Temporal and Spatial Coherence of Shallow Water Acoustic Propagation

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Data Sets

(M-sequence q=4)

- **SW06**
  - Continuous transmission to SHRU receivers. 50 hours

    → temporal properties – fluctuations, coherence in time
  - Periodic transmission to SHARK VLA and HLA

    → spatial properties

- **FSPE** - Florida Straits Propagation Experiment
  - Continuous Transmission 2 -30 day periods.

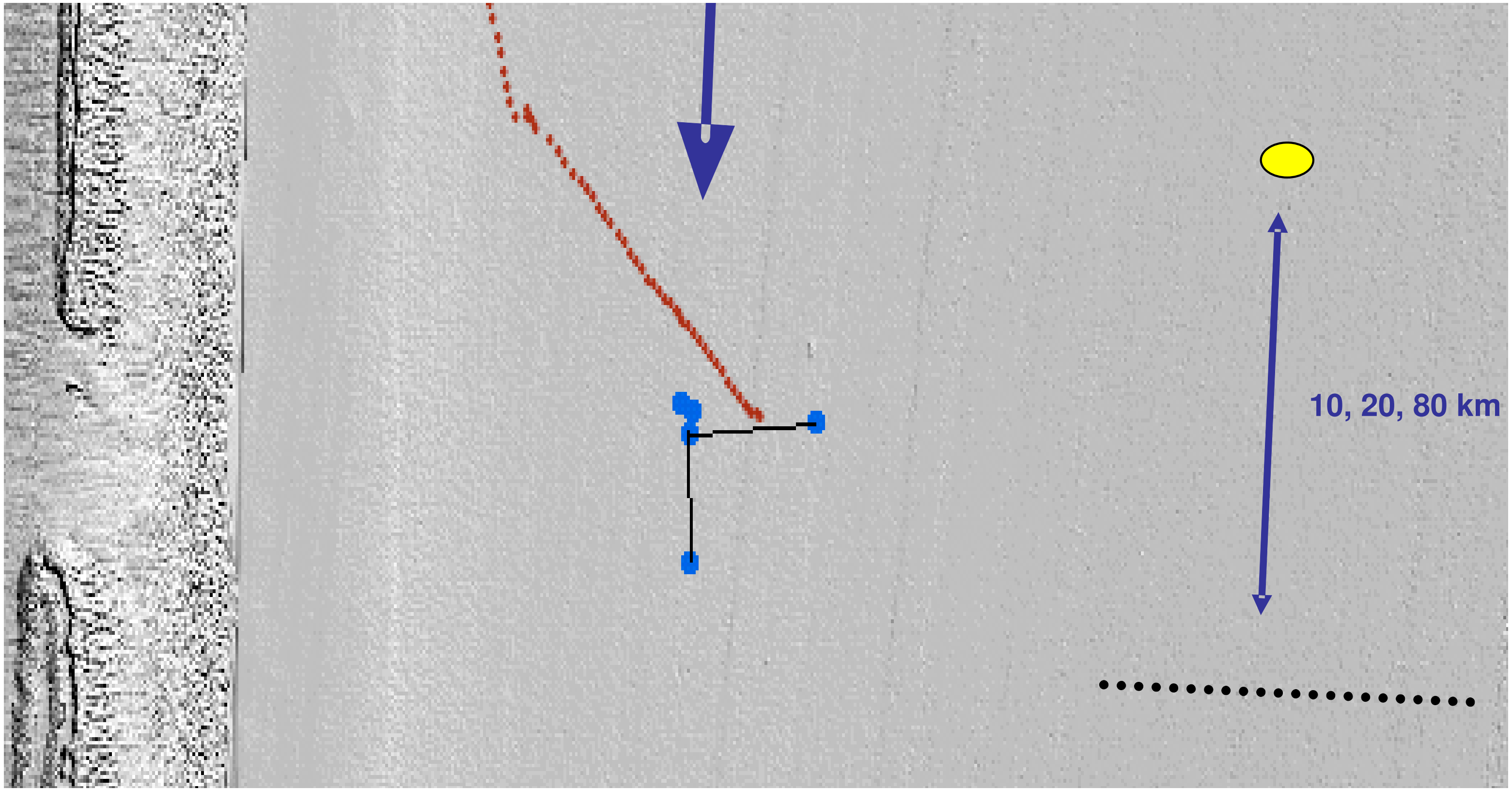
    → temporal properties

- **AO** - Acoustic Observatory
  - Short 20 min Transmission 500 element - HLA

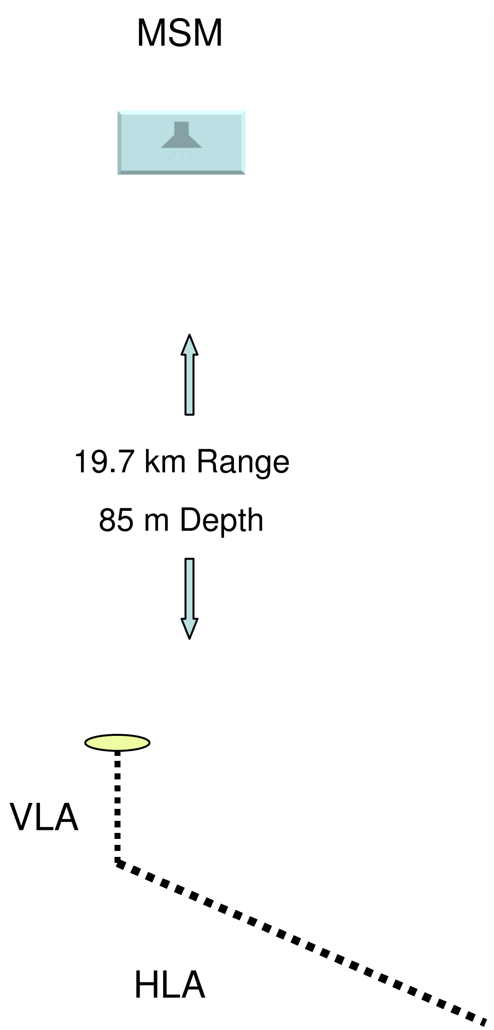
    → spatial properties 20 to 80 km.

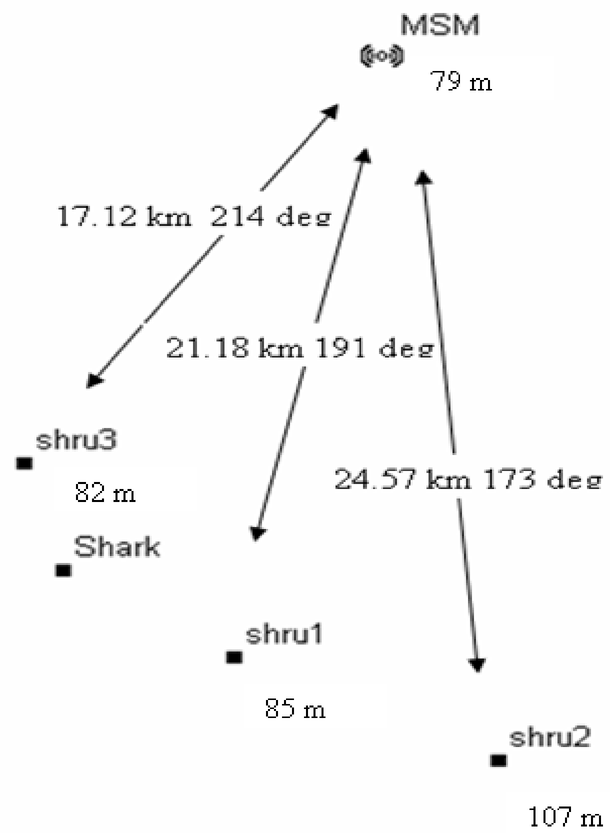
Acoustic Observatory CALOPS Sept 07

Shipboard Suspended and Towed Transmissions



SW06 Experiments – Mid-Atlantic Bight





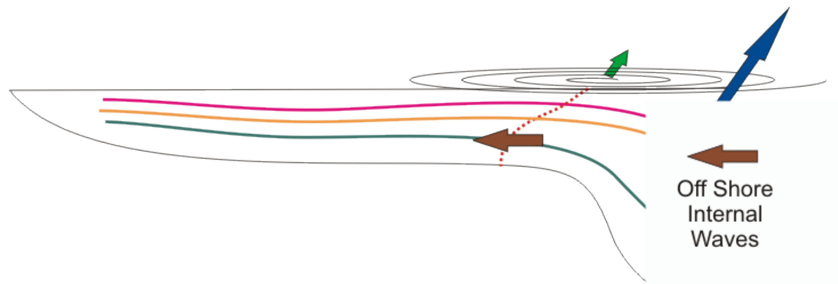
SHARK

VLA 16 phones

HLA 32 phones 468 m (15 m spacing)

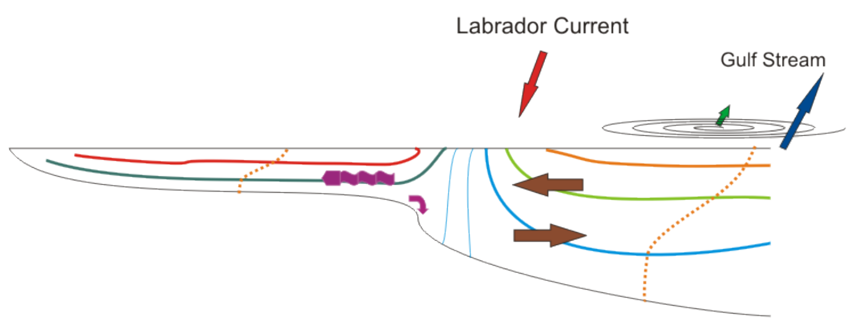
Acoustic propagation shallow shelves inside of western boundary currents

Prograde vs Retograde fronts



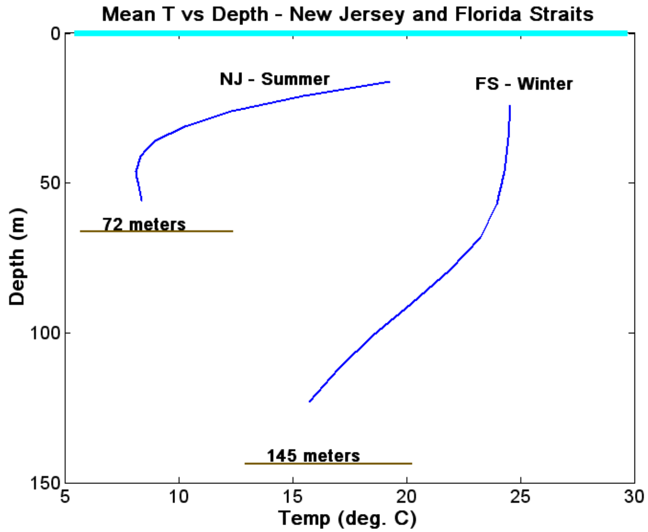
Florida Straits - Prograde Front

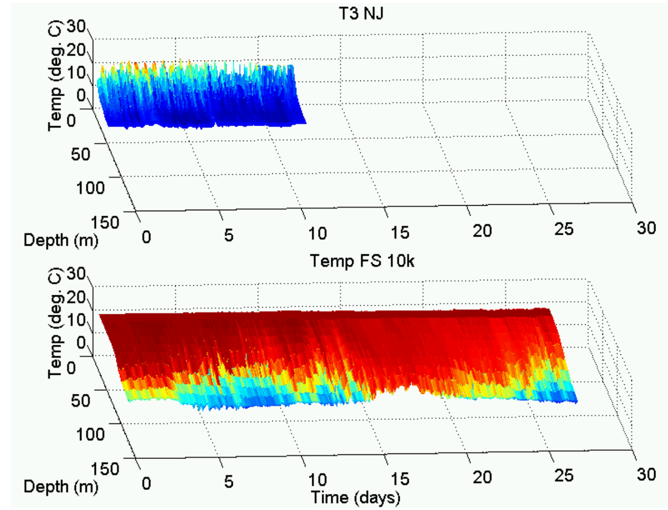
Sea of Japan, East China Sea near the Kuroshio and the South China Sea seasonally.

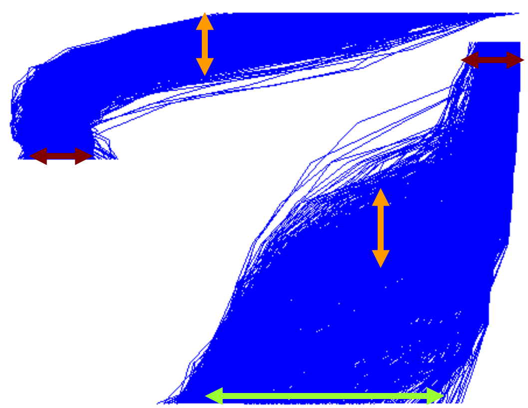


Mid-Atlantic Bight - Retrograde Front

Yellow Sea, East China Sea and the South China Sea seasonally.







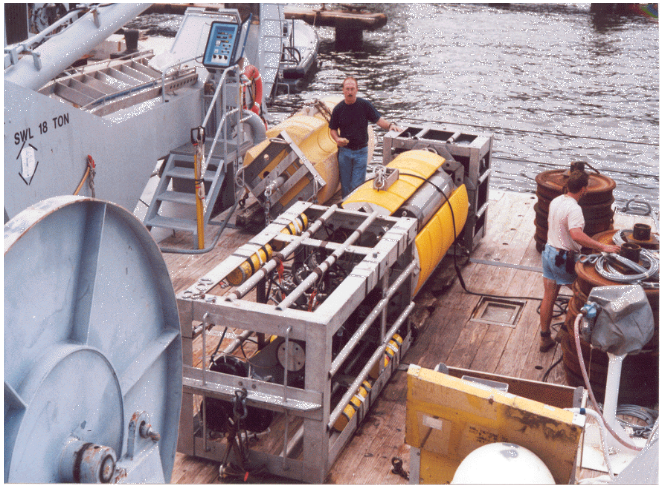
Seasonal

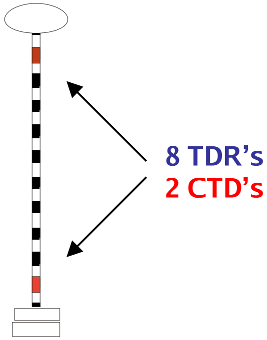
Internal Wave

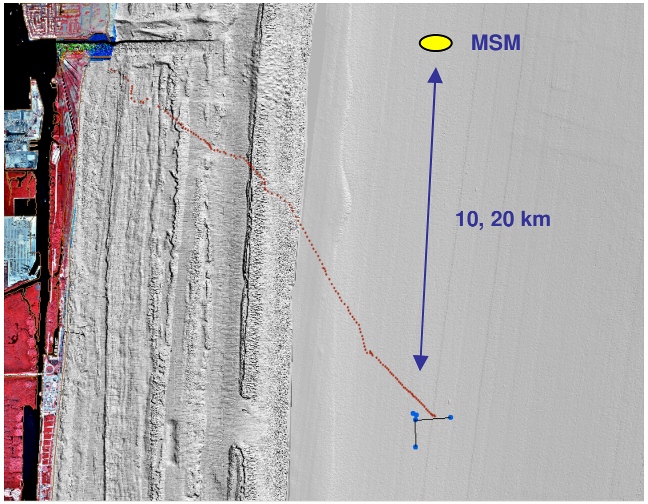
Sub-inertial

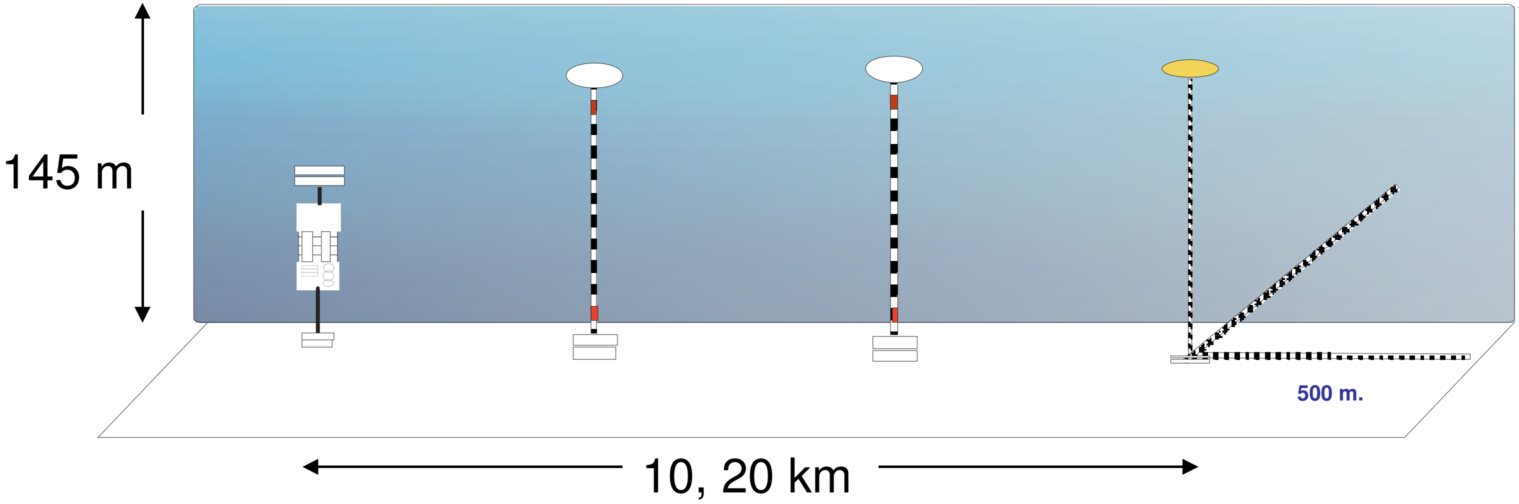
Miami Sound Machine

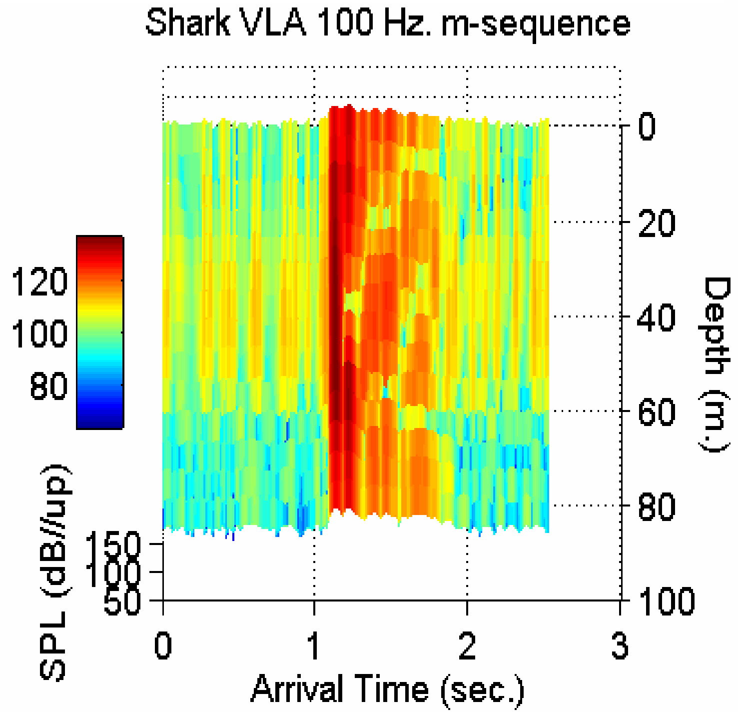
Fc = 100,200,400,800,1600,3200. Hz.
Bw= 25 , 50,100, 200, 400, 800.

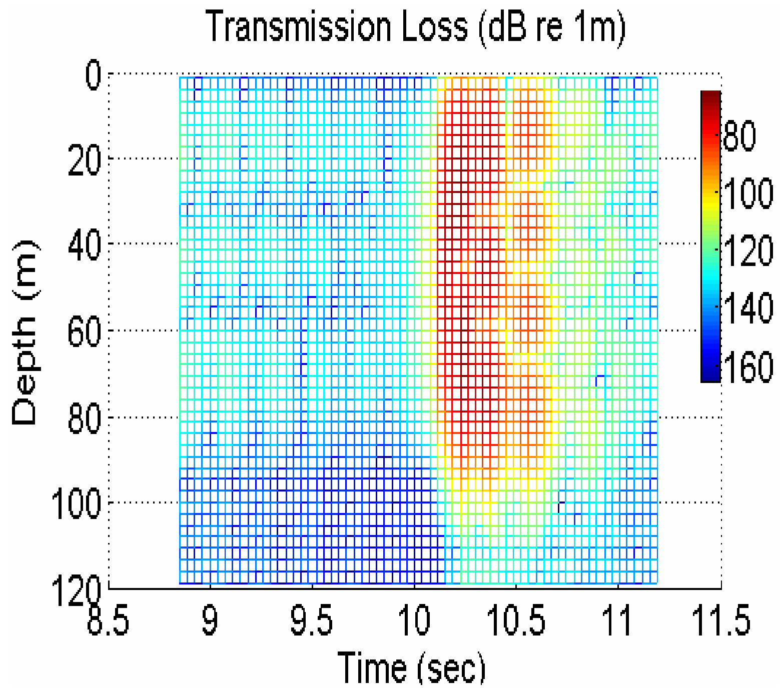












PE Model (first try) → Several extra modes

C_b = 1715 m/s Inversion

by K. Smith and J. Miller

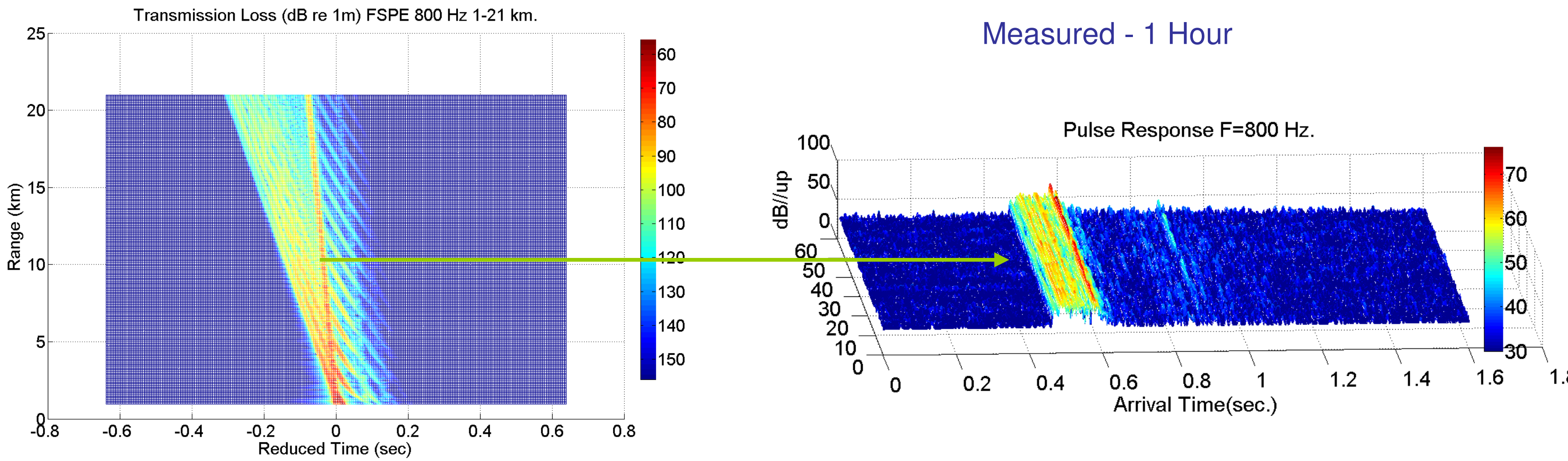
(In the vicinity)

PE (second try) → Good Fit ! Above)

1595 m/s

Measurements by UW (direct method) sediment pool at site of experiment
1600 m/s !

