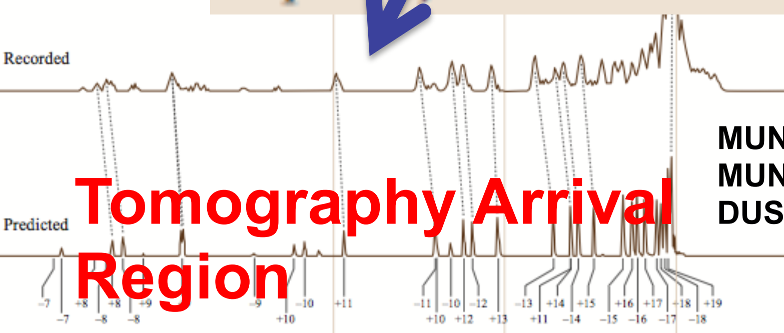
for "Ocean Tomography"

BASIC ISSUE TO STILL OVERCOME:

Extracting time of arrival structure (or equivalent) in short enough time interval to within time scale of ocean phenomenon under study

Tomography with precisely time/positioned source





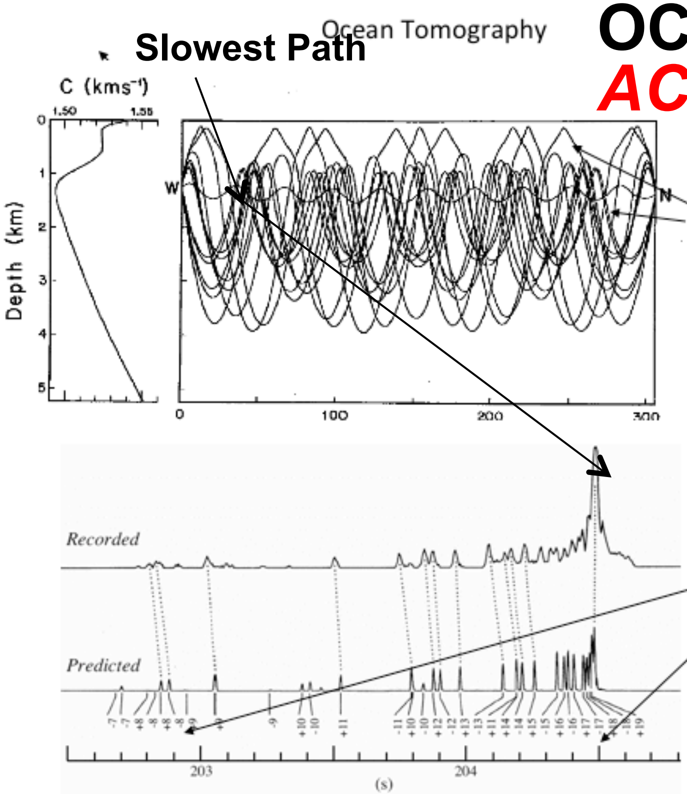
Tomography Arrival Region

MUNK,WUNCH, '82
MUNK,WORCESTER,WUNCH,'95
DUSHAW, ET AL '09,…

Last Arrival Cres

BACKGROUND IIA: IMAGING OCEAN *ACTIVE*

Slowest Path



Different rays have

Different group speeds

Therefore have different

Arrival times

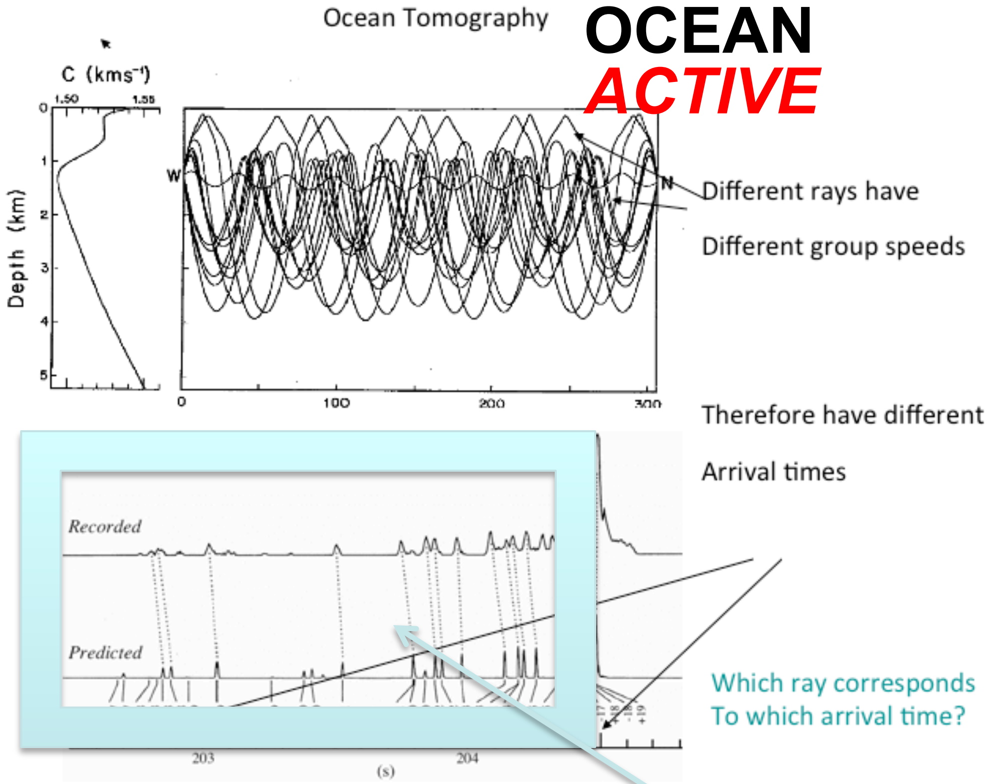
Which ray corresponds
To which arrival time?

REQUIRES ACTIVE SOURCE THAT IS:

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

Fried et al

BACKGROUND IA: IMAGING OCEAN
ACTIVE



WITHOUT ACTIVE SOURCE THAT IS:

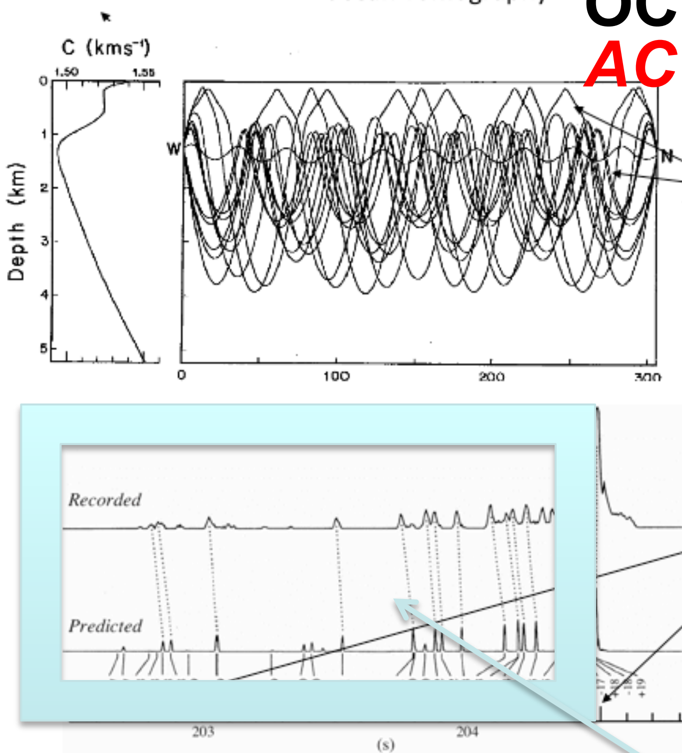
1) **PERFECTLY KNOWN WRT TIME SIGNAL AND SYNCRONIZATION**
2) **PERFECTLY KNOWN WRT SOURCE/ RECEIVER GE0METRY**

GOAL:
IMAGE WITH ONLY RANDOM AMBIENT SOURCES OF OPPORTUNITY

Fried et al

BACKGROUND IIB: IMAGING OCEAN
ACTIVE

Ocean Tomography



Different rays have

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Arrival times

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WITHOUT ACTIVE SOURCE THAT IS:

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2) **PERFECTLY KNOWN WRT SOURCE/ RECEIVER GE0METRY**

VERY HARD

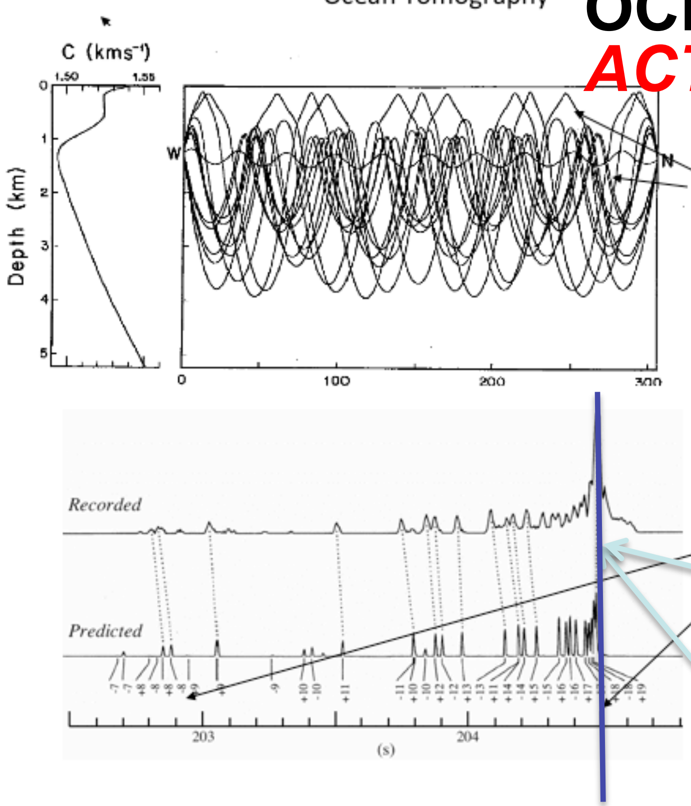
WITHOUT SOURCE INFO

GOAL:
IMAGE WITH ONLY RANDOM AMBIENT SOURCES OF OPPORTUNITY

Fried et al

BACKGROUND IIC: IMAGING OCEAN
ACTIVE

Ocean Tomography



Different rays have

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WITHOUT ACTIVE SOURCE THAT IS:

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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

Background IID: Passive thermometry of the deep ocean

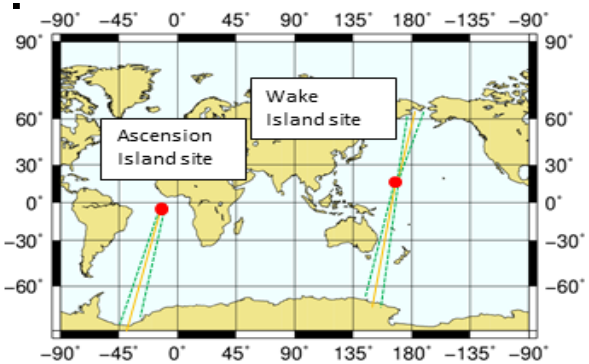
Comparison with ARGO temperature data (*Roemmich, D. and J. Gilson, 2009*)

EstimatingTemperature c

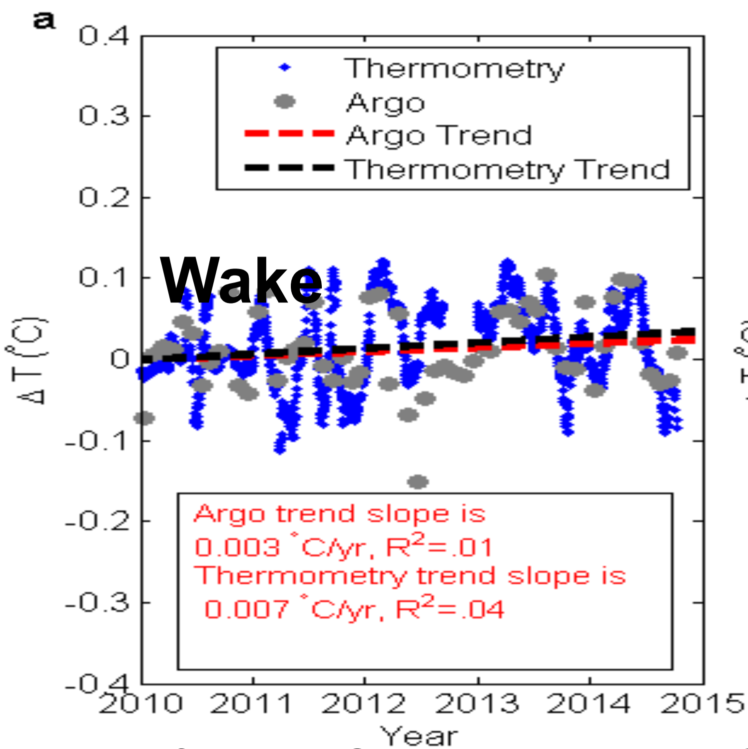
$$\frac{\Delta t}{t_0} = -\frac{\Delta c}{c_0} = \alpha \Delta T \left(1 + \frac{\mu\beta}{\alpha}\right)$$

