Passive acoustic thermometry of the deep water sound channel using ambient noise .

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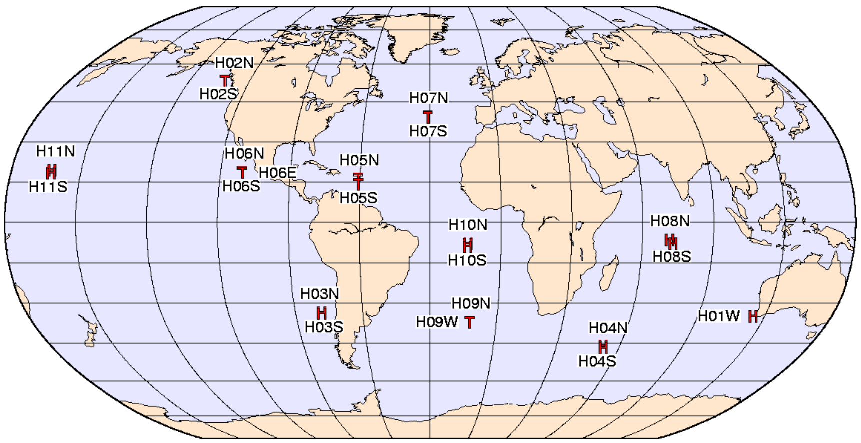

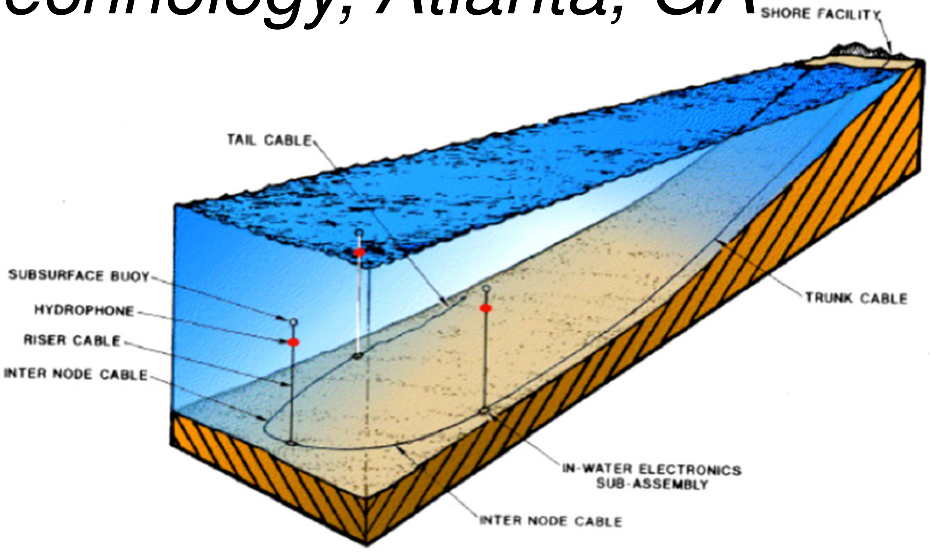

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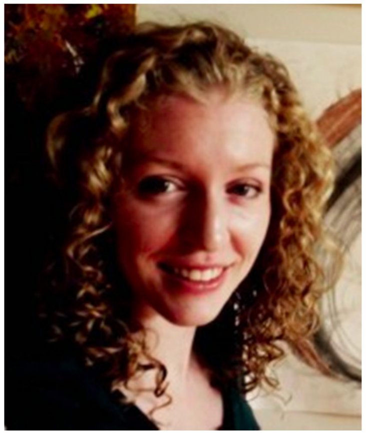
Presentation Outline

1. **Deep water acoustics & low-frequency noise sources**
2. **Monitoring with ambient noise: Background.**
3. **Passive acoustic thermometry of the deep water sound channel using low-frequency ambient noise**
4. **Monitoring with ambient noise: Optimization.**

Shane Lani

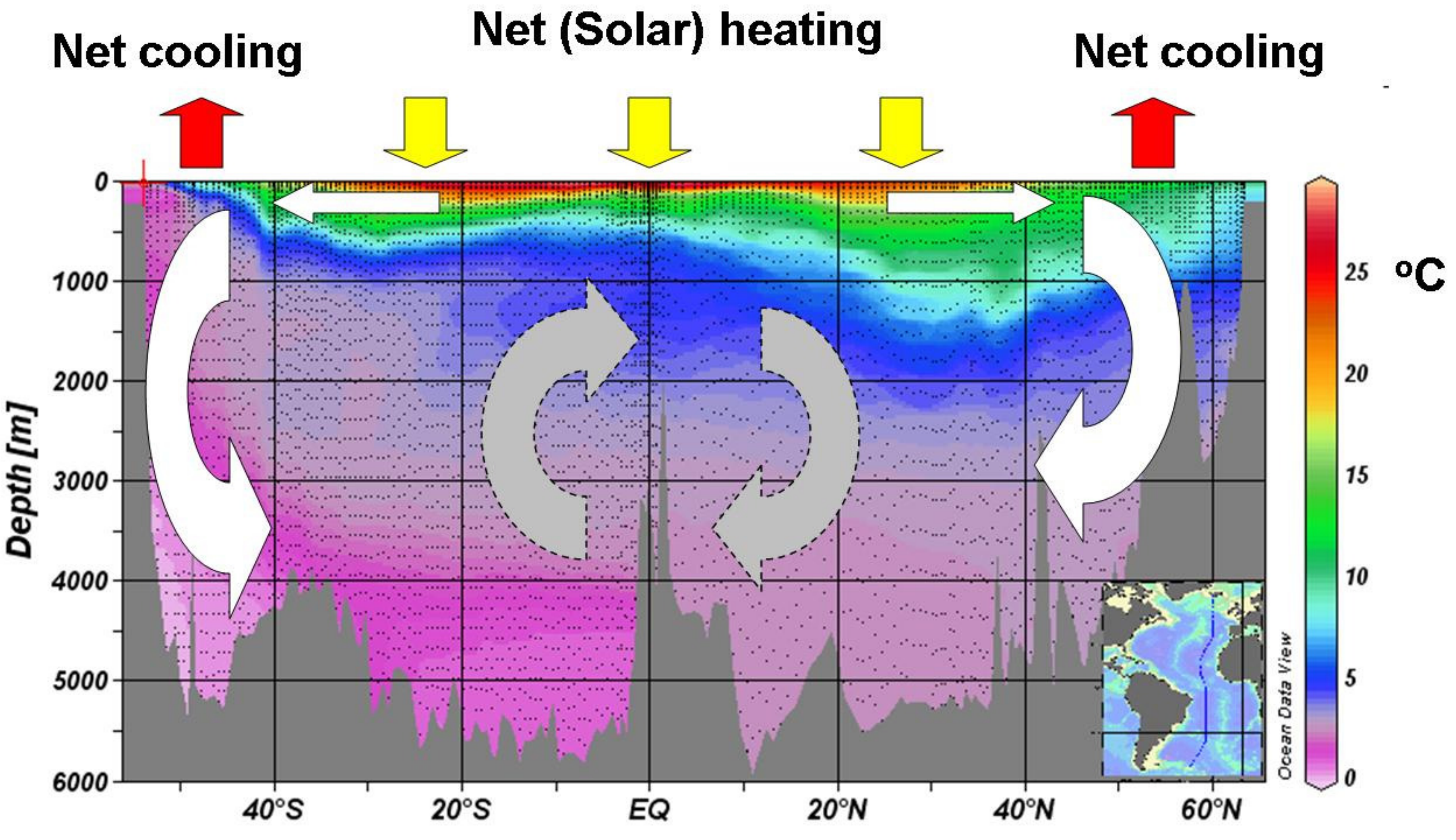
In collaboration with
Bill Kuperman &
Philippe Roux



Katherine Woolfe

Oceans are heat sinks

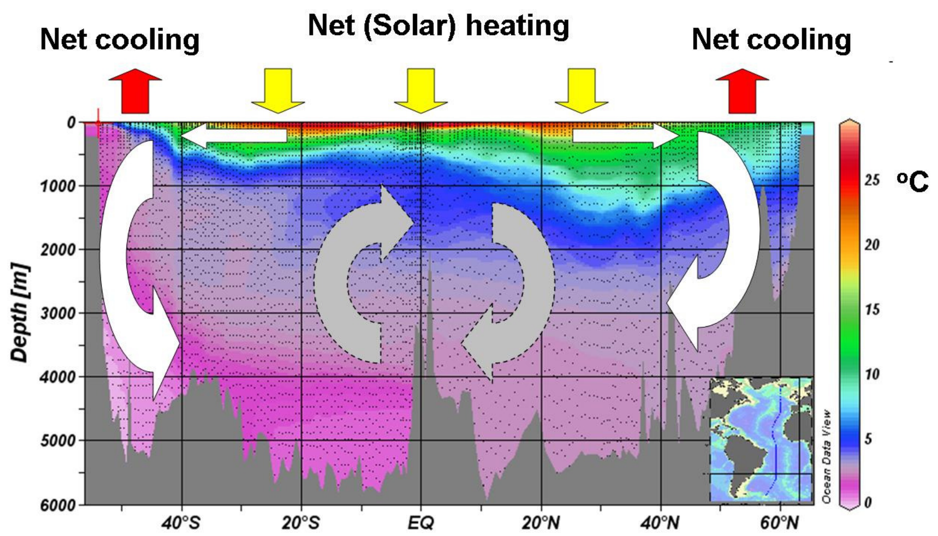
Average Ocean Temperature Distribution with Depth

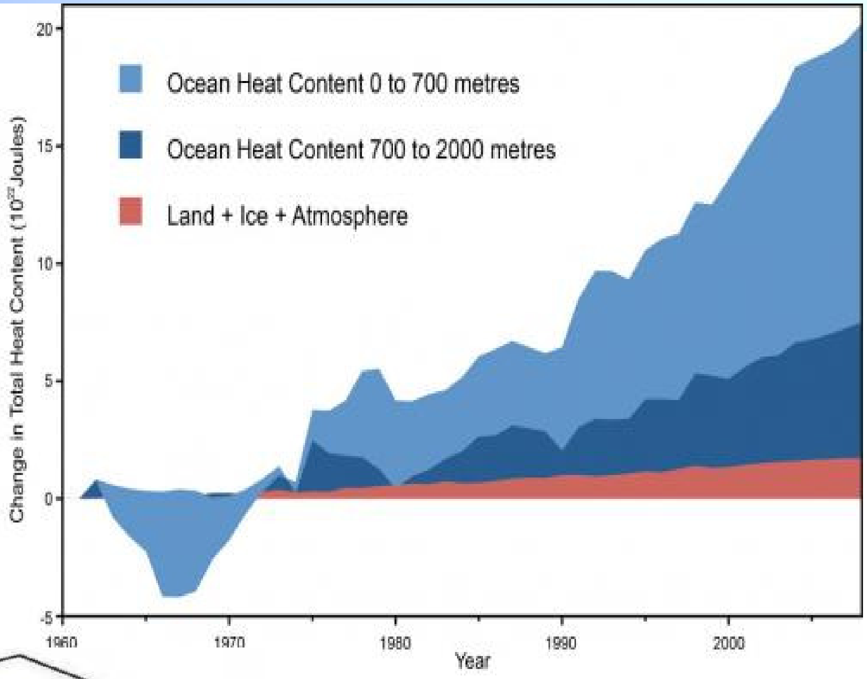


NOAA

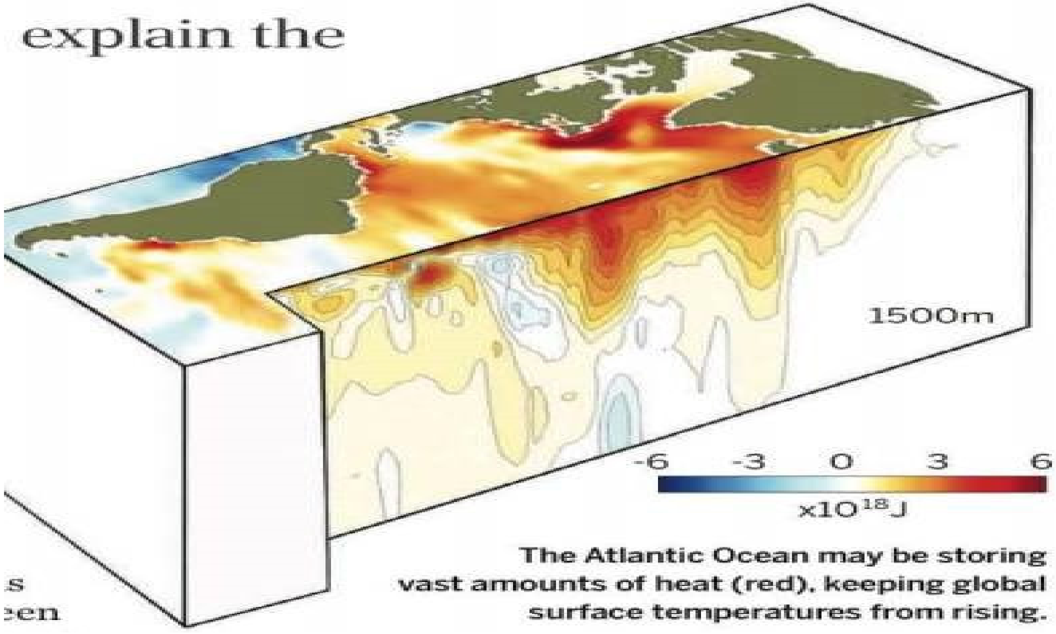
Oceans are Heat sinks

Average Ocean Temperature Distribution with Depth





NOAA

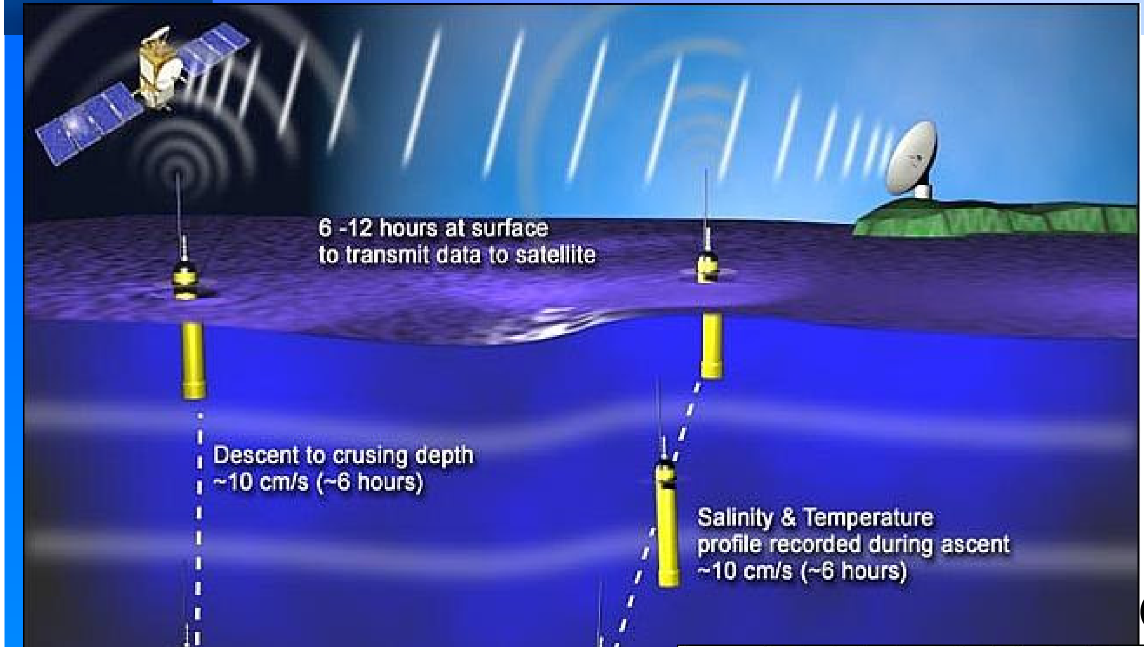


The Atlantic Ocean may be storing vast amounts of heat (red), keeping global surface temperatures from rising.