PE Prediction of 800 Hz. Pulse Response



Data Analysis

Signal Amplitude Data

$t \rightarrow$ $p(t)$

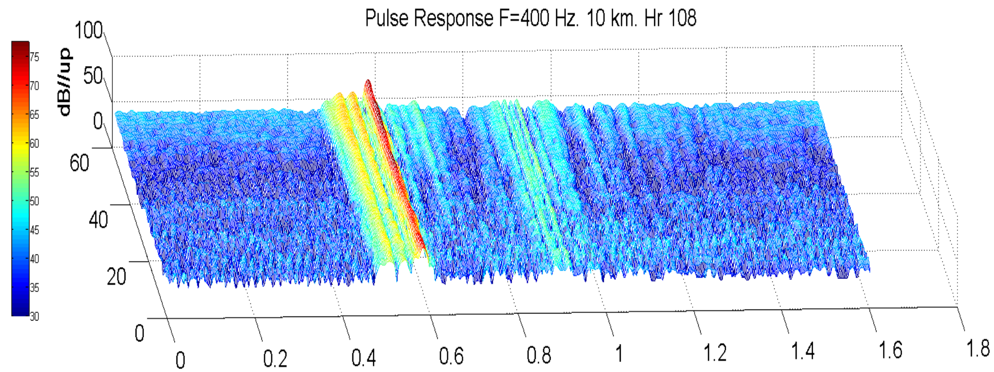
$\tau \downarrow$

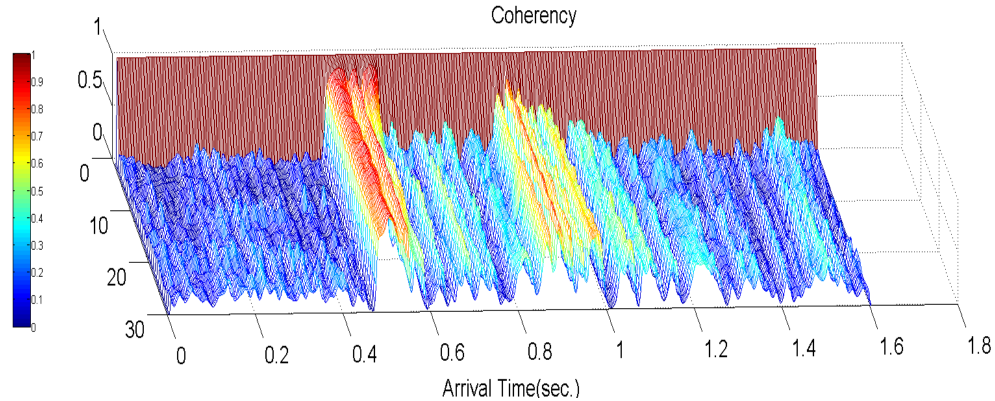
…………………………………………..1
…………...…………………………..2
…………… $p(t+\tau)$ ………………….…..3
…………………………………………..
…………………………………………..
………………………..
………………………
……………..
…………..   240

$\Downarrow$

$$COH(t,\tau)=\frac{\left\langle \left(\ p(t)*p(t+\tau)\ \right)^2\right\rangle_{\Delta t,\Delta T}}{\left\langle p(t)^2\right\rangle_{\Delta t,\Delta T}\left\langle p(t+\tau)^2\right\rangle_{\Delta t,\Delta T}}$$

$\Rightarrow$





Temporal Coherence and Phase Wrapping

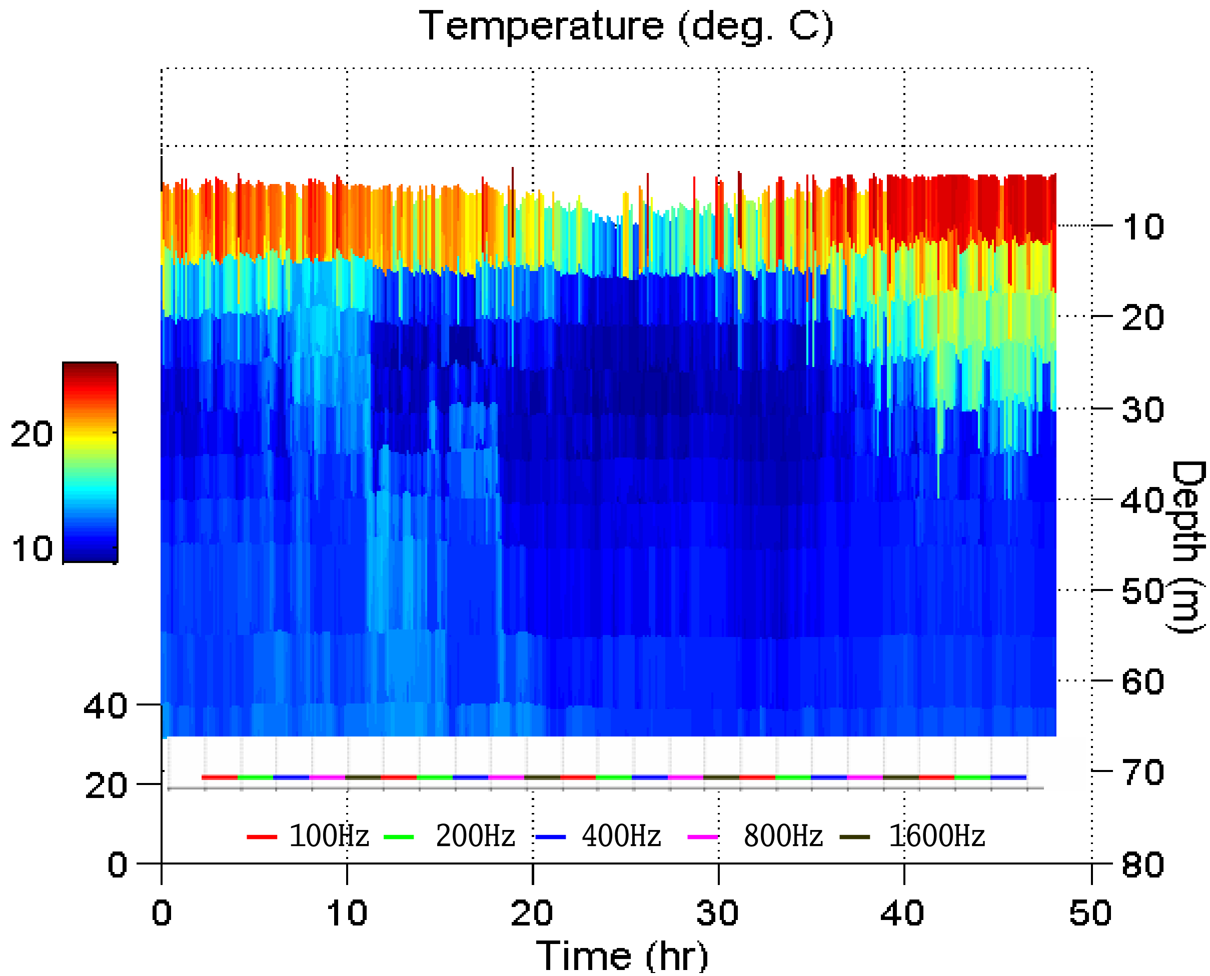
$$COH(t,\tau) = \frac{\left\langle \left(\; p(t)^* p(t+\tau) \; \right)^2 \right\rangle_{\Delta t, \Delta T}}{\left\langle p(t)^2 \right\rangle_{\Delta t, \Delta T} \left\langle p(t+\tau)^2 \right\rangle_{\Delta t, \Delta T}}$$

Coherence is a statistical measure of the change of a waveform with time

Causes:

2. Multimode interference
   - Separate modes
3. Slow phase shifts of undistorted waveform
   - Compute for all phase shifts or phase track.
4. Random waveform distortion
   - Unrecoverable

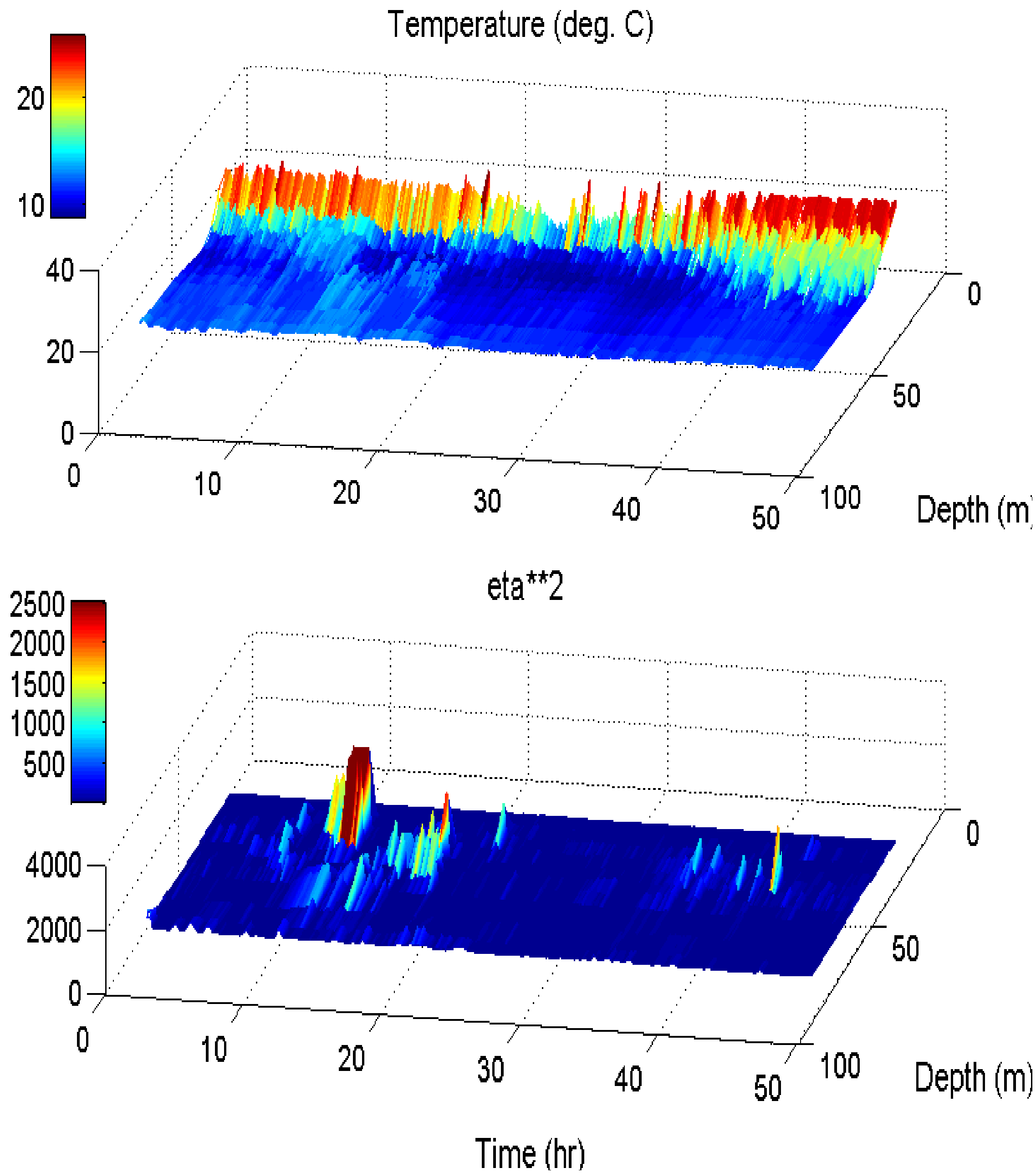
- COH varies from both slow phase shifts in time that cause multipath/mode cancellation and from true randomizing effects.
- Both usually happen at the same time (Phase wrapping, Flatte)

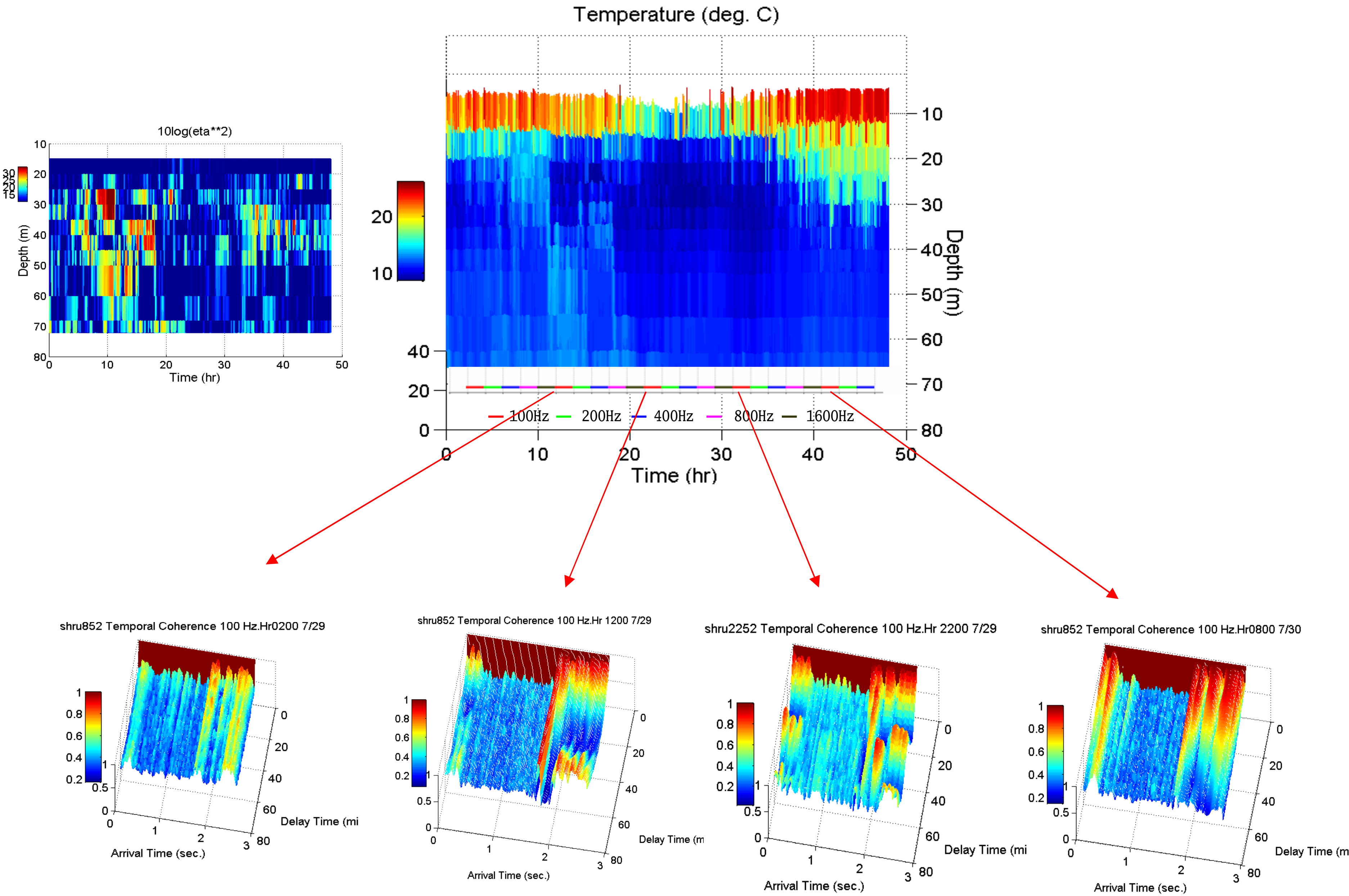


$$PE = (\rho / 2)\eta^2 N^2 ,$$

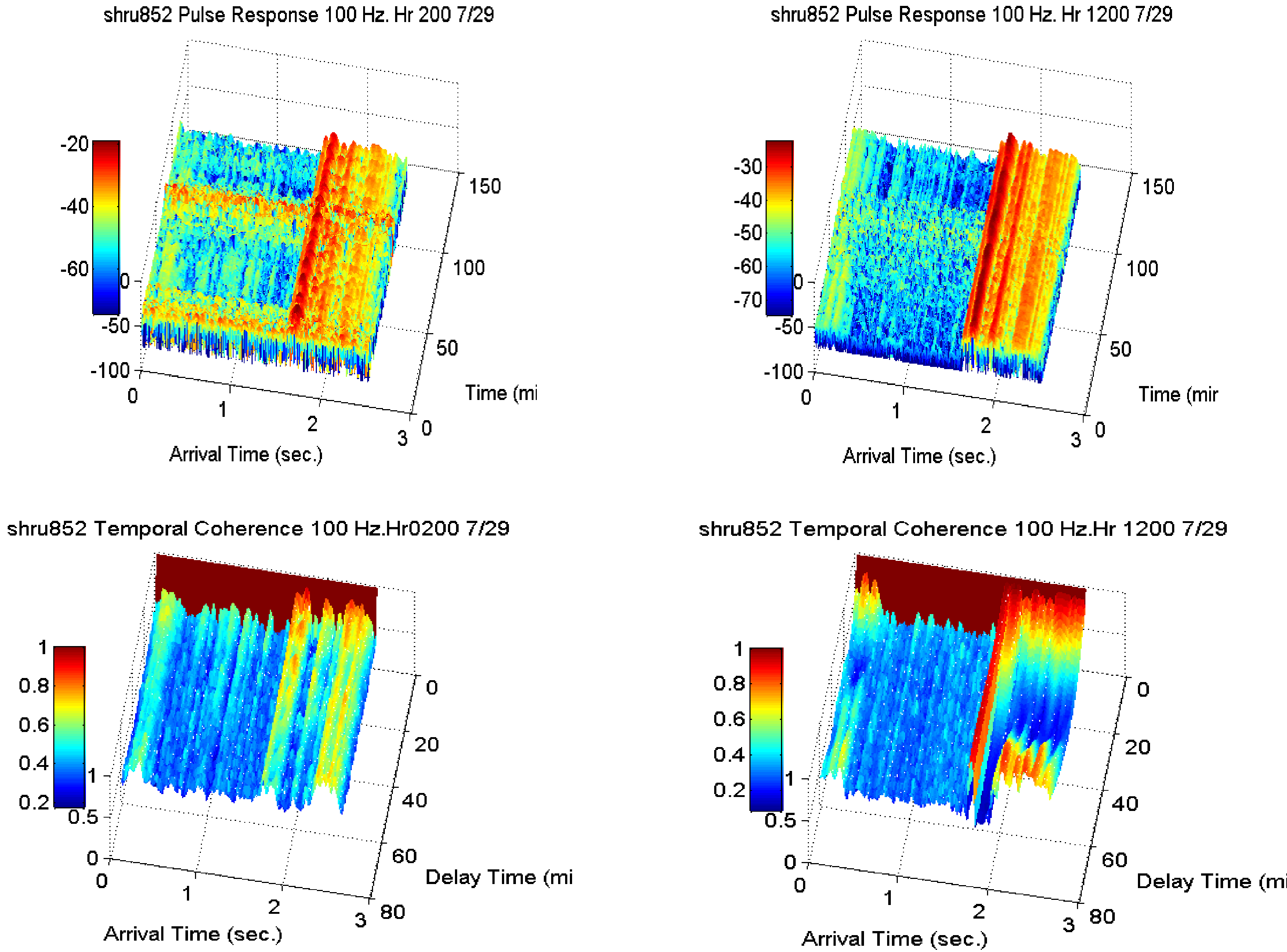
Where, N is the buoyancy frequency,

and $\eta = T^{'} / dT / dz$.


Temperature (deg. C)
20
10
40
20
0
0
10
20
30
40
50
0
50
100
Depth (m)
eta**2
2500
2000
1500
1000
500
4000
2000
0
0
10
20
30
40
50
0
50
100
Depth (m)
Time (hr)



Temperature (deg. C)
10log(eta**2)
Depth (m)
Time (hr)
100Hz
200Hz
400Hz
800Hz
1600Hz
shru852 Temporal Coherence 100 Hz.Hr0200 7/29
shru852 Temporal Coherence 100 Hz.Hr 1200 7/29
shru2252 Temporal Coherence 100 Hz.Hr 2200 7/29
shru852 Temporal Coherence 100 Hz.Hr0800 7/30
Arrival Time (sec.)
Delay Time (mi

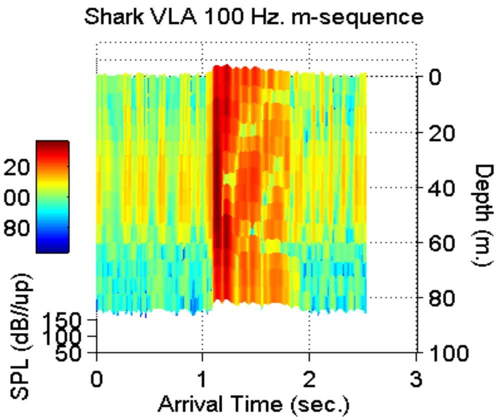


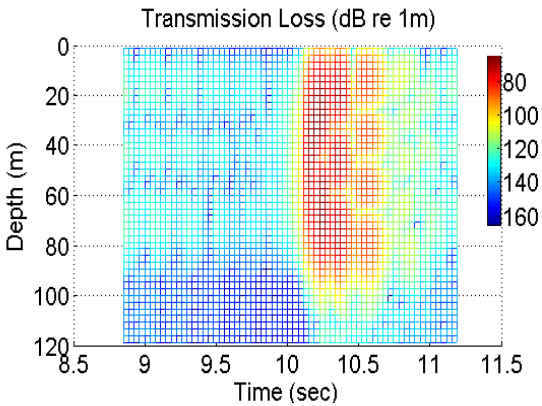
shru852 Pulse Response 100 Hz. Hr 200 7/29
Arrival Time (sec.)
Time (mi
shru852 Pulse Response 100 Hz. Hr 1200 7/29
Arrival Time (sec.)
Time (mir
shru852 Temporal Coherence 100 Hz.Hr0200 7/29
Arrival Time (sec.)
Delay Time (mi
shru852 Temporal Coherence 100 Hz.Hr 1200 7/29
Arrival Time (sec.)
Delay Time (mi