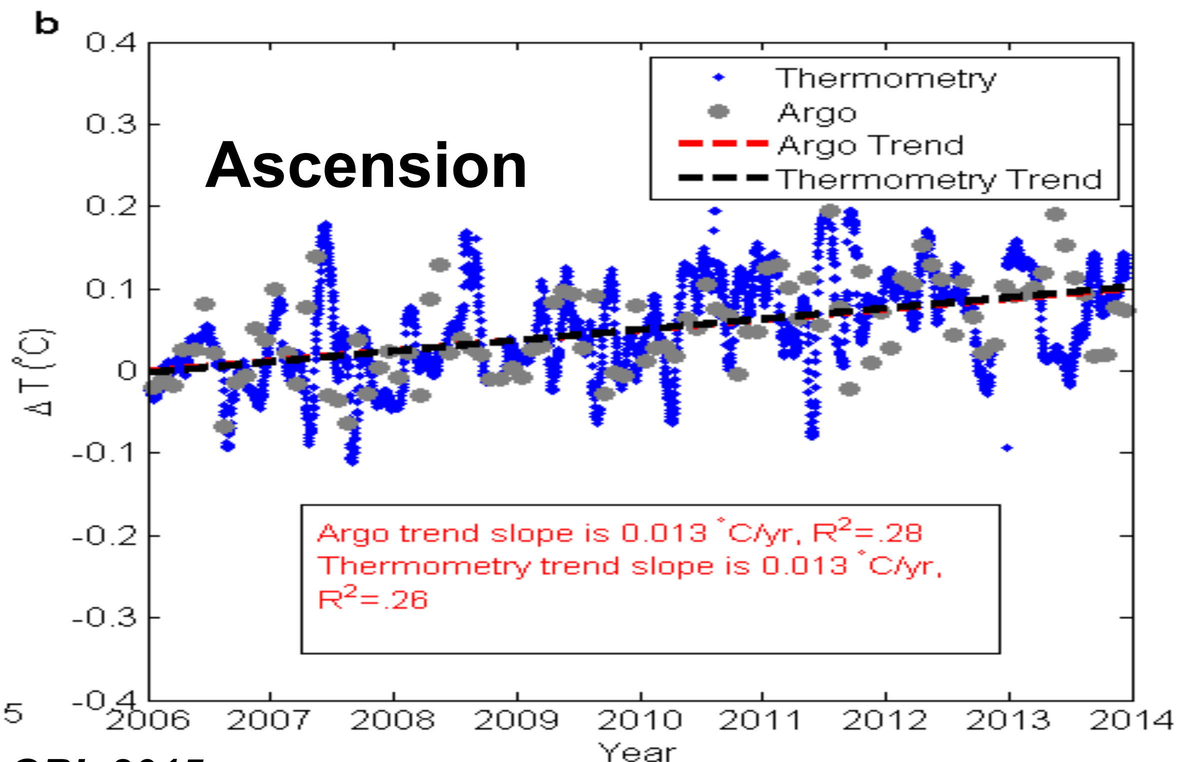
(Munk et al. 2009)

From baseline sound speed profile



Good match between Passive thermometry vs. Argo for linear trend & fluctuations (mesoscale variability ?)





Woolfe, Lani, Sabra, Kuperman., GRL 2015

TAKE AS GIVEN:

- **IMAGING, TOMOGRAPHY AND INVERSION WITH CONTROLLED, PRECISELY POSITIONED, SYNCHRONIZED-SOURCES IS A SOLVED PROBLEM**

GOAL: TOMOGRAPHY from SOURCES OF OPPORTUNITY

- **CONVERT RANDOM, POORLY KNOWN AMBIENT NOISE SOURCES INTO USABLE SOURCES**
- **HIGH-RESOLUTION IMAGE FROM MANY LOW-RESOLUTION IMAGES**
- **EMPLOY DATA (FUSION), ACOUSTIC/OCEAN PHYSICS, SIGNAL PROCESSING, COMPUTER MODELING**

CAN KNOW ~SOURCE POSITION Automatic Identification System (AIS) Ship Tracking Data

What is AIS?

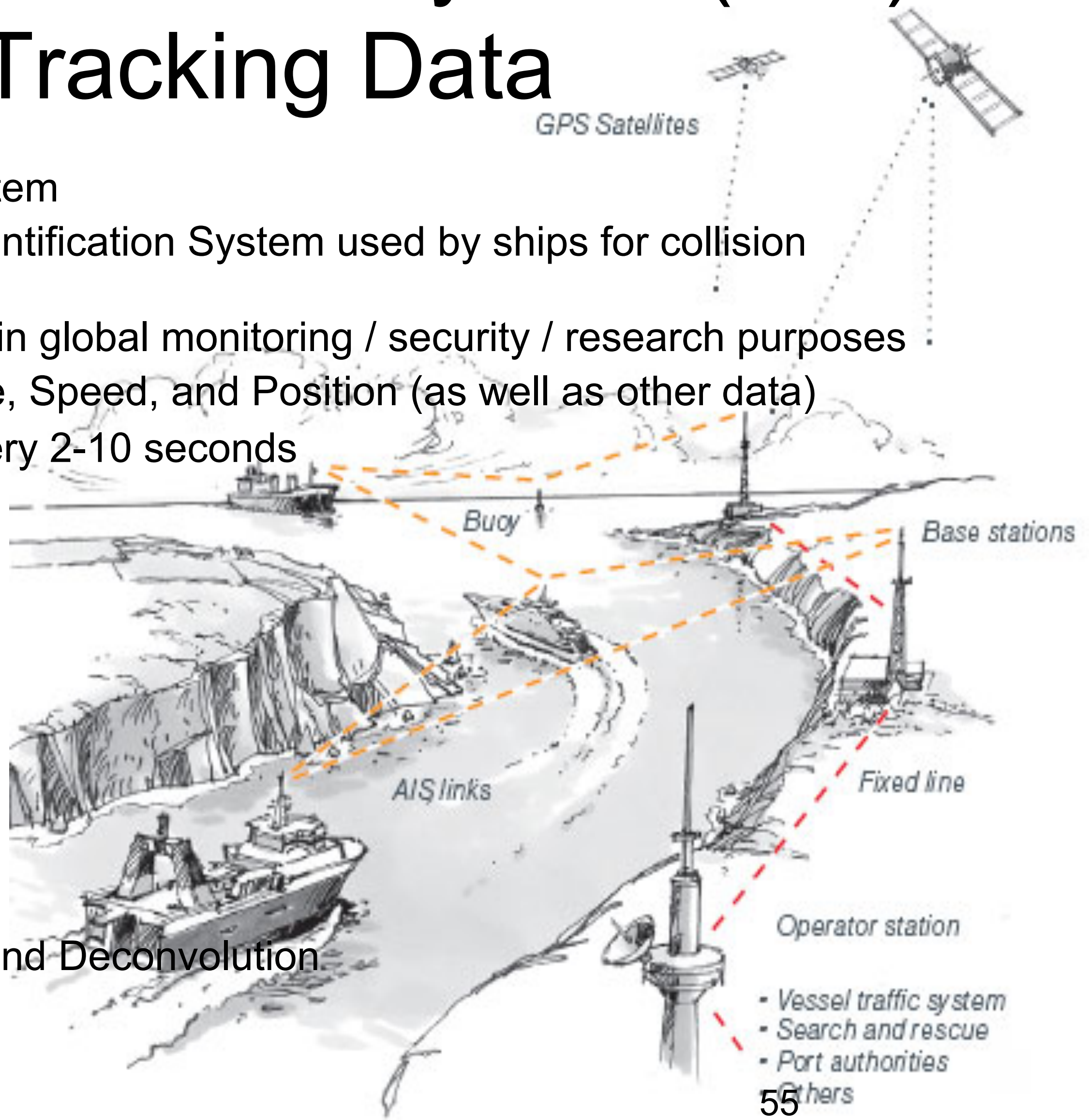
- Automatic Identification System
- Automated Tracking and Identification System used by ships for collision avoidance
  - Never Intended for use in global monitoring / security / research purposes
- Transmits Name, ID, Course, Speed, and Position (as well as other data)
- Accurate to 10 cm; Data every 2-10 seconds

What to we get from AIS?

Location of Ship Noise

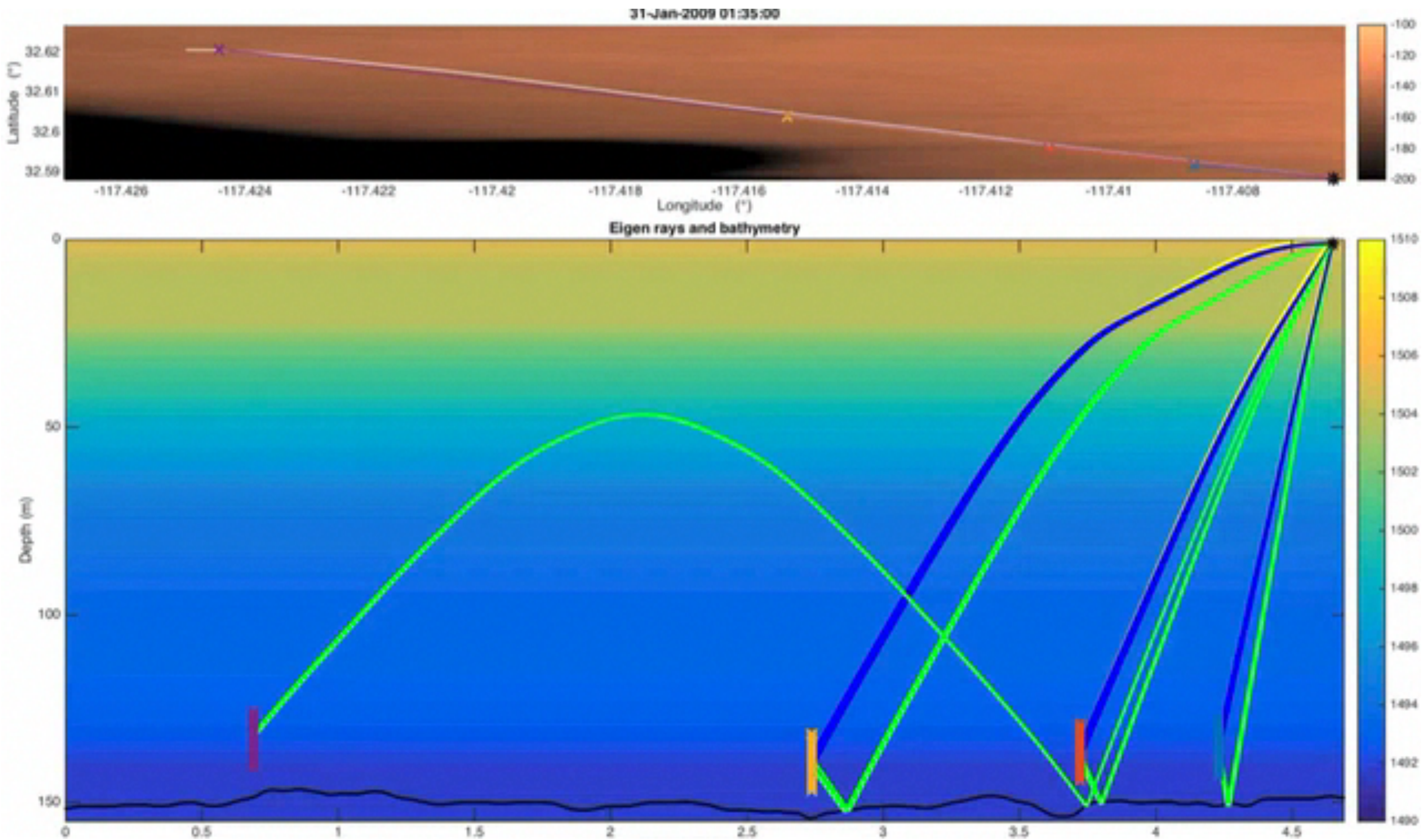
What do we use it for?