Science 22 August 2014: Vol. 345 no. 6199 pp. 860-861 **Is Atlantic holding Earth's missing heat?**

& Variations across ocean bassins…

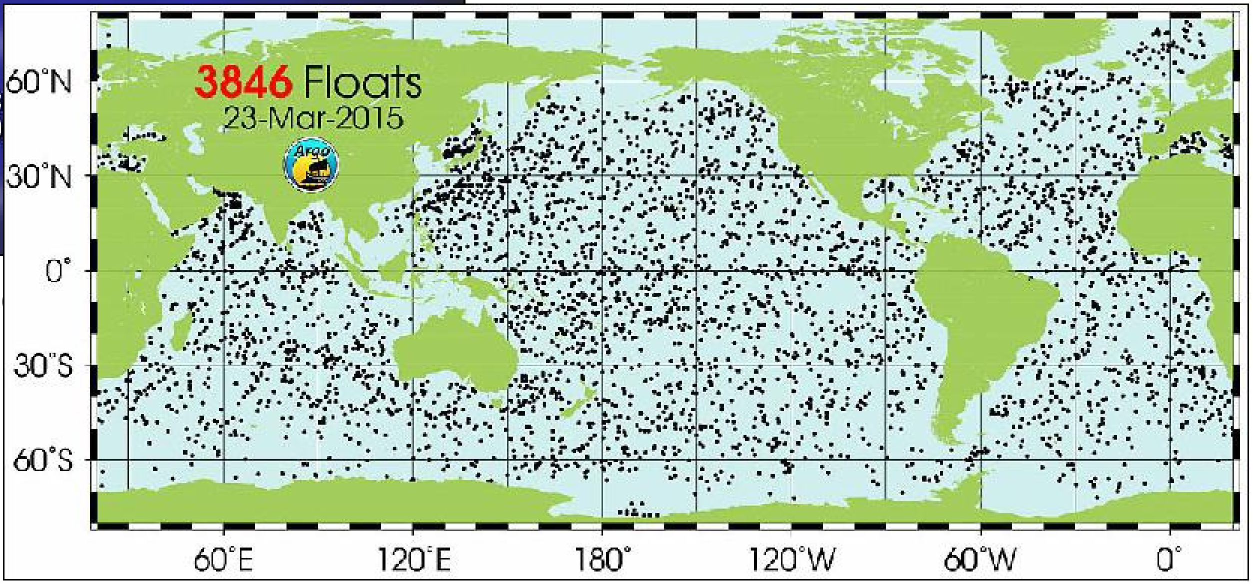
Measuring deep ocean temperatures



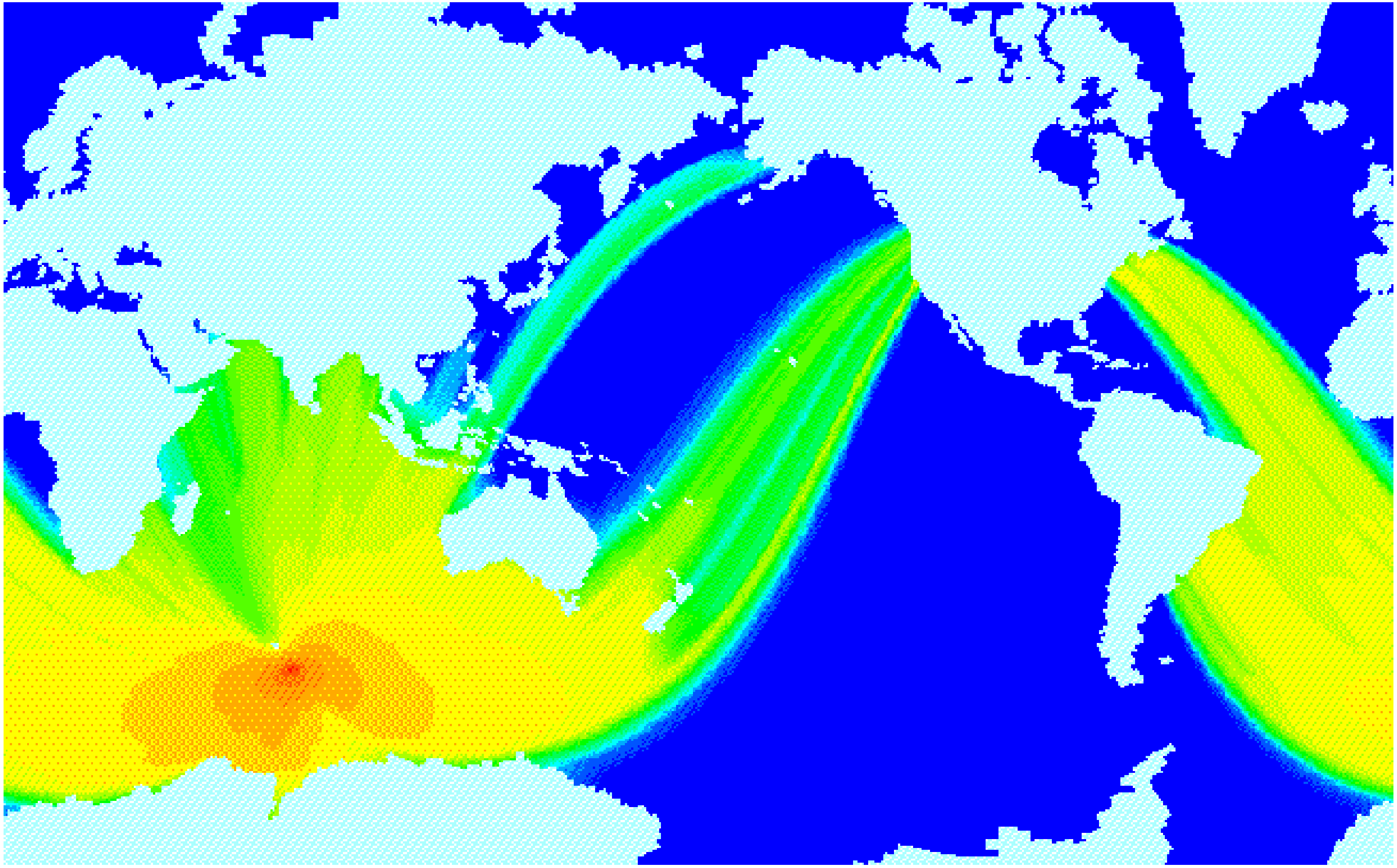
- Satellite observations are most suited for sensing ocean temperature “close” to surface
- Deep oceans most commonly sense with profiling floats.

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

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



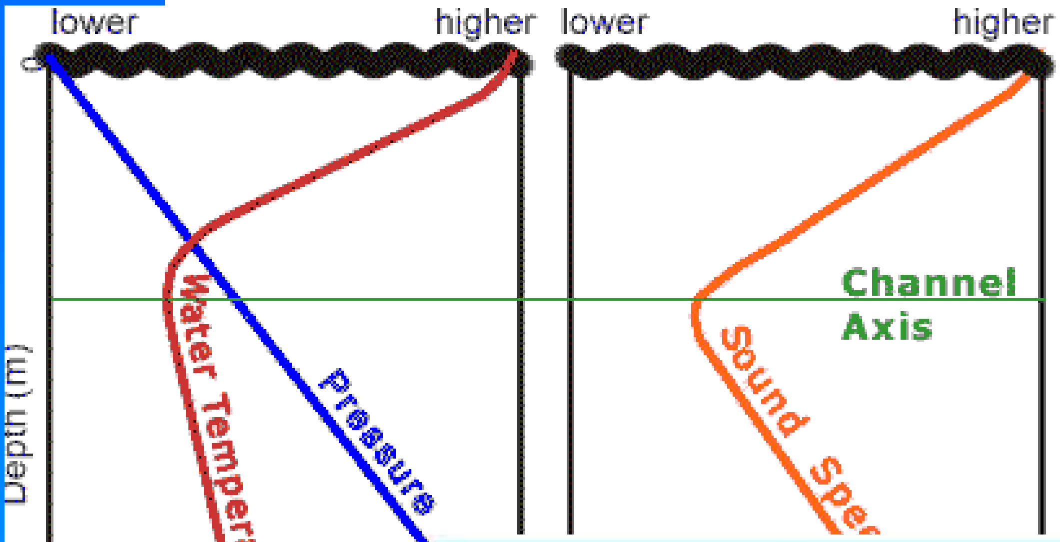
Sound Propagation Around the Globe



(Collins et al., JASA 97(3), p. 1567)

Basis for Acoustic measurements of ocean temperatures:
“Acoustic thermometry & Acoustic tomography..”

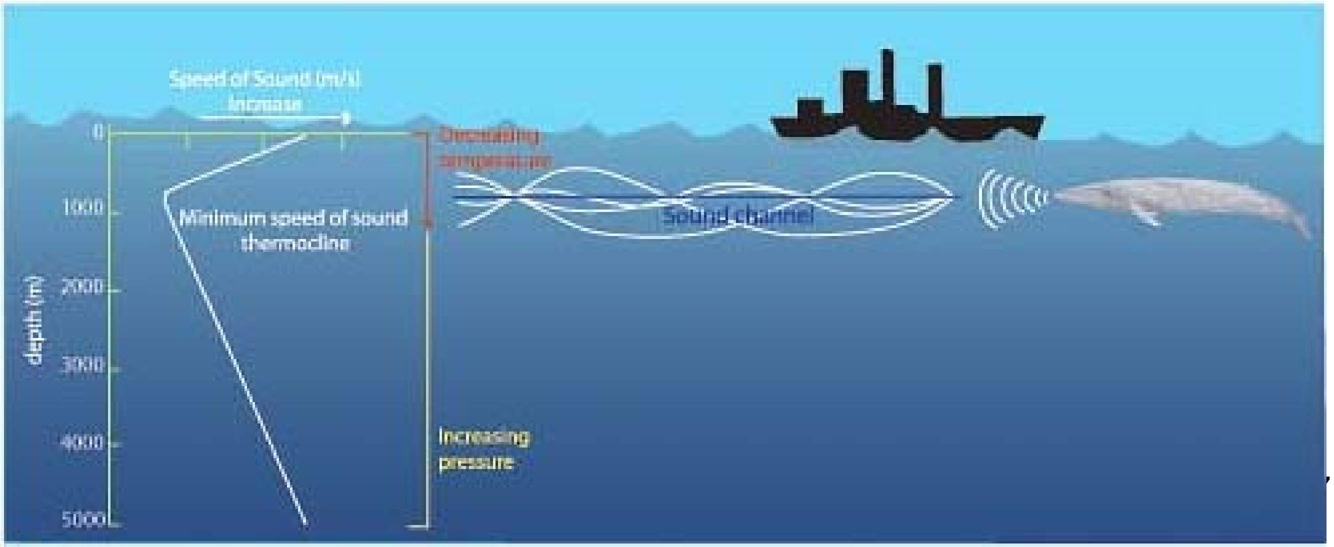
Generic Sound Speed Structure



- Ocean sound-speed depends on:
  - Temperature, (T)
  - Salinity, (S)
  - Depth, (z)
- Speed of sound increases with all

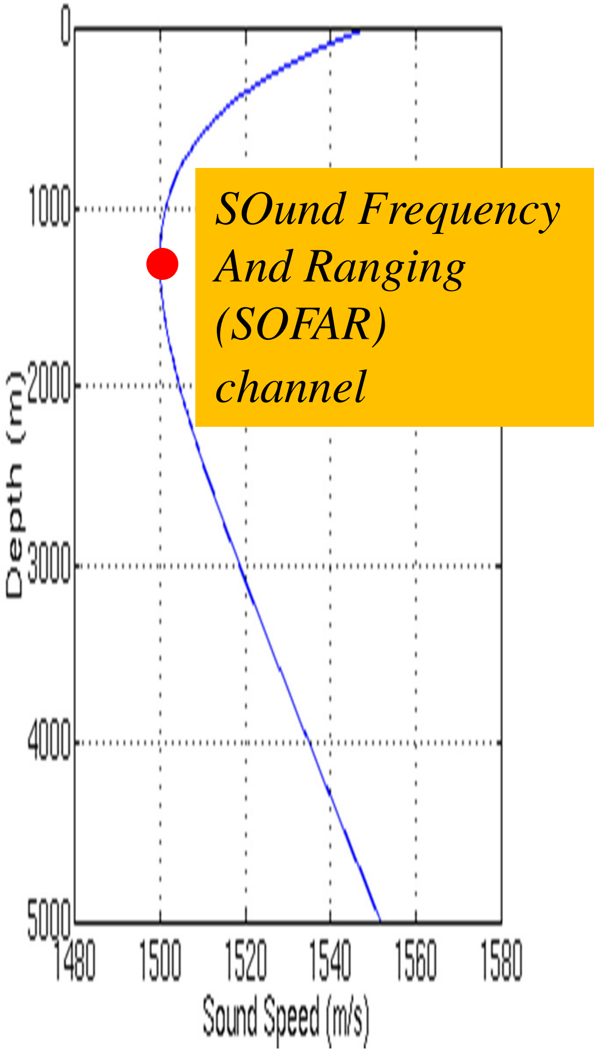
http://www.pmel.noaa.gov/v

Note: In polar regic
at the surface



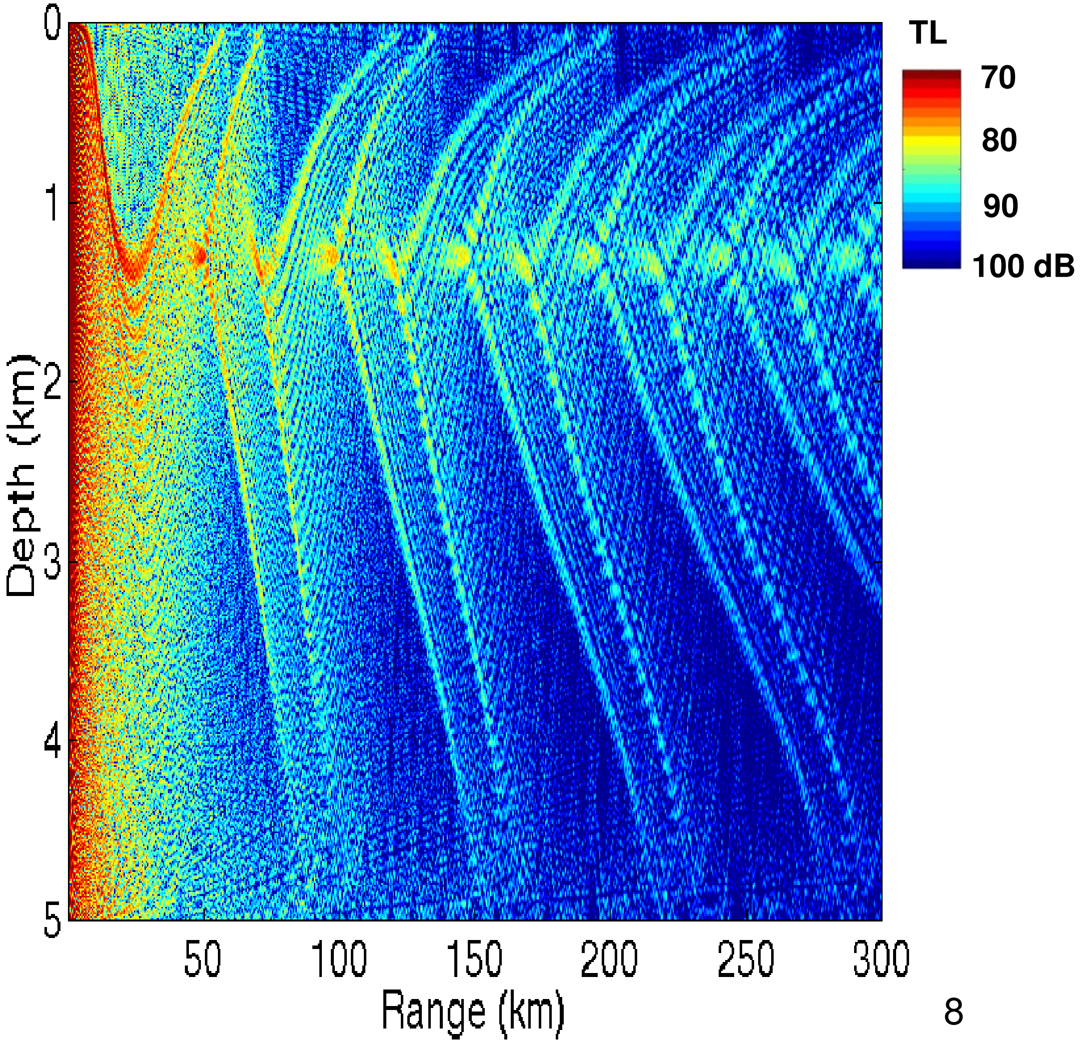
Deep sound channel propagation

Sound Speed profile



SOund Frequency And Ranging (SOFAR) channel

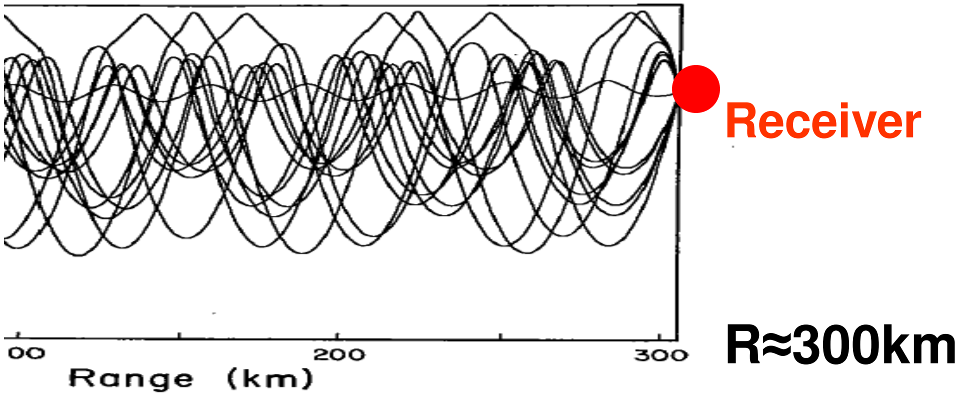
Pressure (R = 300km, SD = 1300m)



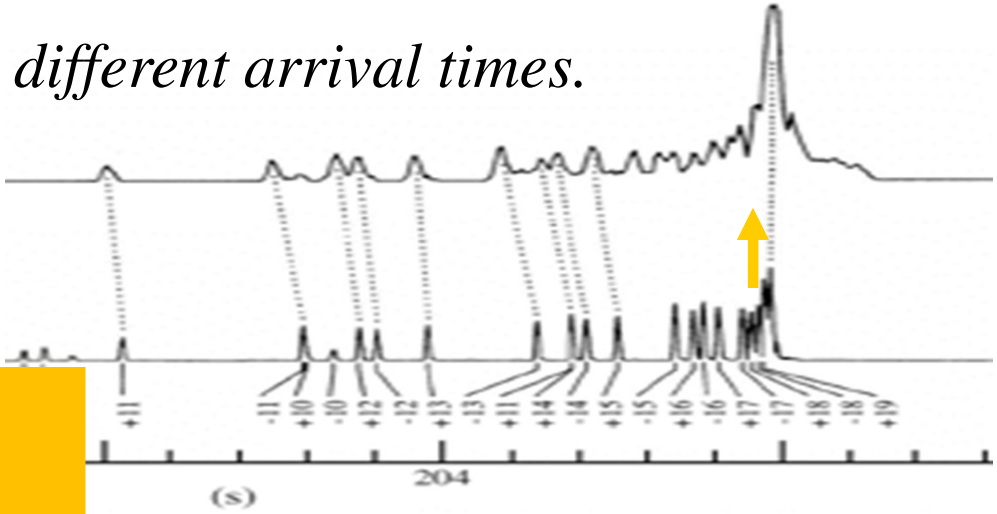
70-80Hz- Normal Modes simulation

Acoustic Thermometry

Different paths have different (group) speeds….



different arrival times.



HLF-5 acoustic source (250 Hz) courtesy of Scripps Institution of Oceanography.