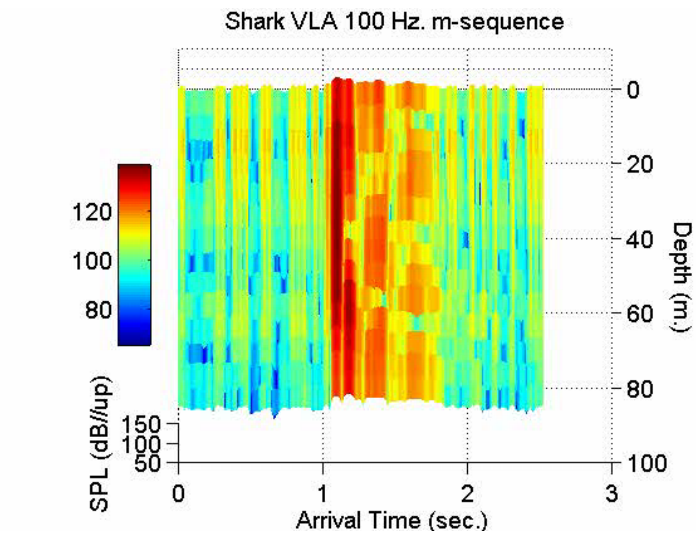
SW06 Modes and Arrivals

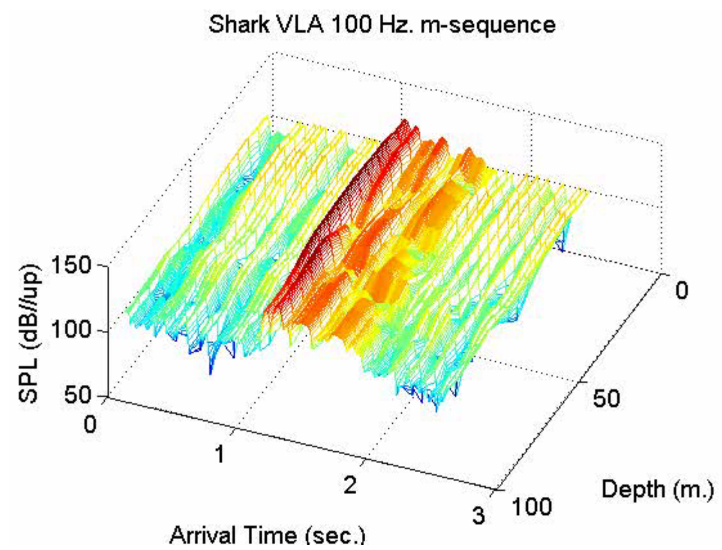
Observed

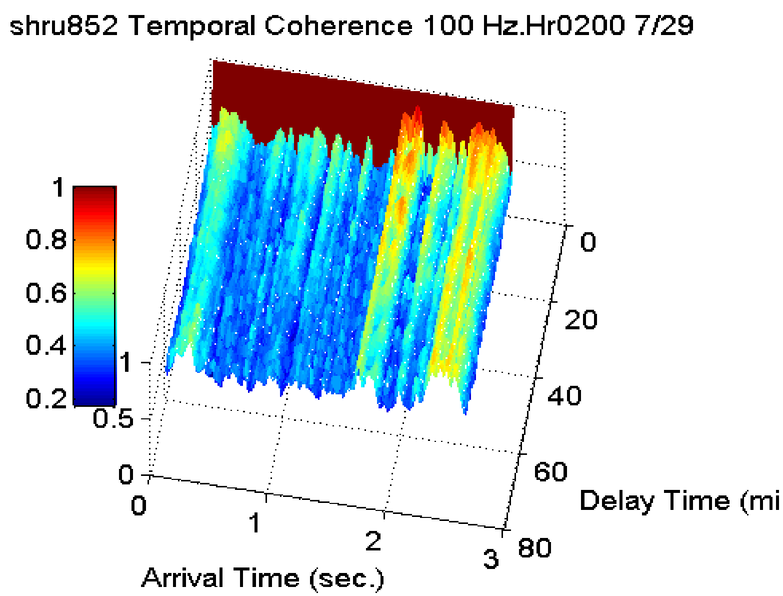
Modeled

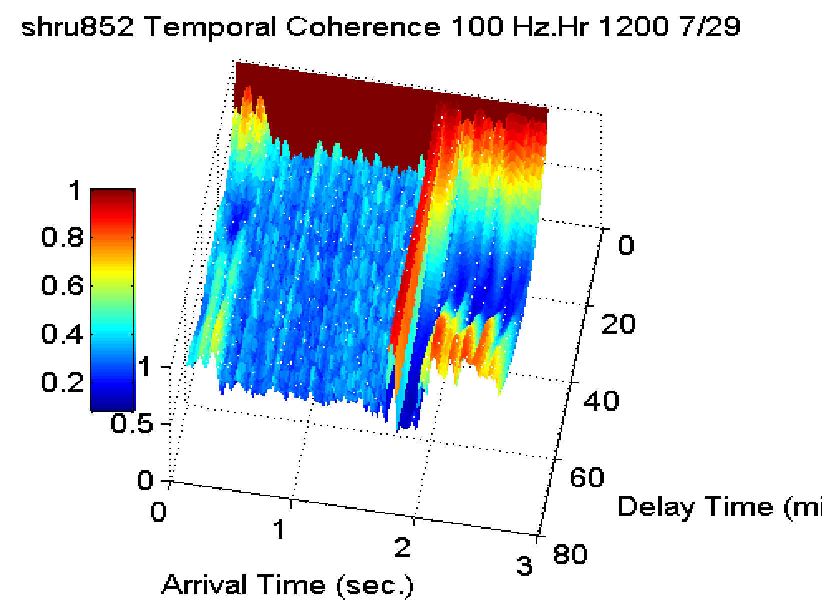


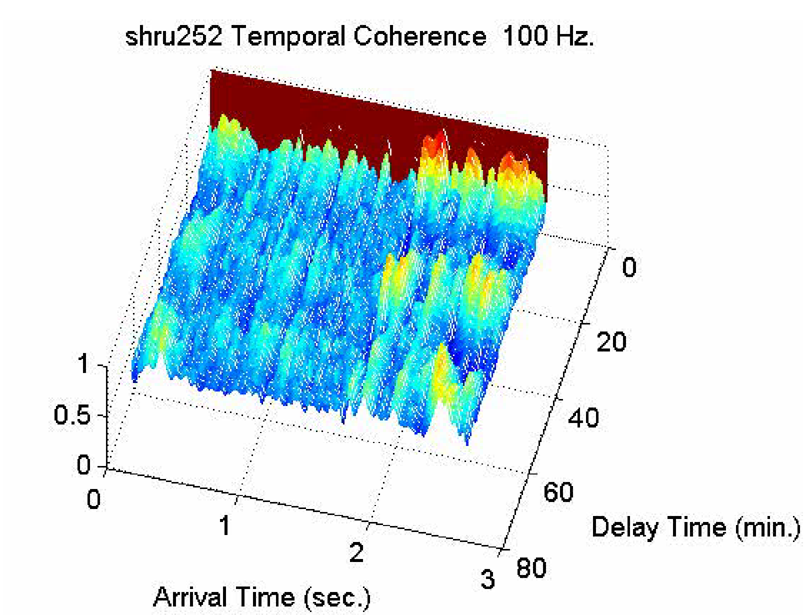


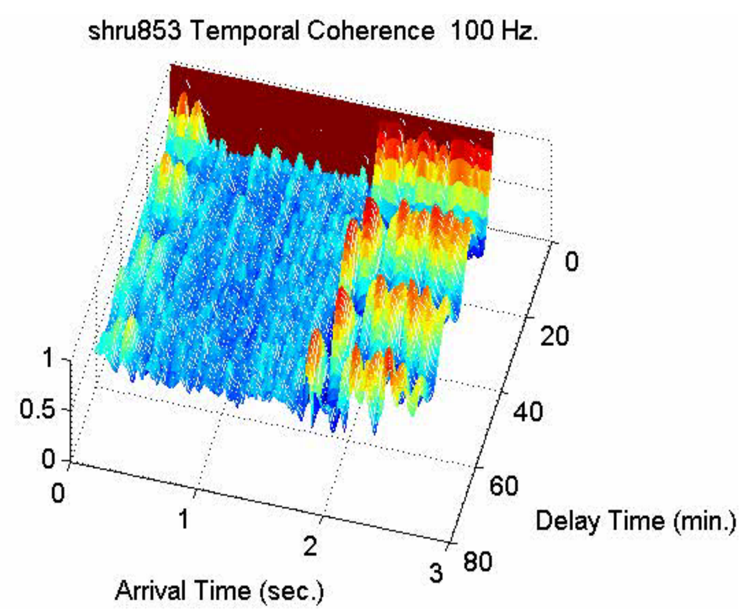


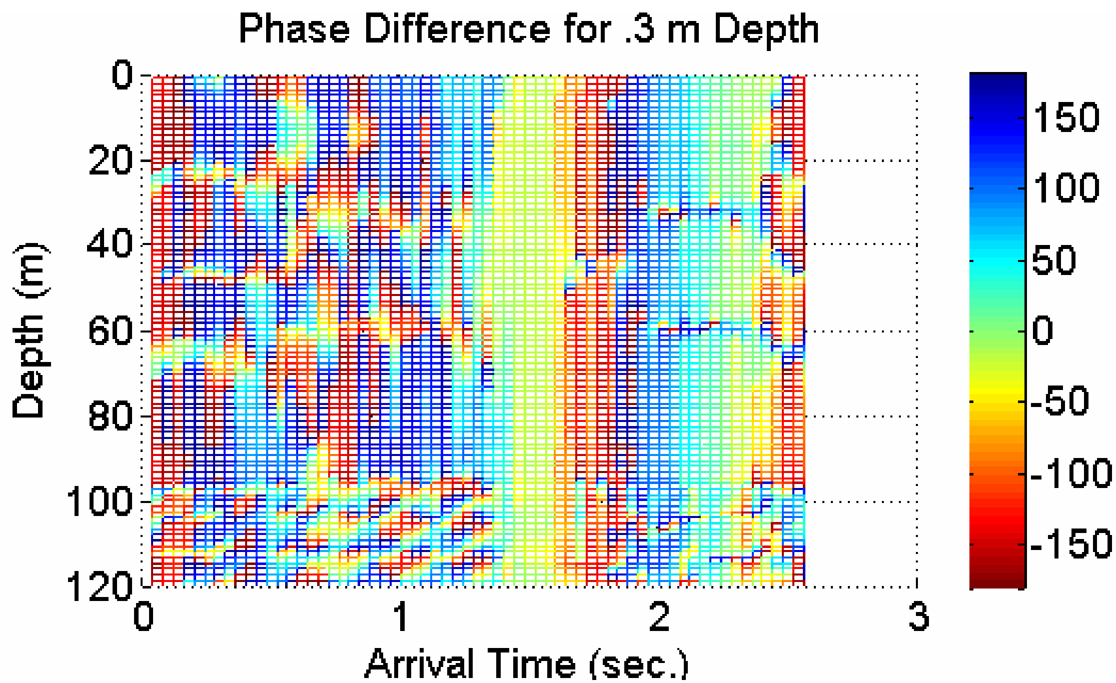



shru852 Temporal Coherence 100 Hz.Hr0200 7/29
Arrival Time (sec.)
Delay Time (mi

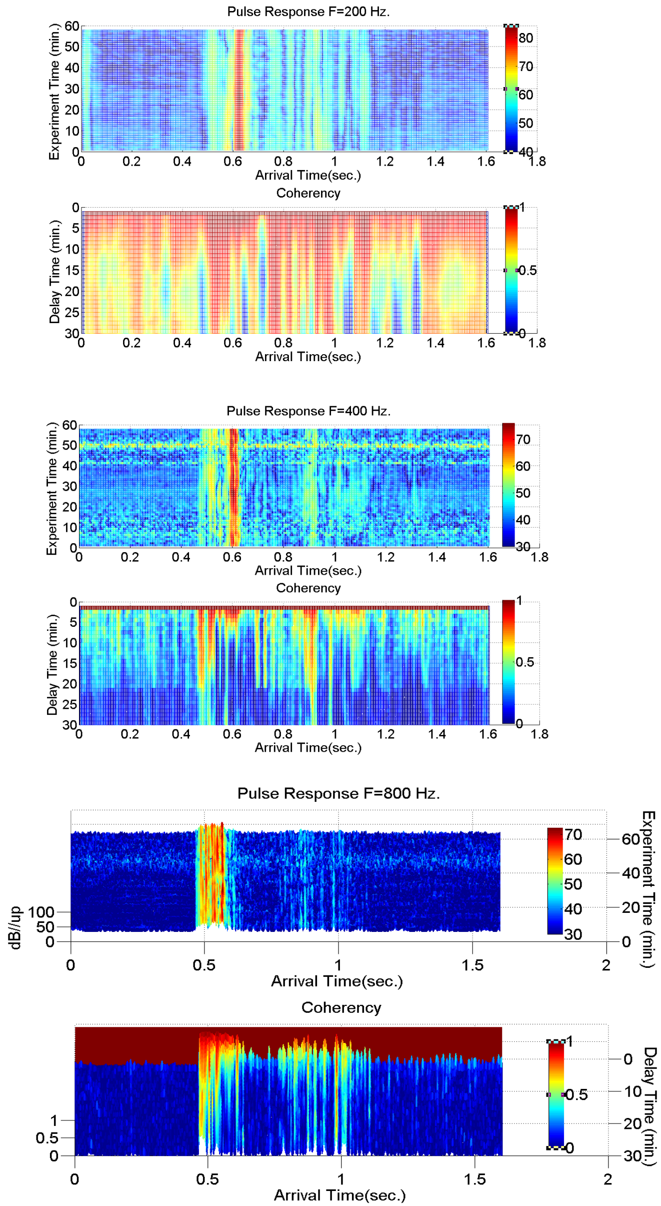

shru852 Temporal Coherence 100 Hz.Hr 1200 7/29
Arrival Time (sec.)
Delay Time (mi


shru252 Temporal Coherence 100 Hz.
Arrival Time (sec.)
Delay Time (min.)

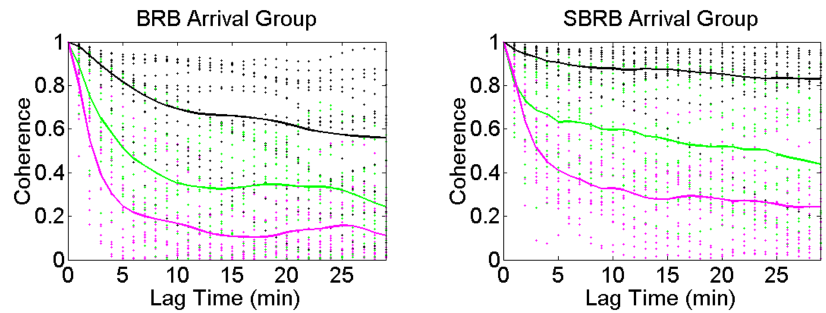

shru853 Temporal Coherence 100 Hz.
Arrival Time (sec.)
Delay Time (min.)


Phase Difference for .3 m Depth
Depth (m)
0
20
40
60
80
100
120
Arrival Time (sec.)
0
1
2
3
150
100
50
0
-50
-100
-150

Temporal Coherence



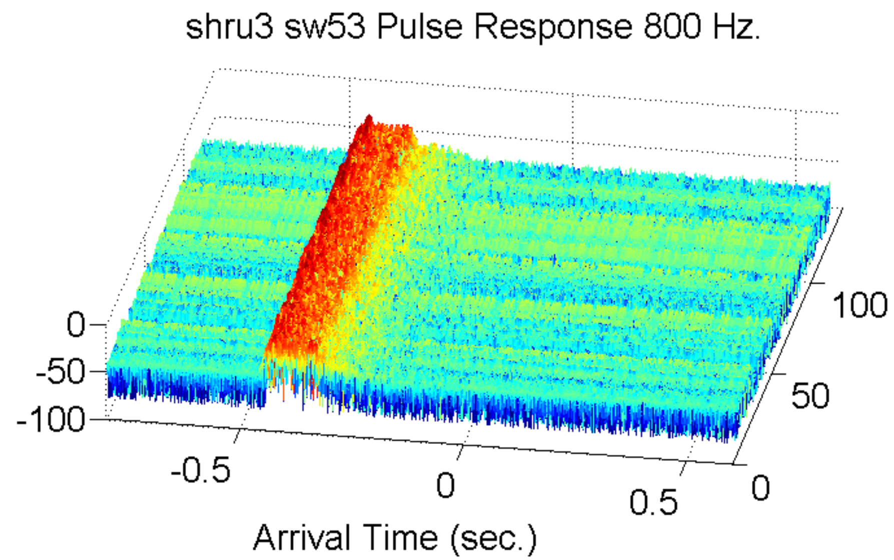
Temporal Coherence

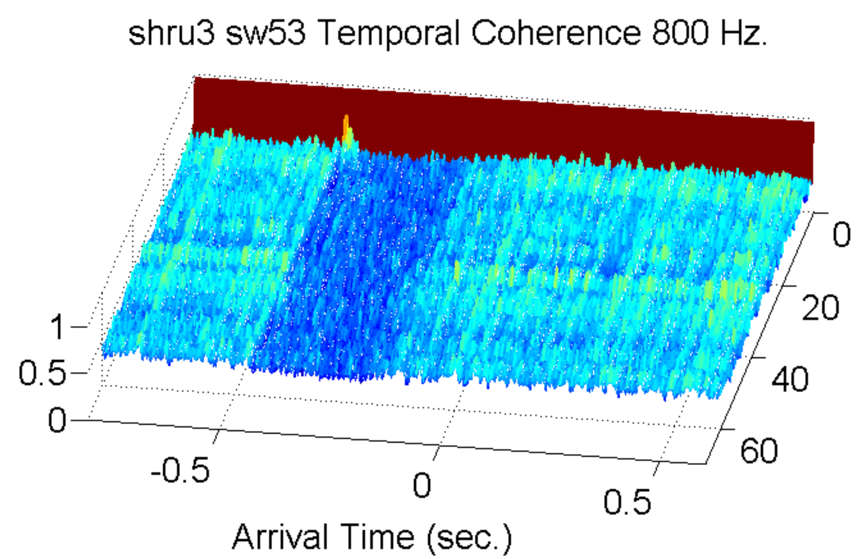


Coherence time (.75 level)

BRB Group			SBRB arrival		
800Hz. mean →	2.1	max → 6.5 minutes	800Hz. mean →	2.8	max → 6.5 minutes
400Hz.	3.4	12.0	400Hz.	4.2	>30
200	8.3	> 30	200	15.0	>> 30

800 Hz.


shru3 sw53 Pulse Response 800 Hz.
0
-50
-100
-0.5
0
0.5
100
50
0
Arrival Time (sec.)


shru3 sw53 Temporal Coherence 800 Hz.
1
0.5
0
-0.5
0
0.5
0
20
40
60
Arrival Time (sec.)

Temporal Coherence

Low Frequency < 100 Hz.

Bottom appears smooth.

No mode distortion from scattering

IW caused mode coupling is evident.

Mid – Frequencies 100 >, < 800 Hz.

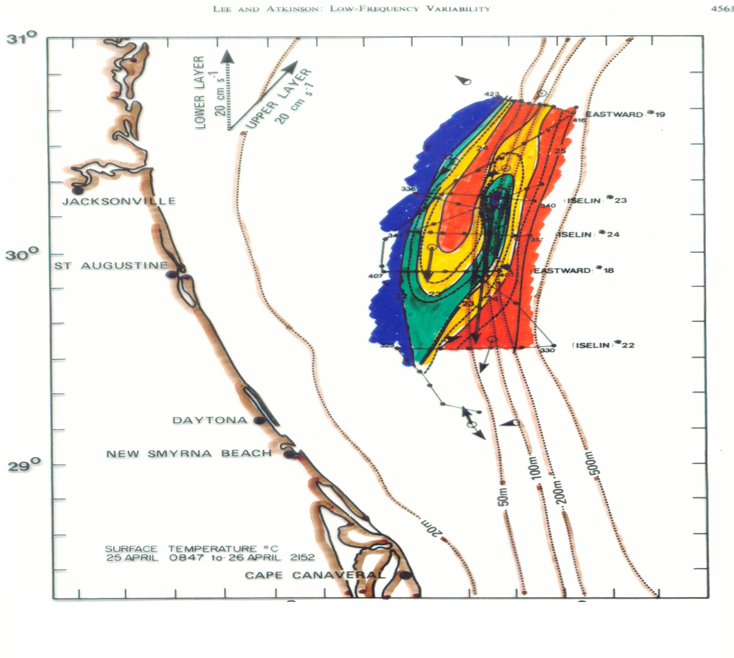
Bottom scattering become important.

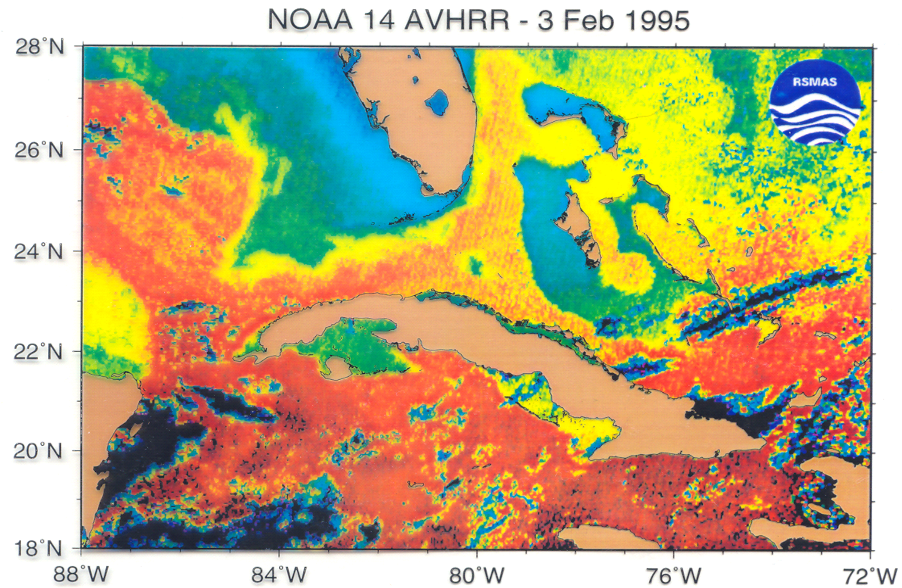
Coherence times decrease with frequency

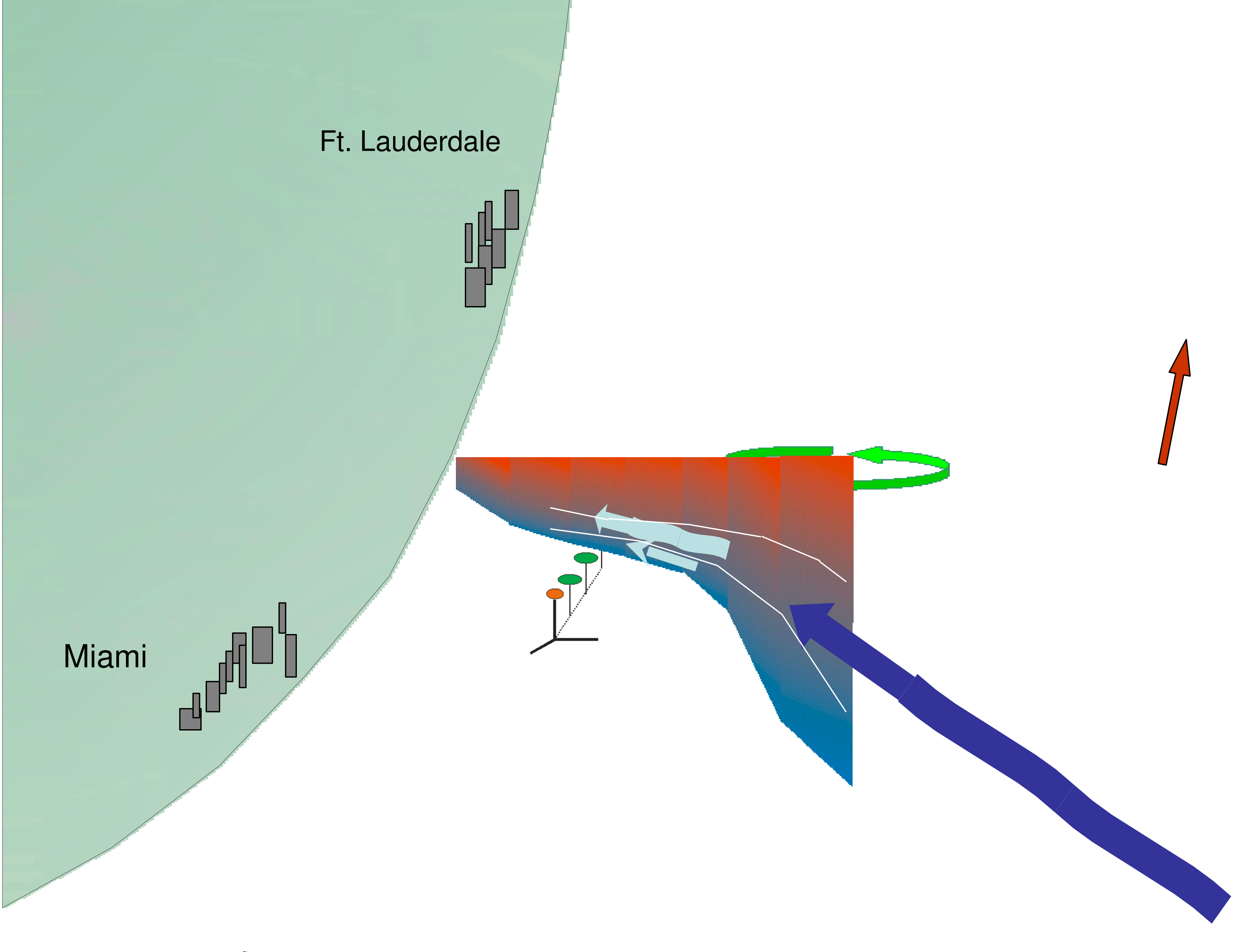
Coherence times decrease with increasing mode number