- Build Localization Library
- Data Assimilation after Blind Deconvolution

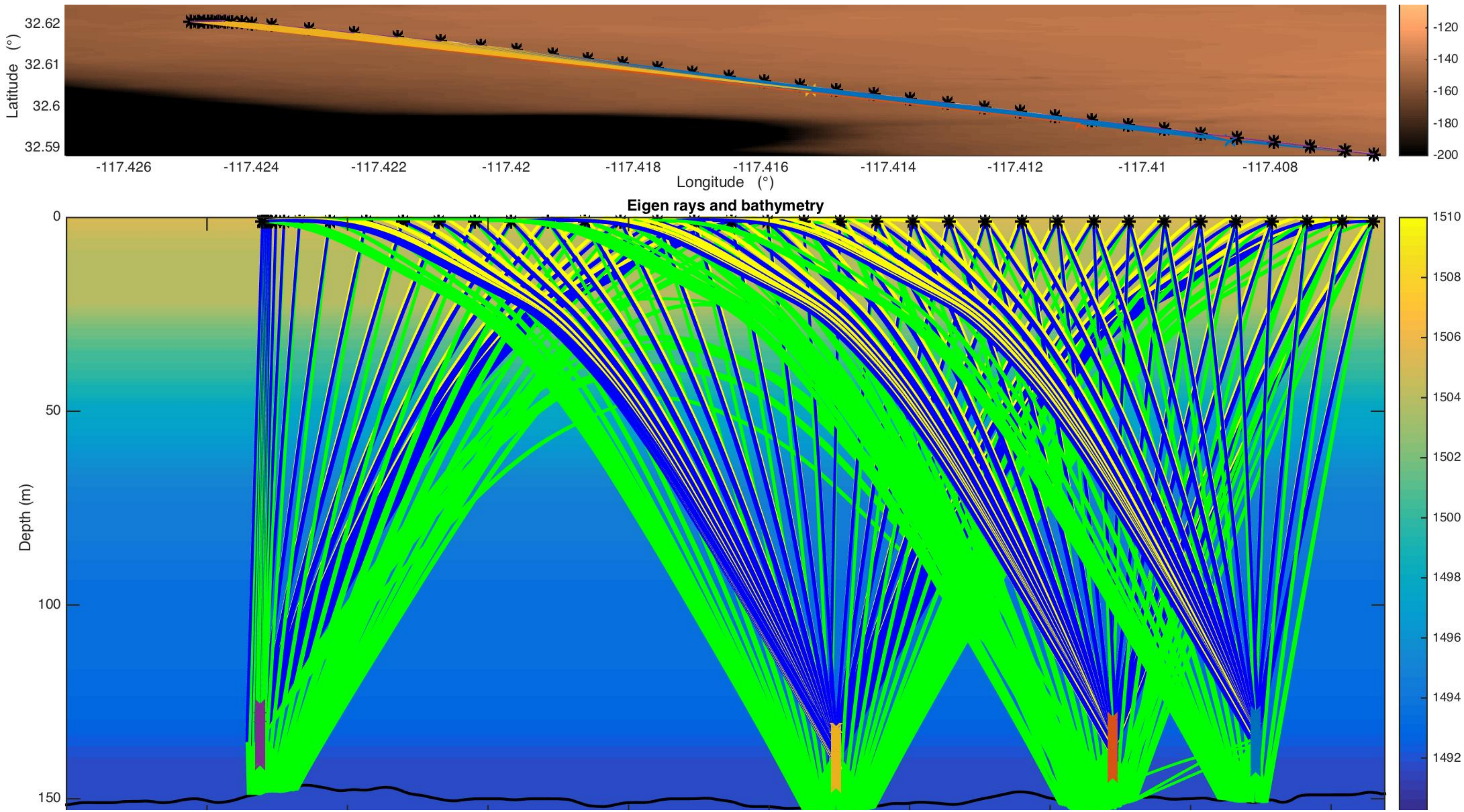


http://www.simrad-yachting.