Munk et al., SCRIPPS- UCSD

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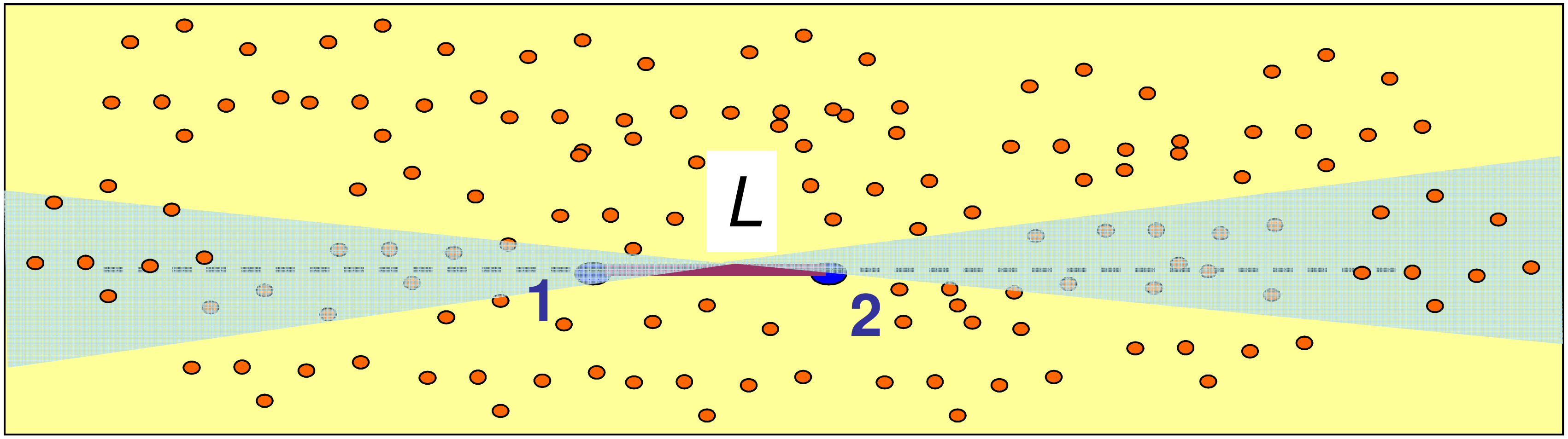
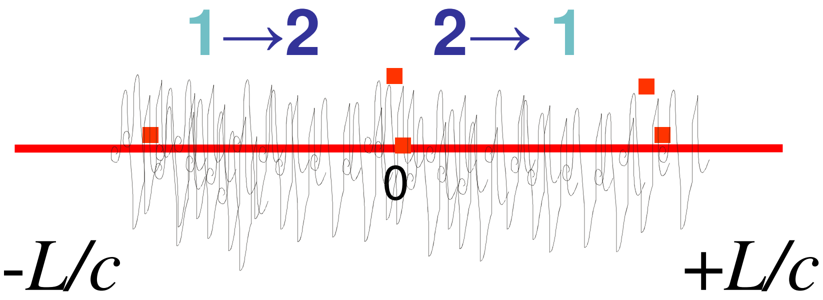
Theory: Free space

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

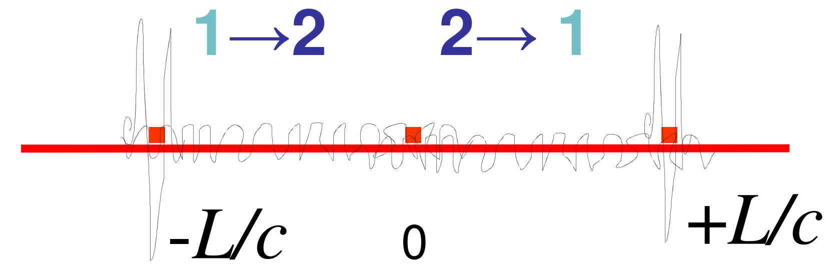


Isotropic distribution of uncorrelated random noise sources

Short-time $C_{12}(\tau)$



Average $C_{12}(\tau)$ over duration T



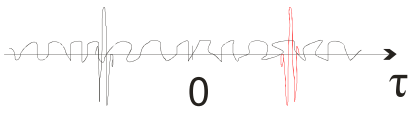
$$\text{SNR} = \frac{\text{Coherent Noise amplitude}}{\text{Incoherent Noise amplitude}} \approx \sqrt{(B \cdot T)/(k \cdot L)}$$

Arrival time rms error:

$$\sigma_t = \left[\omega_0 \sqrt{SNR}\right]^{-1}$$

Practical Limitations…

$$\boxed{C_{12}(t) \approx F(t) \otimes (G_{12}(t) - G_{21}(-t))}$$



Limiting Factors:

1. Spatial Distribution
2. Temporal Distribution
3. Power spectrum
4. Source Directivity

due to the noise sources

5. Attenuation
6. Fluctuations

due to the medium

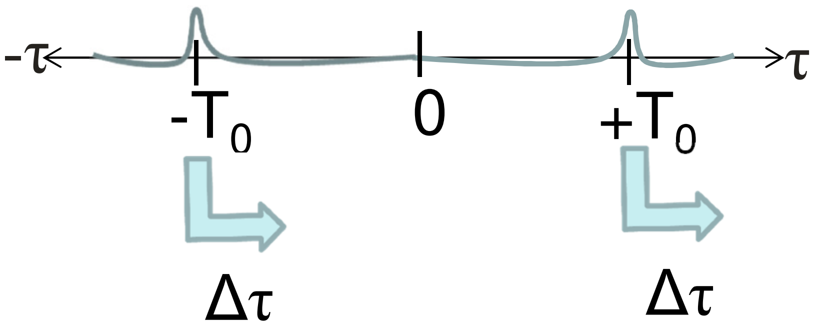
$T_{statistical} < T_{recording} < T_{environmental}$

On short time-scales (< $T_{environmental}$), the cross-correlation process is stationary

Extensive Theoretical Proofs (Rytov, 56; Weaver,2001→Now). Fluctuation-Dissipation Theorem

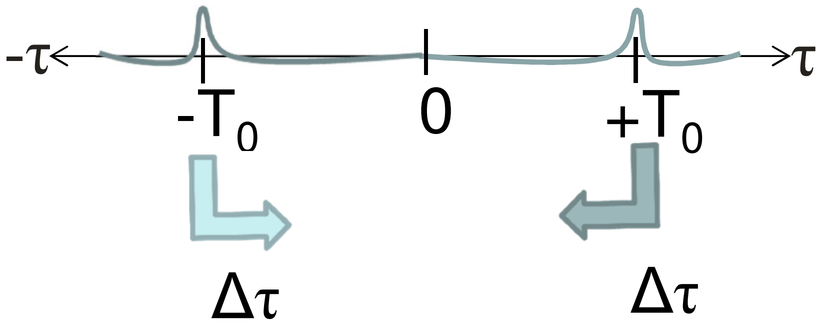
Passive Ocean monitoring ?

Anti-symmetric time shift



Due to “non-reciprocal” environmental changes OR clock-drift between receivers 1 and 2

Symmetric time shift



Due to “reciprocal” environmental changes

$$\Delta c / C_0 = (\Delta\tau / T_0)$$

Sabra et al., 2005; Stehly et al., 2007 Lani et al. (2013)

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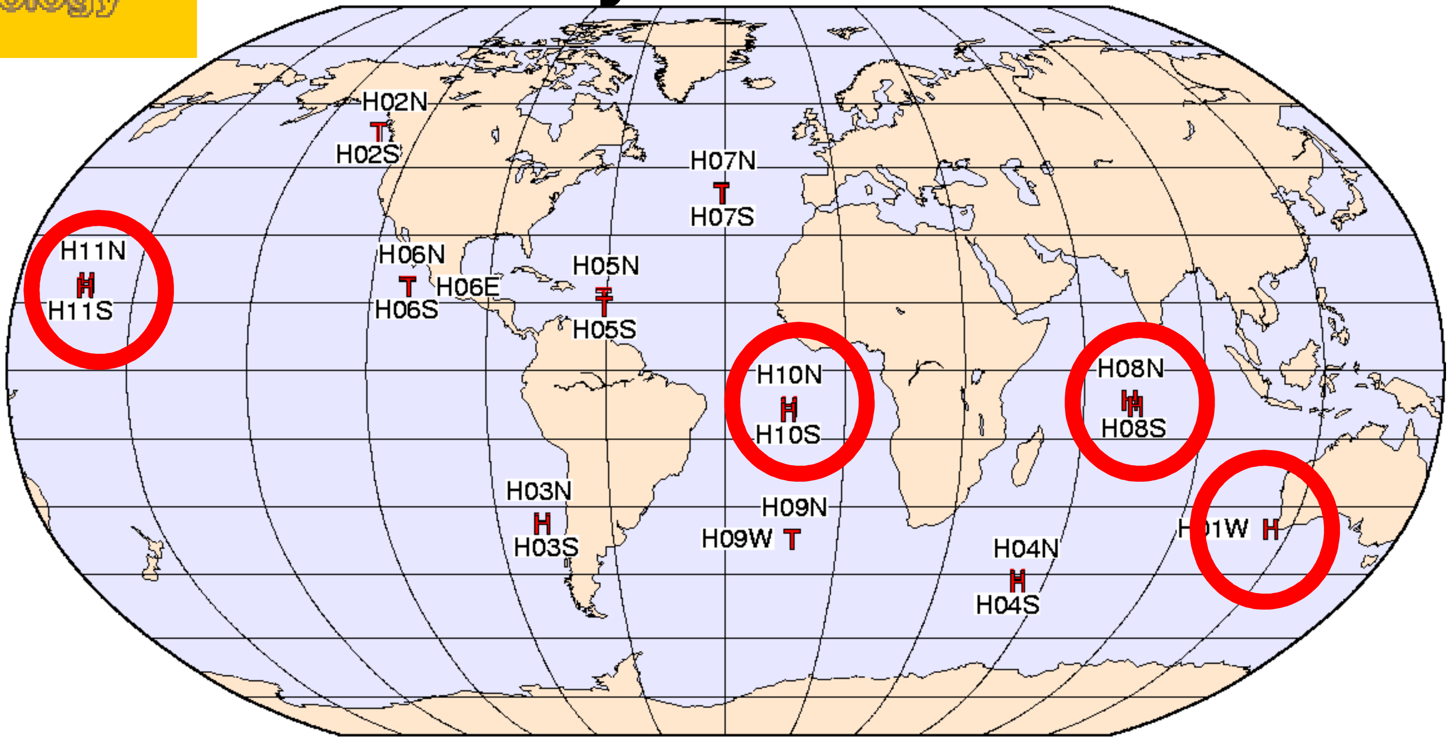
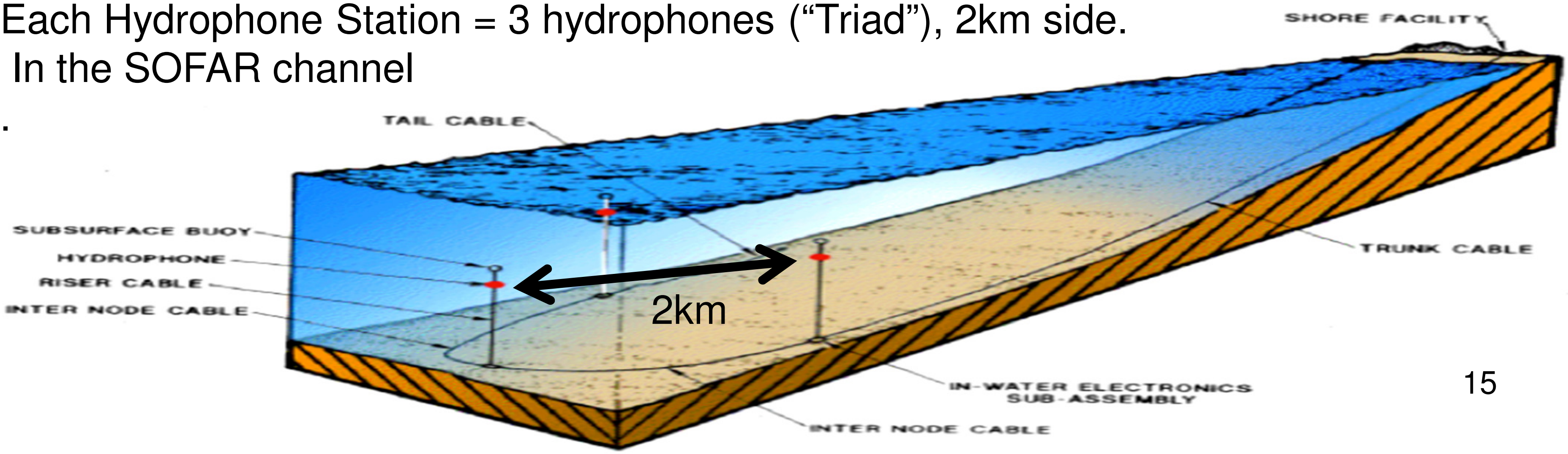
. IMS Hydroacoustic Station

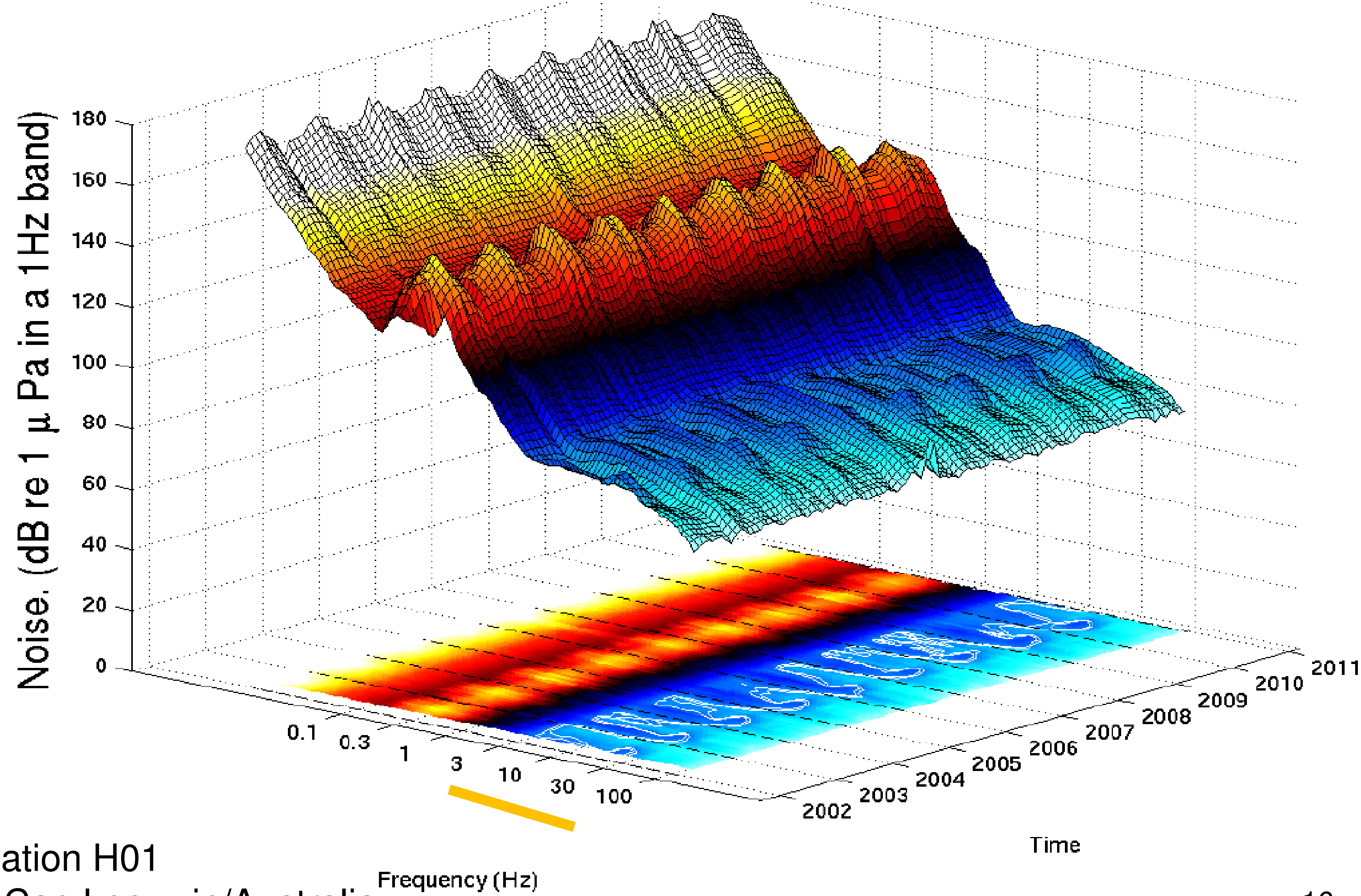


Each Hydrophone Station = 3 hydrophones (“Triad”), 2km side.
In the SOFAR channel

.