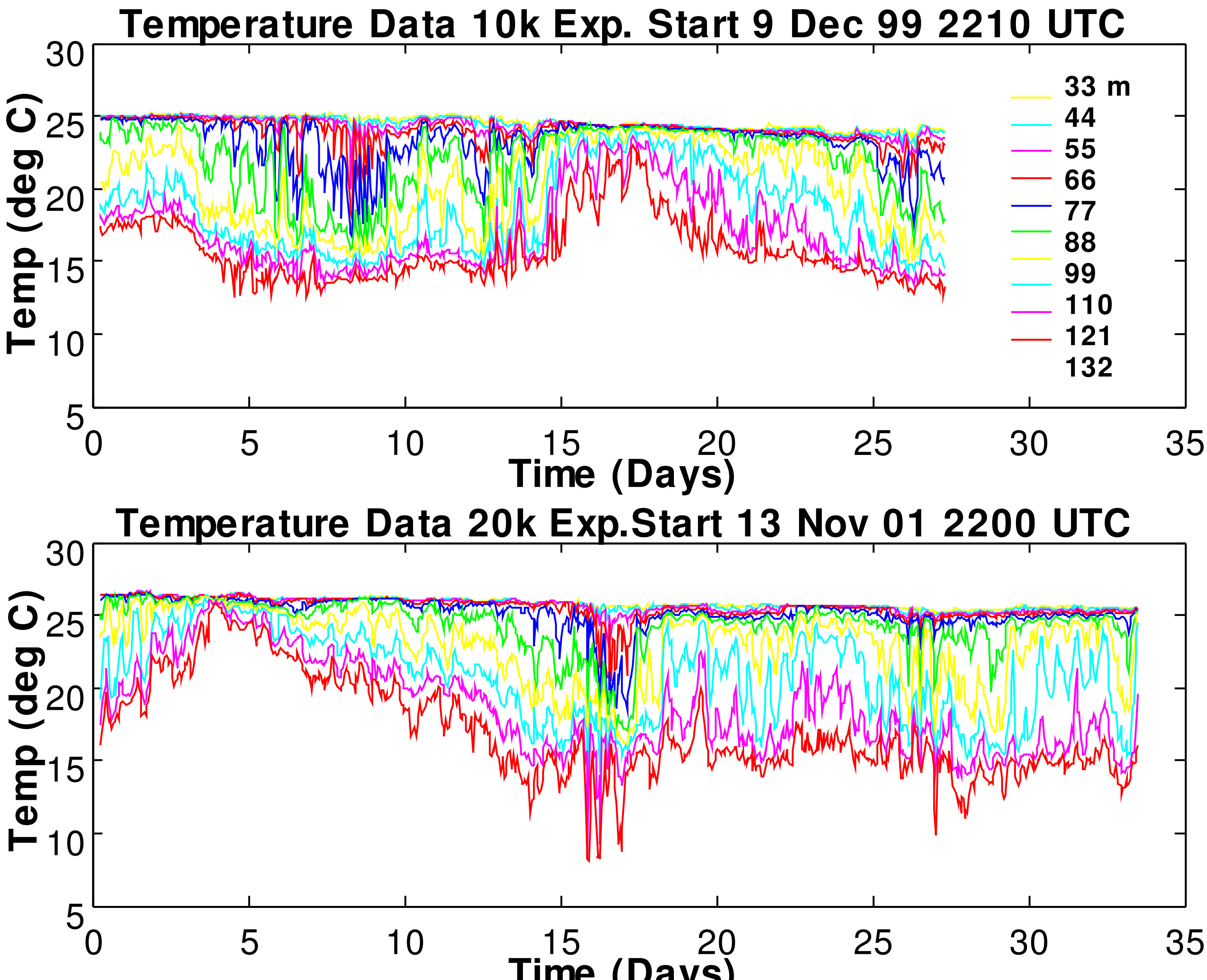
High frequency >1000 Hz.

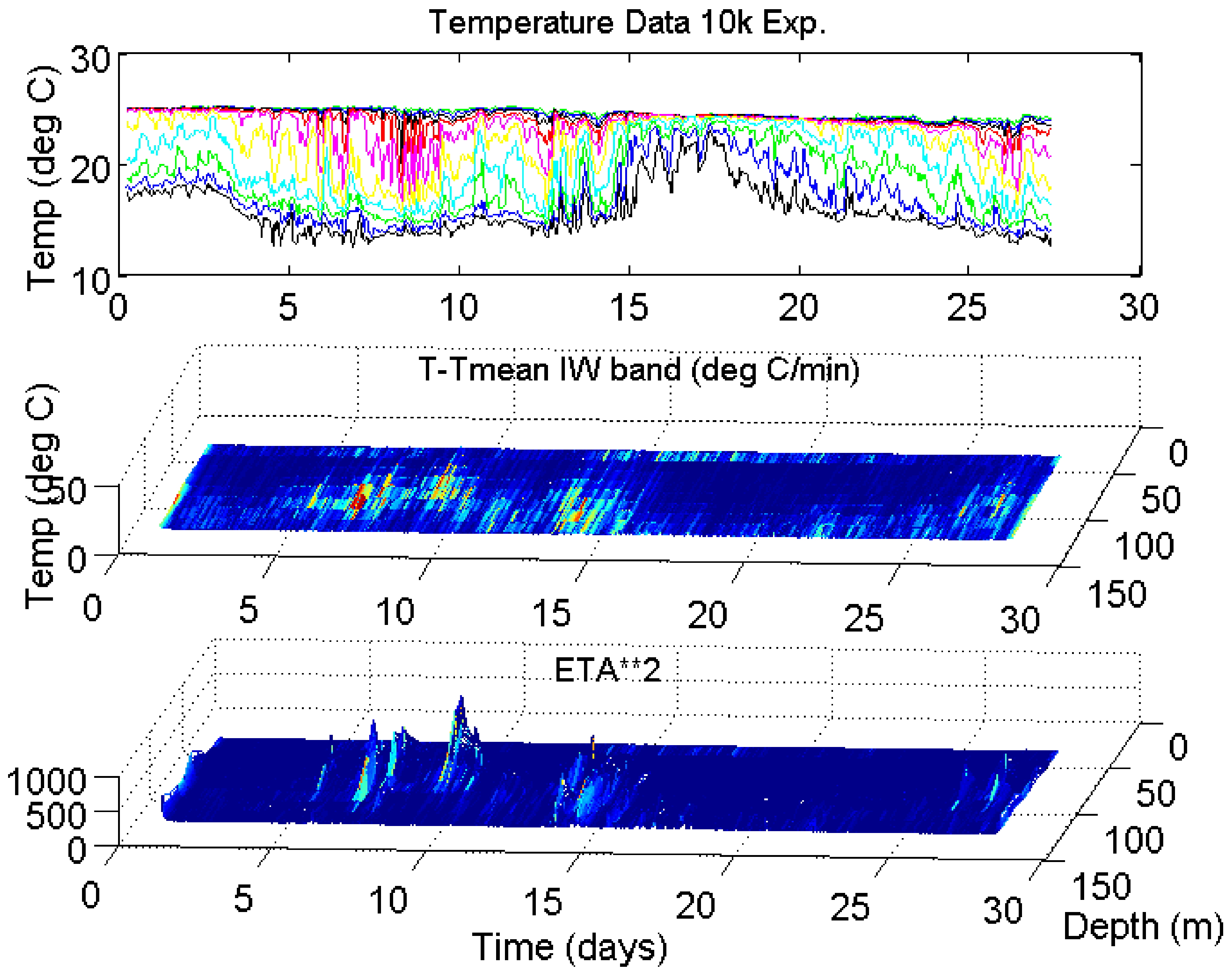
Signals are randomized by bottom scattering


LEE AND ATKINSON: LOW-FREQUENCY VARIABILITY
4561
31°
30°
29°
LOWER LAYER
20 cm s⁻¹
UPPER LAYER
20 cm s⁻¹
JACKSONVILLE
ST AUGUSTINE
DAYTONA
NEW SMYRNA BEACH
CAPE CANAVERAL
EASTWARD 19
ISELIN 23
ISELIN 24
EASTWARD 18
ISELIN 22
20m
50m
100m
200m
500m
SURFACE TEMPERATURE °C
25 APRIL 0847 to 26 APRIL 2152


NOAA 14 AVHRR - 3 Feb 1995
RSMAS
28°N
26°N
24°N
22°N
20°N
18°N
88°W
84°W
80°W
76°W
72°W


Ft. Lauderdale
Miami


Temperature Data 10k Exp. Start 9 Dec 99 2210 UTC
Temp (deg C)
Time (Days)
33 m
44
55
66
77
88
99
110
121
132
Temperature Data 20k Exp.Start 13 Nov 01 2200 UTC
Temp (deg C)
Time (Days)



Temperature Data 10k Exp.
Temp (deg C)
30
20
10
0
5
10
15
20
25
30
T-Tmean IW band (deg C/min)
Temp (deg C)
50
0
100
150
ETA**2
1000
500
Time (days)
Depth (m)

Florida Strait Propagation Experiments

Transmissions

M-Sequences

Hour	Frequency
1	100
2	200
3	400
4	800
5	1600
6	3200
7	100

repeat
*
*

28 days

Range

10km

20km

Reception

VLA
32 – Phones

Coherent Averaging
(1 min)

SHARP
Pulse compression

Pulse Responses
One per minute

Signal Processing of M-sequences:

- Synchronous sampling nxf, n = > 4.
- Coherent averaging for 1 minute.
- Sharp Pulse Compression (SPC) - Hadamard Transforms - a matched filter operation that yields the pulse response instead of the correlation of the pulse response.

Result:

- Gain = 10 log(MxL), =36dB @400 Hz.
- 2x Improvement in time resolution.
- Transparent to end user - no time leakage.
- Robust and well documented.

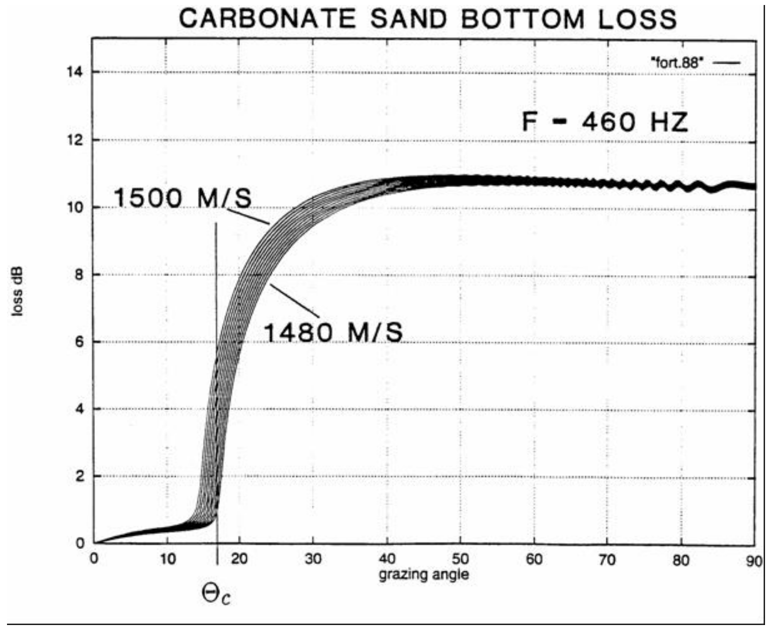
Propagation Modeling

Identifying modes and arrivals

Propagation Modeling

Propagation Models

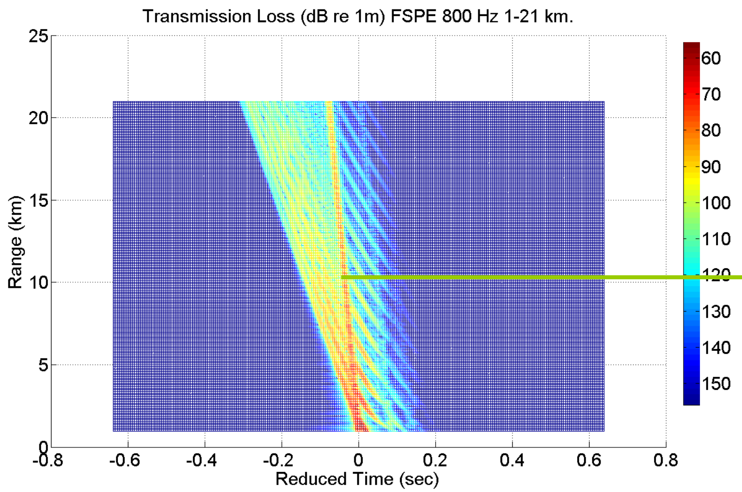
- PE
  - MMPE
- Normal Mode
  - PROSIM
  - SNAP
- SAFARI



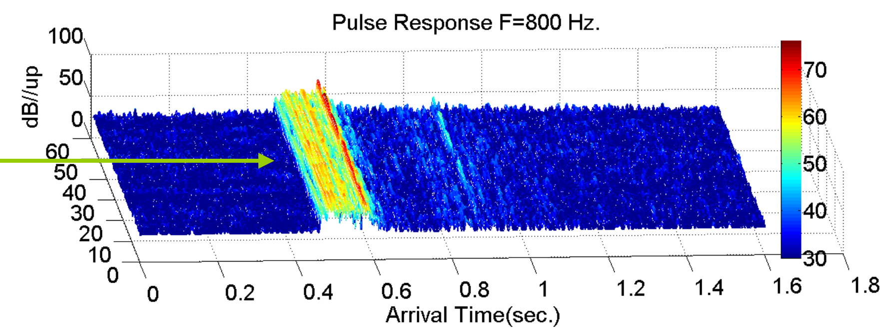
Bottom Models

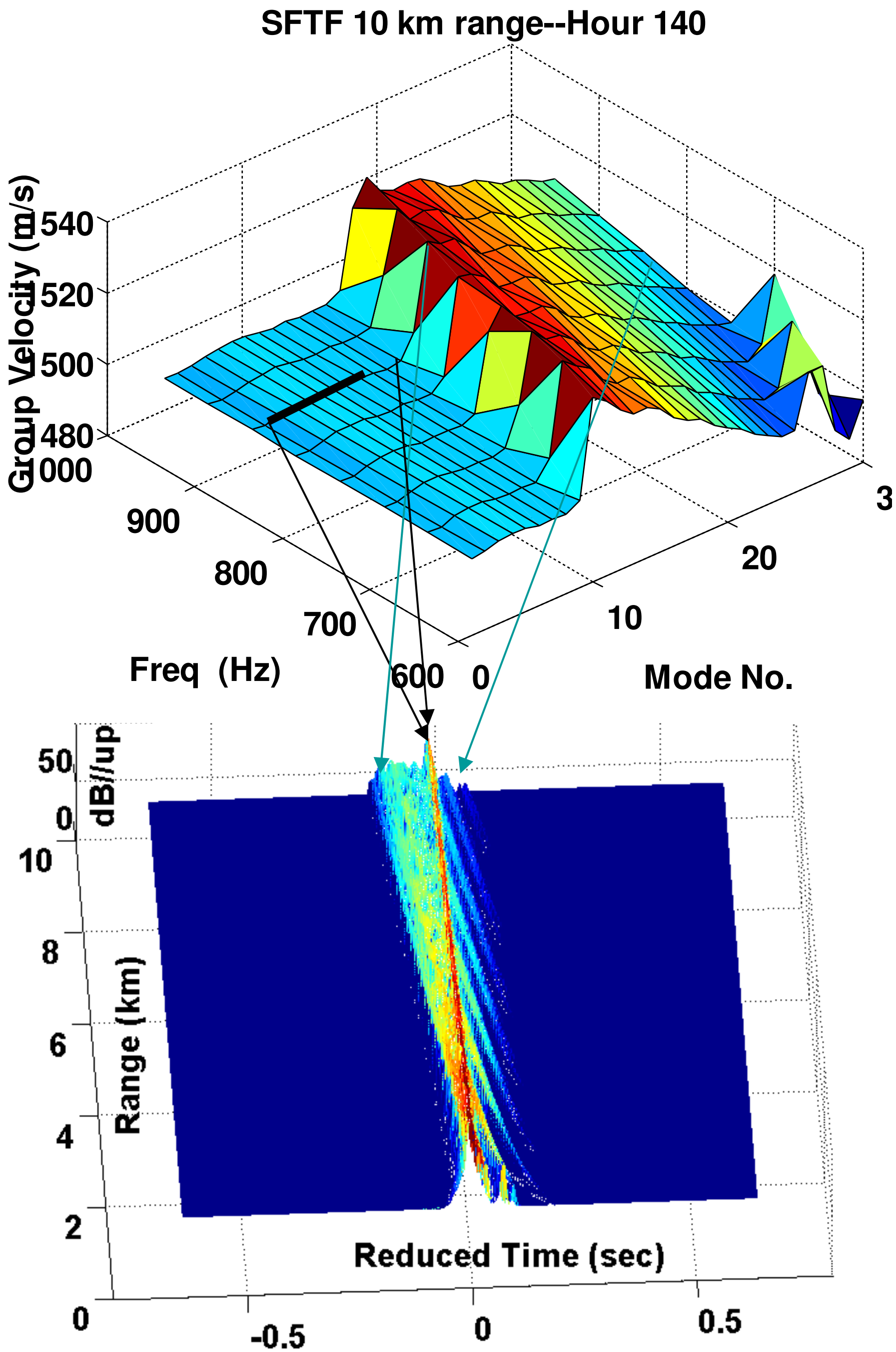
	Velocity (m/s)	Gradient (1/s)	Density	Loss (dB/km/Hz)	Shear (m/s)	Shear Loss (dB/km/Hz)
MONJO	1585	1.4	1.85	.30	300	3.3
MEASURED (cores)	1640	1.4	1.95	.30	300	6.3
CHAPMAN (inv)	1720	1.4	2.06	.60	300	6.3

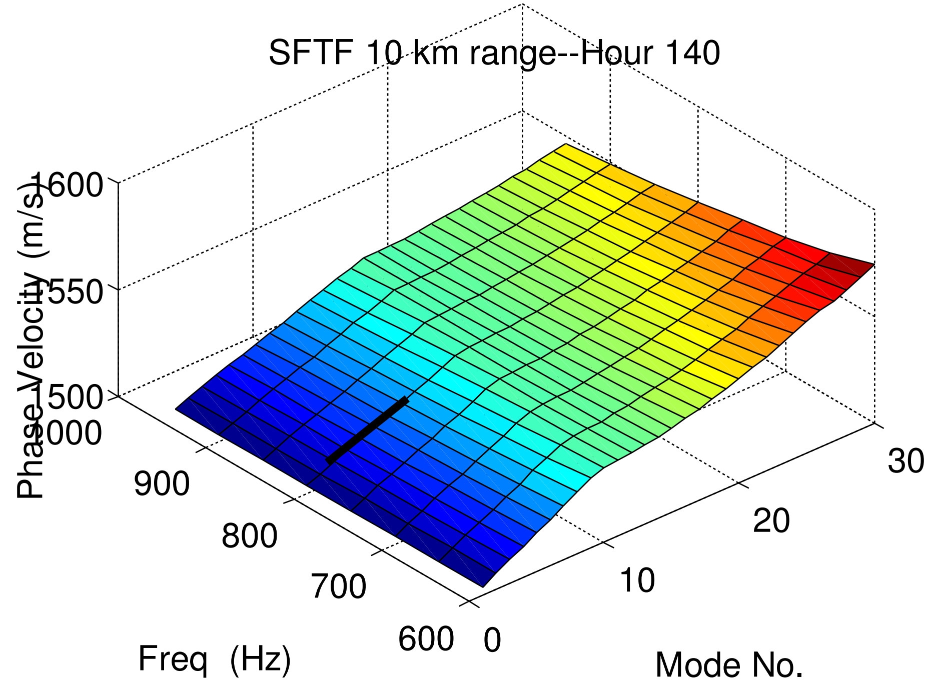
PE Prediction of 800 Hz. Pulse Response



Measured - 1 Hour







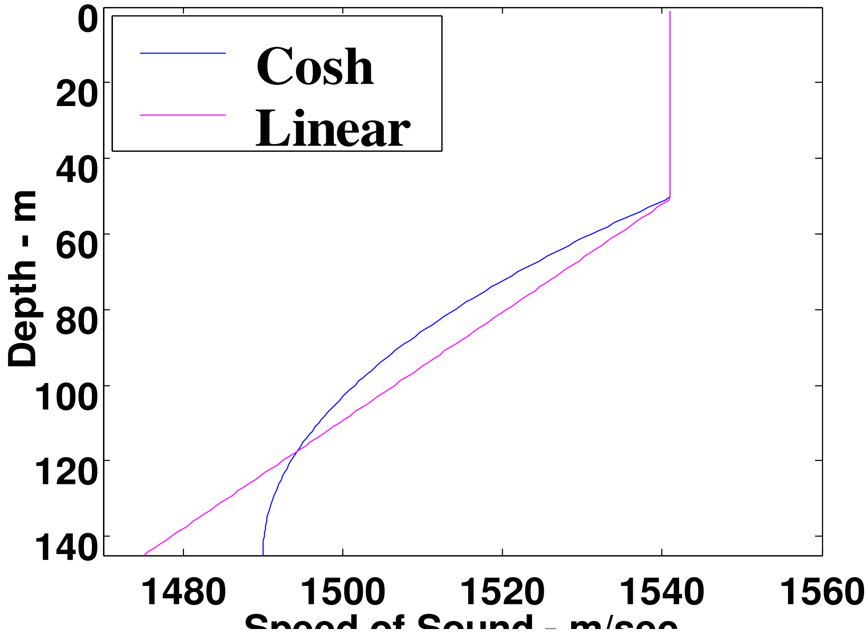
$$\beta^{-1} = -\frac{\Delta s_{g,mn}}{\Delta s_{p,mn}}$$

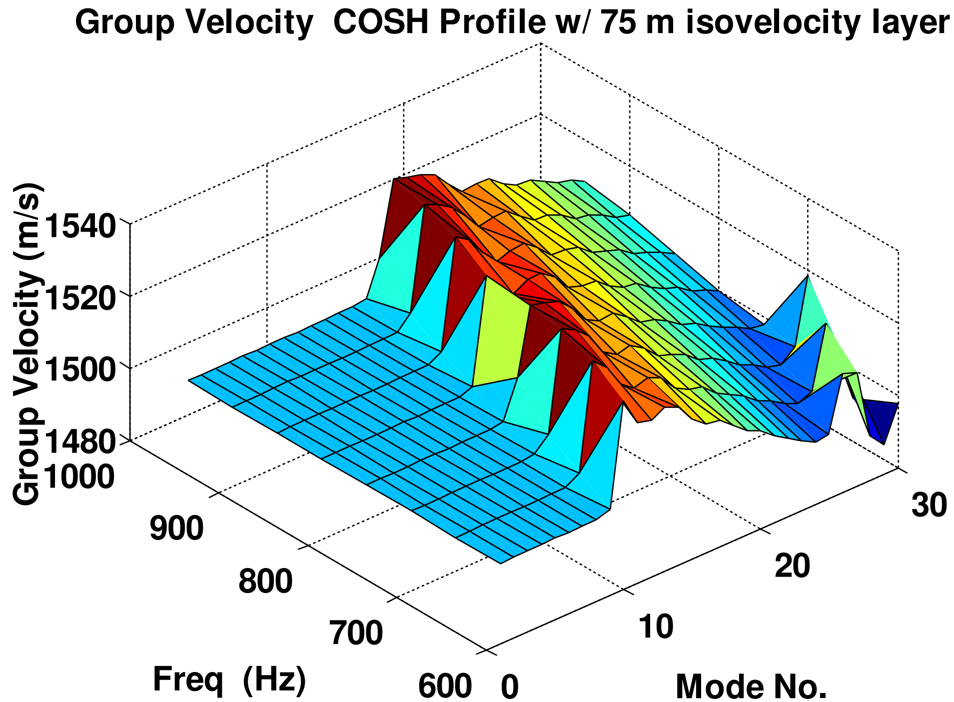
Effects of an eddy

3. **Produces a focusing sound speed profile for RBR Modes**
   - Deep source is amplified relative to shallow source
   - Near perfect multipath recombination
4. **Forms a duct for internal waves to propagate onto the shelf**
   - Orders of magnitude increase in IW energy
   - Corresponding increase is sound speed variability –degrades signal coherence