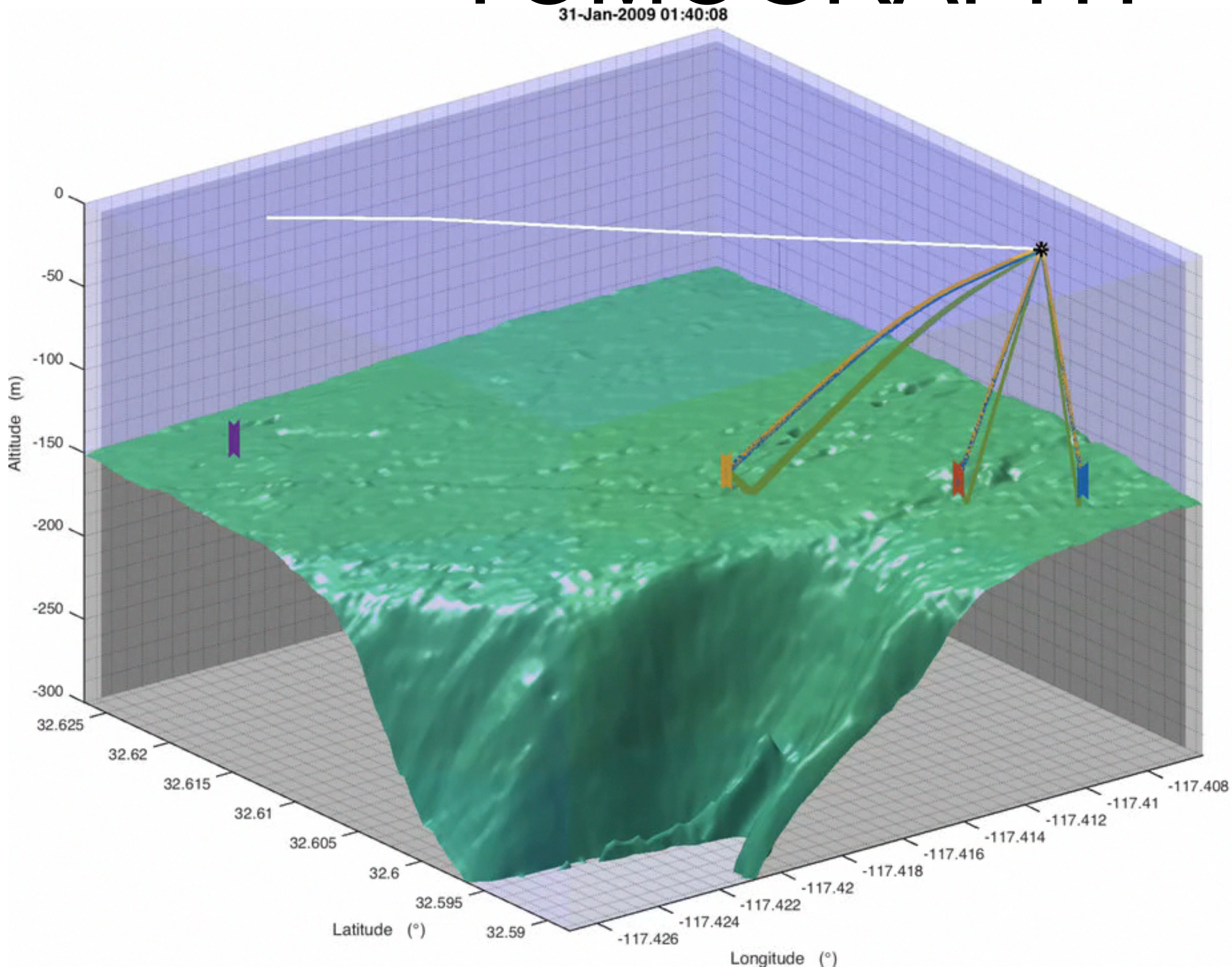
ONCE UPON A TIME…



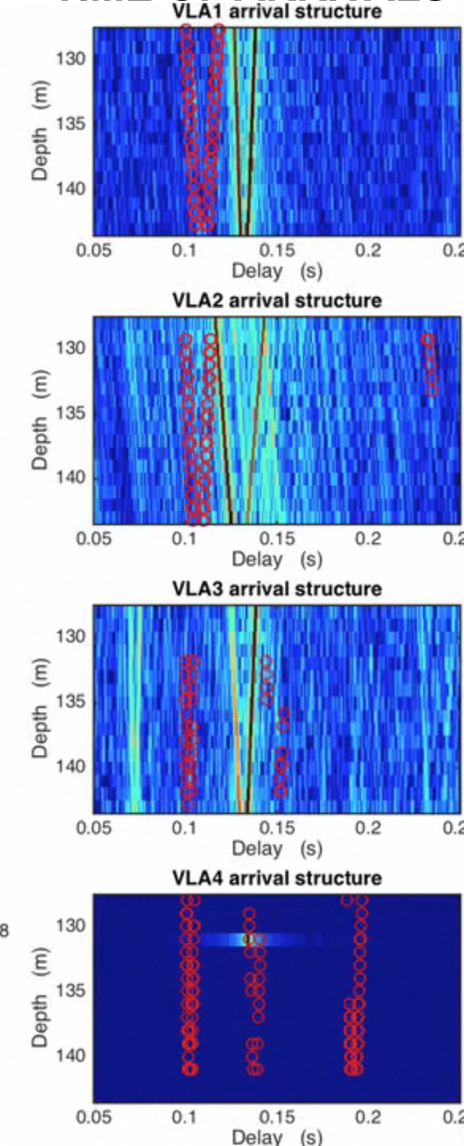
THERE WERE MOVING SHIPS



THAT WERE USED TO DO TOMOGRAPHY



DATA→ACCURATE TIME OF ARRIVALS



REQUIRED ACOUSTIC ACCURACY

ACTIVE

Uncertainty: receiver: ~1 m,

Tomo: source~ 1 m, Clock ~1e-6s

Travel time accuracy needed: ~miliseconds

PASSIVE

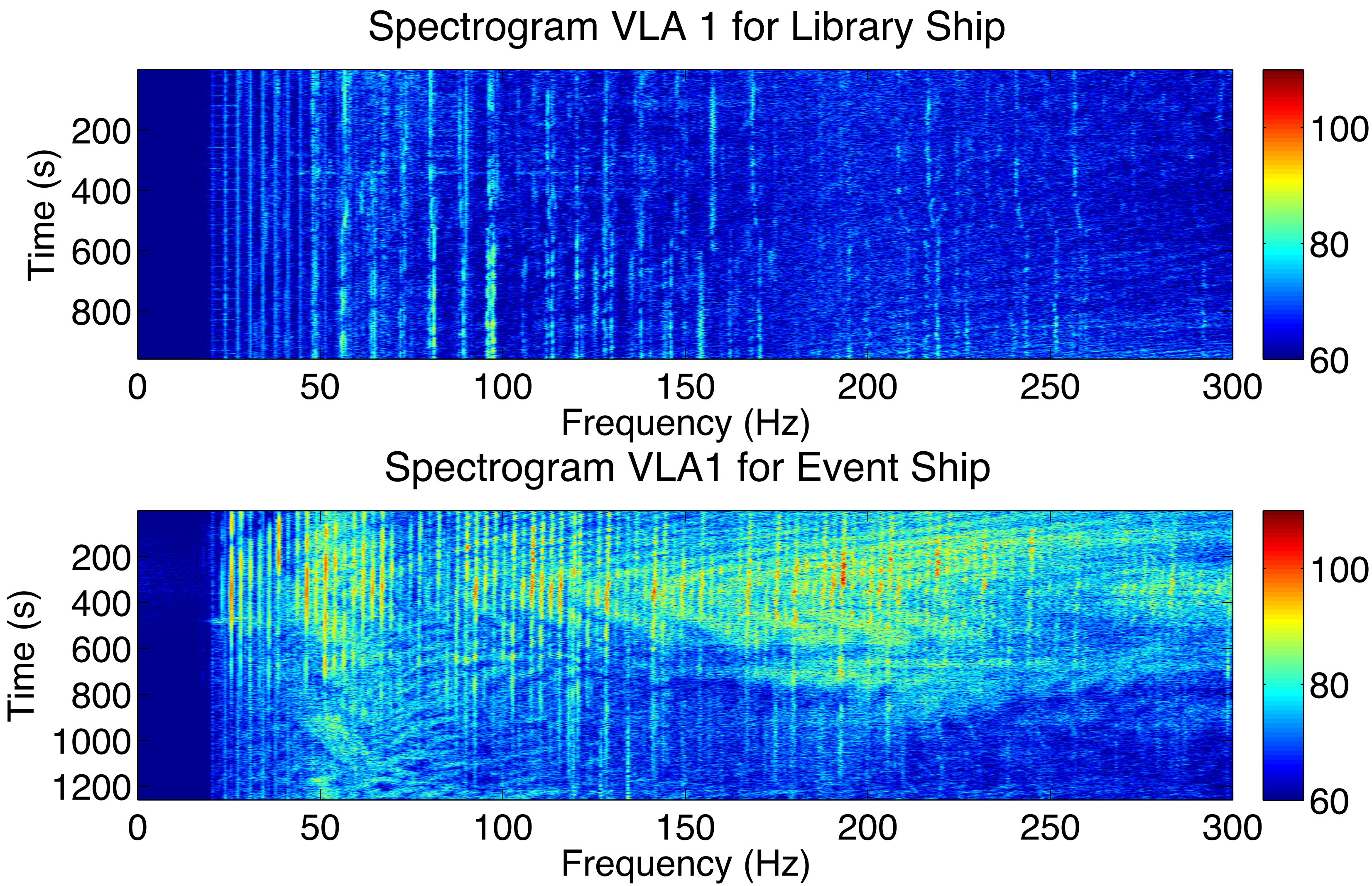
Uncertainty: receiver: ~1 m,

Passive Tomo: source~ 10 m," Clock" ~1e-2s

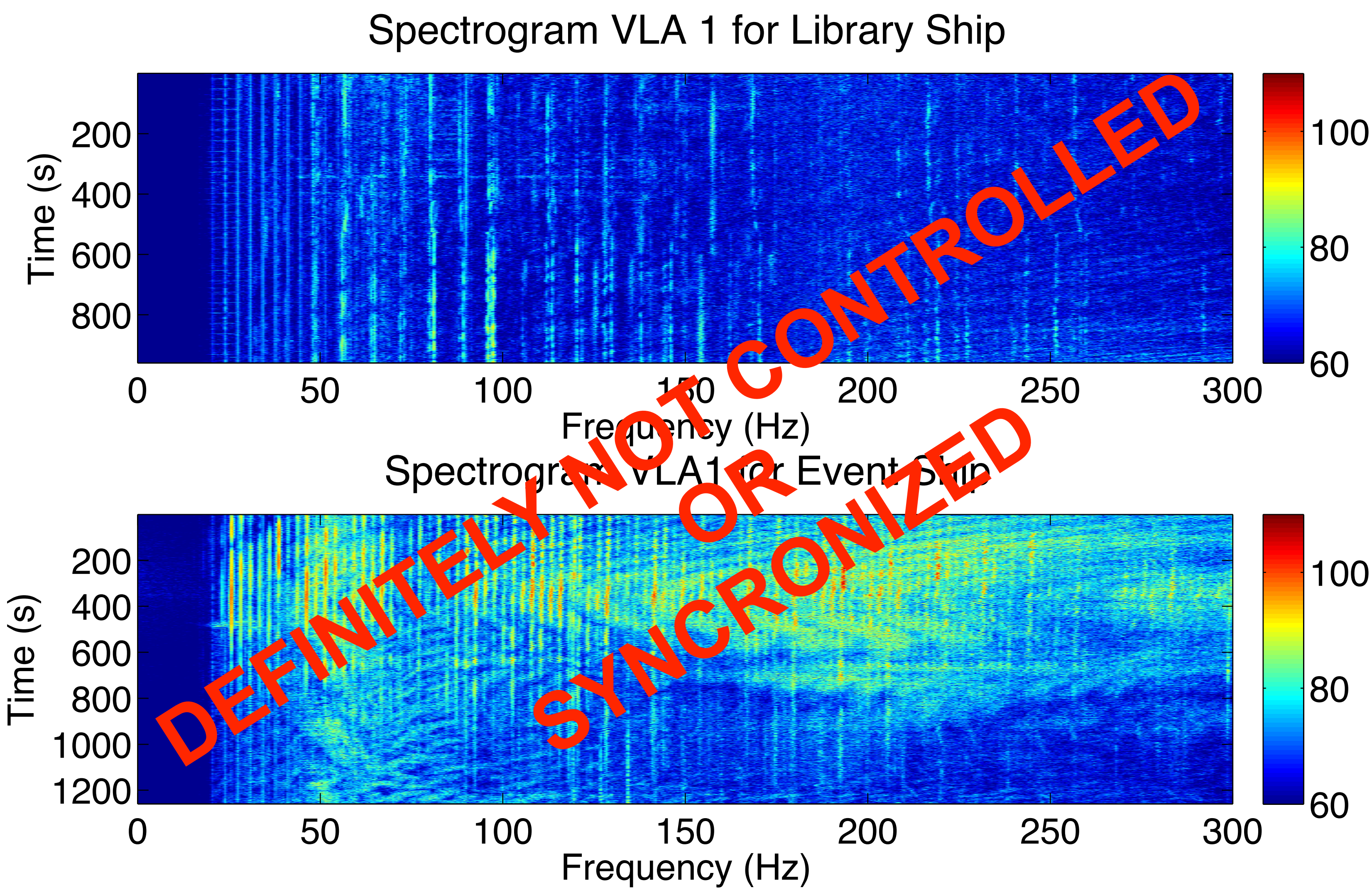
SO, **DIFFERENCE** Between Receivers to get to

Passive Travel time accuracy needed: ~microseconds !!!

SOURCES: Getting Time of Arrival from Different Ships (Spectral Signatures)

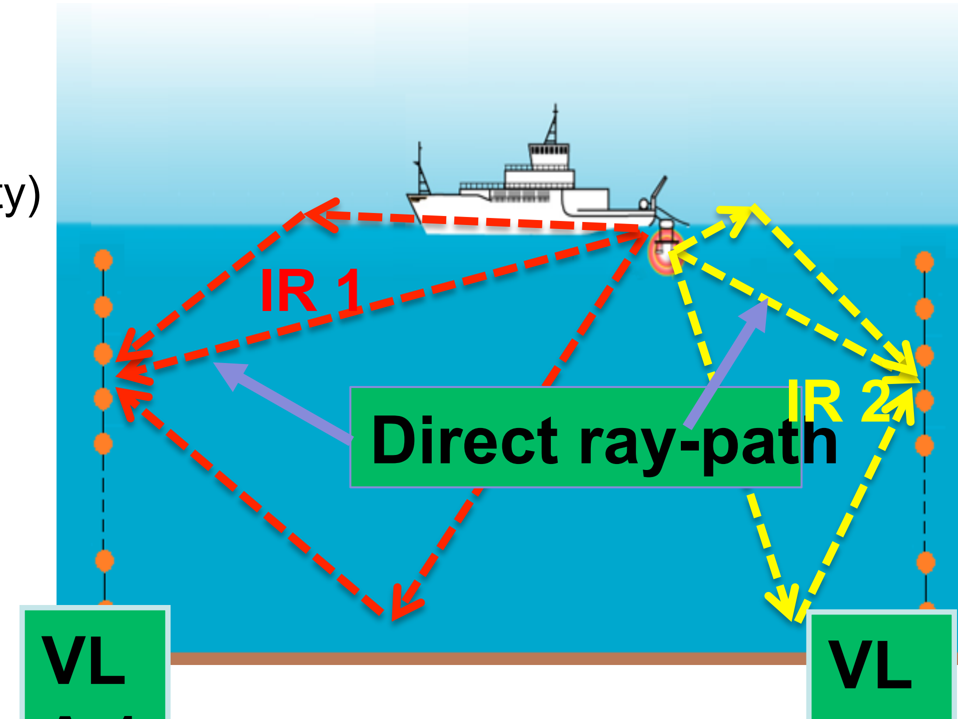


SOURCES: Getting Time of Arrival from Different Ships (Spectral Signatures)

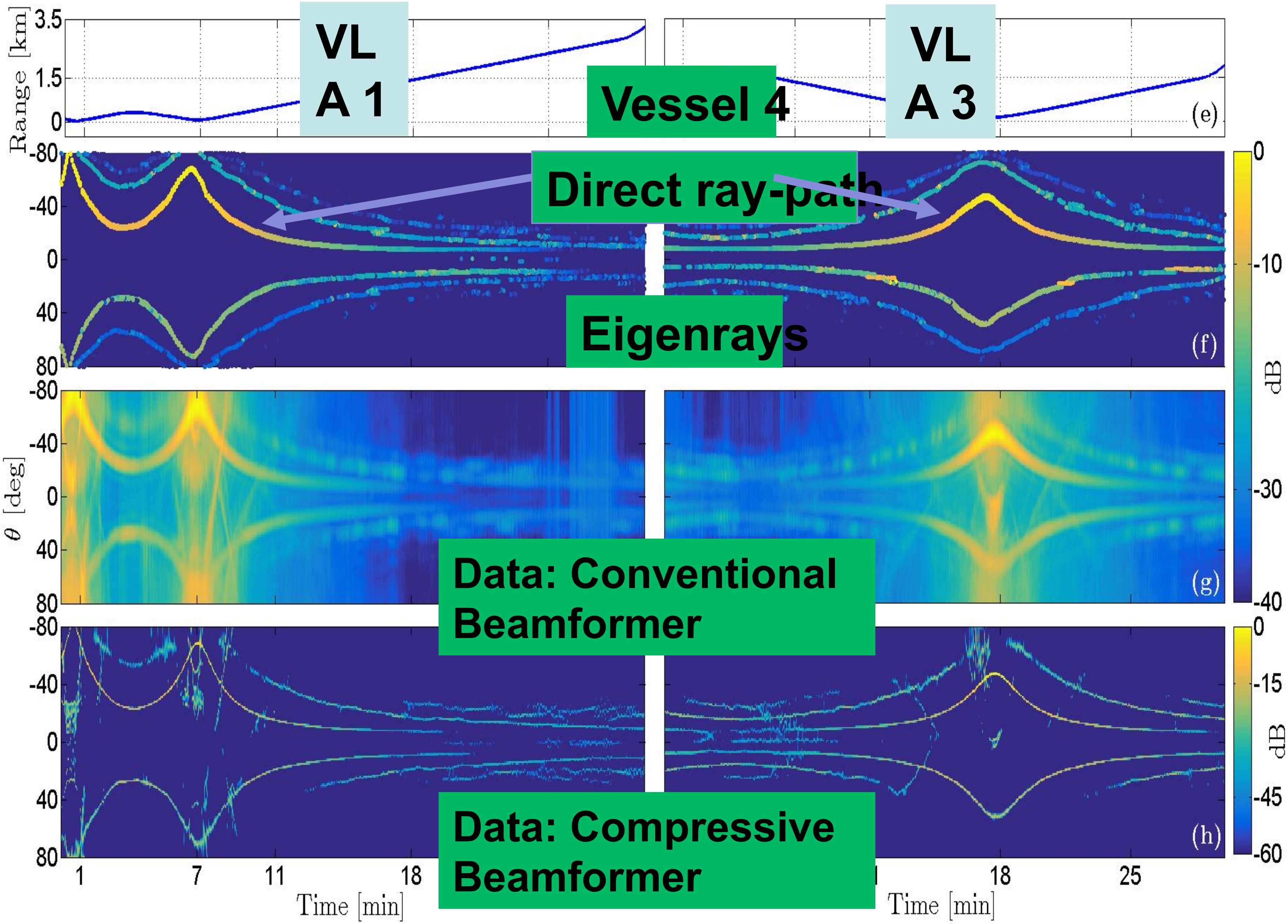


CANDIDATE EXPERIMENTAL CONFIGURATION: DECONVOLUTION

- Exploit information content of a random signal in noise
- Beamforming on a vessel's direct ray-path received on a vertical line array (VLA) yields an estimate of the source signal
  - known signal in noise used as a phase-matched-filter on VLA 1 yields Impulse Response (IR) 1
- Independent array deconvolution: repeat beamforming and IR estimation individually at each VLA
  - source timing uncertainty
- Simultaneous array deconvolution: use the beamformed signal estimated at VLA 1 as a phase-matched-filter on VLA 2
  - Same source signal (reduced uncertainty)
  - requires a more complex model

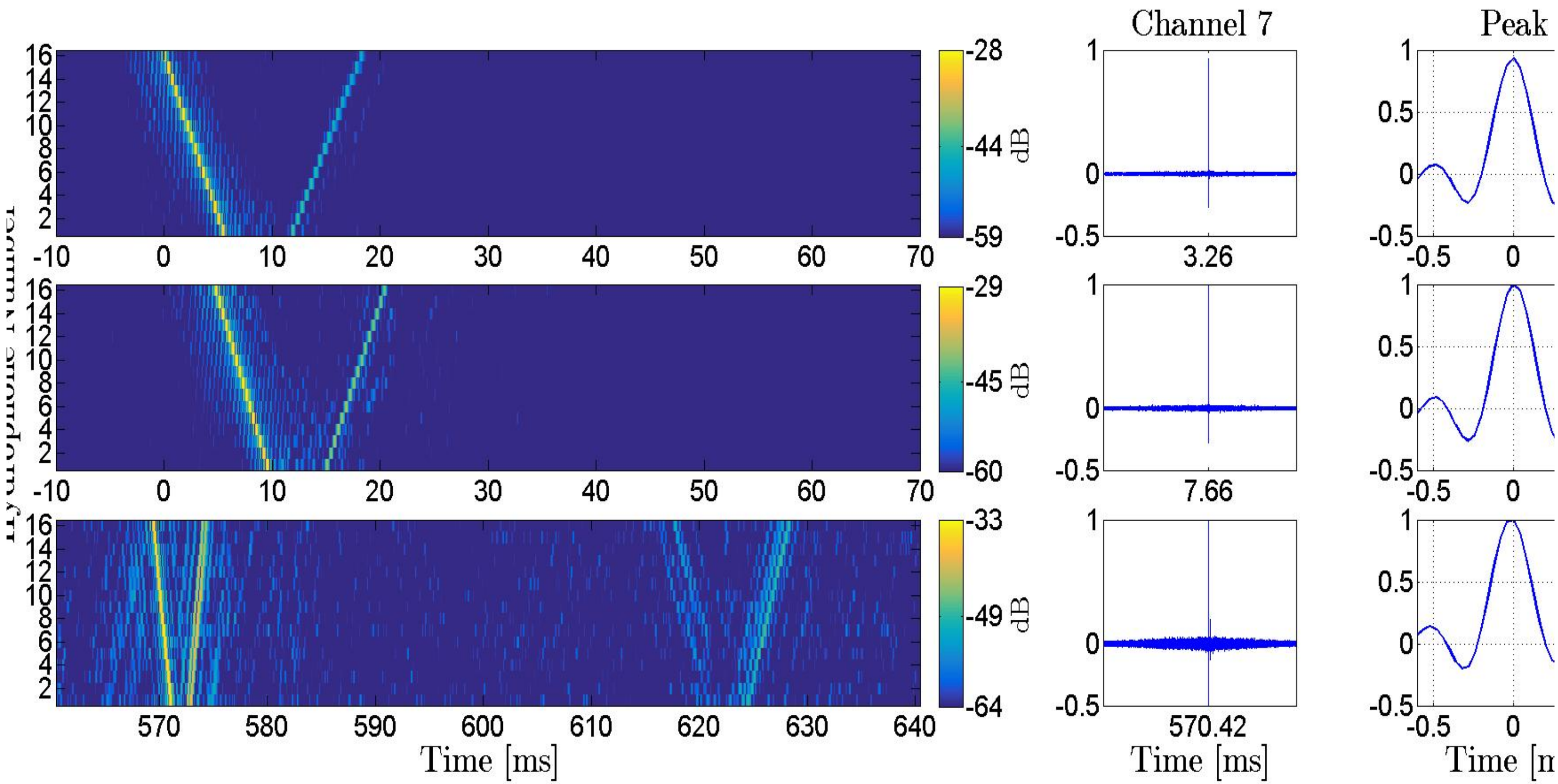


Gemba and Sabra



VL A 1
Vessel 4
VL A 3
Direct ray-path
Eigenrays
Data: Conventional Beamformer
Data: Compressive Beamformer
Range [km]
θ [deg]
Time [min]
dB
(e)
(f)
(g)
(h)