Ambient noise measured by hydroacoustic station

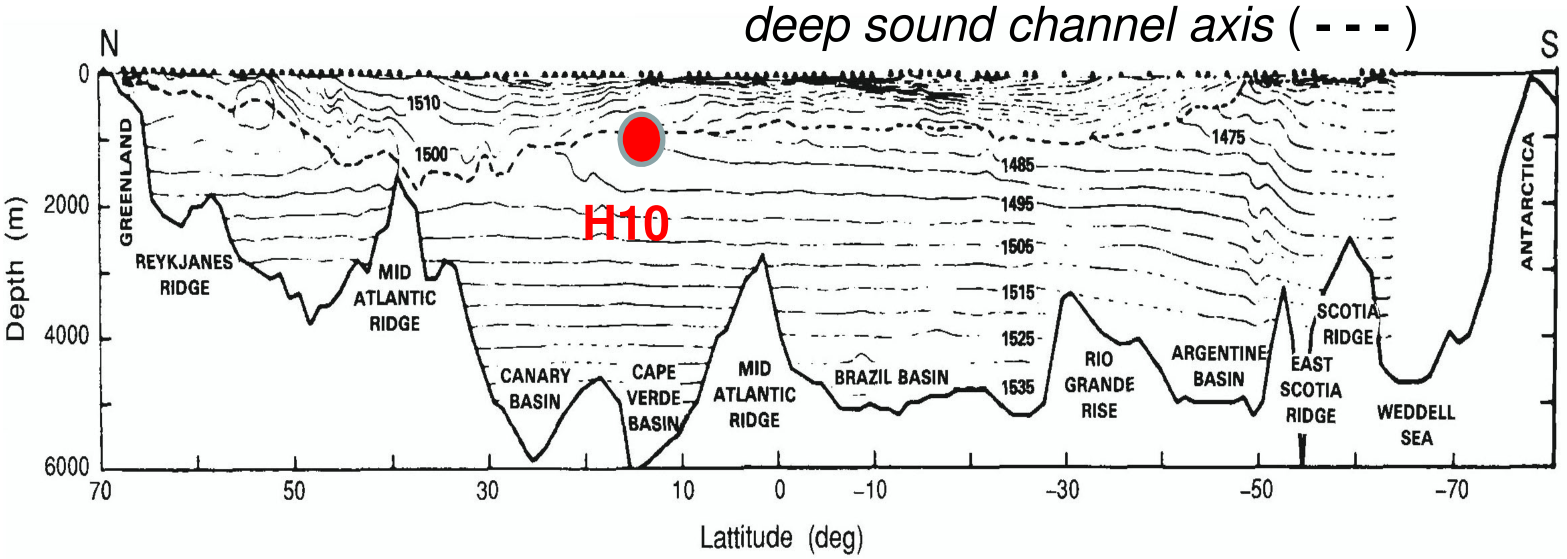


Station H01
@Cap Leeuwin/Australia

PRIOR et al., 2010

Global Sound Speed Structure

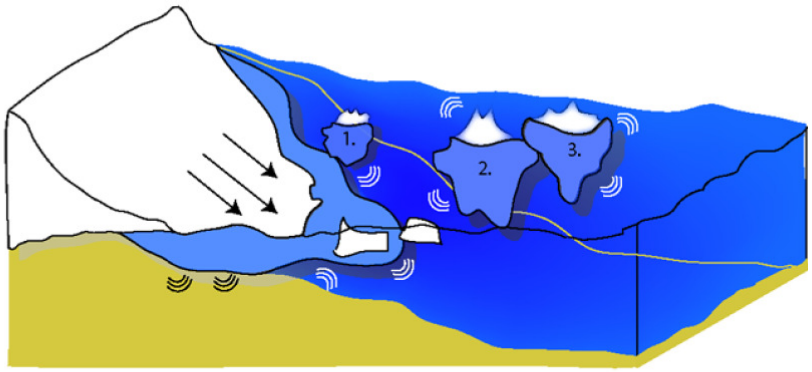
North-South Atlantic along 30.5°N



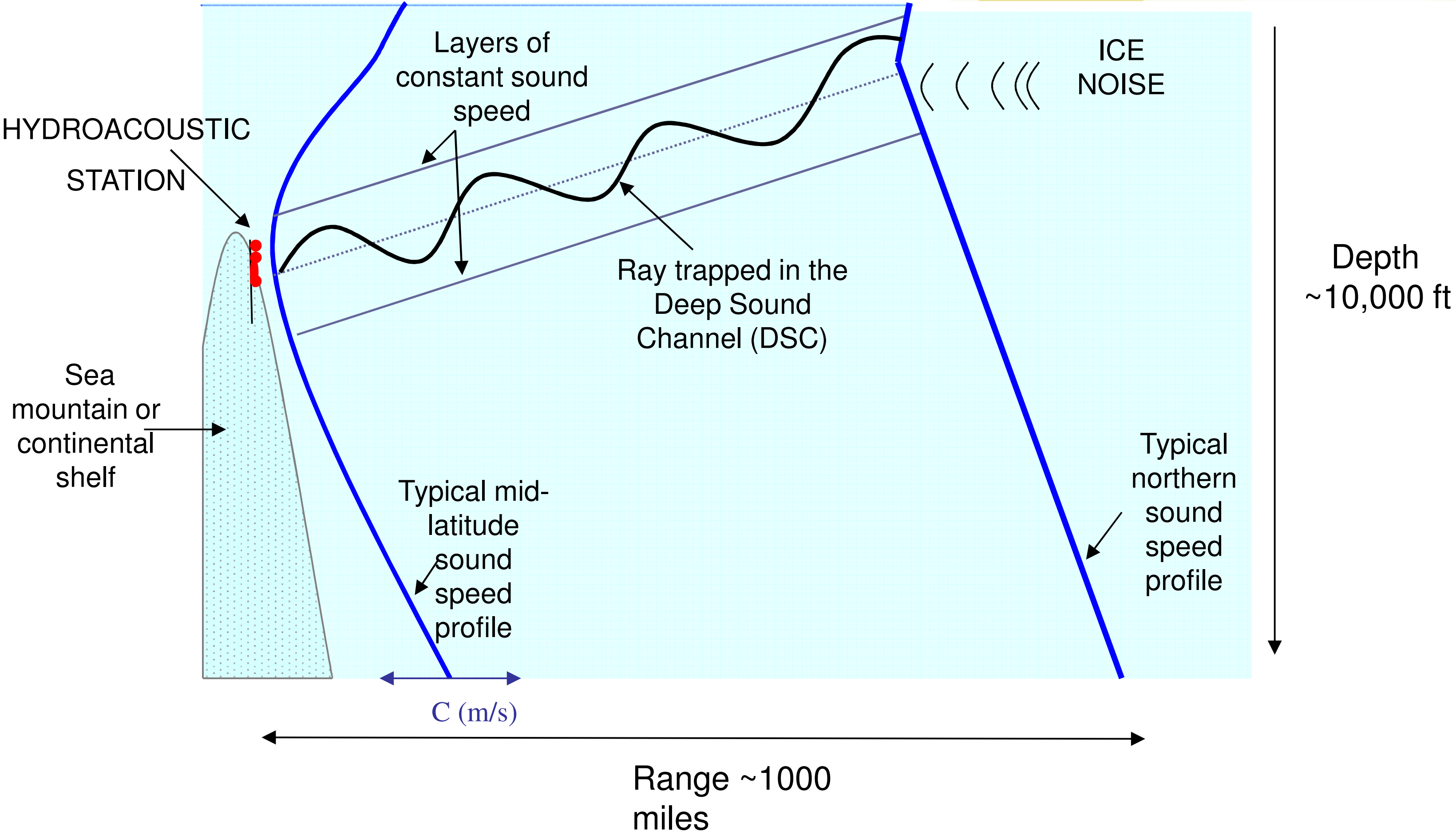
From Northrup and Colborn, JGR, 1974

- Variability of the upper-ocean (<1km) sound speed structure.
- Stability of the deep isothermal layer.
- Axis of the deep sound channel becomes shallower towards both poles and eventually reaches the surface.

Ice noise propagation



Mid latitudes



HYDROACOUSTIC STATION

Layers of constant sound speed

ICE NOISE

Ray trapped in the Deep Sound Channel (DSC)

Sea mountain or continental shelf

Depth ~10,000 ft

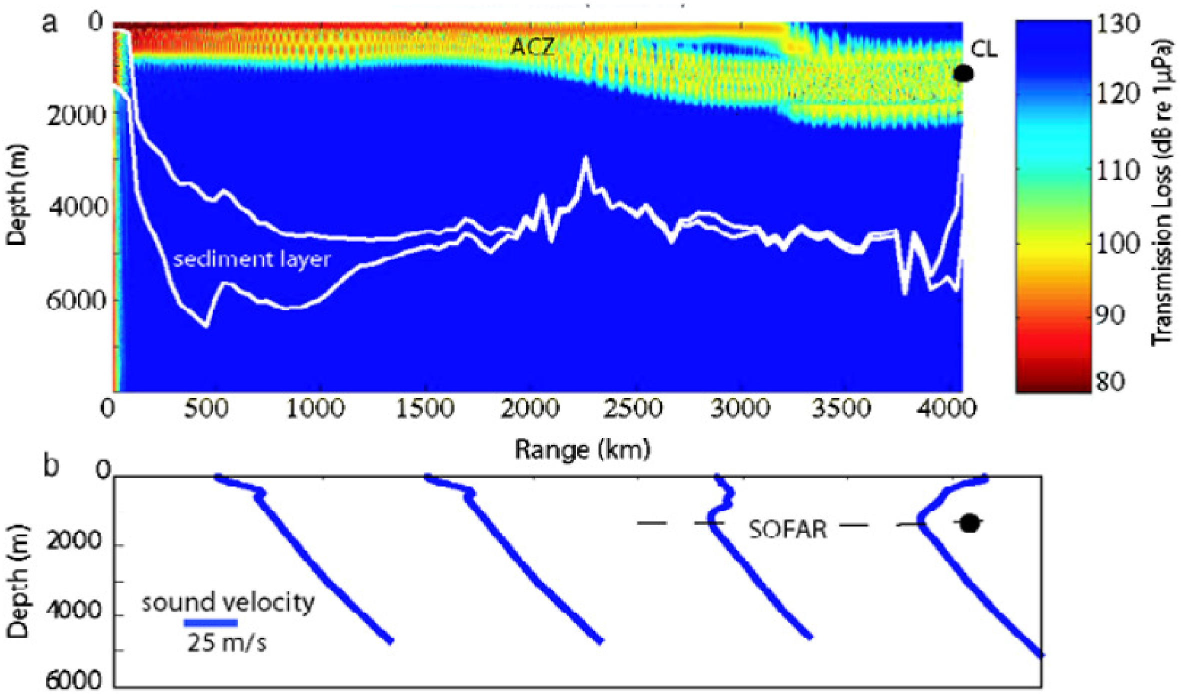
Typical mid-latitude sound speed profile

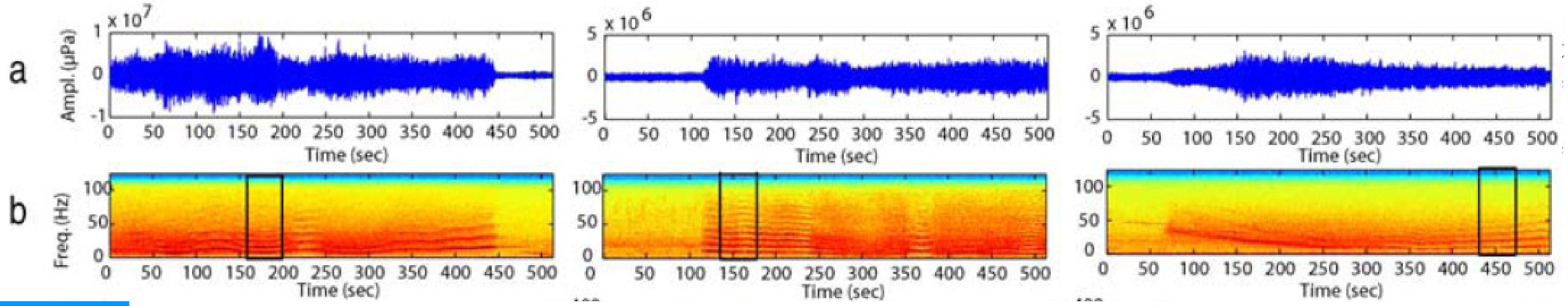
Typical northern sound speed profile

C (m/s)