Mesoscale modulation of cross shelf exchange in the Straits of Florida
D. Olson, H. DeFerrari, N. Shay and W. Johns
Progress in Oceanography

Focused arrivals in shallow water propagation in the Straits of Florida
H. DeFerrari, N. Williams and H. Nguyen
ARLO 4, 106 (2003)

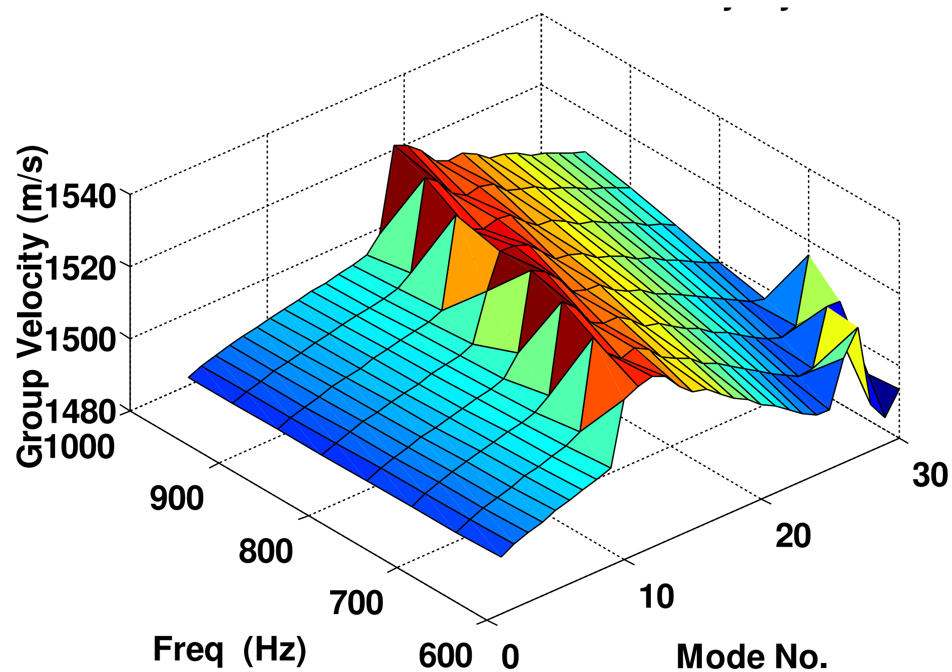




β^{-1}

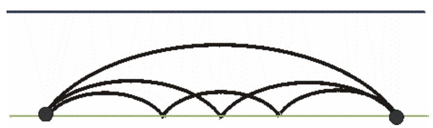
	SRBR	BRB
Linear	1.0	-.5
Cosh	1.2	0.0

$c_o \cosh(g(1\text{-}z/D))$

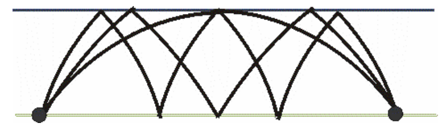


Ray/Mode Equivalence for β^{-1}

RBR



SRBR



$$\textbf{Travel Time} = \int \frac{ds}{c(s)} \propto \frac{PL}{\langle c \rangle}$$

Travel Time dependence on Launch Angle:

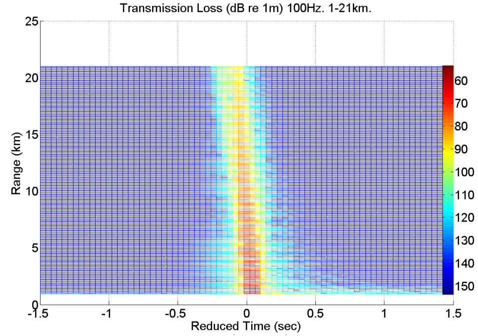
Linear Profile $\langle c \rangle$ **> PL,** $\beta^{-1} = -.5$ **PL >** $\langle c \rangle$, $\beta^{-1} = 1.0$

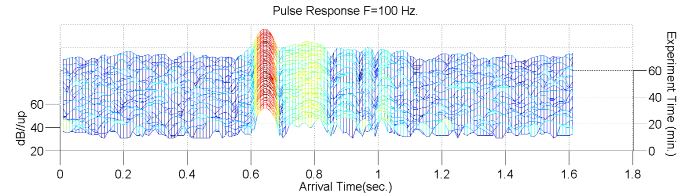
Cosh Profile $\langle c \rangle$ **= PL,** $\beta^{-1} = 0.0$ **PL >** $\langle c \rangle$, $\beta^{-1} = 1.2$

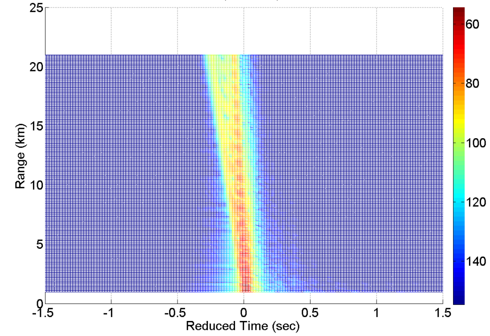
Conclusion: All BRB eigenrays have exact same travel time at each range.

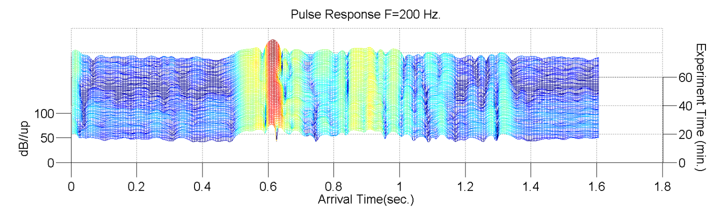
Frequency Dependence

Model < > Measurements





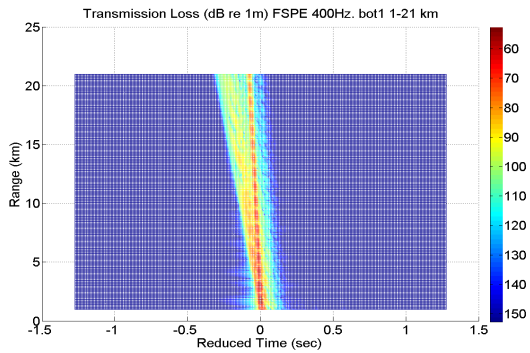


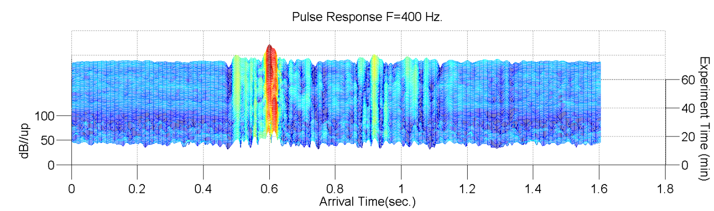


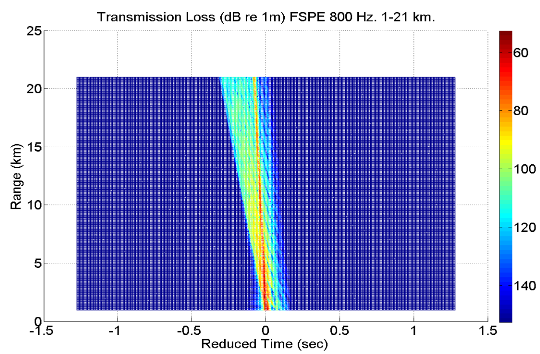
FSPE

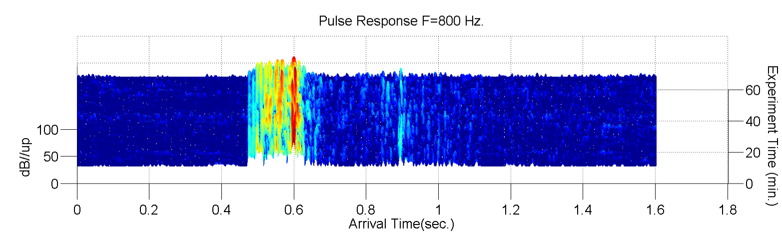
10 km range - f/100 RBR/SRBR modes

- **8 RBR and 8 SRBR @800Hz.**
- **4 RBR and 4 SRBR @400 Hz.**
- **>**
- **1 total @50 Hz.**

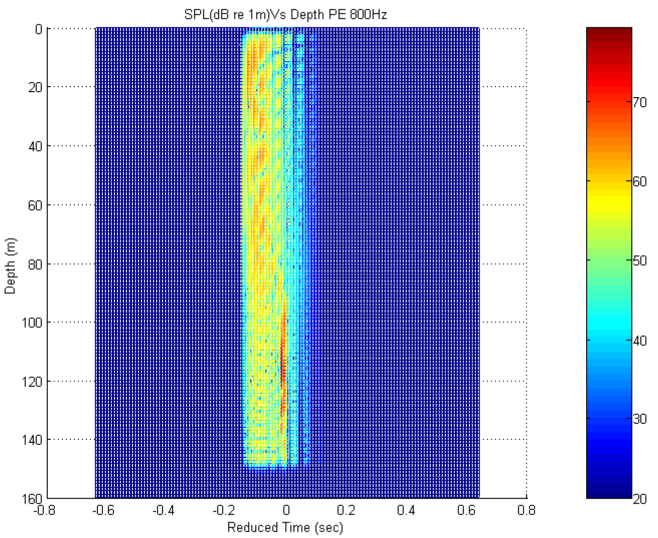




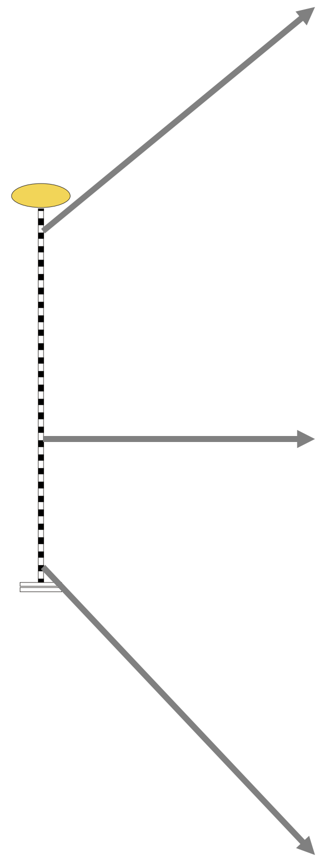


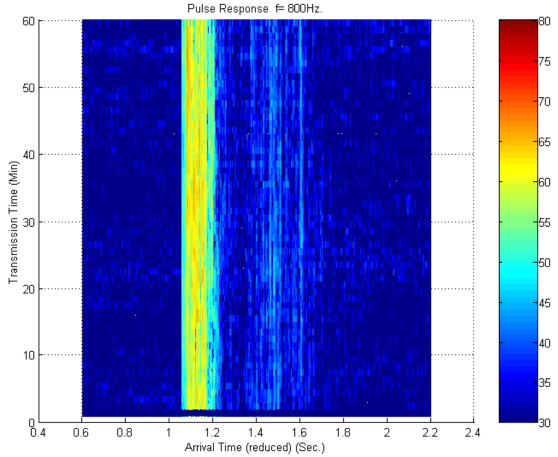


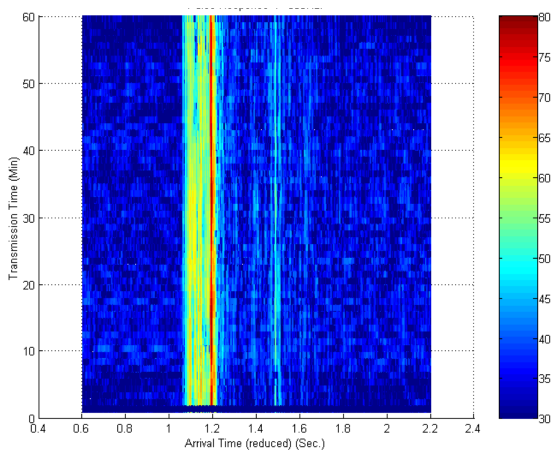
Depth Dependence

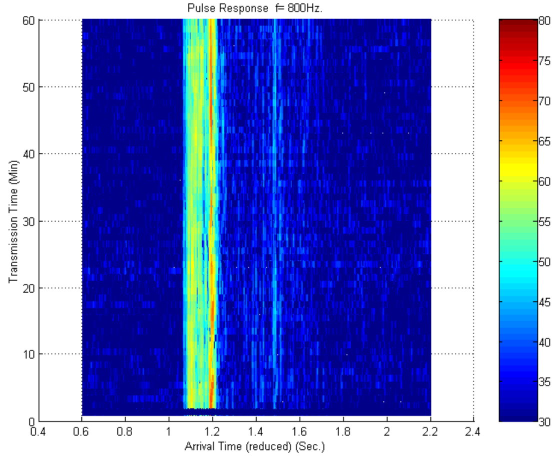


PE Prediction: Pulse Response vs. Depth





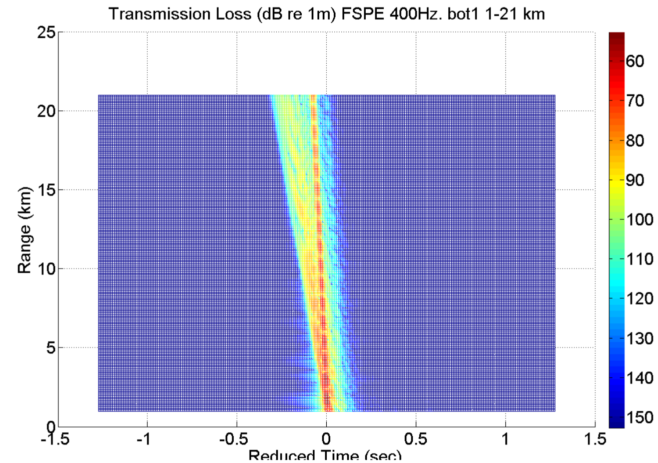




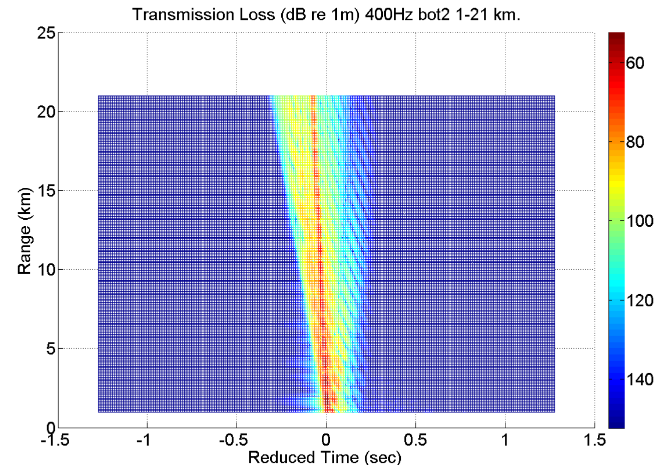
PE Predictions for 3 Bottom Models

Monjo Bottom

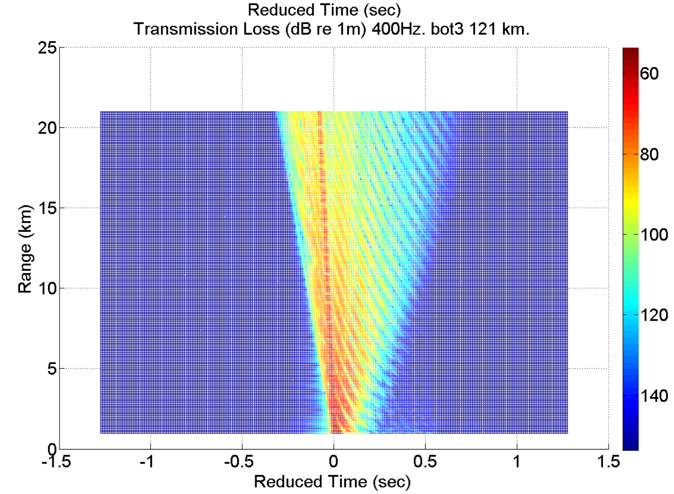
Bottom C = 1580 m/sec.



Bottom C = 1620 m/sec.



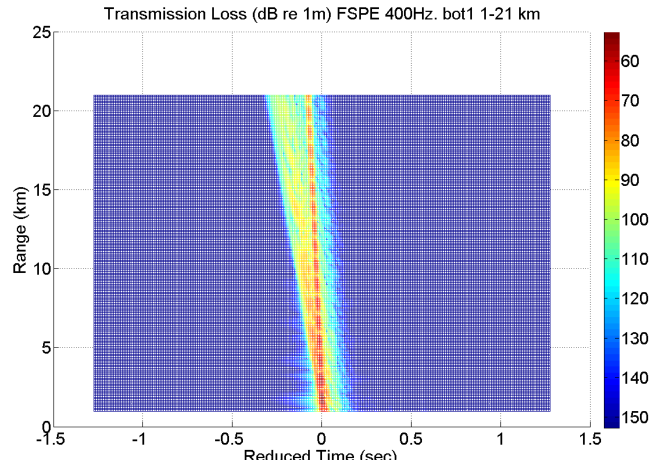
Bottom C = 1720 m/sec.



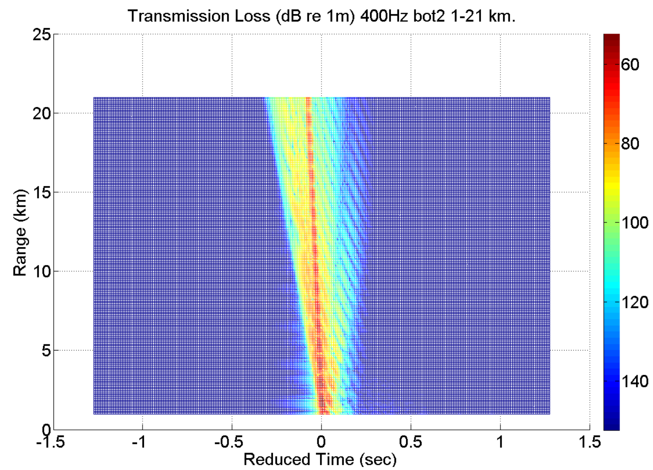
PE Predictions for 3 Bottom Models

Monjo Bottom

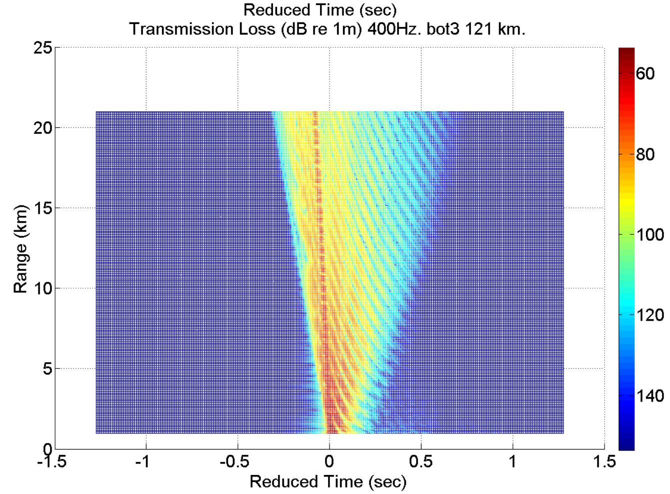
Bottom C = 1580 m/sec.



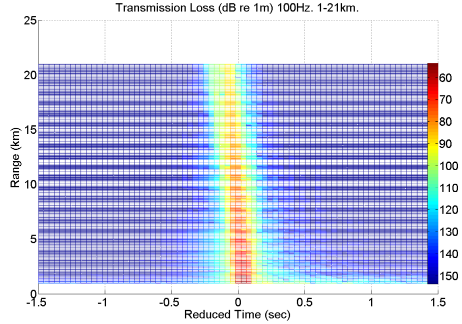
Bottom C = 1620 m/sec.



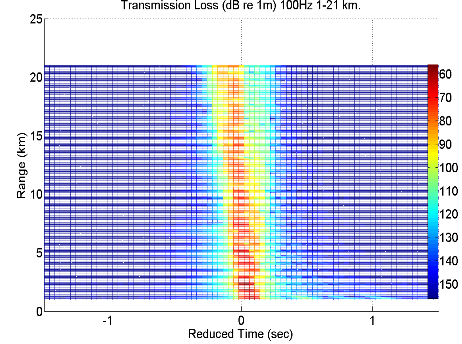
Bottom C = 1720 m/sec.

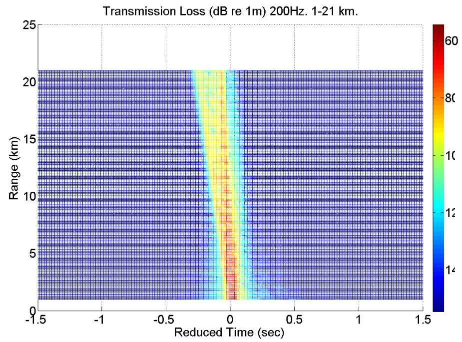


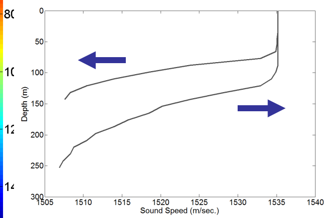
FSPE

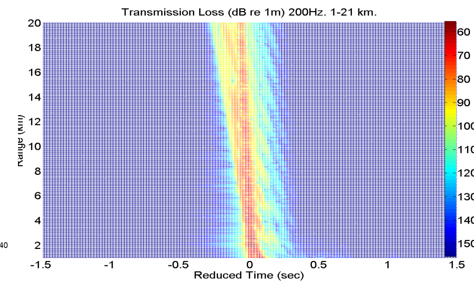

Transmission Loss (dB re 1m) 100Hz. 1-21km.
Range (km)
Reduced Time (sec)

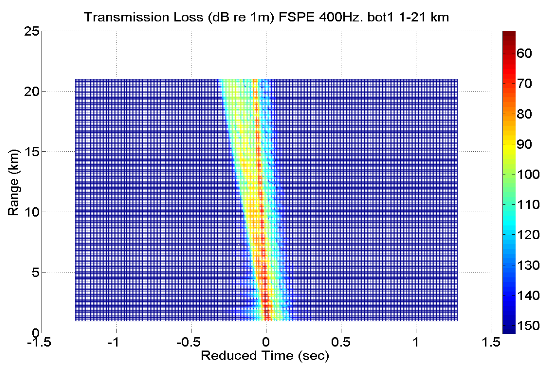
AO

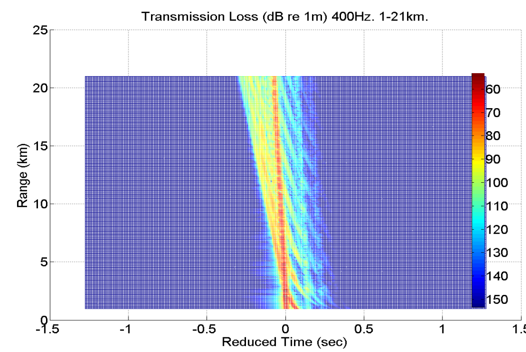

Transmission Loss (dB re 1m) 100Hz 1-21 km.
Range (km)
Reduced Time (sec)

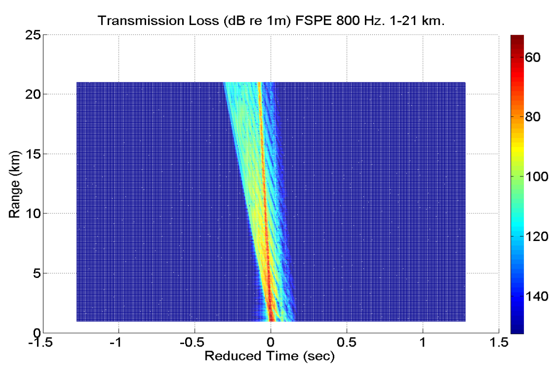

Transmission Loss (dB re 1m) 200Hz. 1-21 km.
Range (km)
Reduced Time (sec)

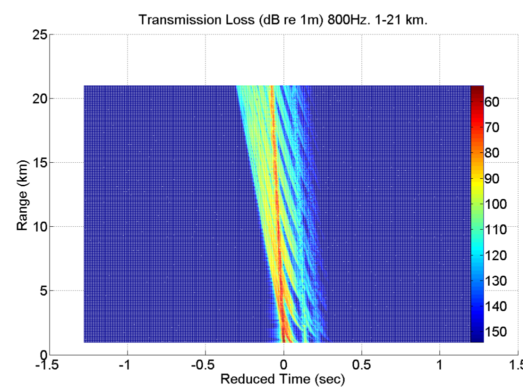

Depth (m)
Sound Speed (m/sec.)