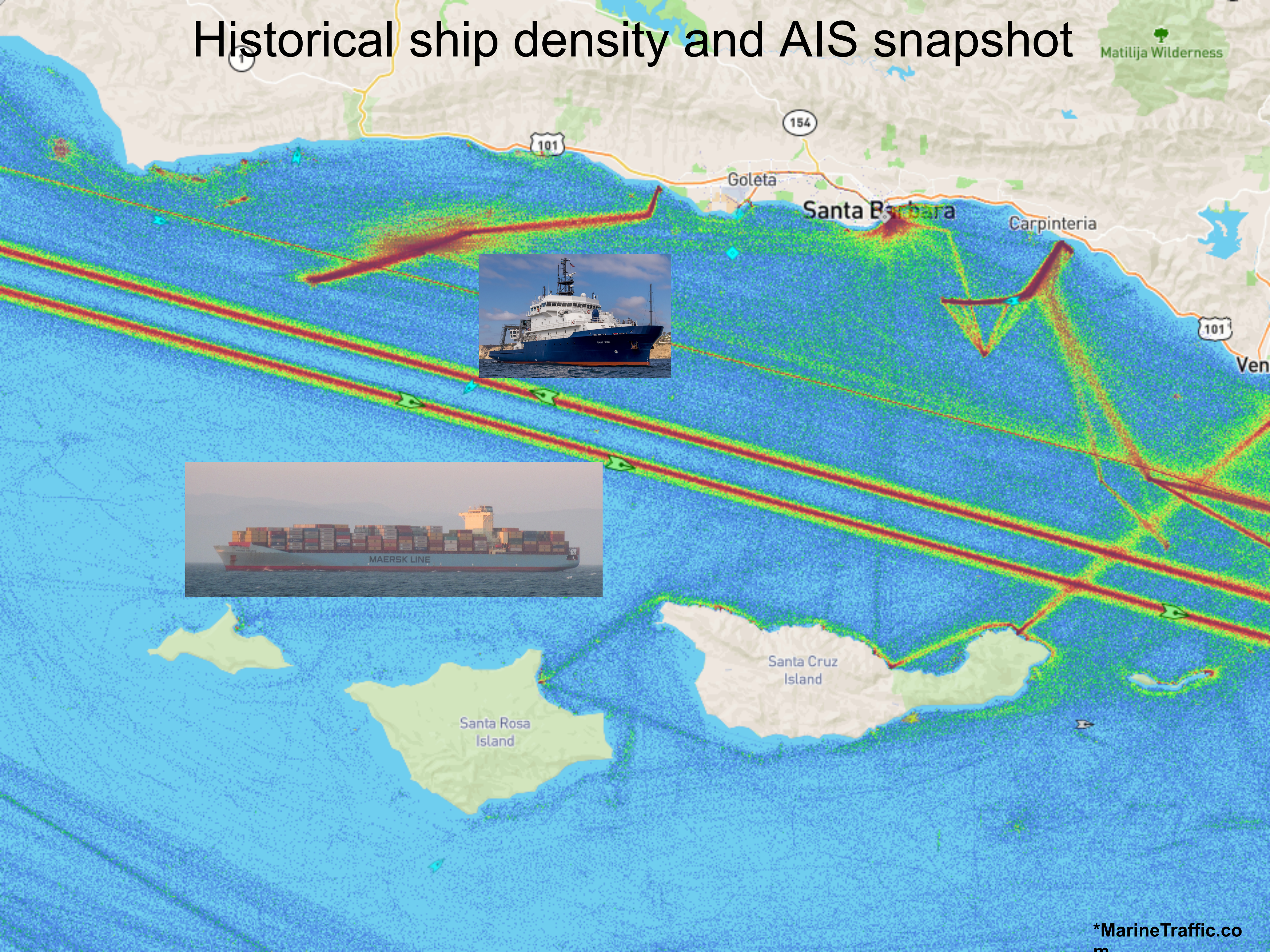
Deconvolution TOA from Passing Ship $\sigma_t \approx 16\ \mu s$



Next steps

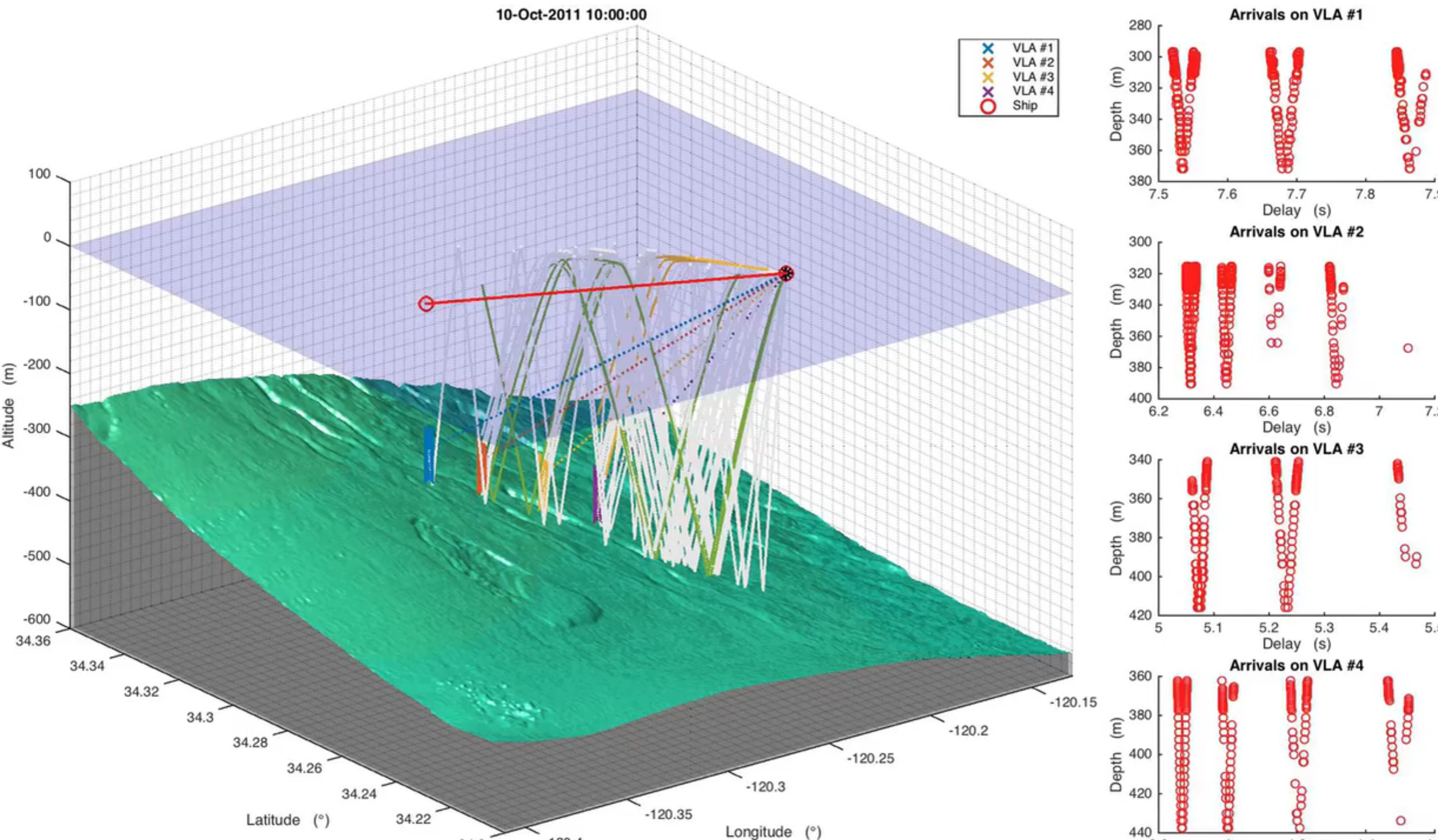
- Quantification of position uncertainty, sensitivity to bottom depth errors, ocean surface depth errors.
- Ocean data assimilation of ray travel times – **done** for other projects, **but** without source/ position uncertainty
- ***THE EXPERIMENT →***