Range ~1000 miles

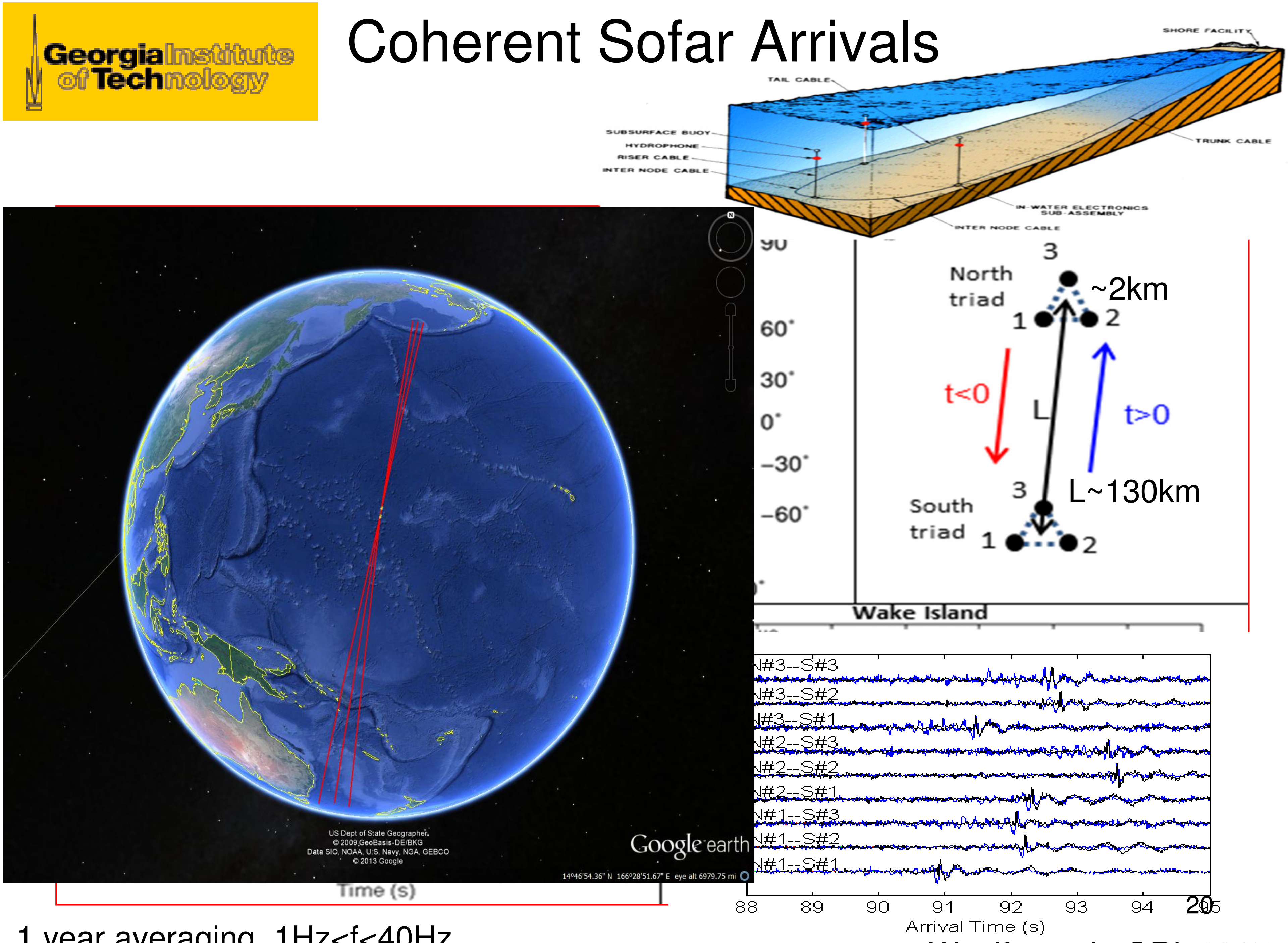
Ice-noise long-range propagation





Chapp et al. 2005, G3

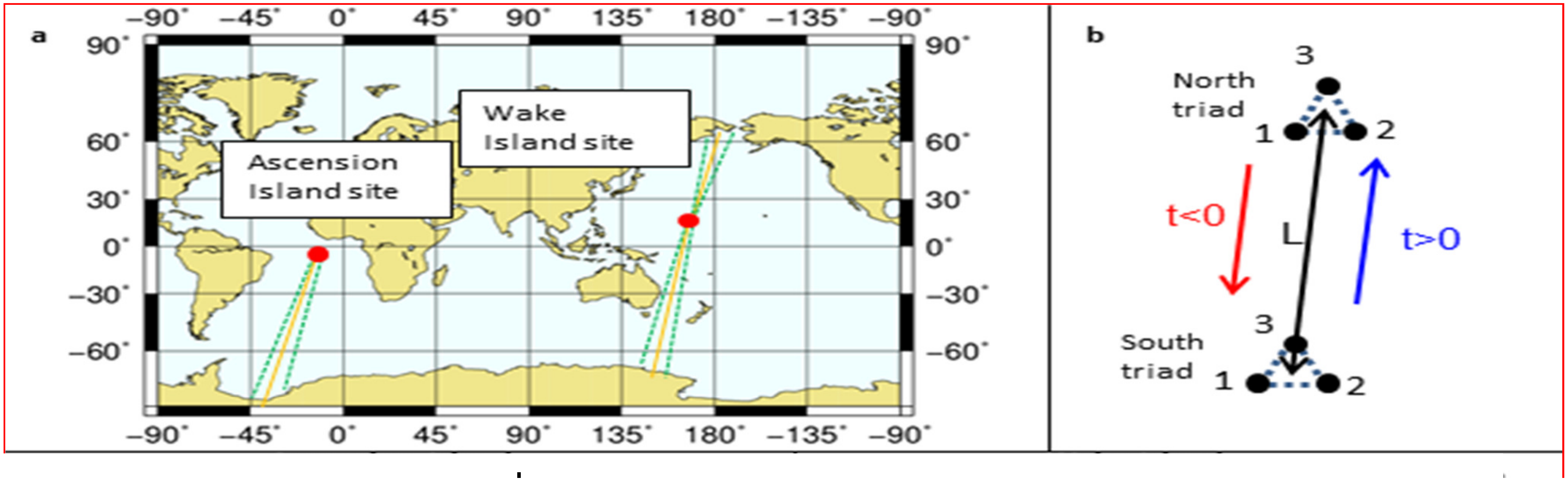
Coherent Sofar Arrivals

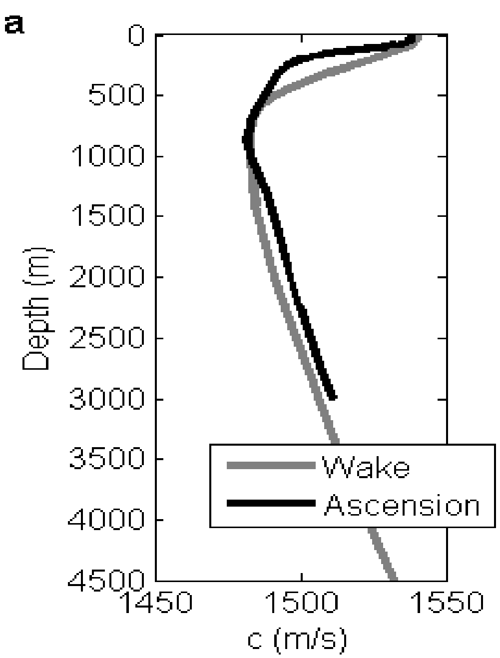


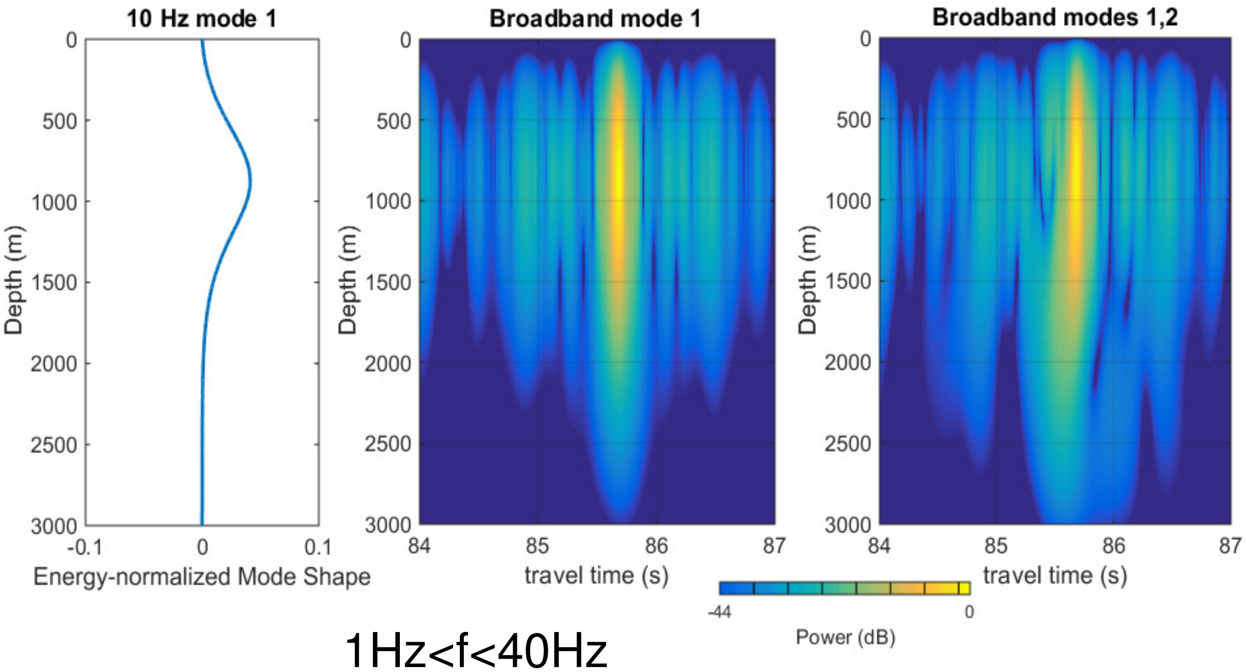
1 year averaging, 1Hz<f<40Hz

Woolfe et al., GRL 2015

SOFAR arrival between Triads

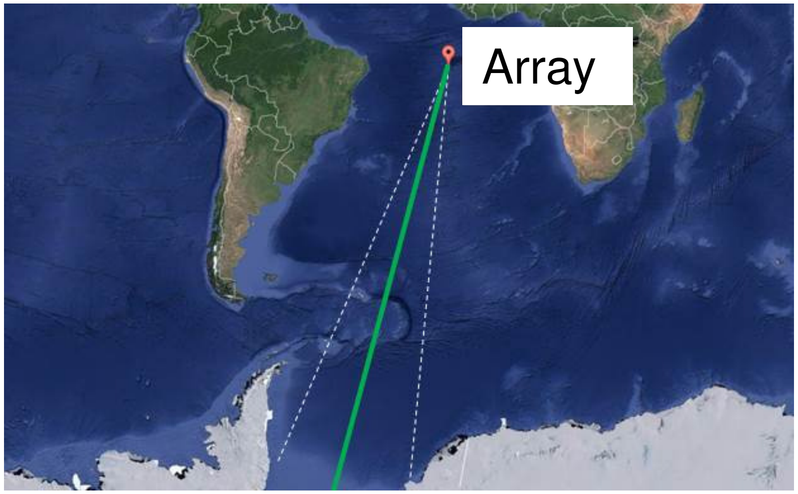


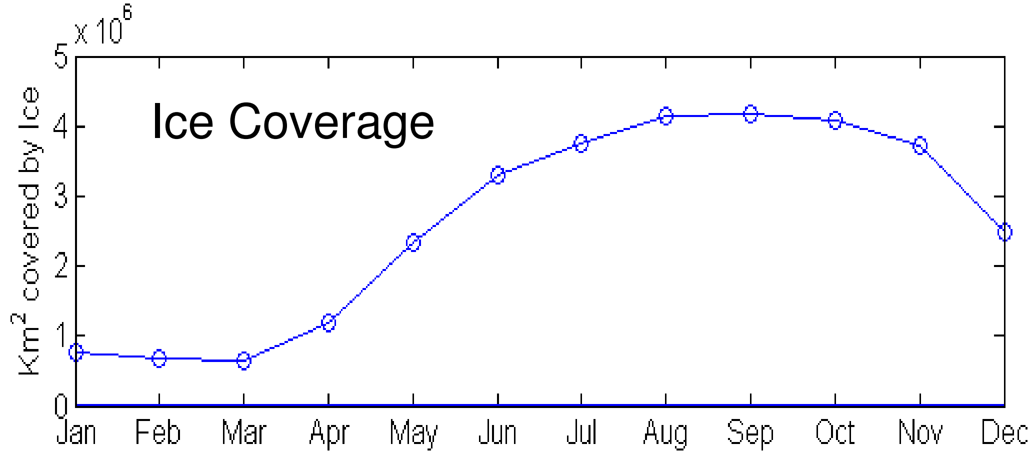


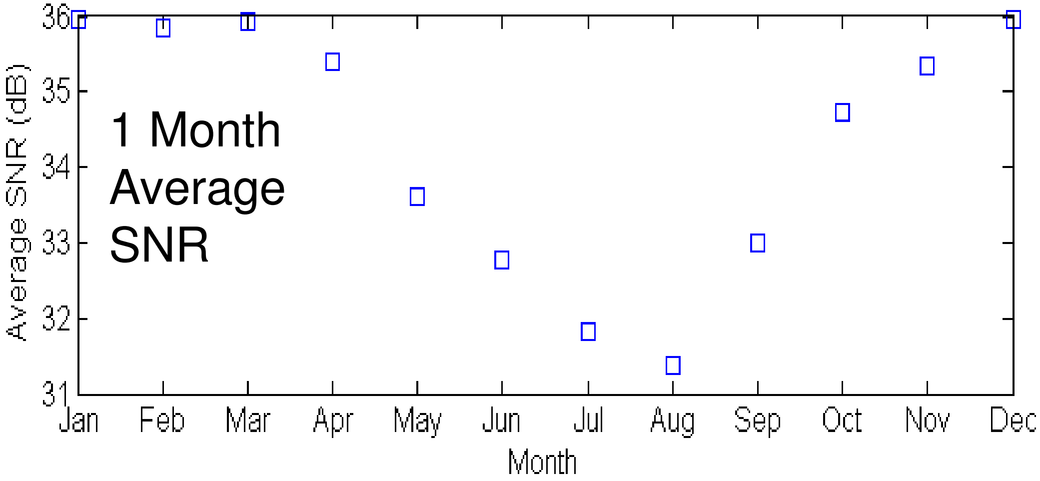


1Hz<f<40Hz

Polar origin of the coherent noise







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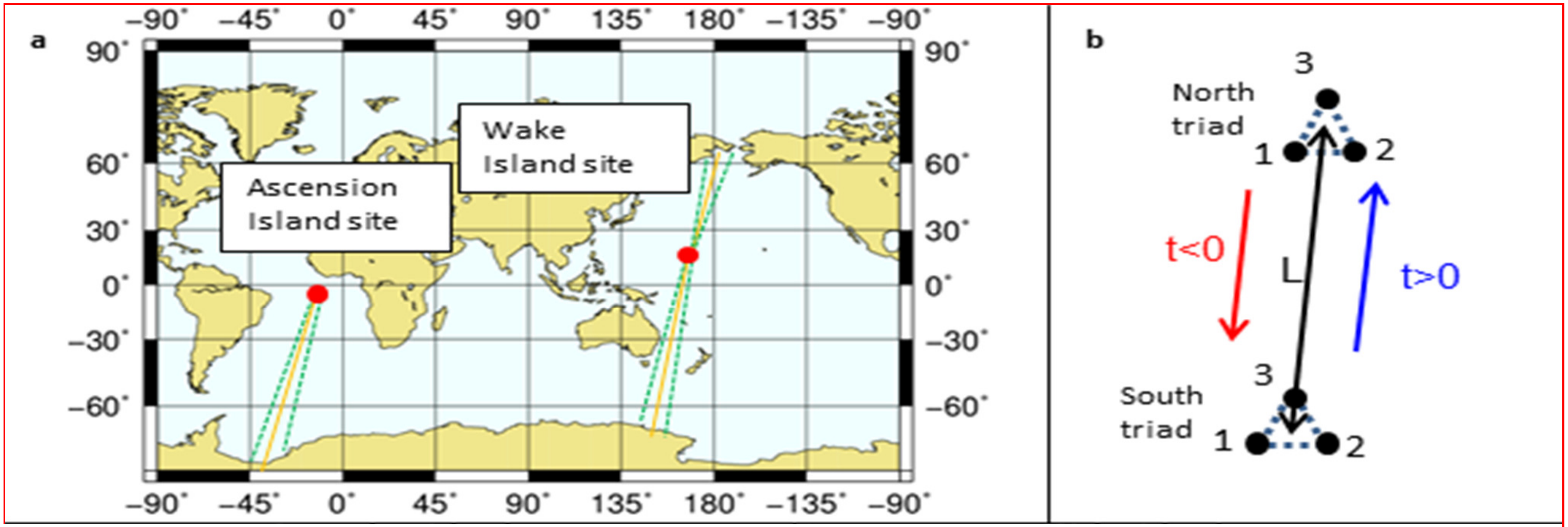
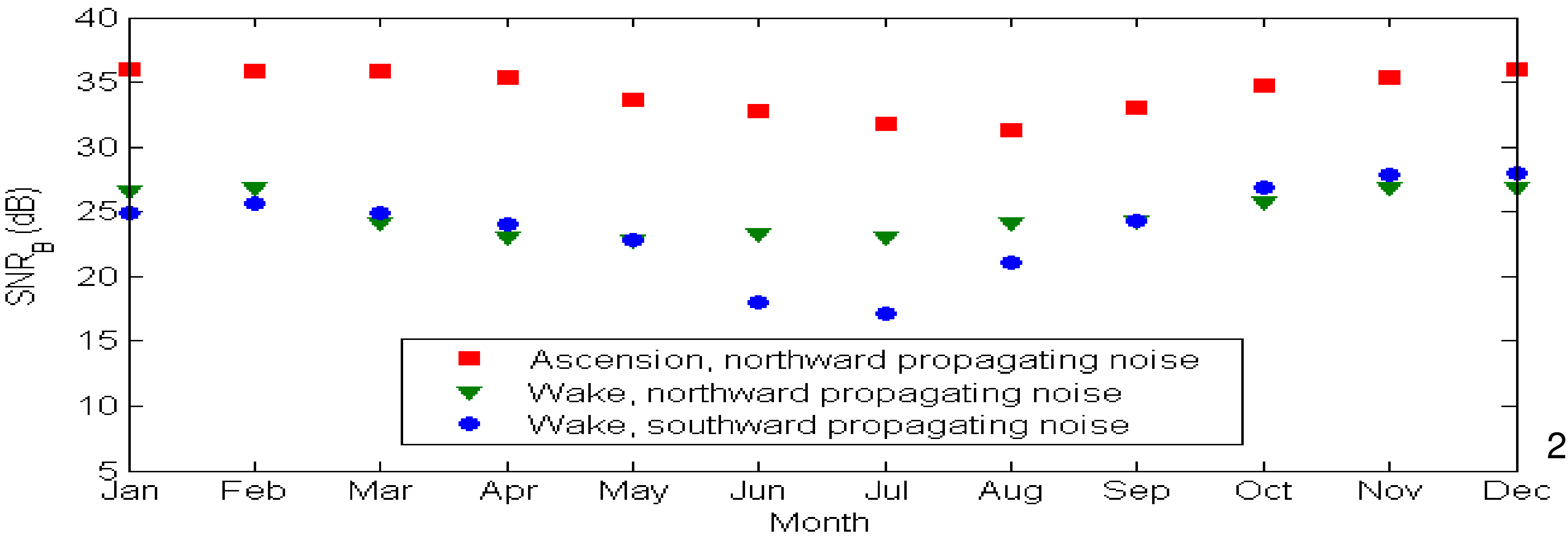
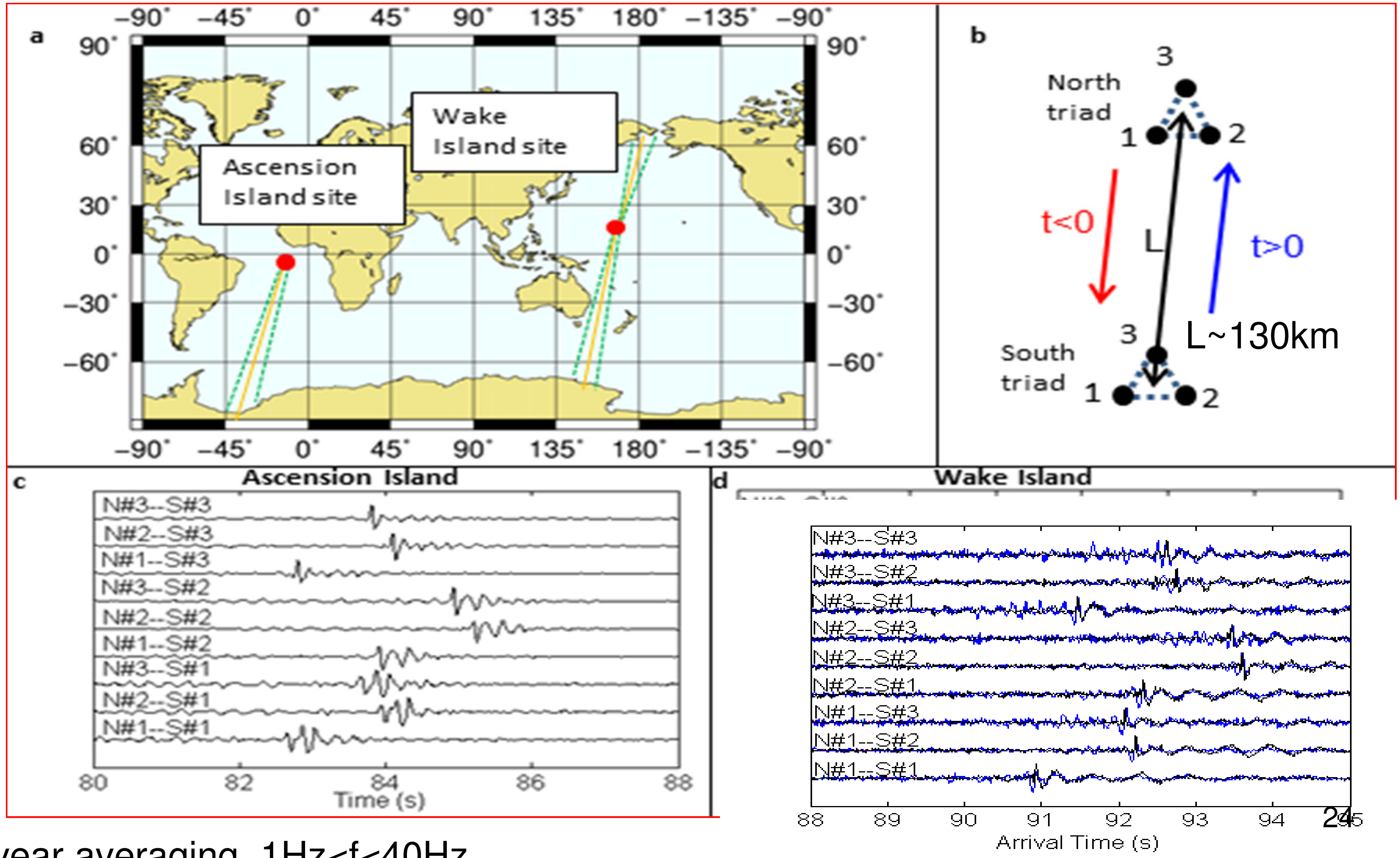