Transmission Loss (dB re 1m) 200Hz. 1-21 km.
Reduced Time (sec)


Transmission Loss (dB re 1m) FSPE 400Hz. bot1 1-21 km
Range (km)
Reduced Time (sec)


Transmission Loss (dB re 1m) 400Hz. 1-21km.
Range (km)
Reduced Time (sec)

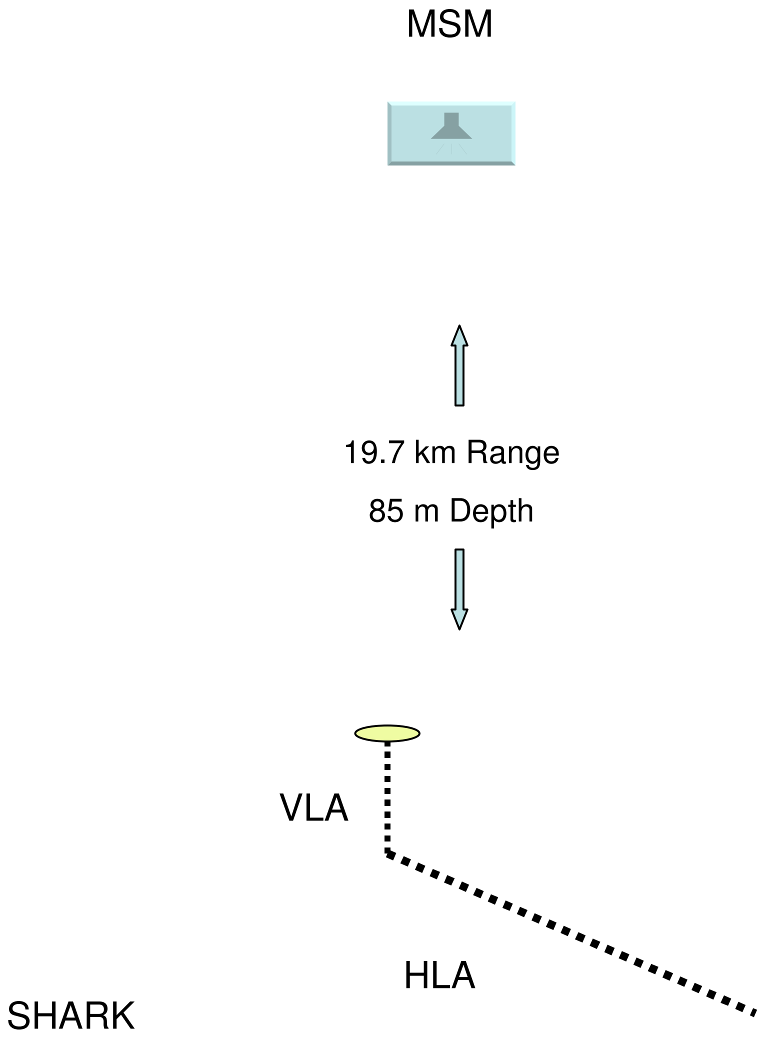

Transmission Loss (dB re 1m) FSPE 800 Hz. 1-21 km.
Range (km)
Reduced Time (sec)


Transmission Loss (dB re 1m) 800Hz. 1-21 km.
Range (km)
Reduced Time (sec)

AO Predictions:

2. Propagation by RBR and SRBR modes/rays. AO interested in SRBR as noise carrying paths.
3. Summer SS profile will narrow the arrival time spread of SRBR's
4. Total number of observable SRBR modes - approx = f/100. e.g. 4 @ 400 Hz. Only 1 mode for frequencies below 100 Hz.
5. Strong downward C(z) gradients and absorbent bottom will result in very large TL for SRBR paths - difficult to measure at long ranges > 30km!
6. Temporal coherence times = >10 min →1 hour+ for lower frequencies with SRBR 50% longer than RBR.
7. Horizontal coherence (radial, bottomed HLA) = > 100wavelengths. e.g. 1500m @100HZ.
8. Propagation model predictions match FSPE measurements best with slower 'Monjo' bottom model than with observed fast "Chapman" bottom. Geo-acoustic reasons unknown.
9. Many low-loss out-of-plane arrivals observed that possibly obscure the detection of low-level late SRBR arrivals. A potential practical problem for noise canceling algorithms.
10. AO measurements results may not differ much from those at FSPE site, (a modeling conclusion!)

SW06 Experiments – Mid-Atlantic Bight



MSM

M-Sequences

Center freq.	Band
4 Hz.	25
200	50
400	100
800	200
1600	400

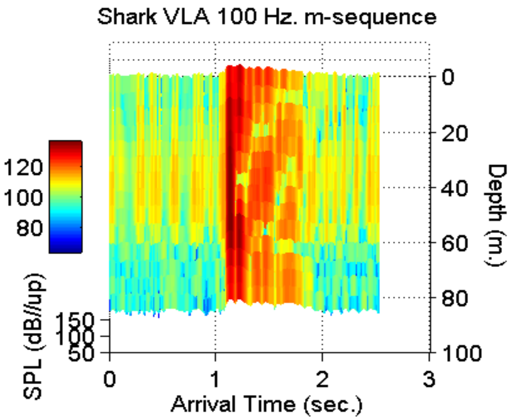
VLA 16 phones

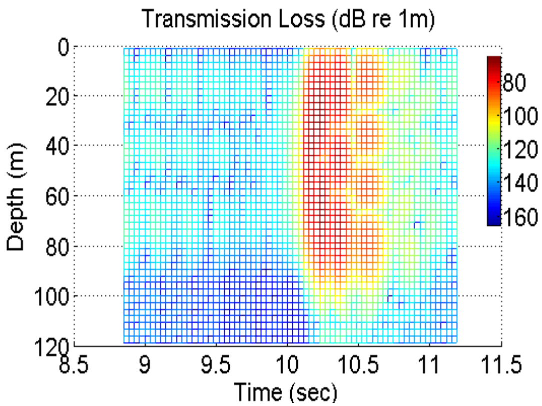
HLA 32 phones 468 m (15 m spacing)

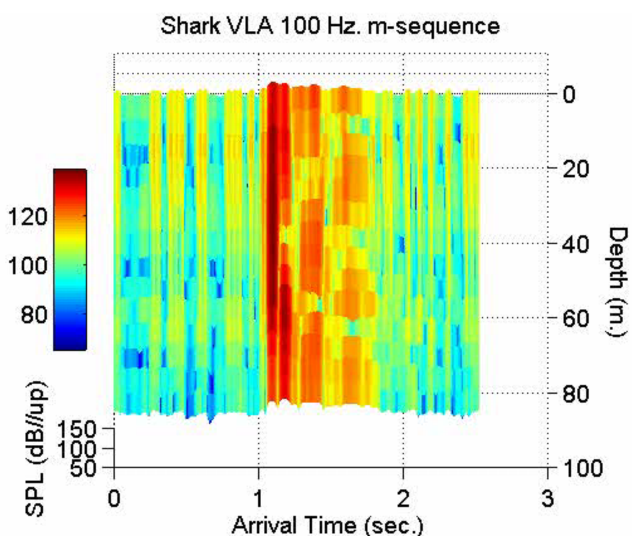
SW06 Modes and Arrivals

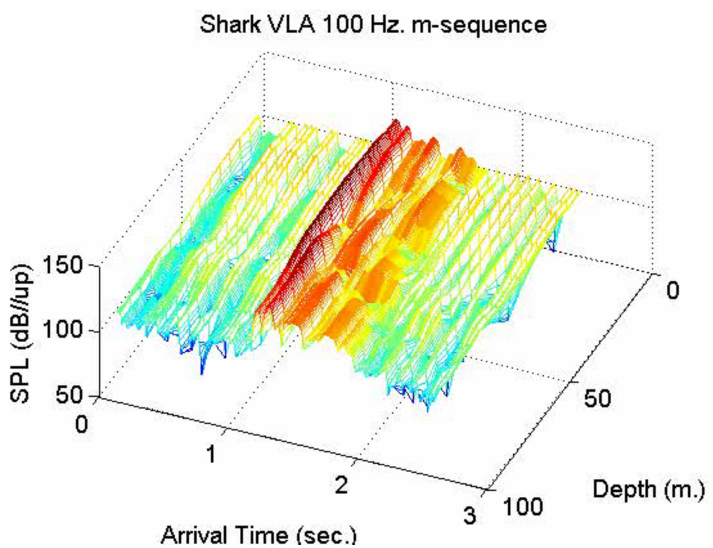
Observed

Modeled



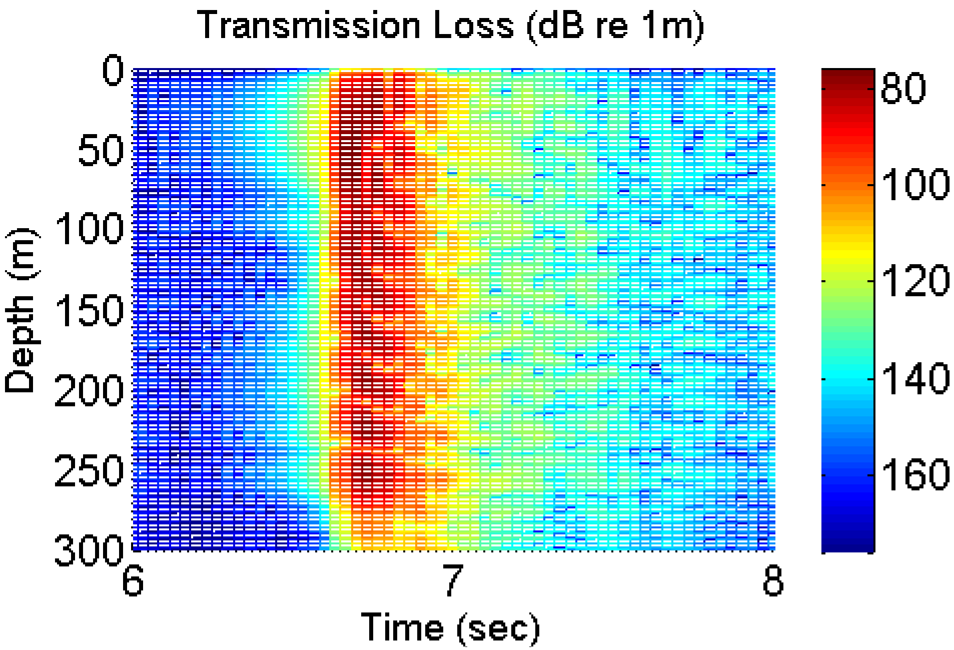






PE Prediction for AO

100 Hz. 25 Hz band 10 km.



Temporal Coherence

Signal Amplitude Data

t $\longrightarrow$ $p(t)$

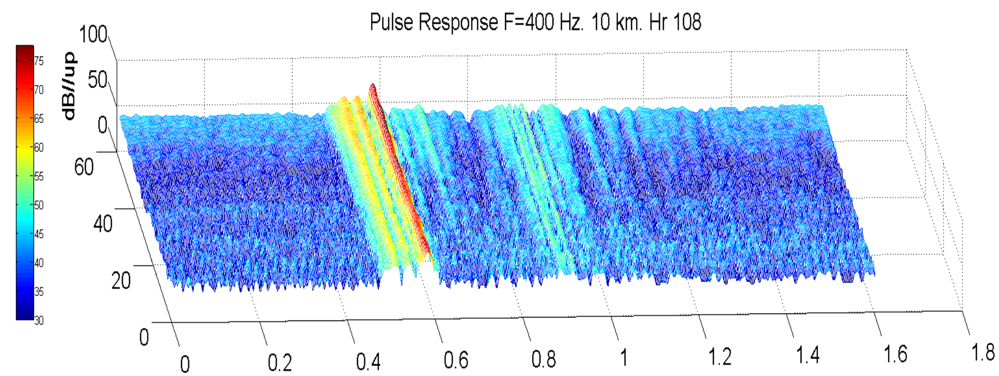
τ $\downarrow$

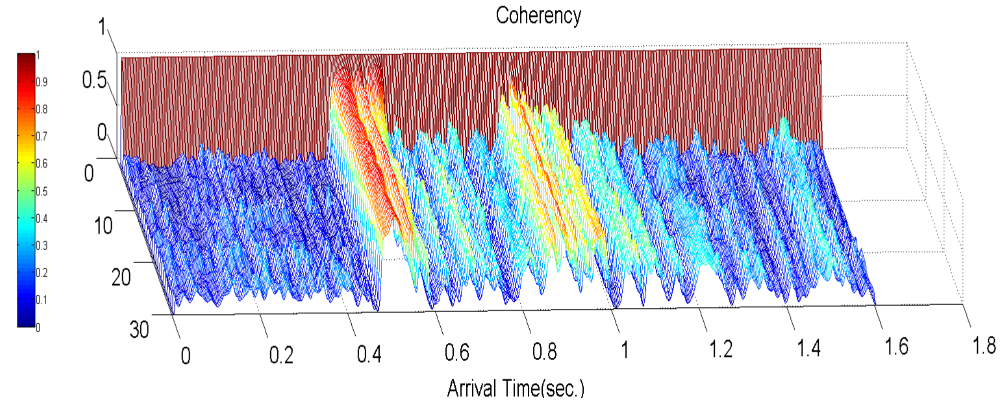
....1
....2
.... $p(t+\tau)$ 3
....
....
....
....
....
.... 240

$\Downarrow$

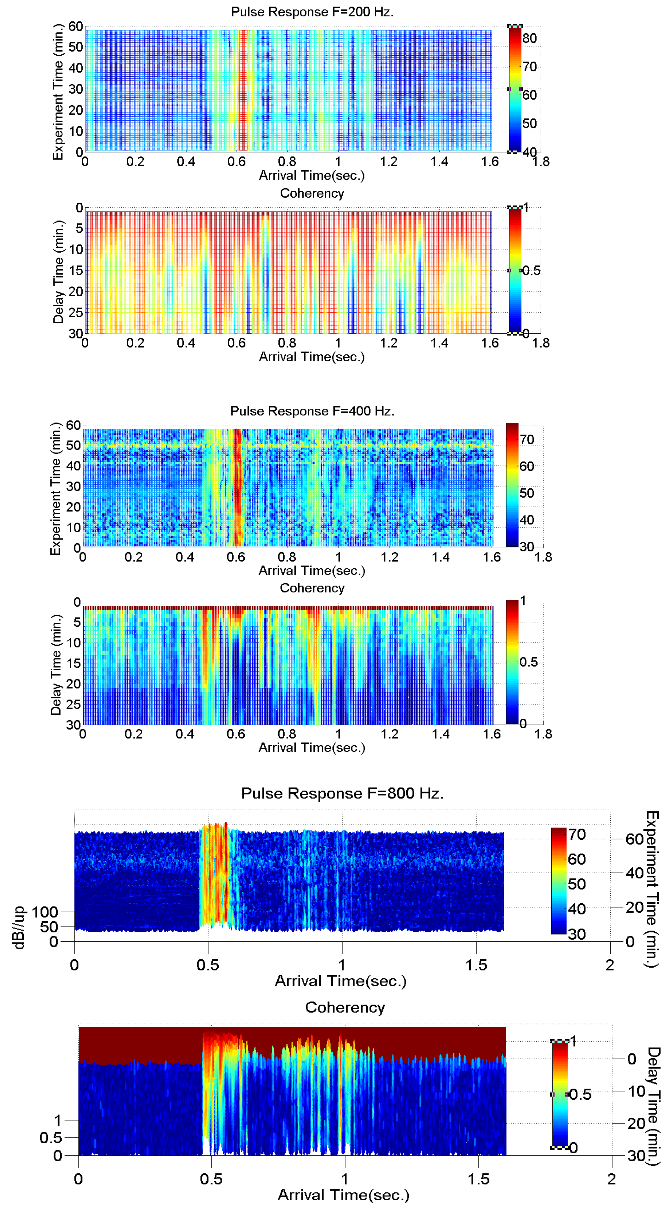
$$COH(t,\tau) = \frac{\left\langle \left(p(t) * p(t+\tau) \right)^2 \right\rangle_{\Delta t, \Delta T}}{\left\langle p(t)^2 \right\rangle_{\Delta t, \Delta T} \left\langle p(t+\tau)^2 \right\rangle_{\Delta t, \Delta T}}$$

$\Rightarrow$

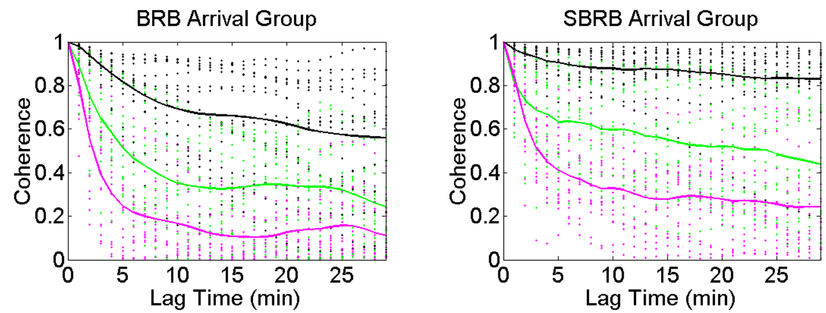




Temporal Coherence

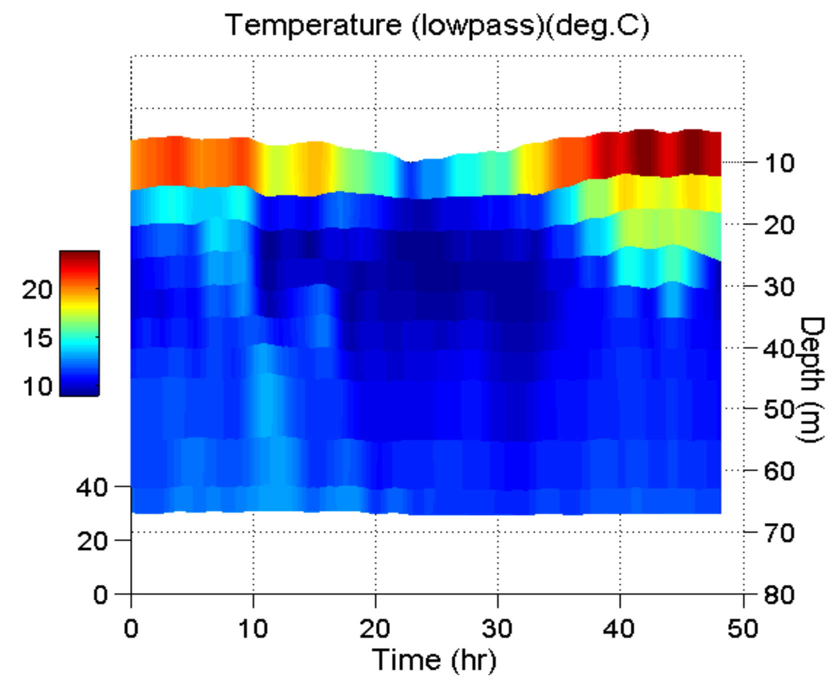


Temporal Coherence

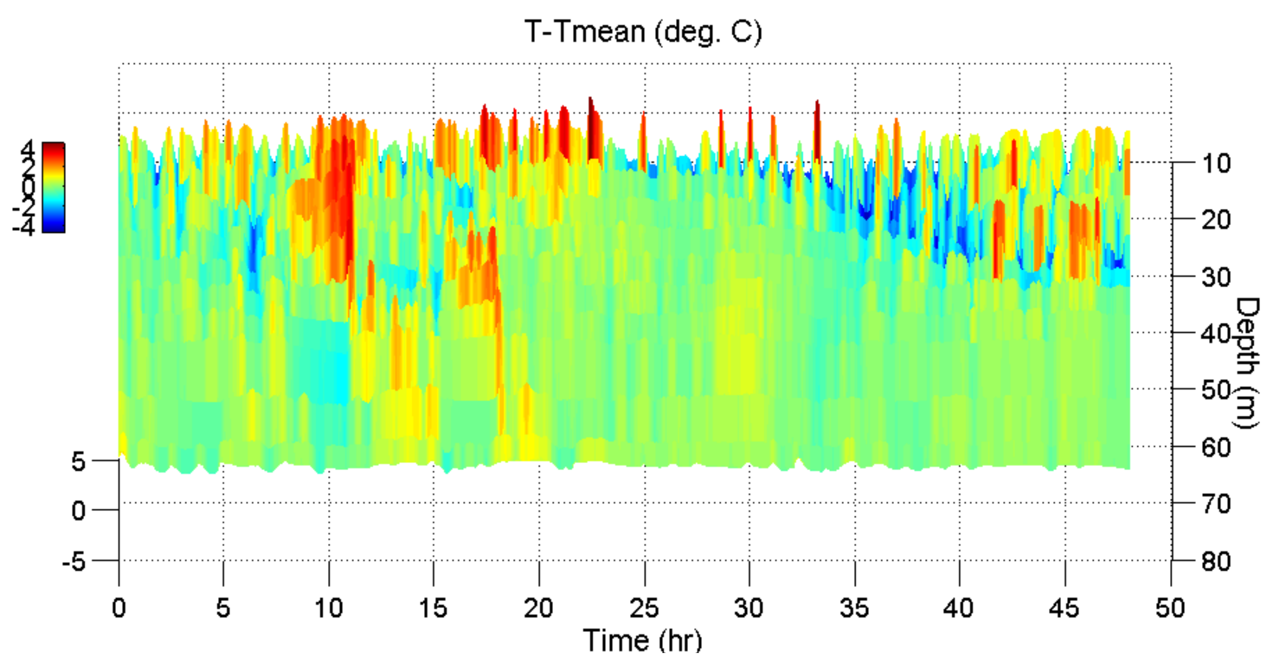


Coherence time (.75 level)