Historical ship density and AIS snapshot



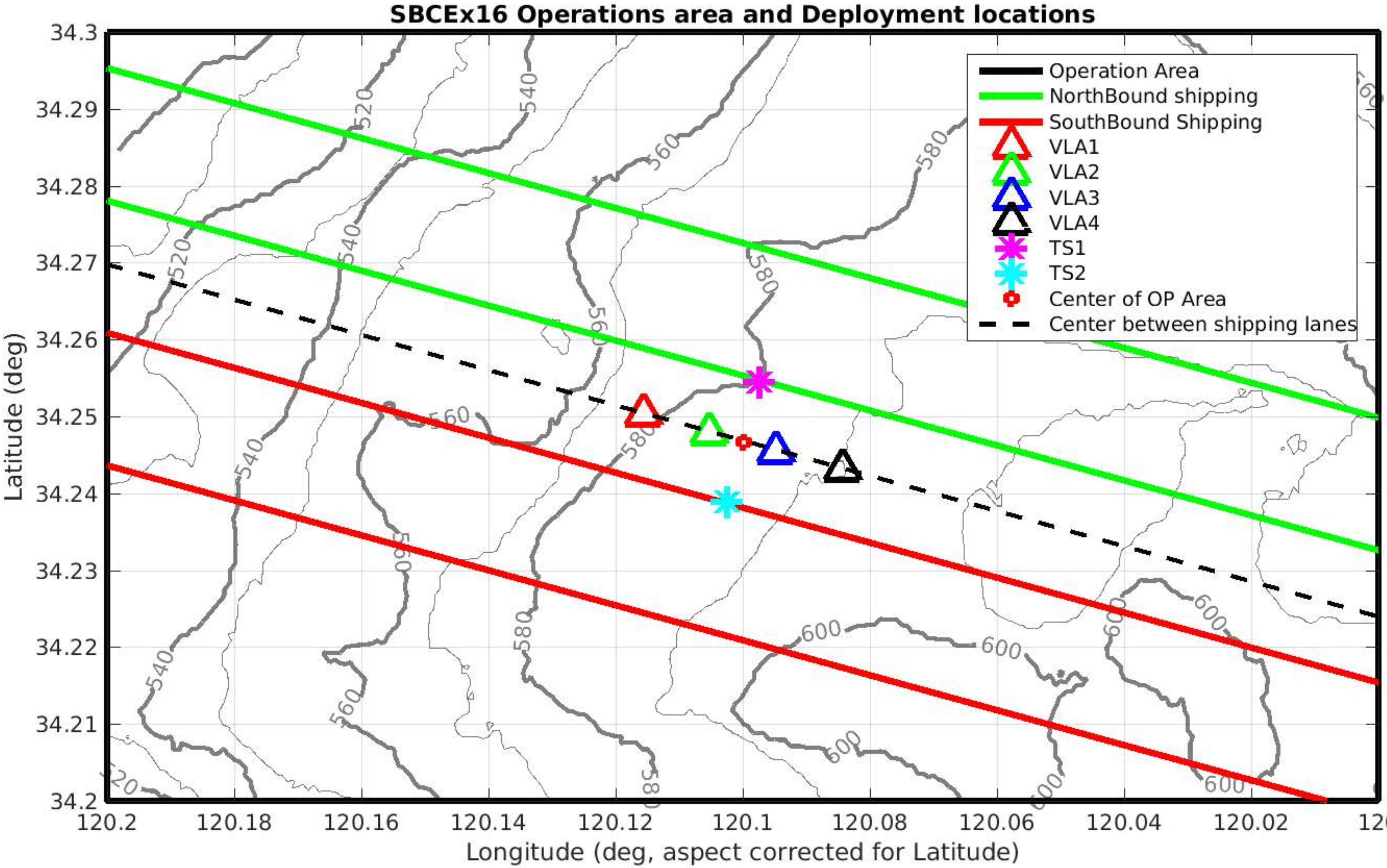
***MarineTraffic.com**

MOVING SHIP in DYNAMIC OCEAN



September 2016 Experiment

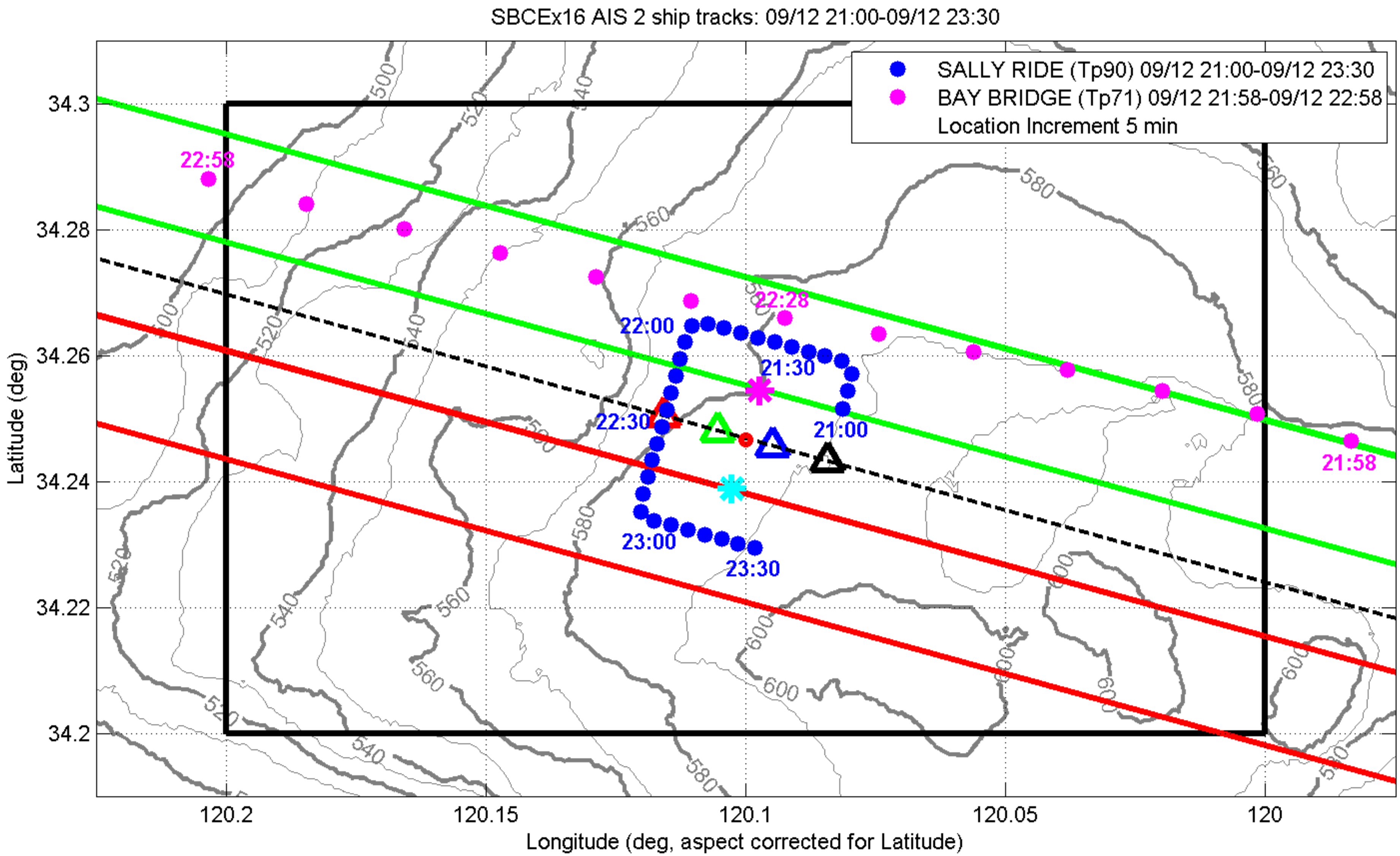
32 EL VLA'S/TS Deployment Locations



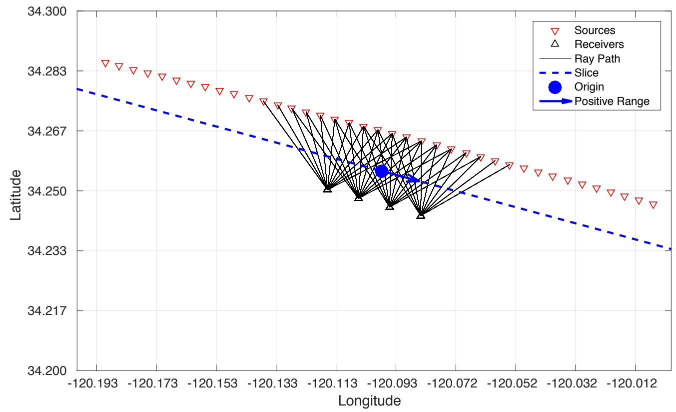
SBCEx16 operational area, bathymetry, shipping lanes, and deployment locations of

September 2016 Experiment- CONTROL X

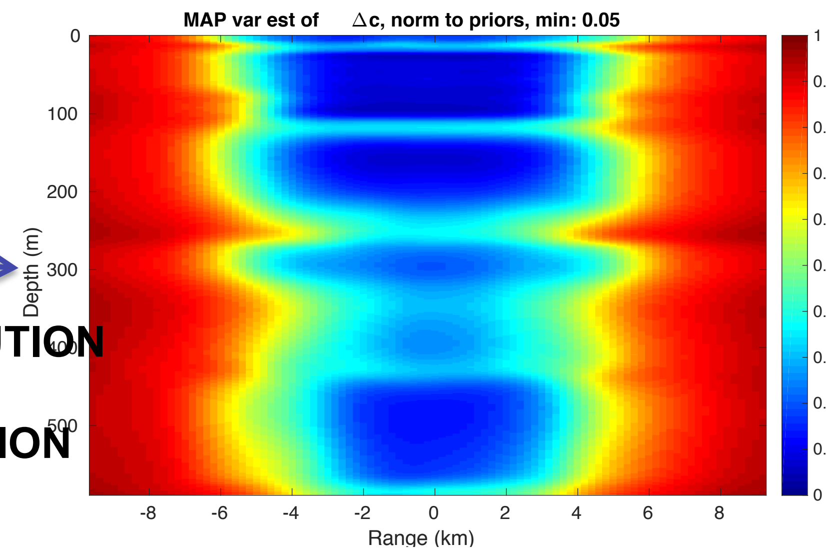
Bay Bridge and Sally Ride: JD 256 2100-2330Z



EXPECTATIONS: ESTIMATE of POSTERIOR UNCERTAINTY



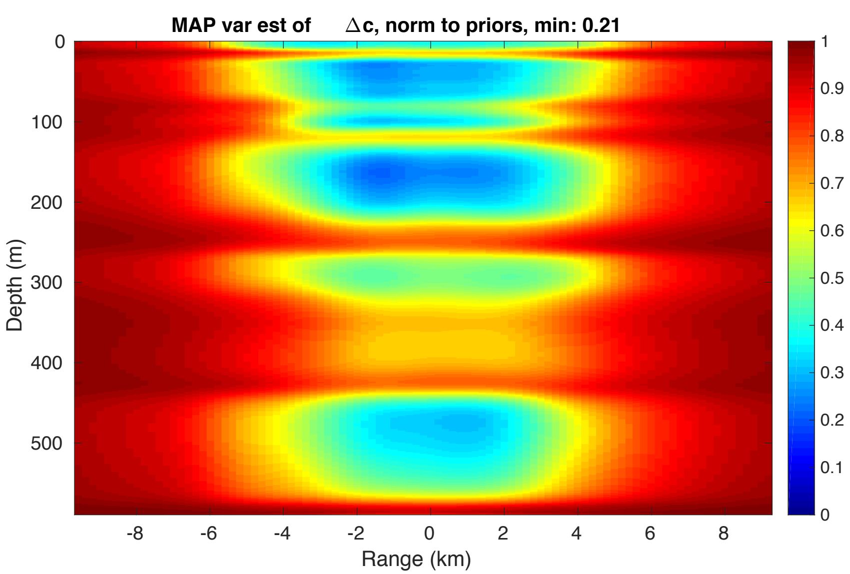
$$\hat{\mathbf{P}} = \left(\mathbf{H}^{\dagger} \mathbf{R}^{-1} \mathbf{H} + \mathbf{P}^{-1} \right)^{-1}$$

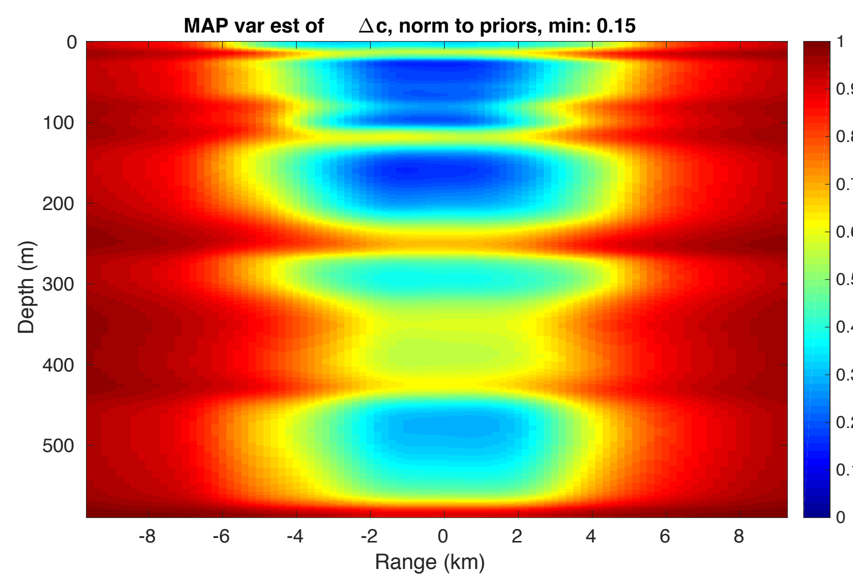


CONTROLLED ACIVE SOURCE

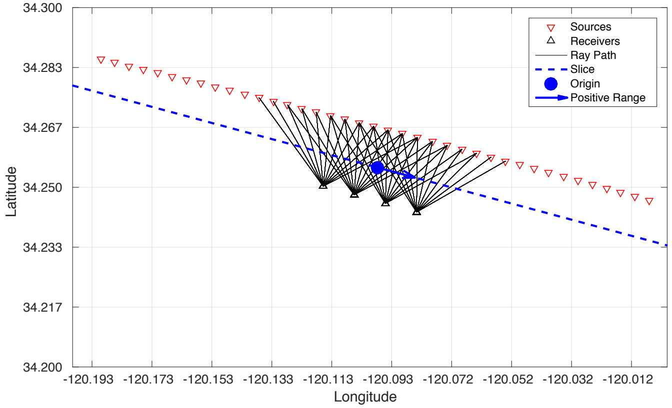
PASSIVE: SIMULTANEOUS ARRAY DOCONVOLUTION

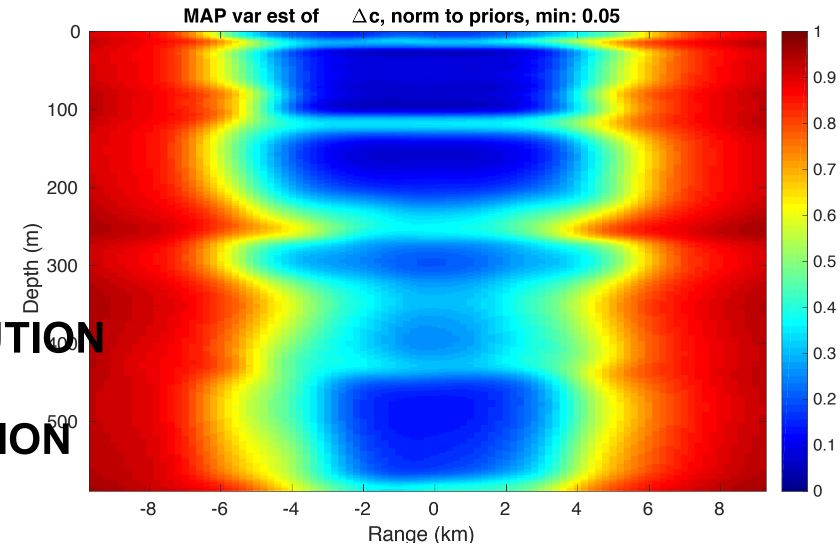
PASSIVE: INDEPENDENT ARRAY DECONVOLUTION





ESTIMATE of POSTERIOR UNCERTAINTY





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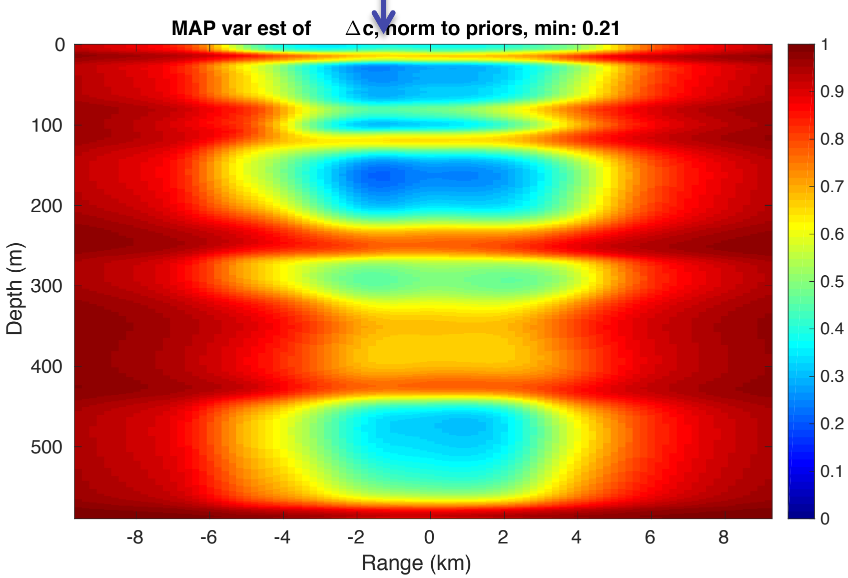
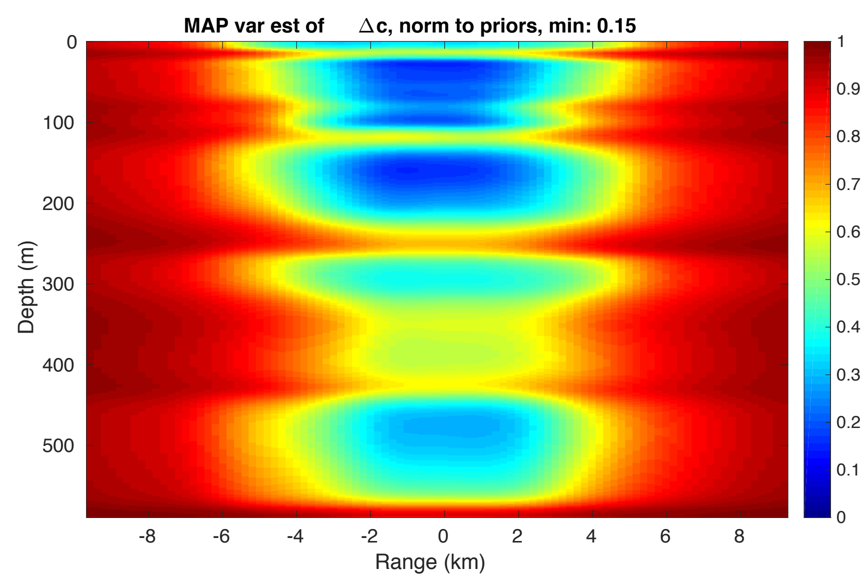