Coherent Sofar Arrivals

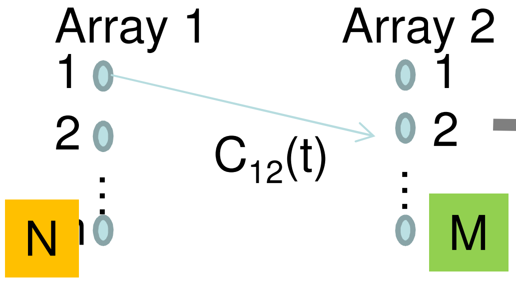


1 year averaging, 1Hz<f<40Hz

Woolfe et al., GRL 2015

Georgia Institute of Technology

Beamforming of Noise Correlations



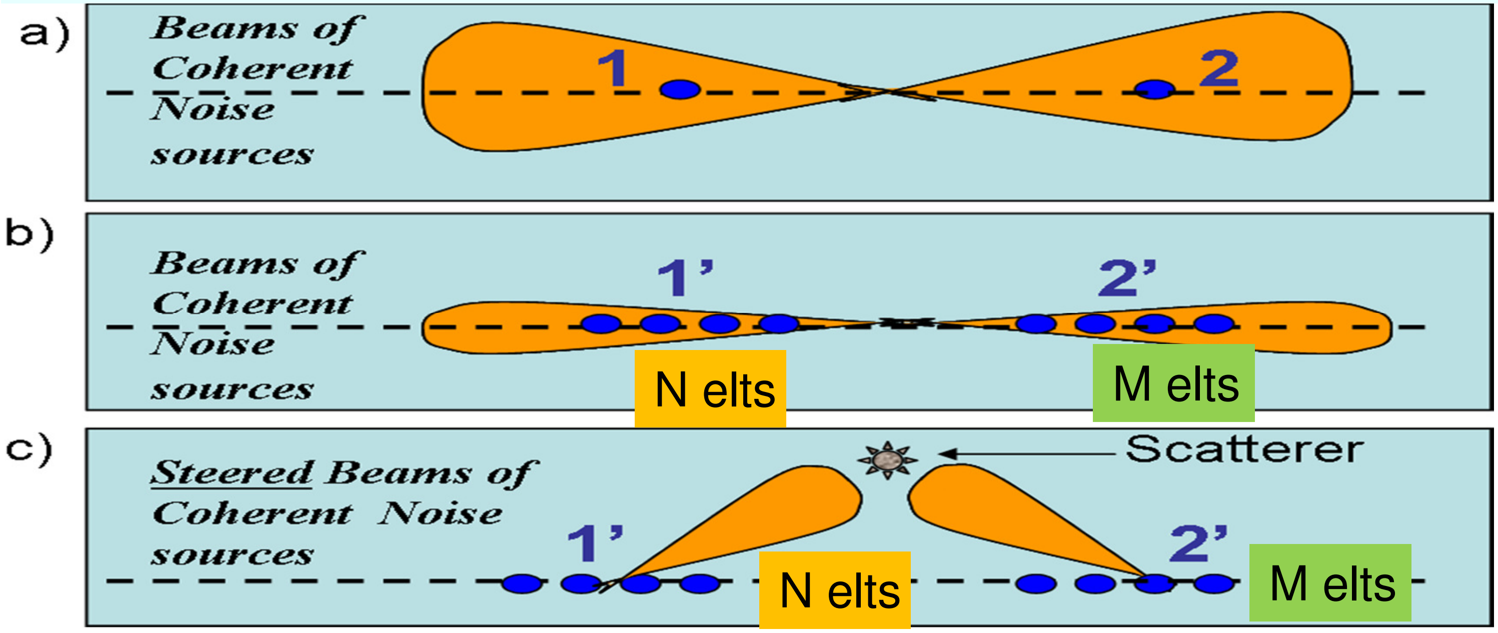
$$\mathbf{C}(t)=\begin{pmatrix} C_{11}(t) & C_{12}(t) & \dots & C_{1n}(t)\\ C_{21}(t) & C_{22}(t) & & \\ \vdots & & \ddots & \\ C_{m1}(t) & & & C_{mn}(t)\end{pmatrix} \rightarrow \hat{\boldsymbol{C}}(f)=fft(\boldsymbol{C}(t))$$

$$\hat{\boldsymbol{B}}(f)=\boldsymbol{W}_1^H(f)\hat{\boldsymbol{C}}(f)\boldsymbol{W}_2(f) \rightarrow$$

Steering vectors (i.e. weights)

Provides a theoretical SNR gain of a factor of $\sqrt{NM}$

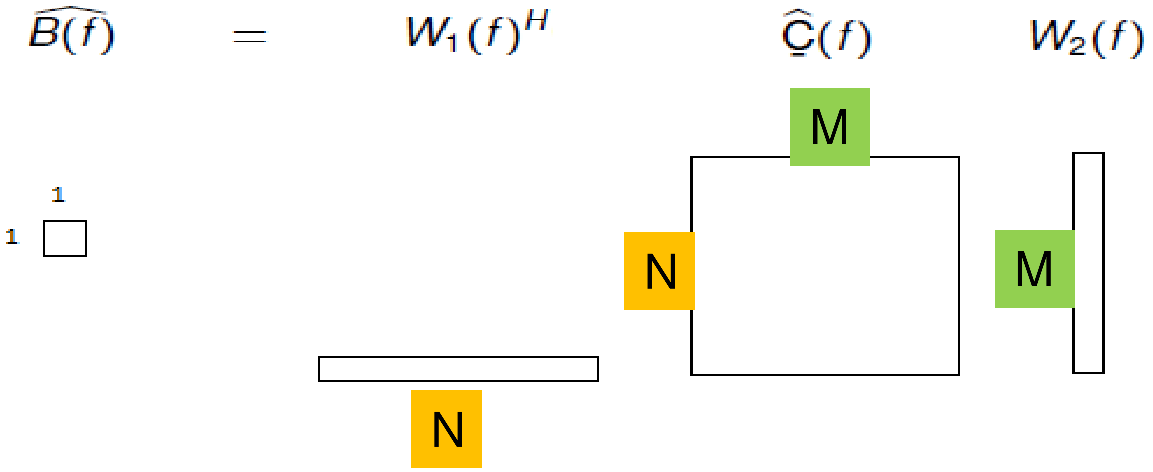
Goal: Increase SNR of cross-correlations using sensor arrays

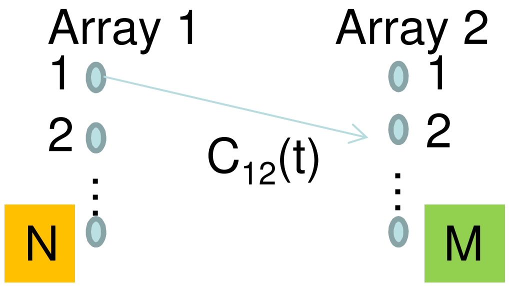


(Leroy et. al. JASA, 2012)

Beamforming formulation

$$\boxed{\hat{\boldsymbol{B}}(f) = \boldsymbol{W}_1^H(f)\hat{\boldsymbol{C}}(f)\boldsymbol{W}_2(f)}$$

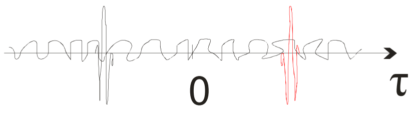




- $\widehat{B(f)}$ beamformer output (scalar)
- $\widehat{C}(f)$ noise cross-covariance matrix (size N × M)
- $W_1(f)$ array weight vector (size N × 1)
- $W_2(f)$ array weight vector (size M × 1)

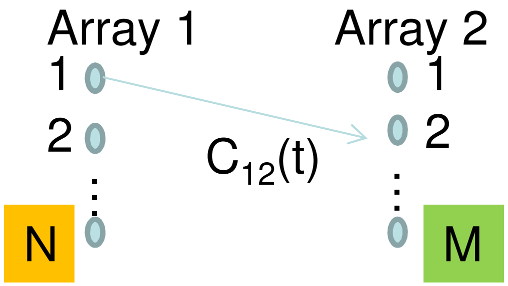
Advantage: enhances the SNR (“Signal” over “Noise” Ratio)

$$\text{SNR} = \frac{\text{Coherent Noise amplitude}}{\text{Incoherent Noise amplitude}} \approx \sqrt{(B \cdot T) \cdot (N \cdot M)}$$



Enhancing the emergence rate of coherent wavefronts from ocean ambient noise correlations using spatio-temporal filters (Leroy et. al 2012, JASA)

Beamforming Noise Correlations for monitoring



$$\boxed{\hat{B}(f) = W_1^H(f)\underset{\uparrow}{\hat{C}(f)}W_2(f)}$$

Cross-correlations obtained using Short averaging time

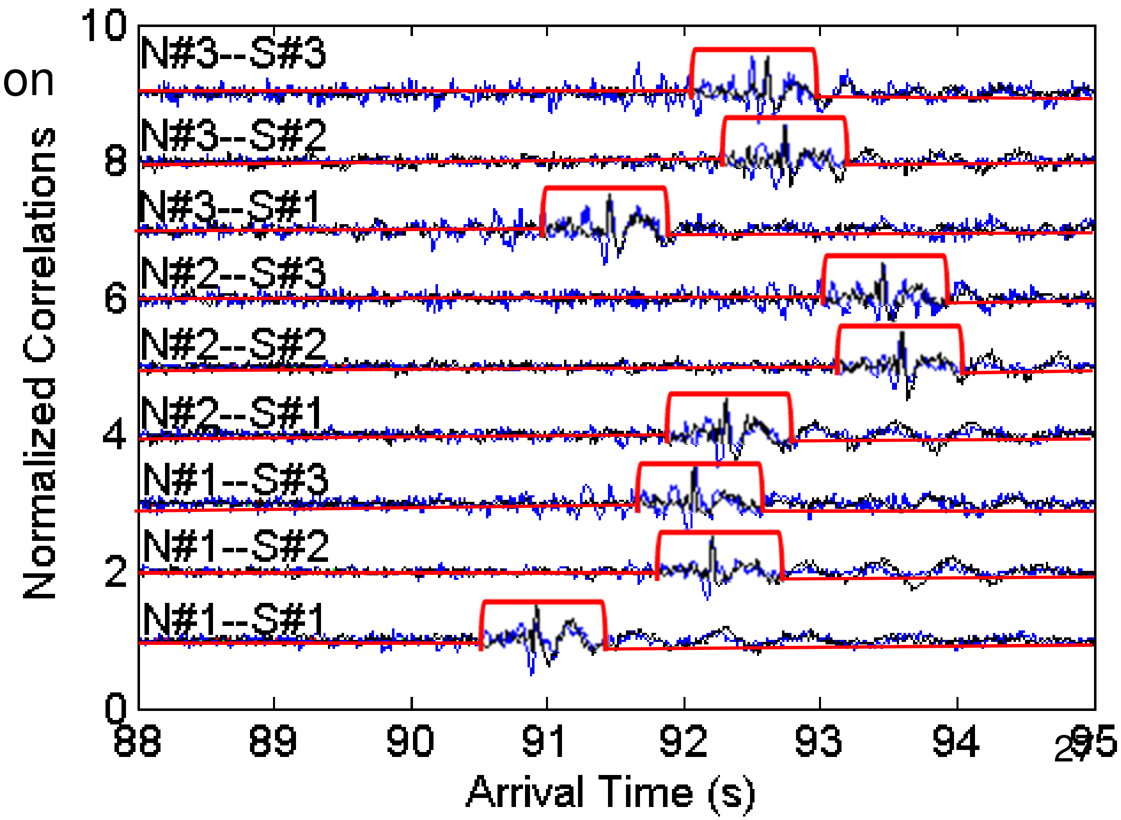
How to select the Array steering vectors $W_1(f)$ and $W_2(f)$?

- Model-based (Rays- DBF, Mode)
- Data-derived

Using Singular Value Decomposition

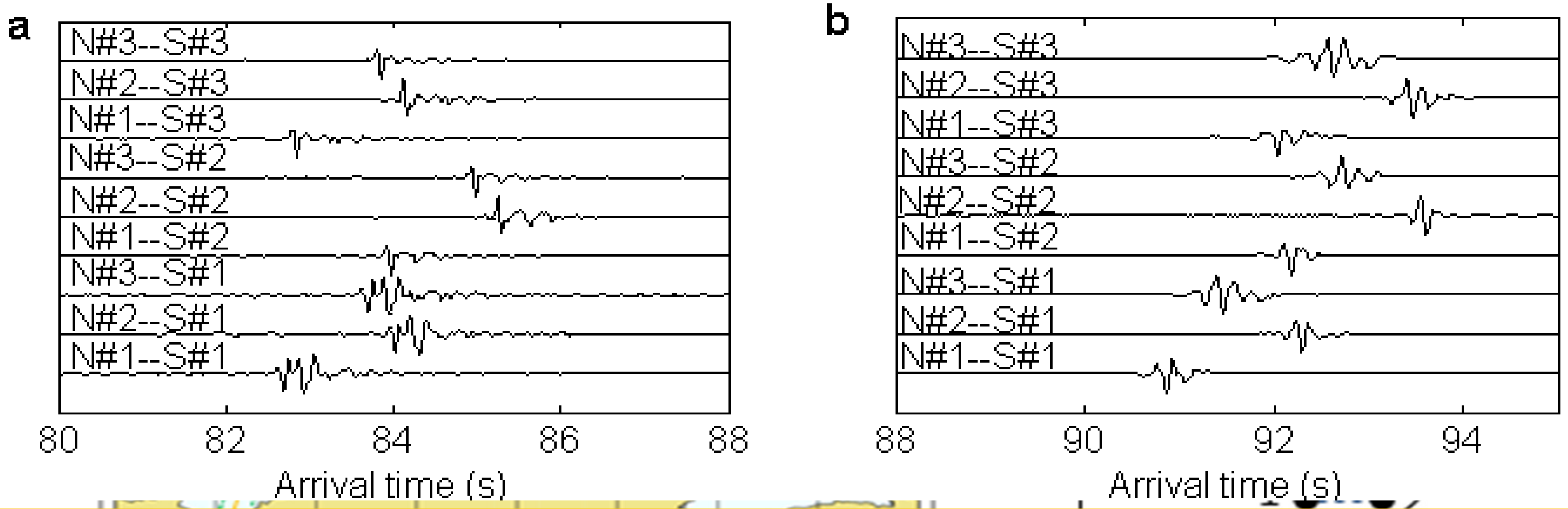
$$\hat{C}_{ref}(f) = U(f)\Sigma(f)V(f)^H$$

$$\sim \sigma_1 \underset{\underset{W_1(f)}{\uparrow}}{U_1(f)}\underset{\underset{W_2(f)}{\uparrow}}{V_1(f)^H},$$

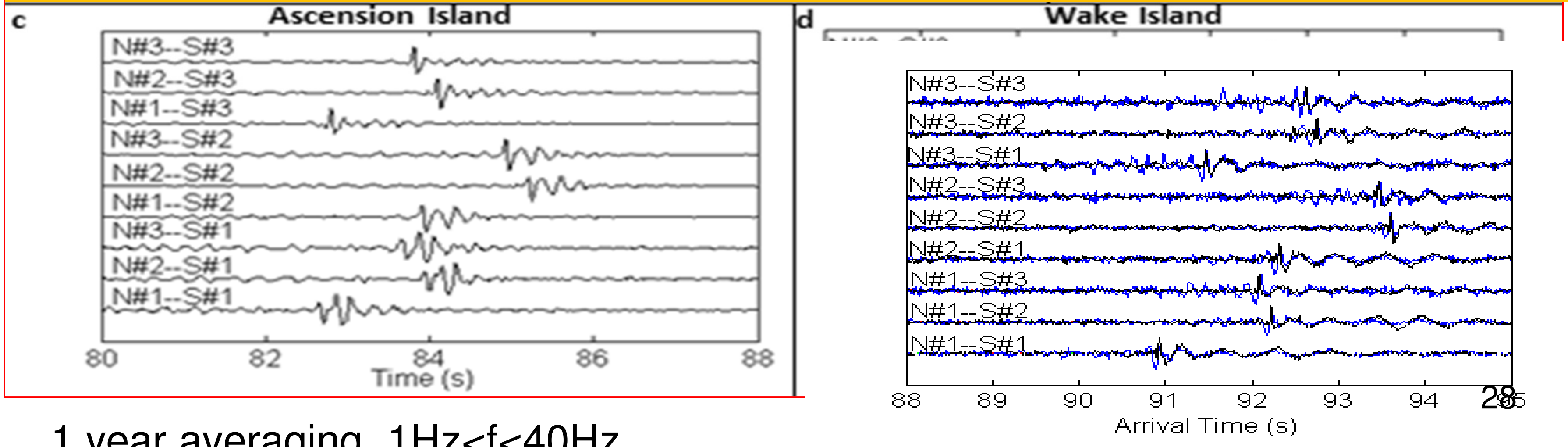


Spatio-temporal filter for Coherent Arrivals

inverse Fourier transform of the first principal component $\sigma_1(f)W_1(f)W_2(f)^H$



Original 1 year average Correlations

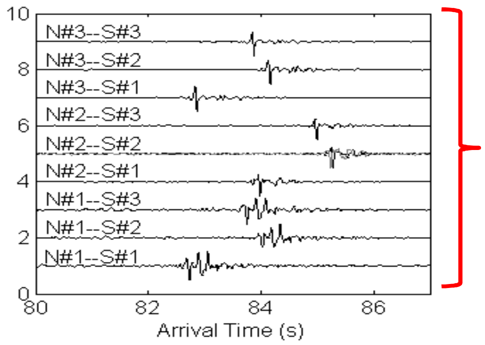


1 year averaging, 1Hz<f<40Hz

Georgia Institute of Technology

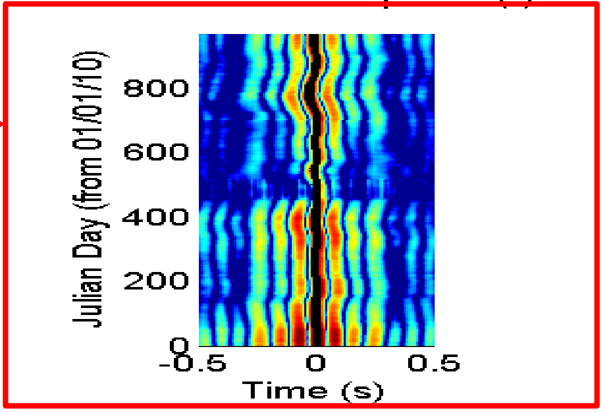
Passive thermometry of the deep ocean

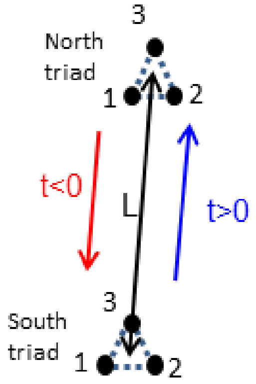
Result: Trackishifts in arrival time of beamformed cross-correlations (1 week average) over multiple years



Adaptive Beamformer

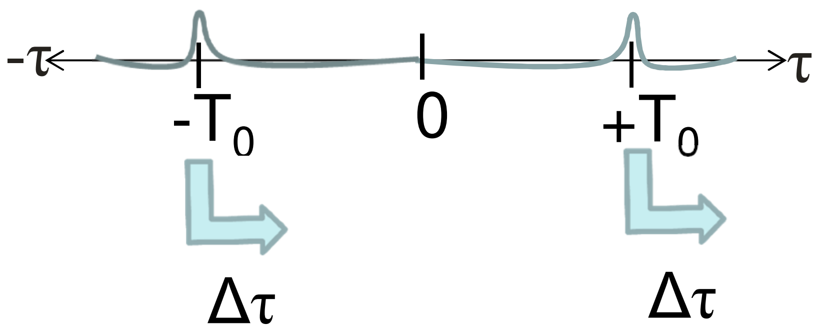
Beamformer Output B(t)