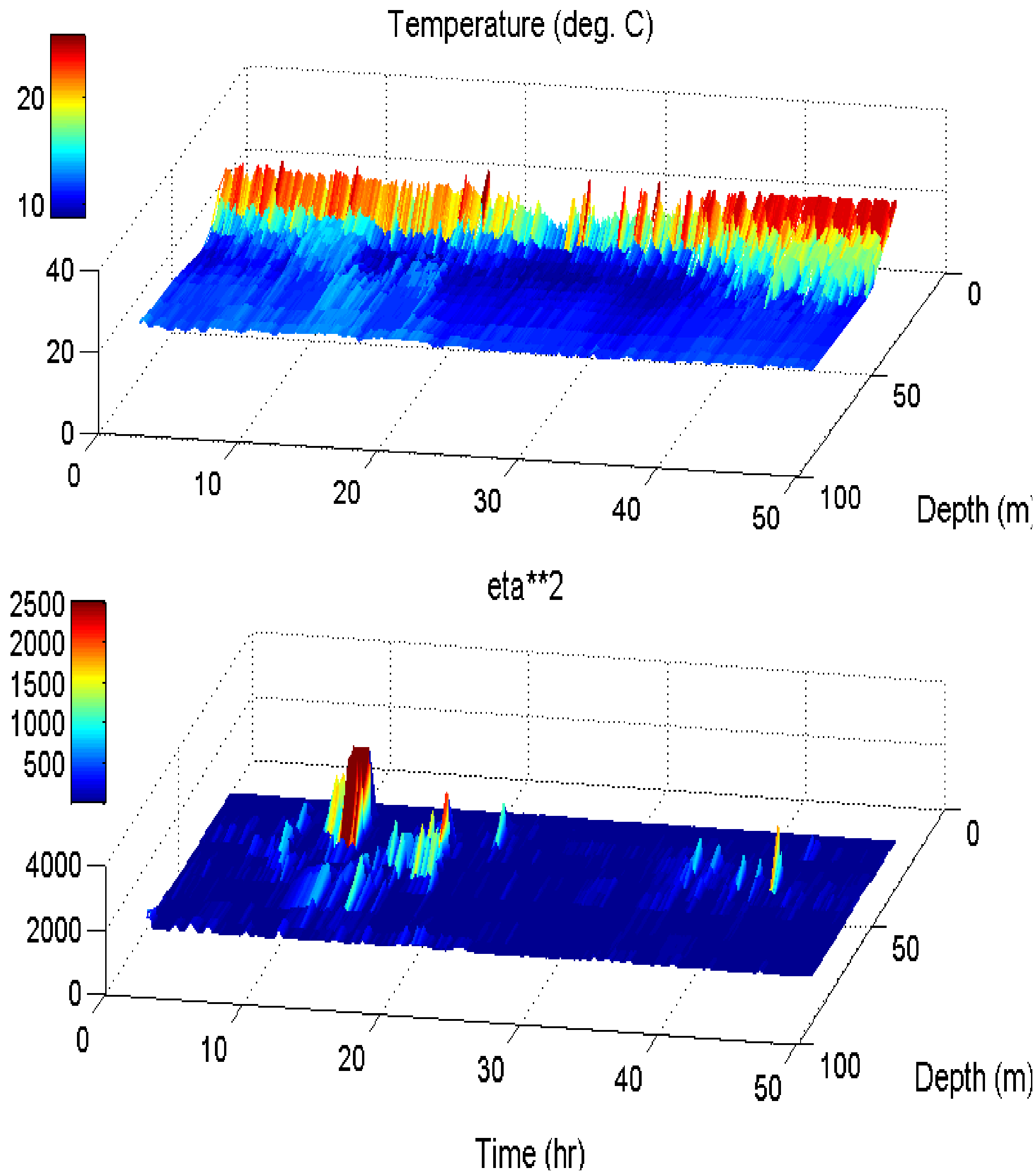
BRB Group			SBRB arrival		
800Hz. mean →	2.1	max → 6.5 minutes	800Hz. mean →	2.8	max → 6.5 minutes
400Hz.	3.4	12.0	400Hz.	4.2	>30
200	8.3	> 30	200	15.0	>> 30

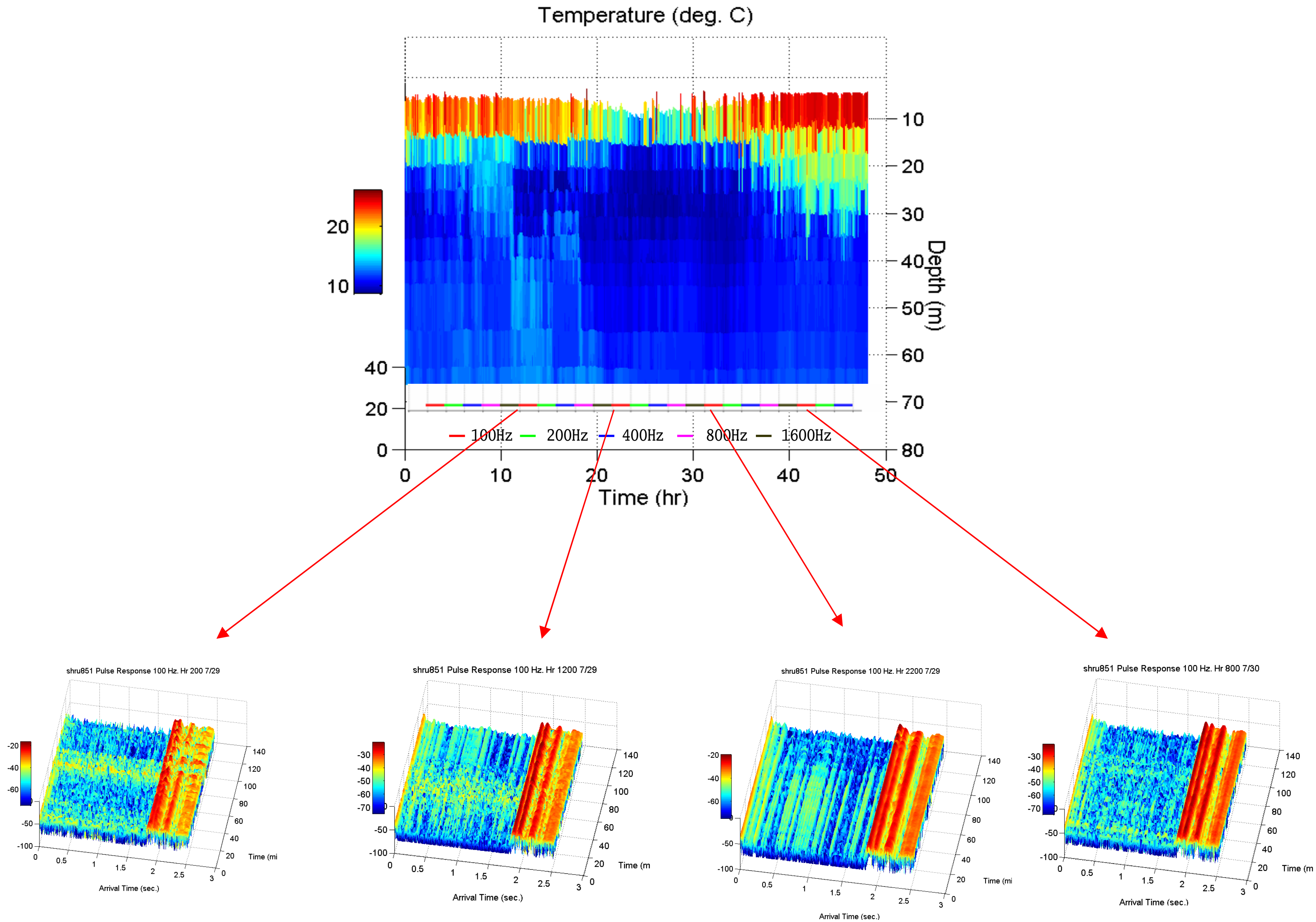


Temperature (lowpass)(deg.C)
20
15
10
40
20
0
0
10
20
30
40
50
Time (hr)
10
20
30
40
50
60
70
80
Depth (m)

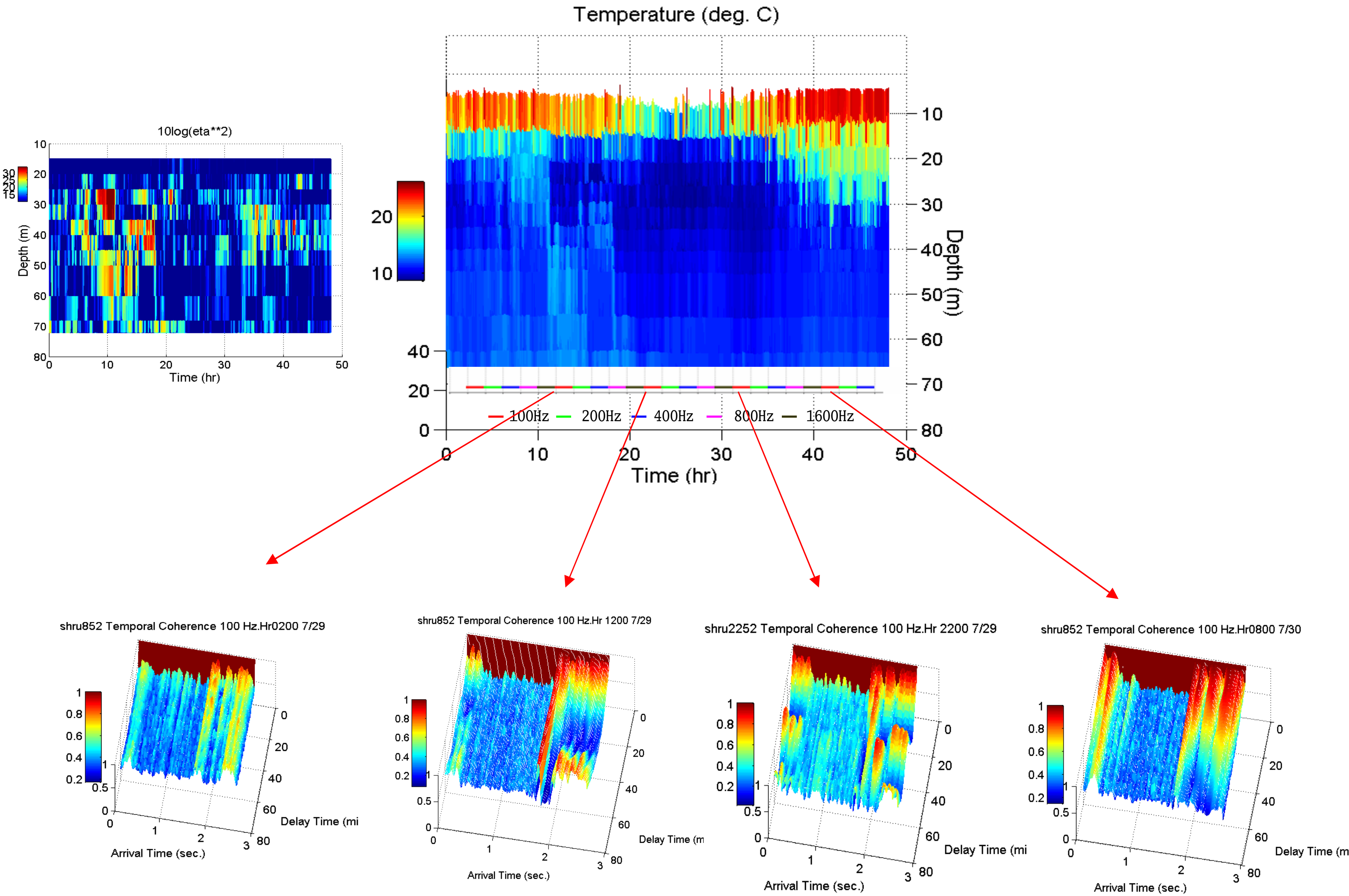


T-Tmean (deg. C)
4
2
0
-2
-4
5
0
-5
0
5
10
15
20
25
30
35
40
45
50
Time (hr)
10
20
30
40
50
60
70
80
Depth (m)


Temperature (deg. C)
20
10
40
20
0
0
10
20
30
40
50
0
50
100
Depth (m)
eta**2
2500
2000
1500
1000
500
4000
2000
0
0
10
20
30
40
50
0
50
100
Depth (m)
Time (hr)



Temperature (deg. C)
20
10
40
20
0
10
20
30
40
50
60
70
80
Depth (m)
0
10
20
30
40
50
Time (hr)
100Hz
200Hz
400Hz
800Hz
1600Hz
shru851 Pulse Response 100 Hz. Hr 200 7/29
Arrival Time (sec.)
shru851 Pulse Response 100 Hz. Hr 1200 7/29
Arrival Time (sec.)
shru851 Pulse Response 100 Hz. Hr 2200 7/29
Arrival Time (sec.)
shru851 Pulse Response 100 Hz. Hr 800 7/30
Arrival Time (sec.)



10log(eta**2)
Depth (m)
Time (hr)
Temperature (deg. C)
Depth (m)
Time (hr)
100Hz
200Hz
400Hz
800Hz
1600Hz
shru852 Temporal Coherence 100 Hz.Hr0200 7/29
shru852 Temporal Coherence 100 Hz.Hr 1200 7/29
shru2252 Temporal Coherence 100 Hz.Hr 2200 7/29
shru852 Temporal Coherence 100 Hz.Hr0800 7/30
Arrival Time (sec.)
Delay Time (mi
Delay Time (m

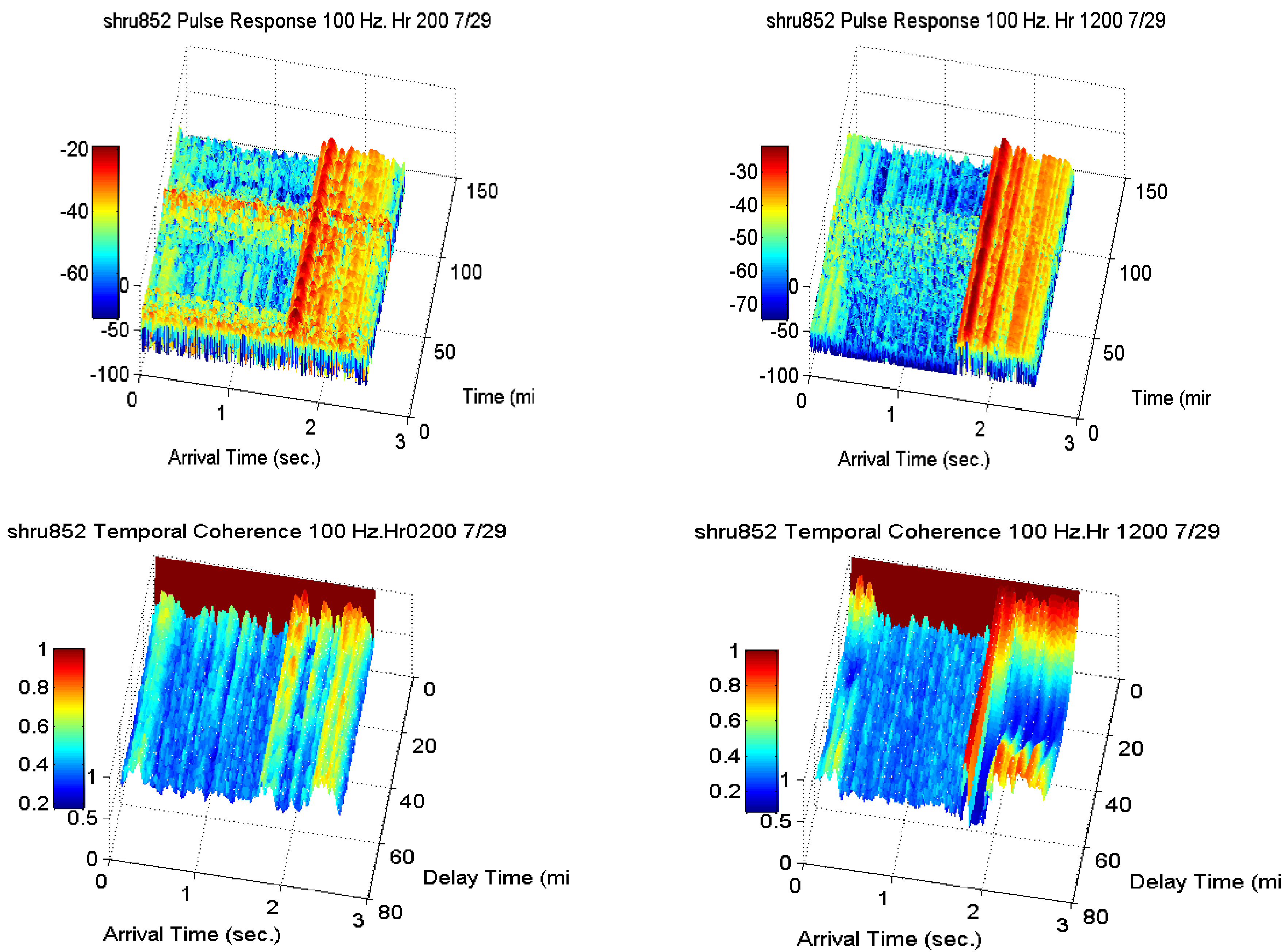
Removing Phase Wrapping

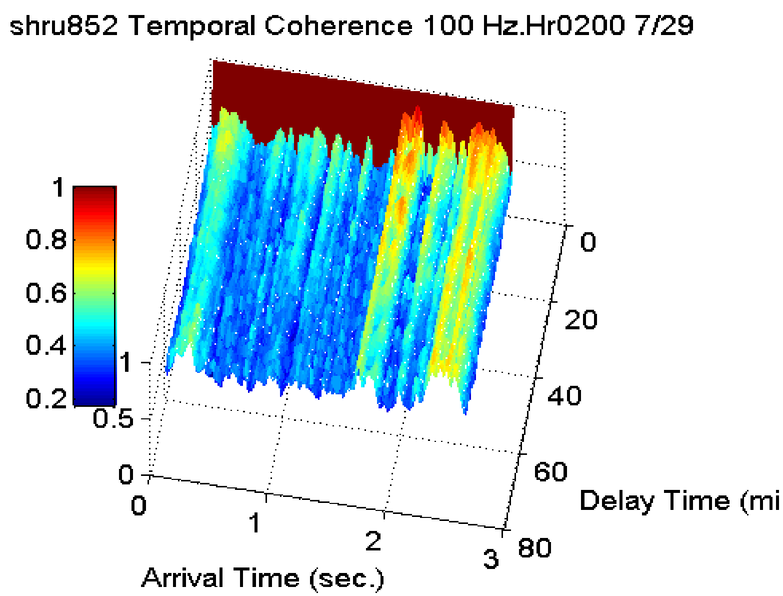
Approach:

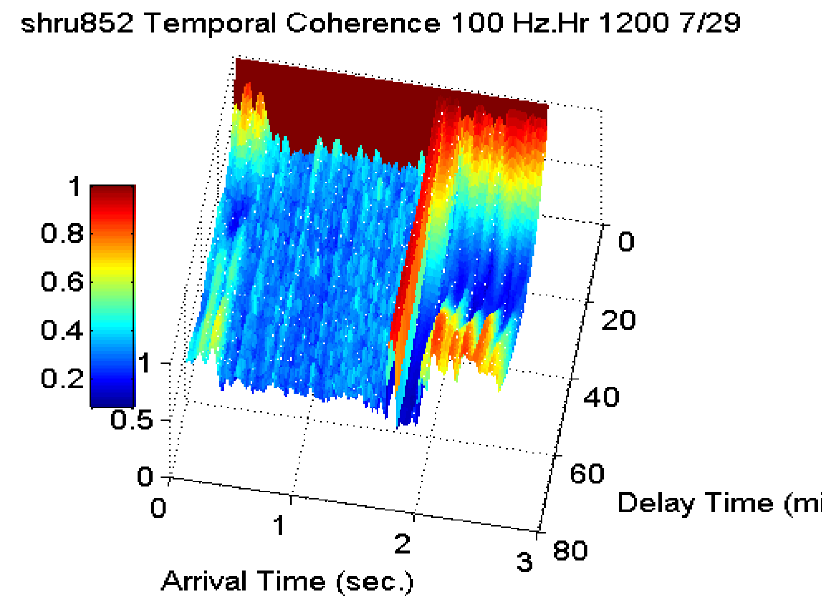
- Back out dT/dt
- Loop through small increments of linear time shifts and re-compute COH
- Look for maximum.

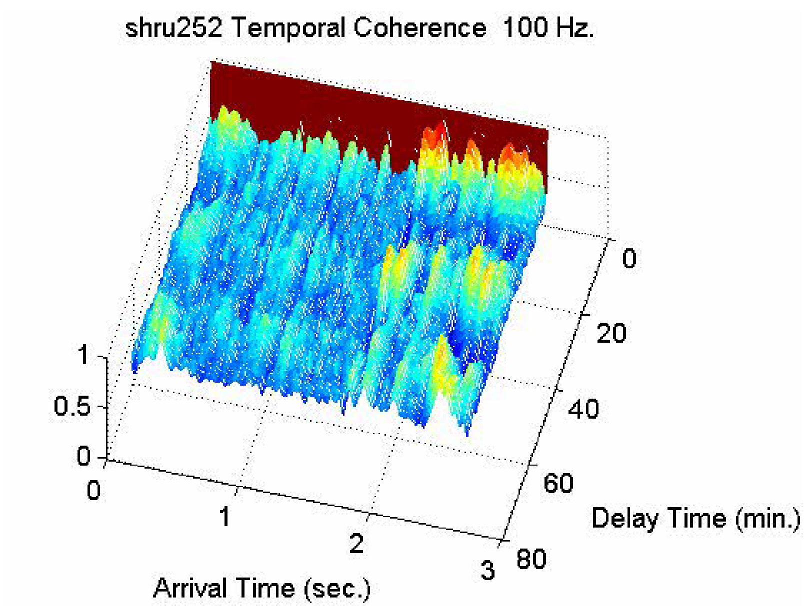
Each pulse p(t) is time shifted by tau using the shifting theorem.

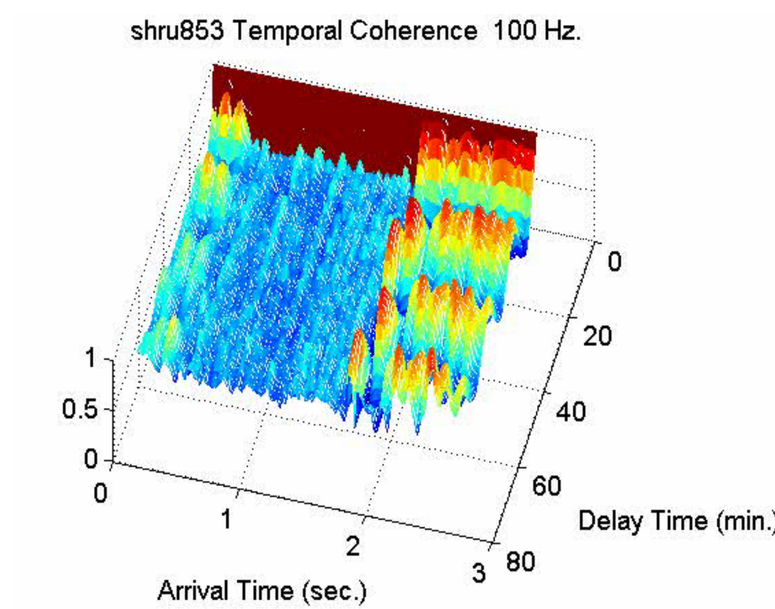
$$F^{-1}\left(F(p(t))e^{i\omega\tau}\right)$$

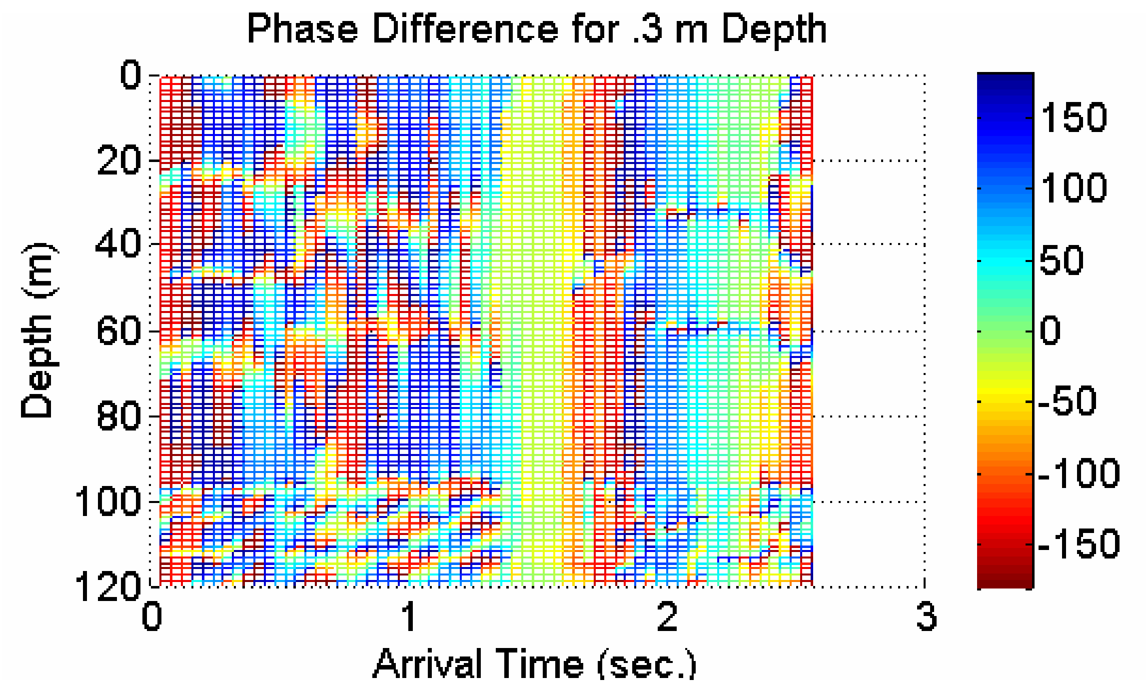

shru852 Pulse Response 100 Hz. Hr 200 7/29
-20
-40
-60
0
-50
-100
150
100
50
0
Time (mi
0
1
2
3
Arrival Time (sec.)
shru852 Pulse Response 100 Hz. Hr 1200 7/29
-30
-40
-50
-60
-70
0
-50
-100
150
100
50
0
Time (mir
0
1
2
3
Arrival Time (sec.)
shru852 Temporal Coherence 100 Hz.Hr0200 7/29
1
0.8
0.6
0.4
0.2
1
0.5
0
0
20
40
60
80
Delay Time (mi
0
1
2
3
Arrival Time (sec.)
shru852 Temporal Coherence 100 Hz.Hr 1200 7/29
1
0.8
0.6
0.4
0.2
1
0.5
0
0
20
40
60
80
Delay Time (mi
0
1
2
3
Arrival Time (sec.)