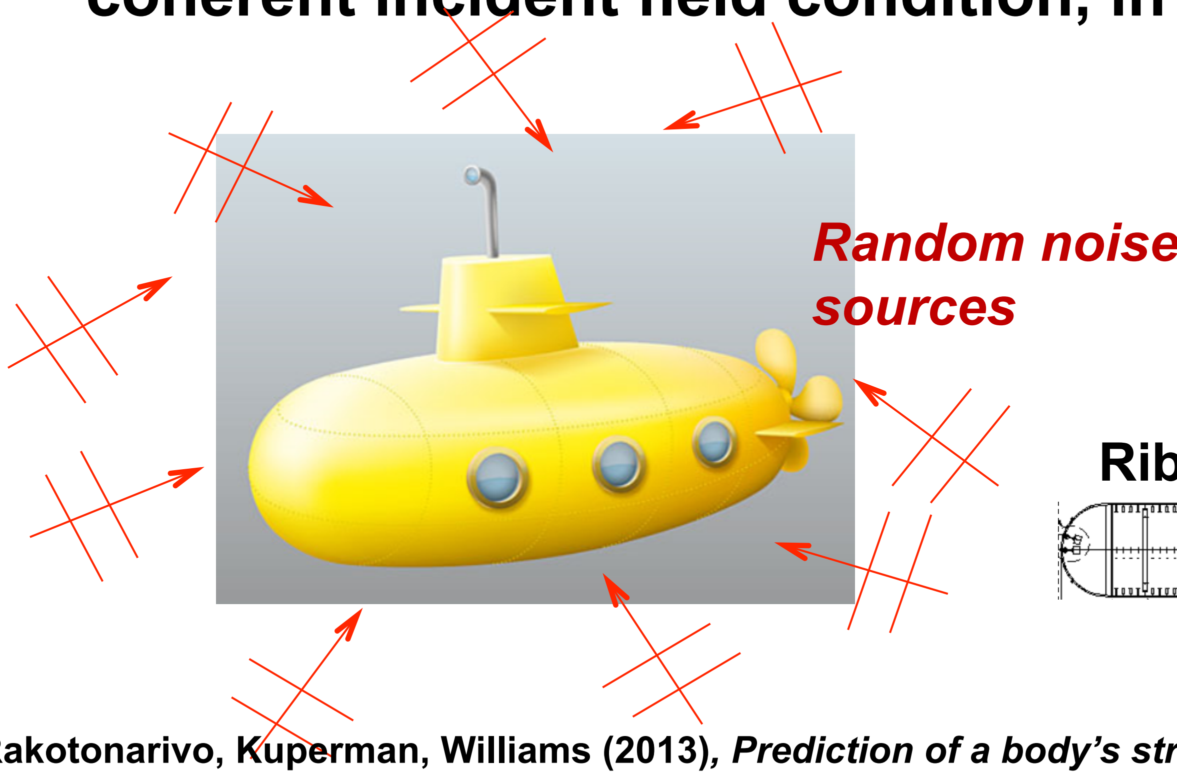
DATA BEING ANALYZED

Underwater Acoustics Motivated Problem: Object Scattering

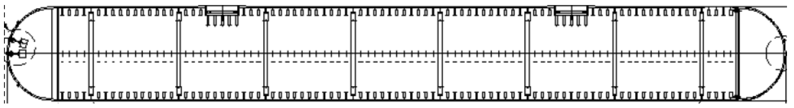
- Examples: Submarines, Mines…
- Issue: Determining Sattering Properties of Object is Difficult
  - Experimentally {Huge Effort/Facility}
  - Computationally {e.g., gazillion degrees of freedom(DOF) finite element calculation}
- BUT: Scatterer is ultimately observed by system with limited DOF
- **SOLUTION: NOISE!!!**

OBJECTIVES

- **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)

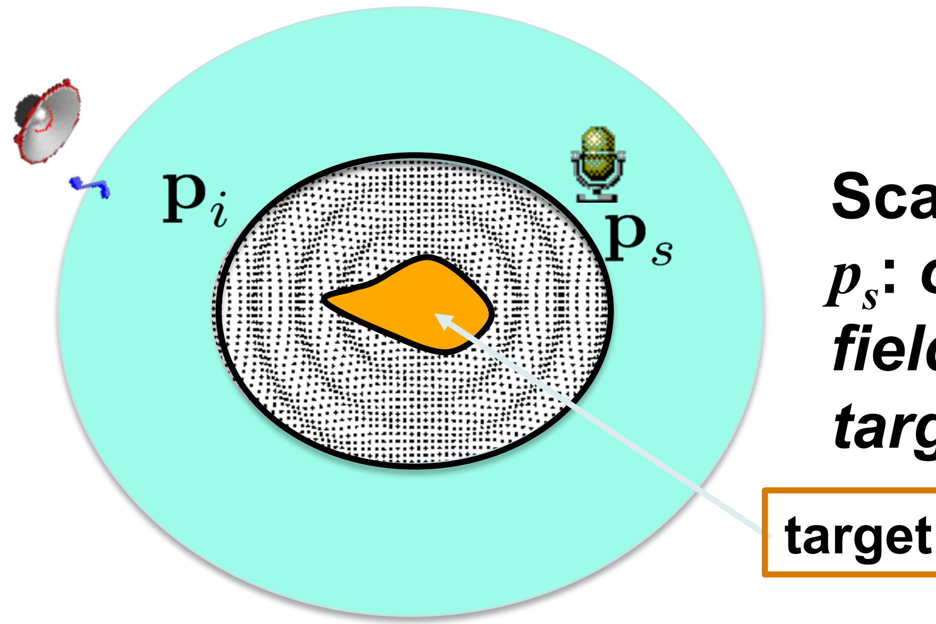


Rakotonarivo, Kuperman, Williams (2013), ***Prediction of a body's structural impedance and scattering properties using correlation of random noise*** **, JASA**

GOVERNING MATRIX – THE S MATRIX

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

Incident field ***p_i*: *the source field without the target***



Scattered field ***p_s*: *outgoing field due to target scattering***

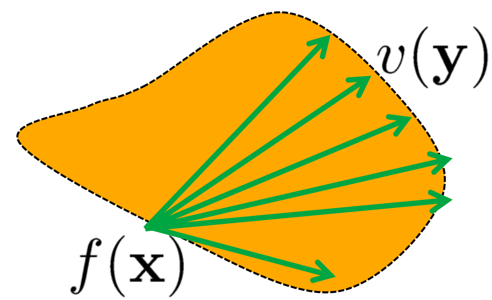
$$\underbrace{\begin{pmatrix} p_{s1} \\ p_{s2} \\ \vdots \\ p_{sM} \end{pmatrix}}_{\mathbf{p}_s} = \underbrace{\begin{pmatrix} S_{11} & S_{12} & \cdots & S_{1M} \\ S_{21} & S_{22} & \cdots & S_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ S_{M1} & S_{M2} & \cdots & S_{MM} \end{pmatrix}}_{\mathbf{S}} \underbrace{\begin{pmatrix} p_{i1} \\ p_{i2} \\ \vdots \\ p_{iM} \end{pmatrix}}_{\mathbf{p}_i}$$

M **points on the target surface**

WHAT is the STRUCTURAL IMPEDANCE?

Structural admittance Green's function definition:

Discretize & Invert G: $\mathbf{f} = \mathbf{Z_s}\mathbf{v}$



Structural impedance matrix

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

$$\begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ p_N \end{pmatrix} = -\underbrace{\begin{pmatrix} Z_{11} & Z_{12} & \cdots & Z_{1N} \\ Z_{21} & Z_{22} & \cdots & Z_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N1} & Z_{N2} & \cdots & Z_{NN} \end{pmatrix}}_{\mathbf{Z_s}} \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{pmatrix}$$

Pressure field <u>at the object surface</u> ($\mathbf{p}$)

Normal velocity <u>at the object surface</u> ($\mathbf{v}$)

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

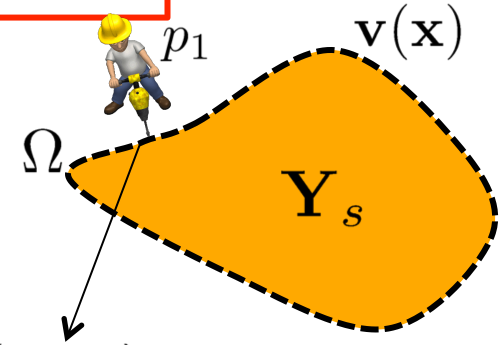
Isolation of the target physics – The Structural Admittance Matrix

The structural Admittance $\mathbf{Y}_s$ relates the surface velocity to the surface normal stresses $\tau_{\nu\nu}$ of an applied load when the object is in a vacuum. It describes the physics of the elastic body.

$$v(\mathbf{x}) = \int_\Omega Y_s(\mathbf{x},\mathbf{y})\tau_{\nu\nu}(\mathbf{y})d^2\mathbf{y}$$

discretized $\tau_{\nu\nu}(y_i) = p_i$

$$\mathbf{v} = -\mathbf{Y}_s\mathbf{p}$$



$\mathbf{Y}_s$ is the <u>in vacuo</u> structural admittance matrix

Discretize surface with M points

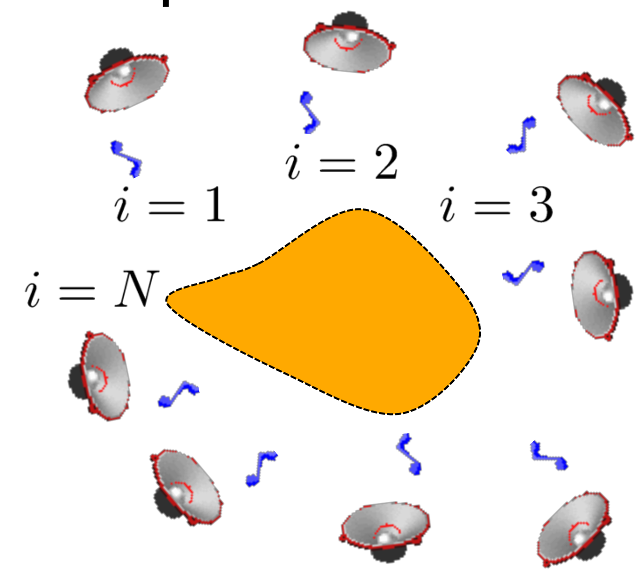
$$\underbrace{\begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_M \end{pmatrix}}_{\mathbf{v}} = -\underbrace{\begin{pmatrix} Y_{11} & Y_{12} & \cdots & Y_{1j} & \cdots & Y_{1M} \\ Y_{21} & Y_{22} & \cdots & Y_{2j} & \cdots & Y_{2M} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ Y_{M1} & Y_{M2} & \cdots & Y_{Mj} & \cdots & Y_{MM} \end{pmatrix}}_{\mathbf{Y}_s} \underbrace{\begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ p_j \\ \vdots \\ p_M \end{pmatrix}}_{\mathbf{p}}$$

Admittance Measurement Procedure

- Consider a single measurement of the total velocity $\mathbf{v}^{(1)}$ & pressure $\mathbf{p}^{(1)}$ (incident + scattered) using an external source

$$\begin{pmatrix} v_1^{(1)} \\ v_2^{(1)} \\ \vdots \\ v_M^{(1)} \end{pmatrix}^{M\times 1} = -\mathbf{Y_s} \begin{pmatrix} p_1^{(1)} \\ p_2^{(1)} \\ \vdots \\ p_M^{(1)} \end{pmatrix}^{M\times 1}$$

***N* loudspeaker sources**



- Now do a 2nd measurement $\mathbf{v}^{(2)}$ & $\mathbf{p}^{(2)}$ with another external source; append vectors:

$$\begin{pmatrix} v_1^{(1)} & v_1^{(2)} \\ v_2^{(1)} & v_2^{(2)} \\ \vdots & \vdots \\ v_M^{(1)} & v_M^{(2)} \end{pmatrix}^{M\times 2} = -\mathbf{Y_s} \begin{pmatrix} p_1^{(1)} & p_1^{(2)} \\ p_2^{(1)} & p_2^{(2)} \\ \vdots & \vdots \\ p_M^{(1)} & p_M^{(2)} \end{pmatrix}^{M\times 2}$$