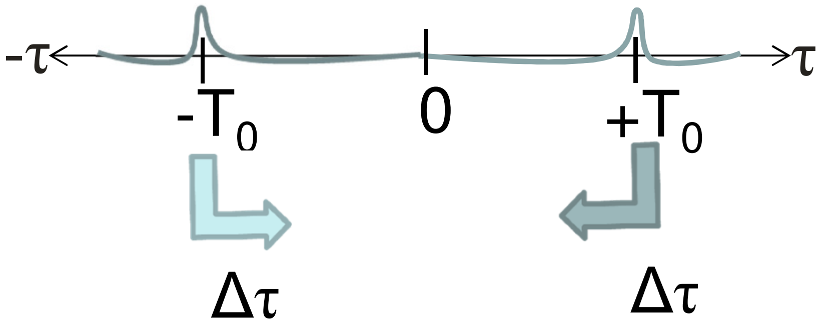
$$\hat{\boldsymbol{B}}(f) = \boldsymbol{W}_1^H(f)\hat{\boldsymbol{C}}(f)\boldsymbol{W}_2(f)$$

Anti-symmetric time shift



“non-reciprocal”changes OR clock-drift between receivers 1 and 2

Symmetric time shift

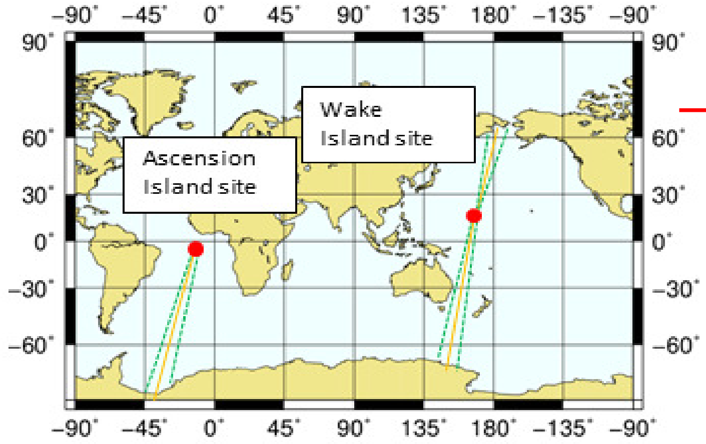


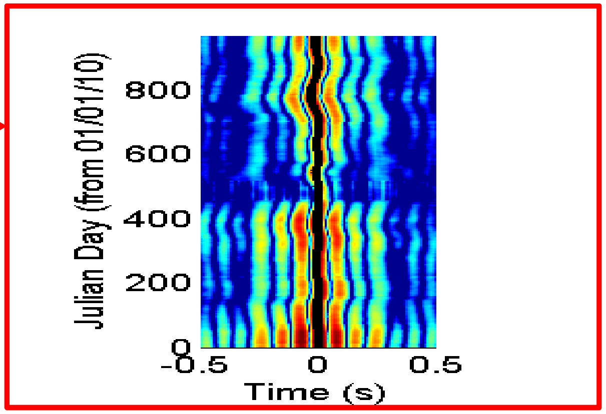
reciprocal”changes

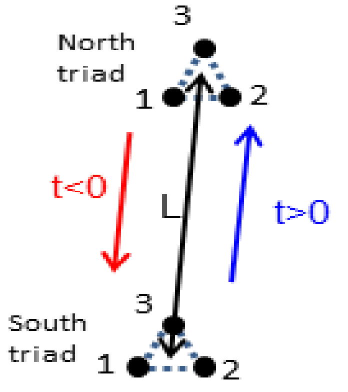
$\Delta c / C_0 = (\Delta\tau / T_0)$

Georgia Institute of Technology

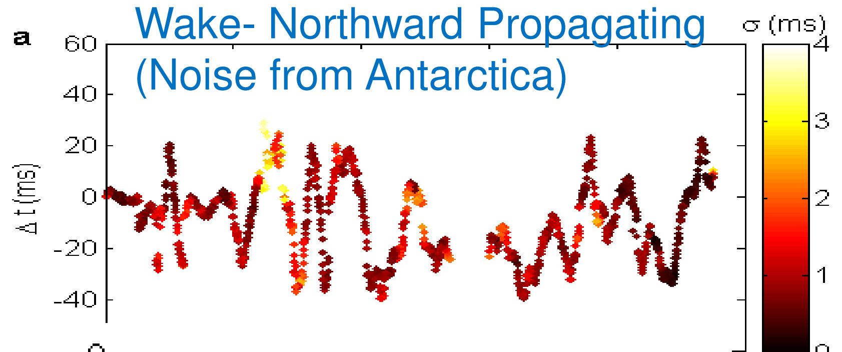
Passive thermometry of the deep ocean

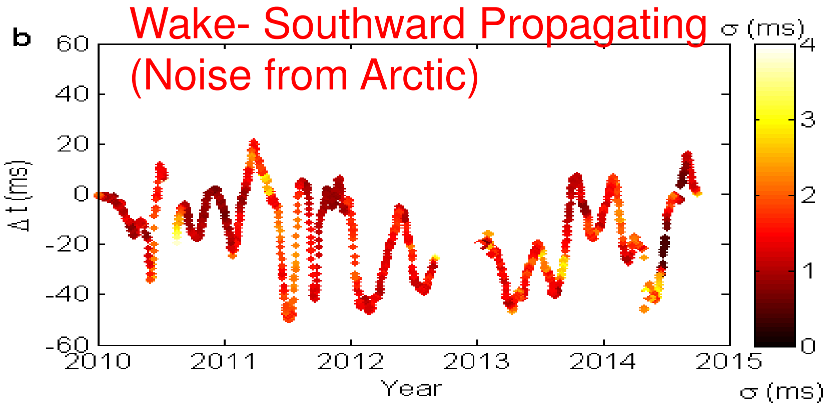


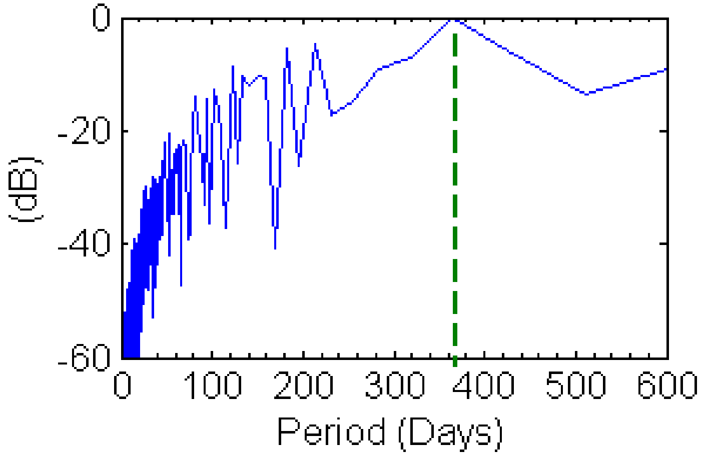


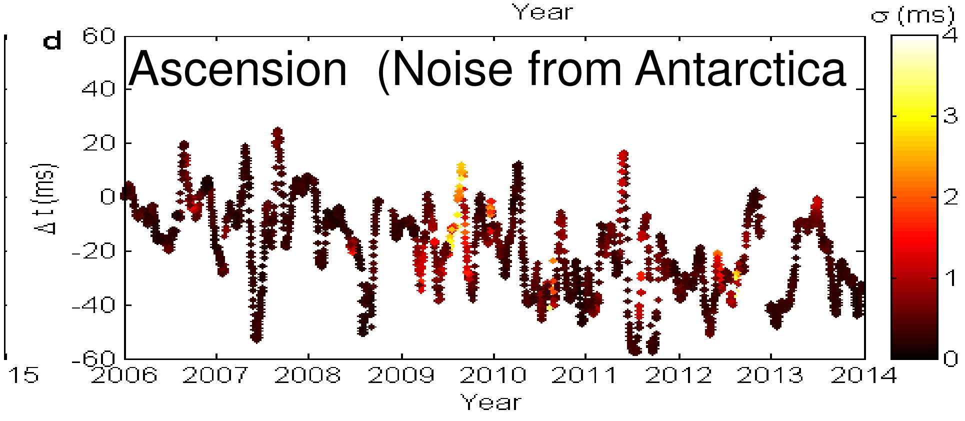


$$\sigma_t = \left[\omega_0 \sqrt{SNR}\right]^{-1}$$







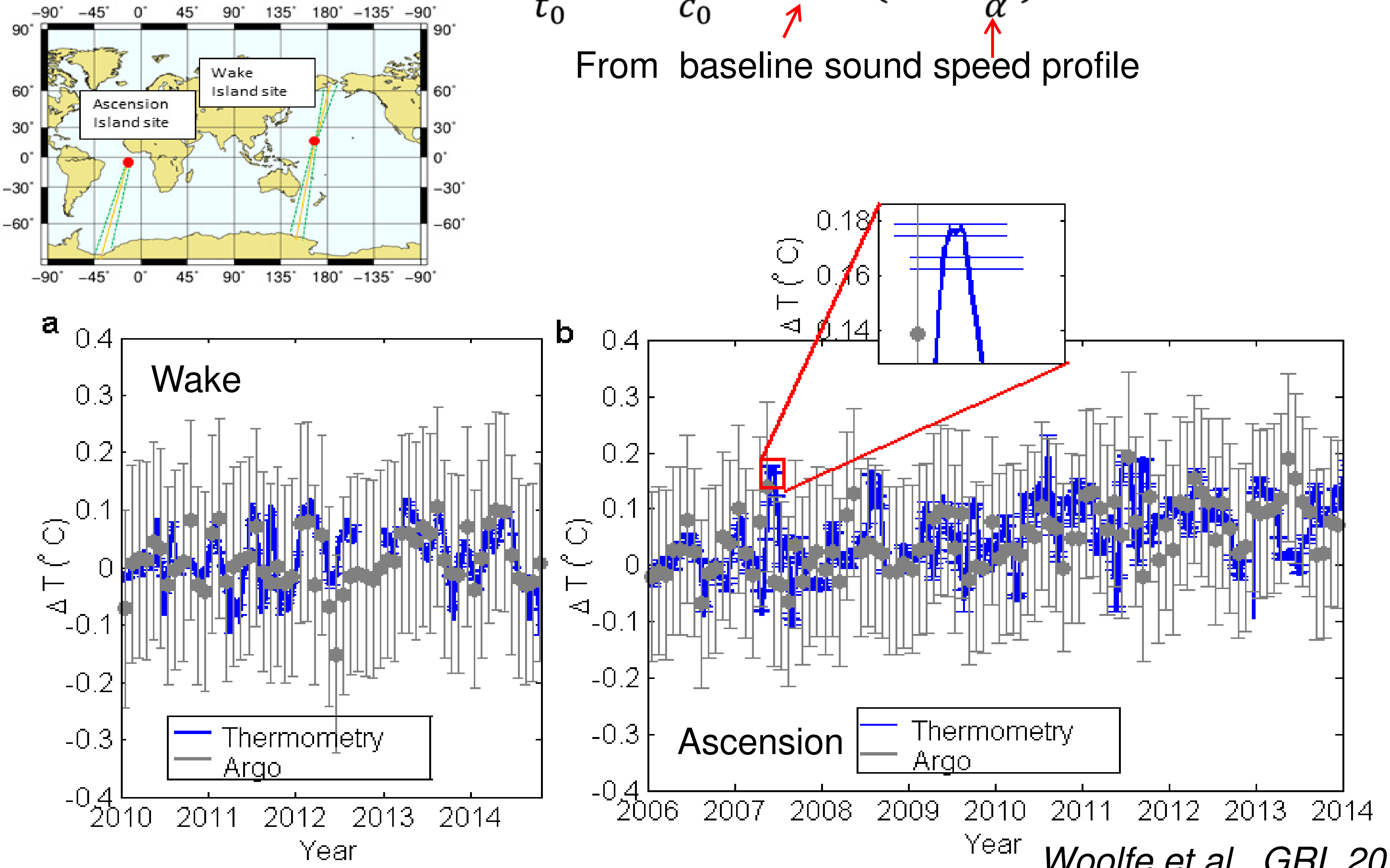


Passive thermometry of the deep ocean

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

EstimatingTemperature changes: $\frac{\Delta t}{t_0} = -\frac{\Delta c}{c_0} = \overset{\nearrow}{\alpha}\Delta T(1+\frac{\mu\beta}{\underset{\uparrow}{\alpha}})$ (Munk et al. 2009)

From baseline sound speed profile



Woolfe et al., GRL 2015

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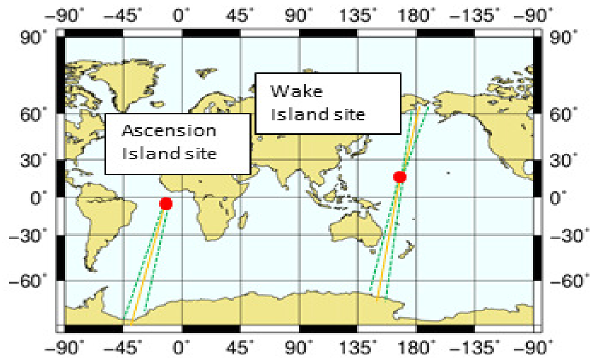
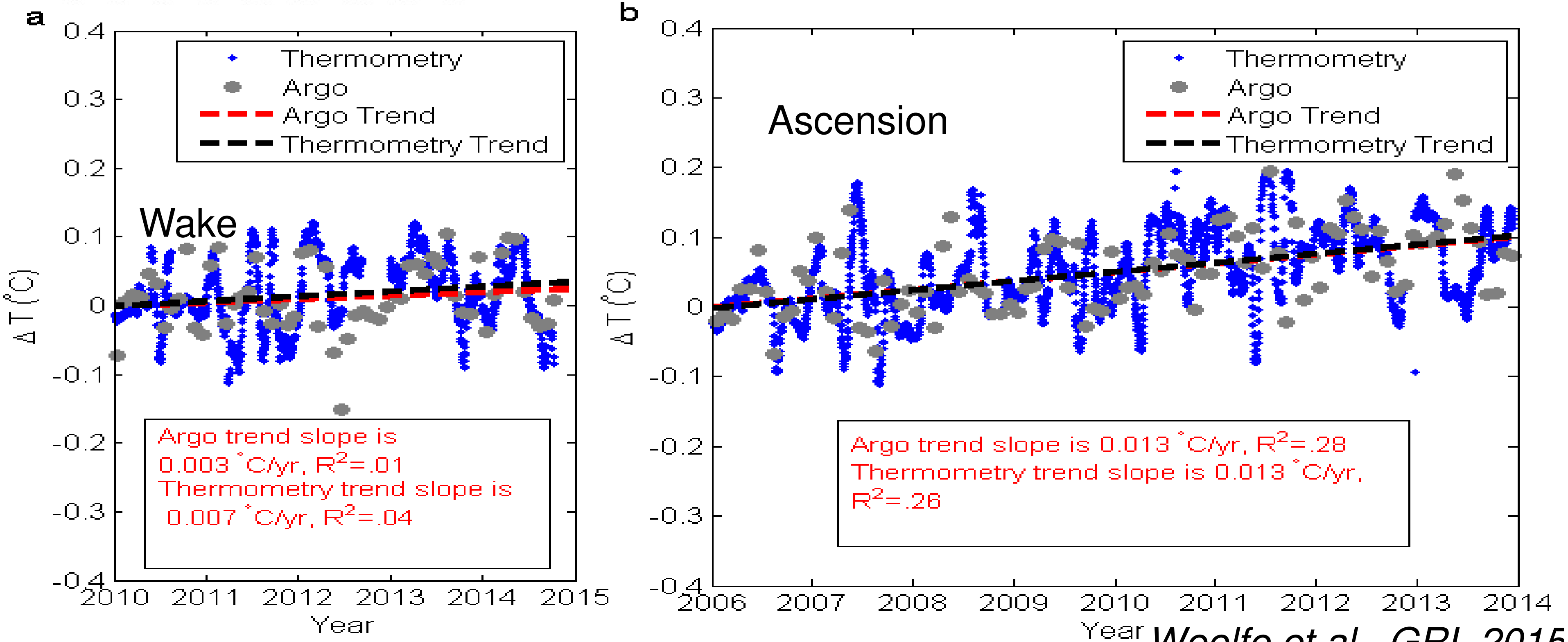




Argo trend slope is 0.003 ˚C/yr, R^2=.01
Thermometry trend slope is 0.007 ˚C/yr, R^2=.04

Argo trend slope is 0.013 ˚C/yr, R^2=.28
Thermometry trend slope is 0.013 ˚C/yr, R^2=.26

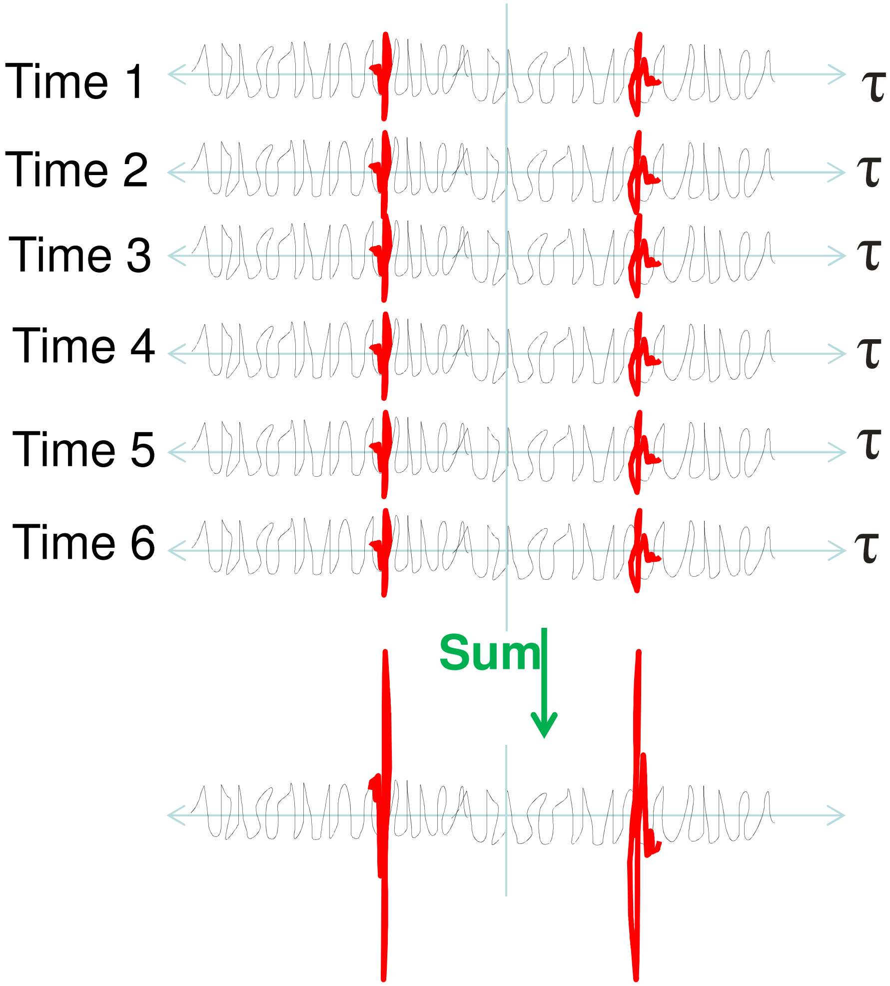
Woolfe et al., GRL 2015

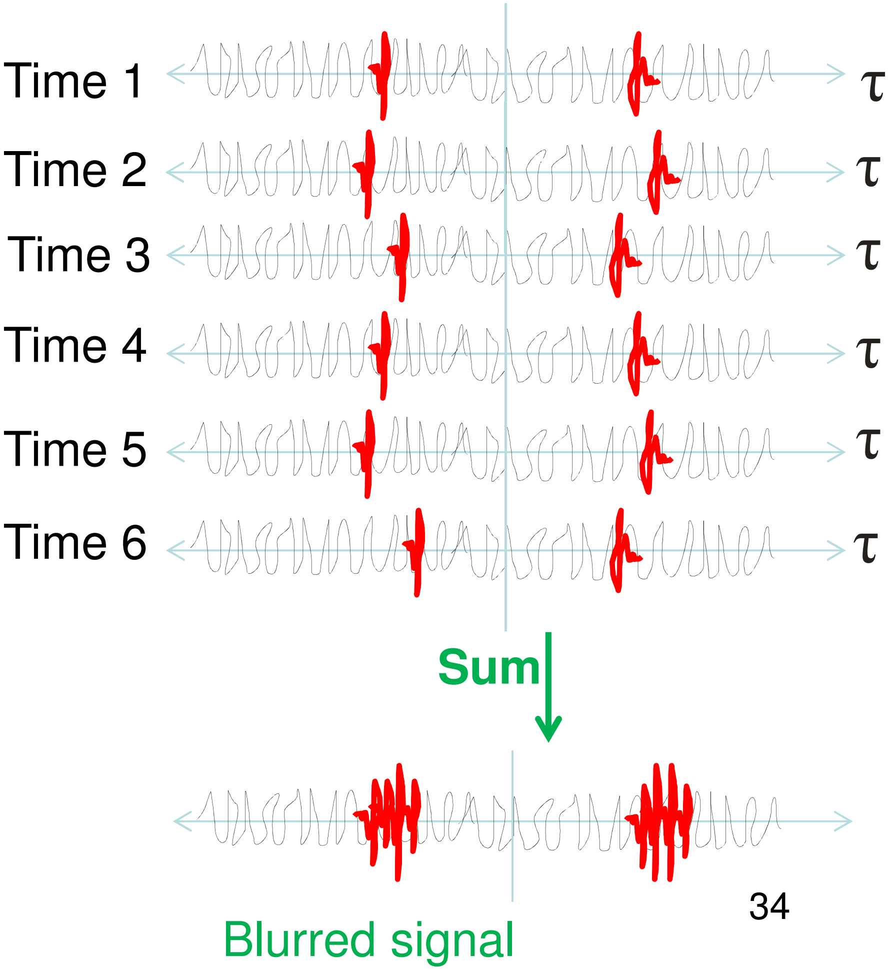
Presentation Outline

1. **Deep water acoustics & low-frequency noise sources**
2. **Monitoring with ambient noise: Background.**
3. **Passive acoustic thermometry of the deep water sound channel using low-frequency ambient noise**
4. **Monitoring with ambient noise: Optimization.**

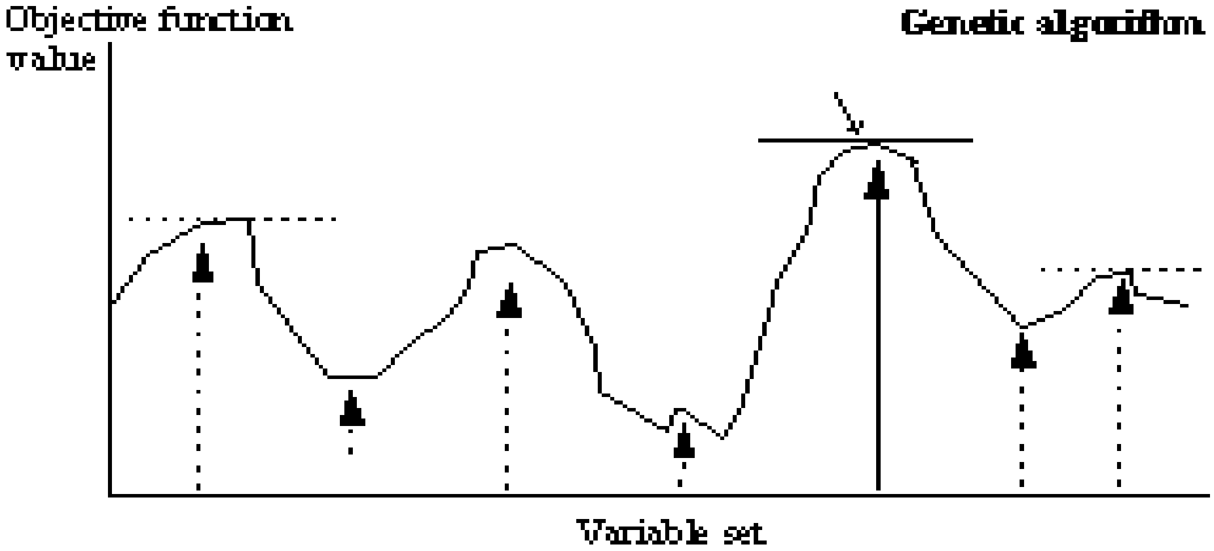
Enhancing the emergence rate of coherent arrivals using optimization

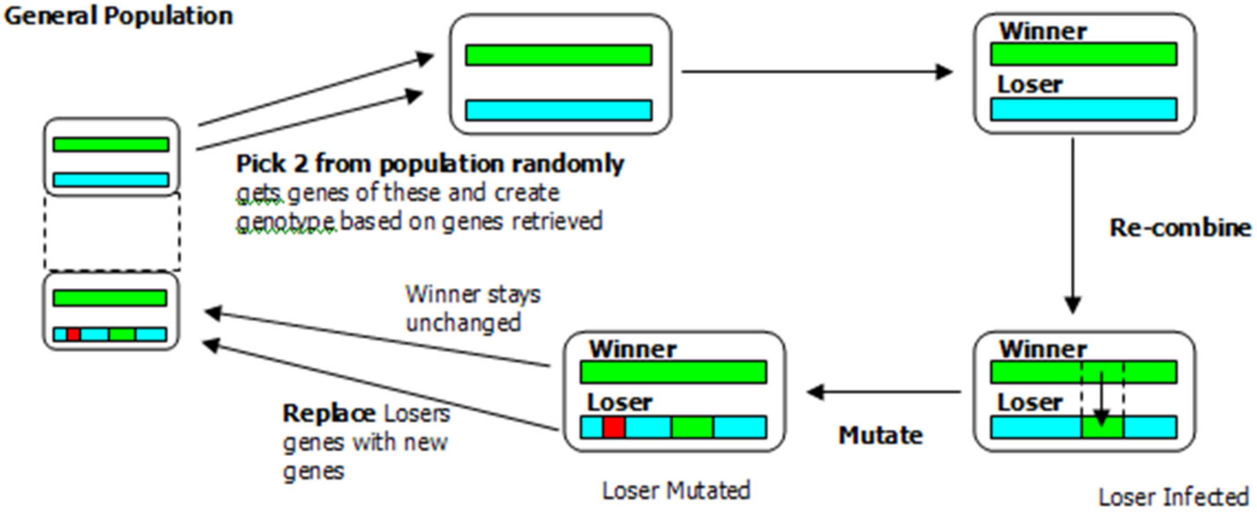
How can the amount of time needed to extract a coherent arrival be minimized?





Principles of Genetic Algorithm.





General Population

Pick 2 from population randomly
gets genes of these and create
genotype based on genes retrieved

Winner
Loser

Re-combine

Winner
Loser

Loser Infected

Mutate

Winner
Loser

Loser Mutated

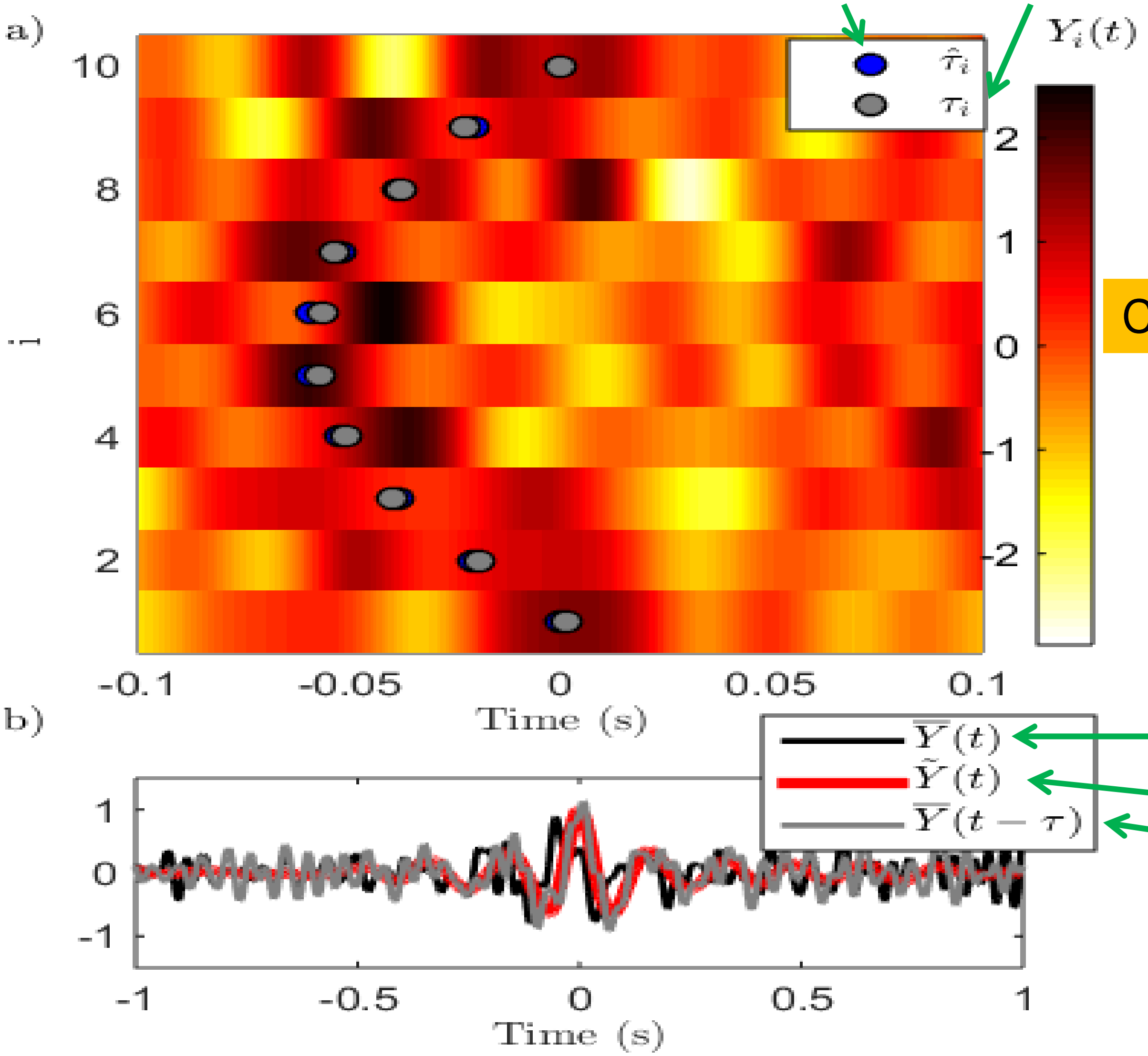
Winner stays
unchanged

Replace Losers
genes with new
genes

Optimization –”delay search”: Numerical results

True Delays

Estimated Delays



$$Y_i(t) = \tilde{Y}(t - \hat{\tau}_i) + N_i(t)$$

Shifted Reference waveform

Cost function for GA optimization

$$P(\tau_i, i = 1..N) = \left(\left[\sum_{i=1}^{N} Y_i(t - \tau_i) \right] * \tilde{Y}(t) \right) \Bigg|_{t=0}$$

Regular Average

“Reference” waveform

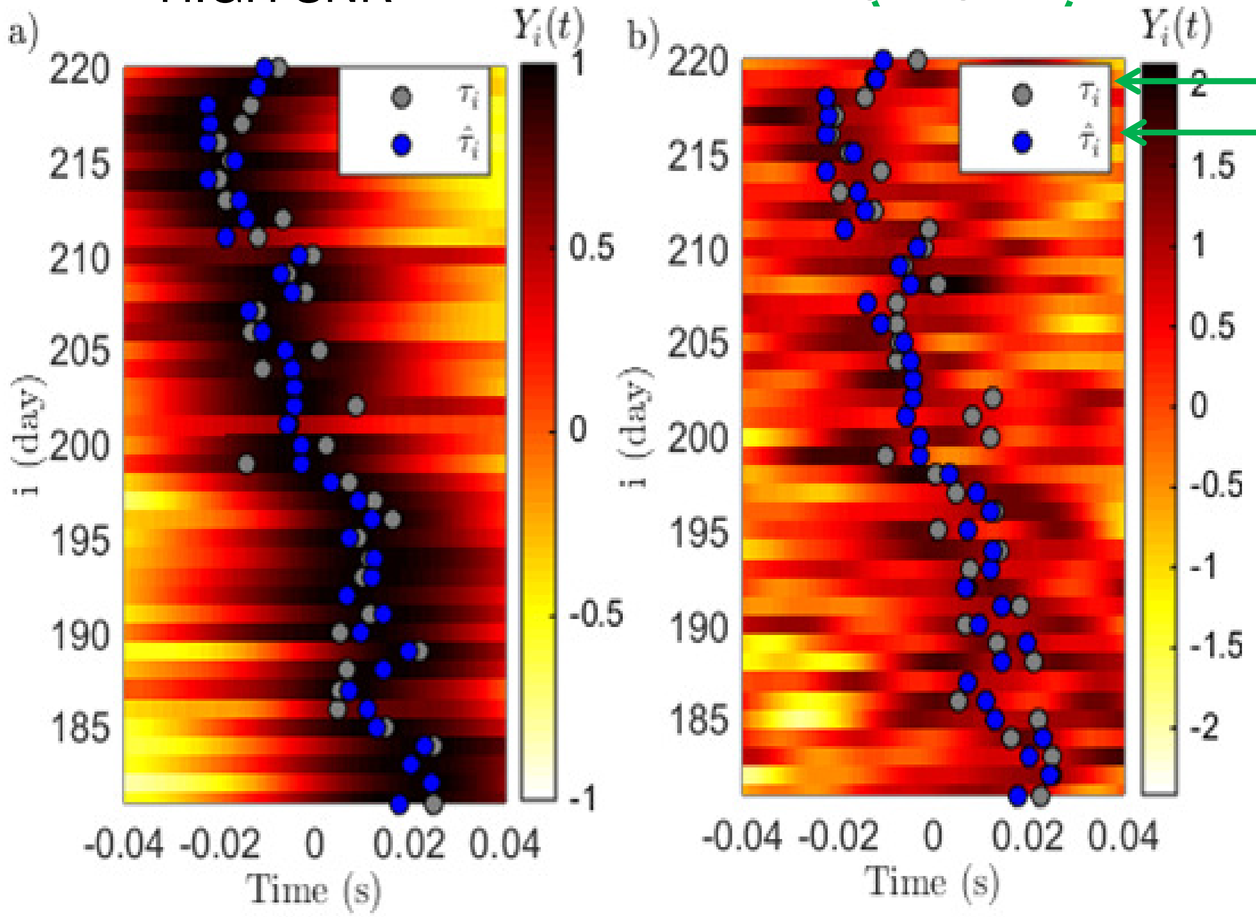
Optimized Average

1Hz<f<40Hz

Optimization –"delay search": Experimental results

HIGH SNR

LOW SNR



Estimated Delays

True Delays (from High SNR

Cost function for GA optimization

$$P(\tau_i, i = 1..N) = \left(\left[\sum_{i=1}^{N} Y_i(t-\tau_i) \right] * \widetilde{Y}(t) \right) \Big|_{t=0}$$

- Track arrival time of Beamformer Noise correlations (on SOFAR arrivals) over 40days
- 1Hz<f<40Hz

Conclusions

Emergence rate of coherent arrivals from ambient noise correlations can be enhanced using:

- Array beamforming (Increase Spatial diversity -> Reduce Averaging time)
- Optimization/Search Algorithm ("Unravel" medium fluctuations)

Applications to various domains…

- "Faster" passive monitoring (on shorter time scales)
- "Selective" monitoring (select spatial regions)
- Mitigate environmental variations (e.g. for passive target detection)

Requires a good understanding of..

- noise sources characteristics /physics
- spatial & temporal scales of medium variations

Questions?

Thank you