- Repeat N times to get MxN matrices V and P

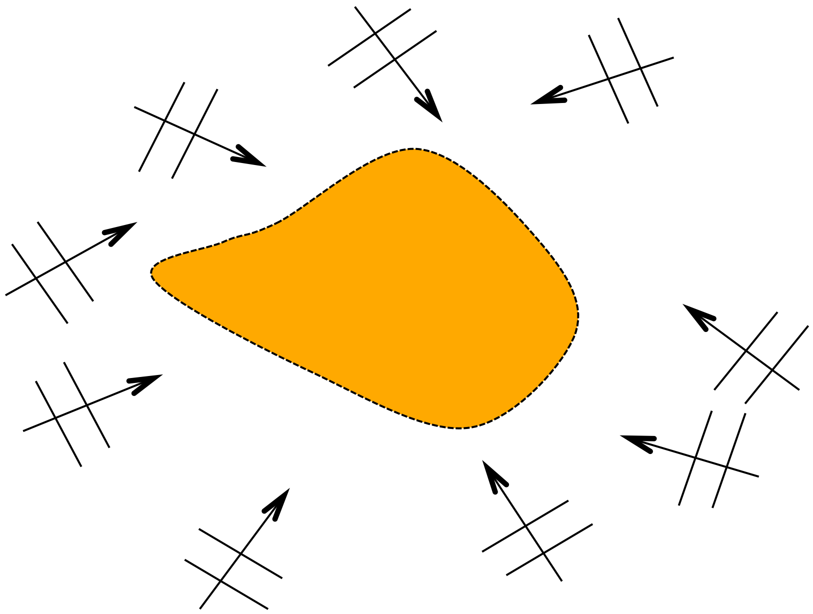
$$\mathbf{V} \equiv (\mathbf{v}^{(1)}\mathbf{v}^{(2)}\cdots\mathbf{v}^{(N)}) = -\mathbf{Y}_s(\mathbf{p}^{(1)}\mathbf{p}^{(2)}\cdots\mathbf{p}^{(N)})$$

MEASUREMENT of the STRUCTURAL IMPEDANCE

After ensemble averaging:

$$\langle \mathbf{p}\mathbf{p}^H \rangle = -\mathbf{Z}_\mathbf{s} \langle \mathbf{v}\mathbf{p}^H \rangle$$

All are N x N matrices



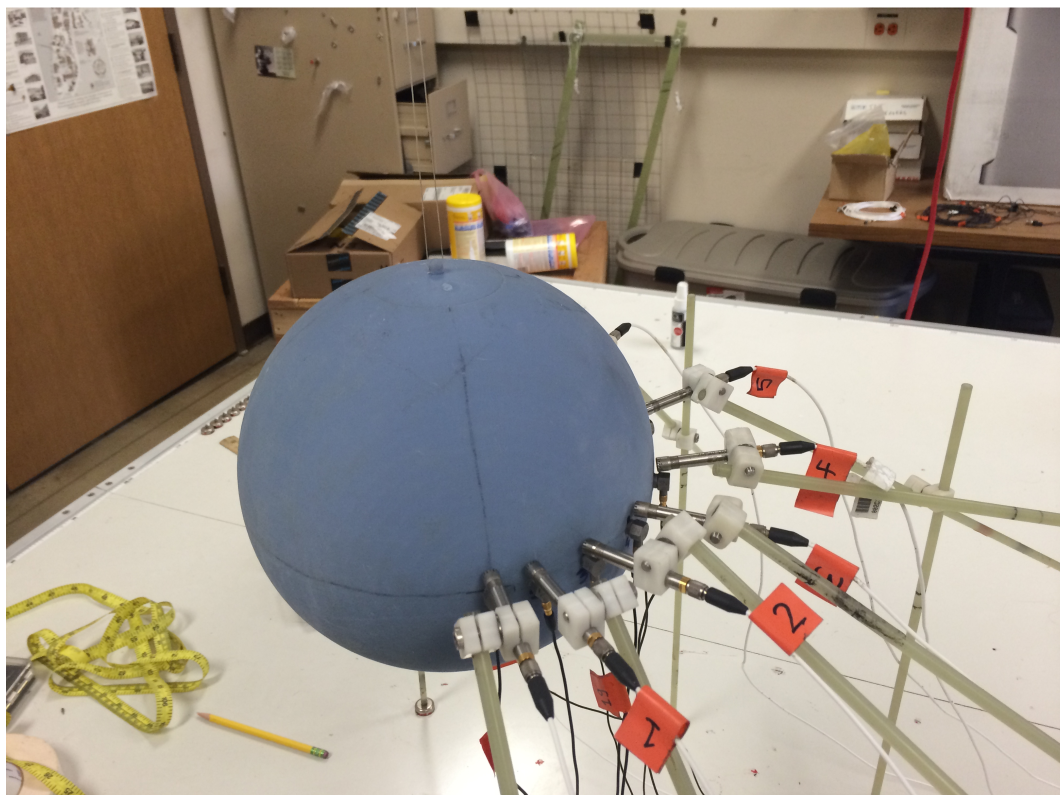
If sufficient number of spatially random realizations, we can invert : $\langle \mathbf{v}\mathbf{p}^H \rangle$

$$\mathbf{Z}_\mathbf{s} = -\langle \mathbf{p}\mathbf{p}^H \rangle \langle \mathbf{v}\mathbf{p}^H \rangle^{-1}$$

Rakotonarivo, Williams, Kuperman (2013)

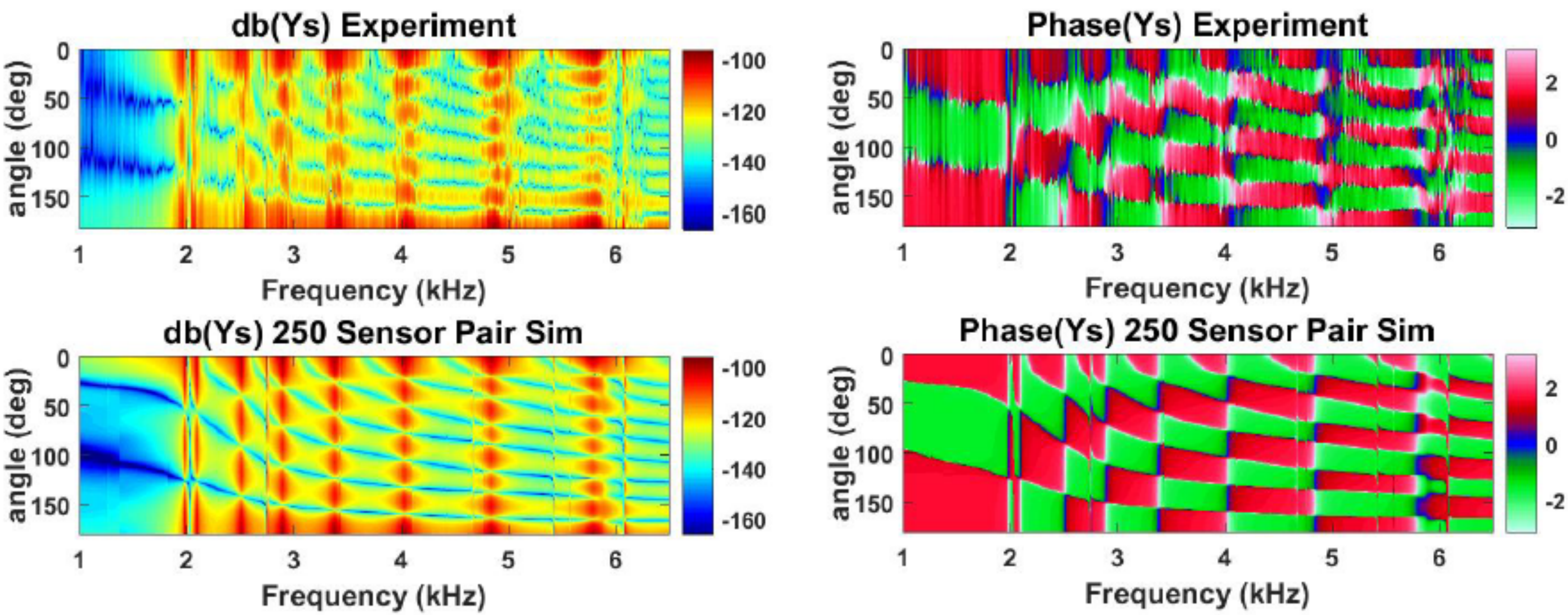
INITIAL EXPERIMENT/DEMONSTARION OF METHOD

- **Correlation method to predict the structural impedance using random noise sources, ESM to yield radiation impedance and internal impedance**
- **Scattered field prediction for a given incident field**
- **Coming Next: Experimental investigation – spherical shell**



Experiment – Results

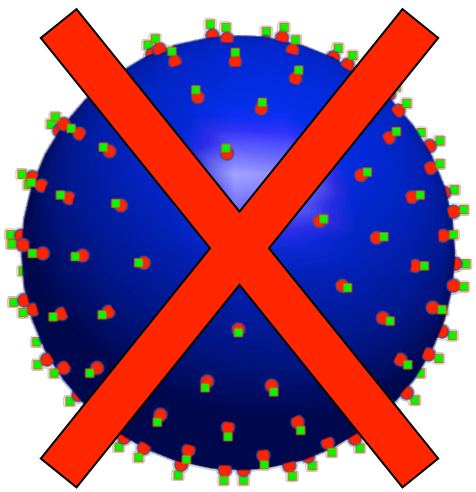
- Successful construction of $\mathbf{Y}_s$ - top panels amplitude and phase (experiment). Bottom panels 250 accels/mikes (simulations)

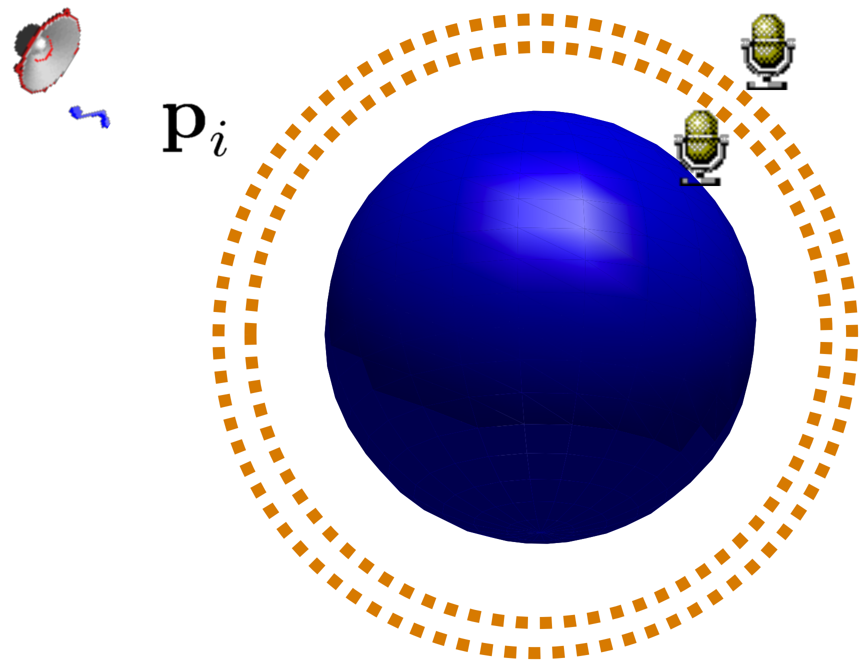


- Successful construction of $\mathbf{Y}_s$
- BUT Insufficient accuracy to get $\mathbf{S}$ matrix in water
- For arbitrary scatterer need around 250 accels & mikes

NEXT: Avoiding Surface Accelerometers

- **Propose two conformal arrays of MEMS microphones supported in a 3D printed structure**
- **Use dual surface Nearfield Acoustical Holography to get v and p on the surface, & construct Y_s as described.**

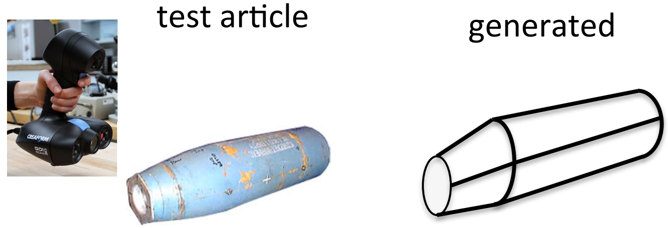




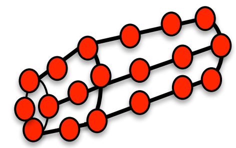
LAB UNDER CONSTRUCTION

(1) 3D Scan of test article

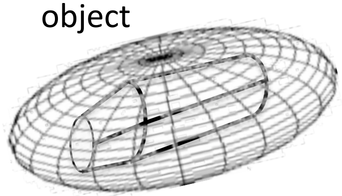
CAD model generated



(2) Grid points designed for matrix representation



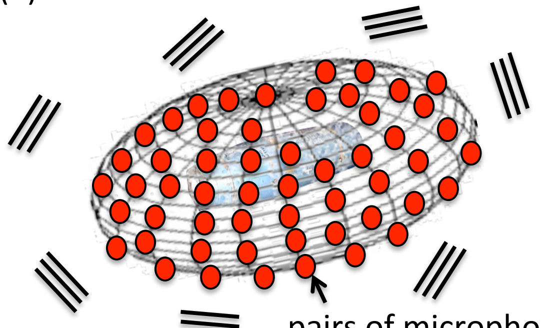
(3) Support structure designed around object



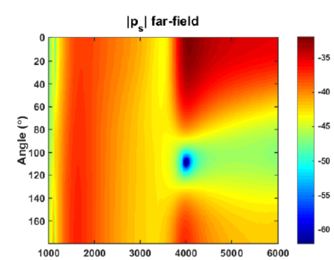
Proposed hardware includes:
-Scanner
-Manufacturing unit
-512 channel microphone system

(4) 3D printing of structure

(5) Experiment conducted in diffuse field



(6) Determine scattering signature in any medium



THEME OF WORKSHOP

NOISE→

DON'T LOSE IT:

USE IT!