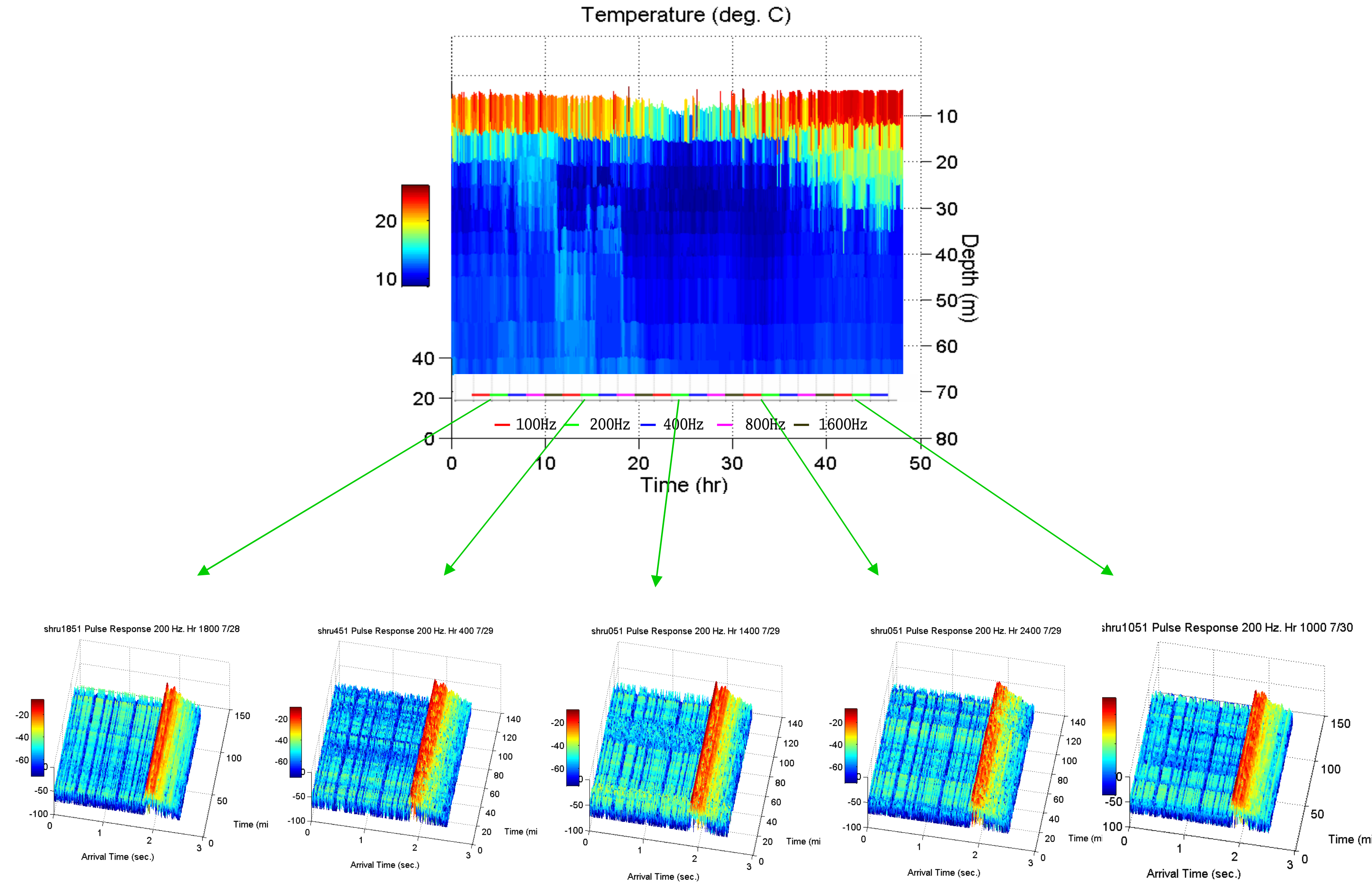

shru852 Temporal Coherence 100 Hz.Hr0200 7/29
Delay Time (mi
Arrival Time (sec.)


shru852 Temporal Coherence 100 Hz.Hr 1200 7/29
Delay Time (mi
Arrival Time (sec.)

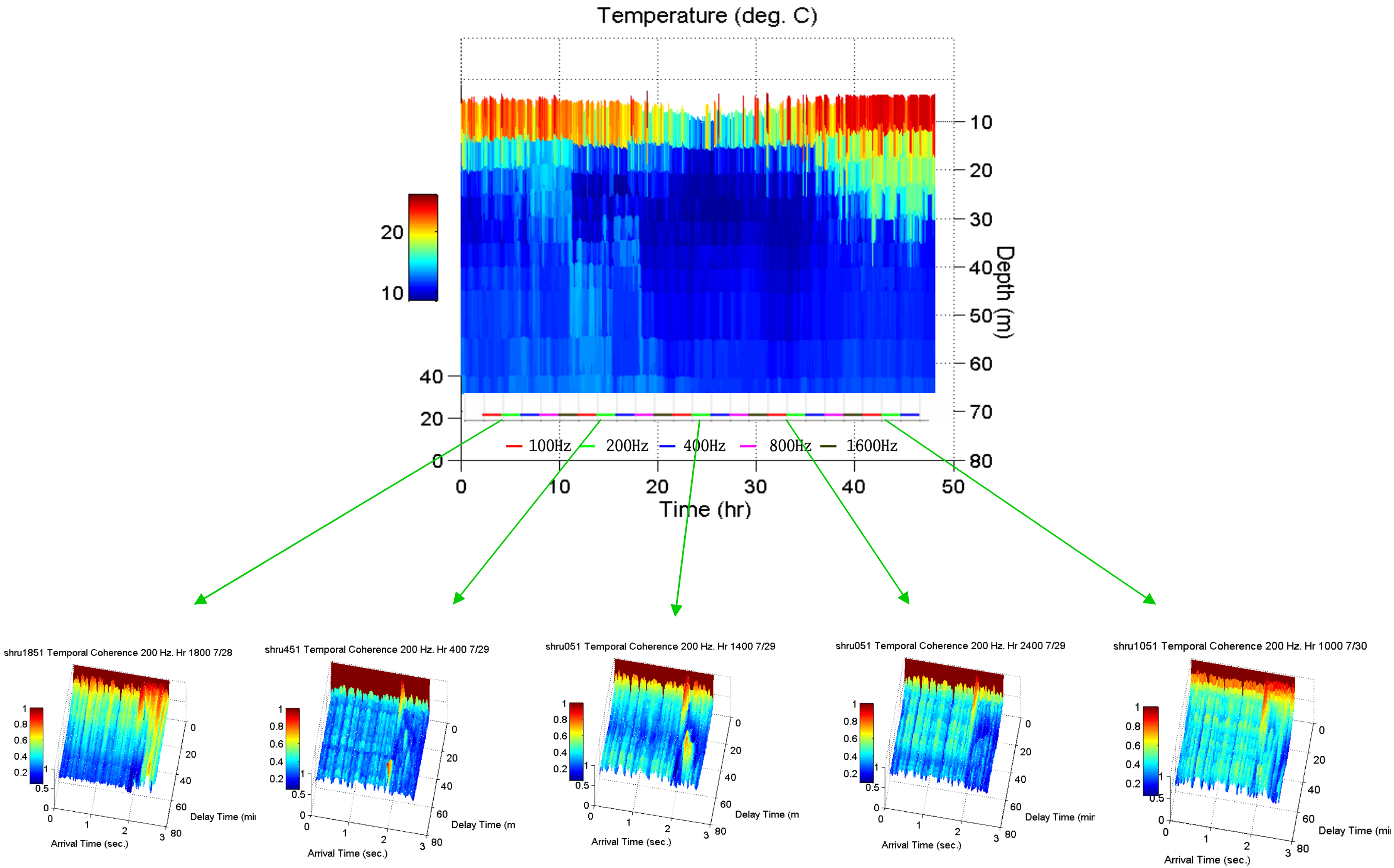

shru252 Temporal Coherence 100 Hz.
Delay Time (min.)
Arrival Time (sec.)


shru853 Temporal Coherence 100 Hz.
Delay Time (min.)
Arrival Time (sec.)

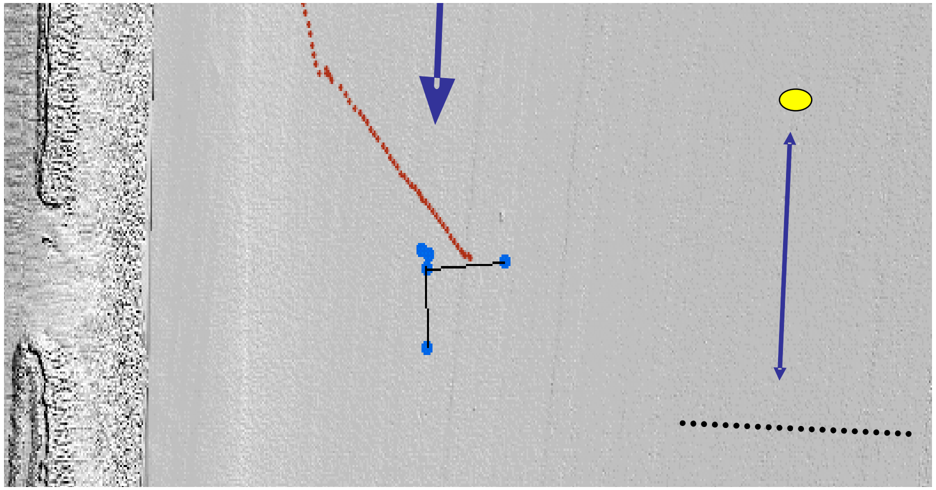

Phase Difference for .3 m Depth
Depth (m)
0
20
40
60
80
100
120
0
1
2
3
Arrival Time (sec.)
150
100
50
0
-50
-100
-150



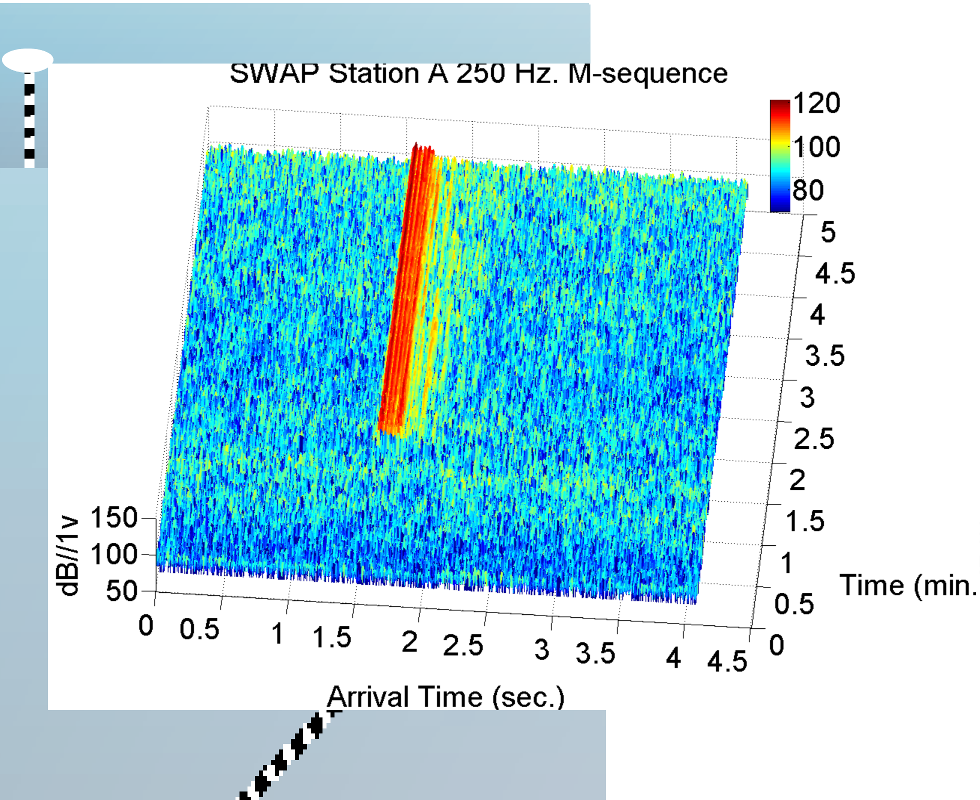
Temperature (deg. C)
20
10
40
20
0
10
20
30
40
50
60
70
80
Depth (m)
100Hz
200Hz
400Hz
800Hz
1600Hz
0
10
20
30
40
50
Time (hr)
shru1851 Pulse Response 200 Hz. Hr 1800 7/28
shru451 Pulse Response 200 Hz. Hr 400 7/29
shru051 Pulse Response 200 Hz. Hr 1400 7/29
shru051 Pulse Response 200 Hz. Hr 2400 7/29
shru1051 Pulse Response 200 Hz. Hr 1000 7/30
Arrival Time (sec.)

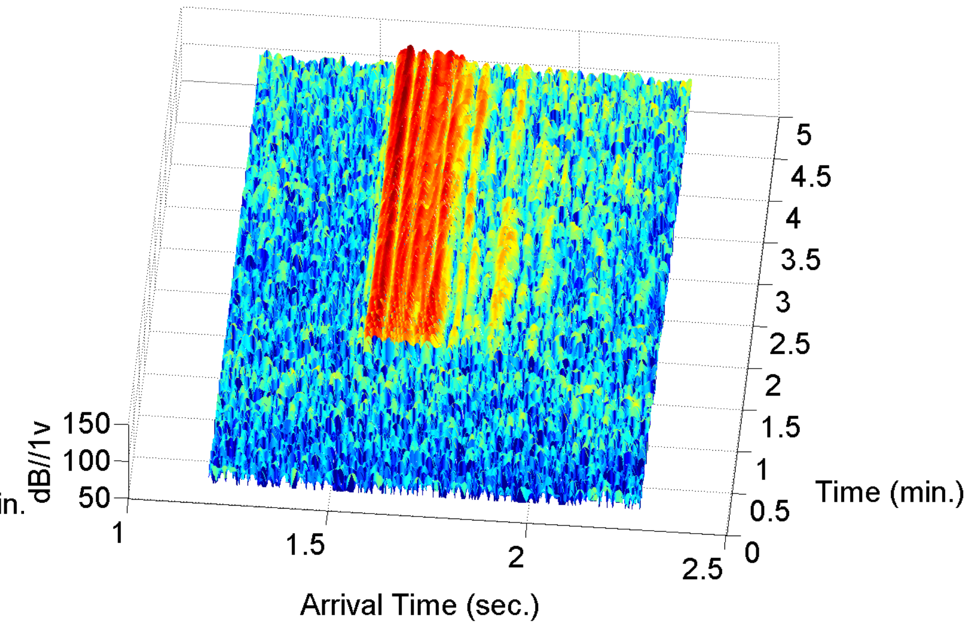


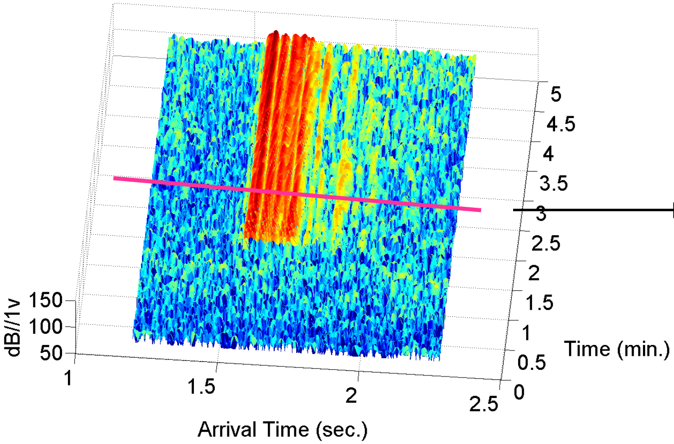
Temperature (deg. C)
20
10
40
20
0
10
20
30
40
50
60
70
80
Depth (m)
0
10
20
30
40
50
Time (hr)
100Hz
200Hz
400Hz
800Hz
1600Hz
shru1851 Temporal Coherence 200 Hz. Hr 1800 7/28
shru451 Temporal Coherence 200 Hz. Hr 400 7/29
shru051 Temporal Coherence 200 Hz. Hr 1400 7/29
shru051 Temporal Coherence 200 Hz. Hr 2400 7/29
shru1051 Temporal Coherence 200 Hz. Hr 1000 7/30
Arrival Time (sec.)
Delay Time (mi



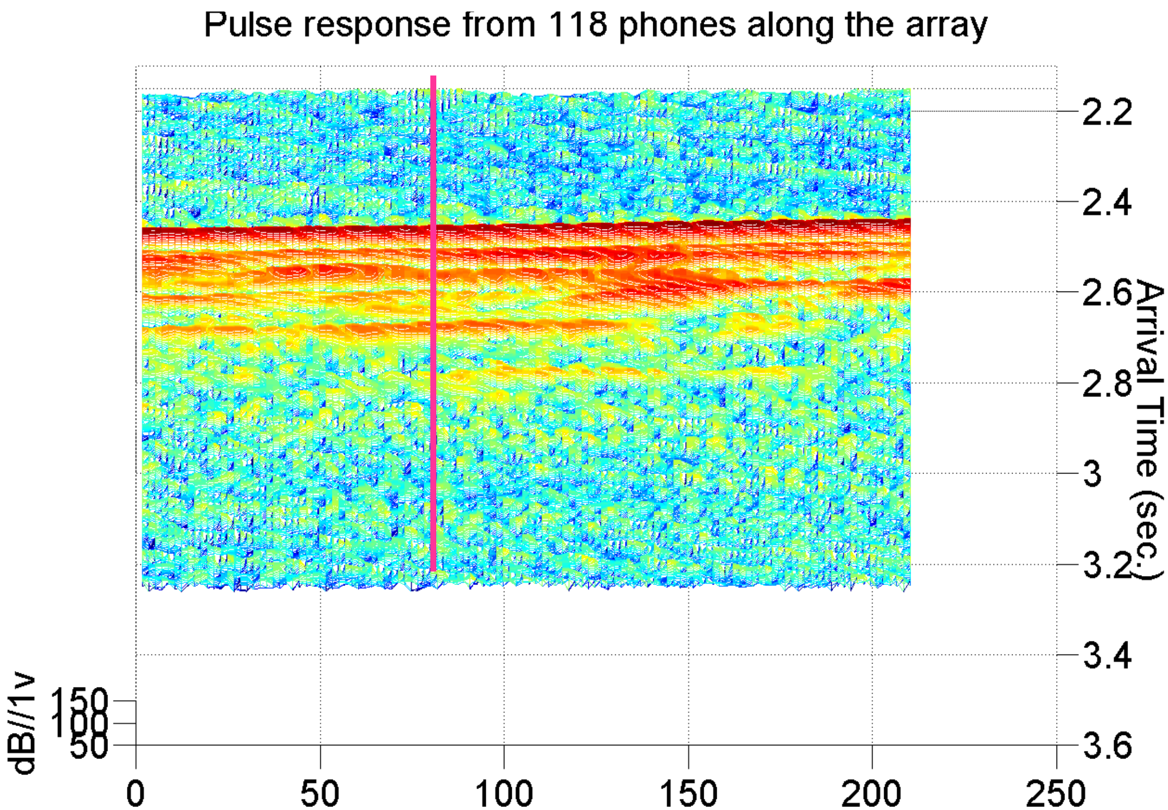
Acoustic Observatory Receiving Arrays
CALOPS Sept 07
Shipboard Suspended and Towed Transmissions






dB//1v
150
100
50
1
1.5
2
2.5
Arrival Time (sec.)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (min.)

Time slice


Pulse response from 118 phones along the array
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
Arrival Time (sec.)
dB//1v
150
100
50
0
50
100
150
200
250

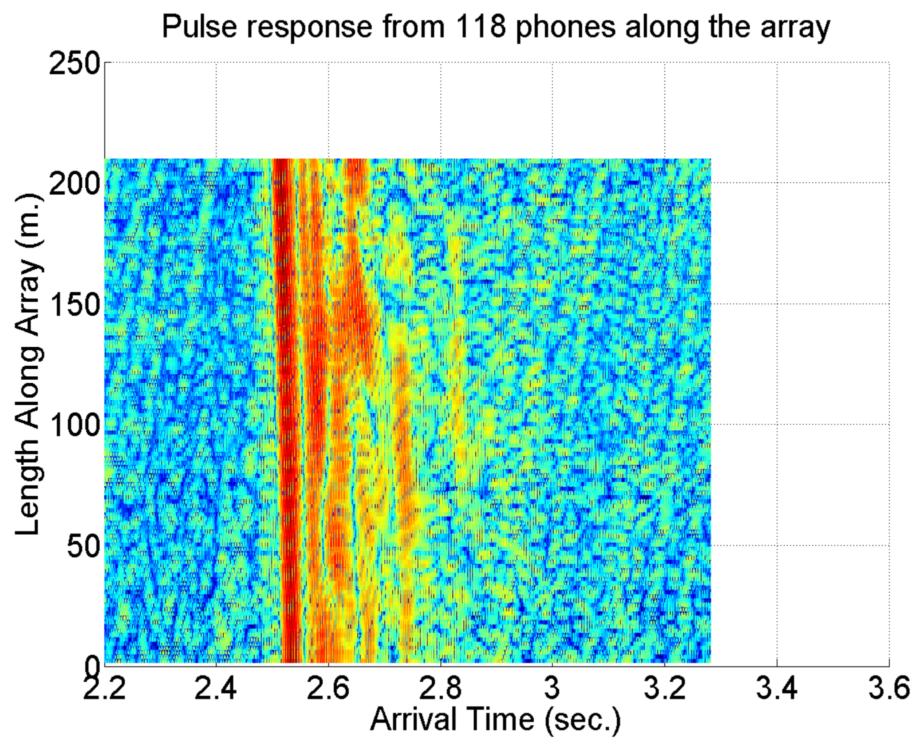
Signal Amplitude Data

$t \longrightarrow$ $p(t)$

$\tau \downarrow$

……………………………………………1
……………………………………………2
…………… $p(t+\tau)$ ……………………3
……………………………………………
……………………………………………
………………………
………………………
………………
…………… 240

$$COH(t,\tau) = \frac{\left\langle \left(p(t) * p(t+\tau) \right)^2 \right\rangle_{\Delta t, \Delta T}}{\left\langle p(t)^2 \right\rangle_{\Delta t, \Delta T} \left\langle p(t+\tau)^2 \right\rangle_{\Delta t, \Delta T}}$$



Change tau to dx - distance along the array

Same calculation yields spatial coherence for every arrival of the pulse response!

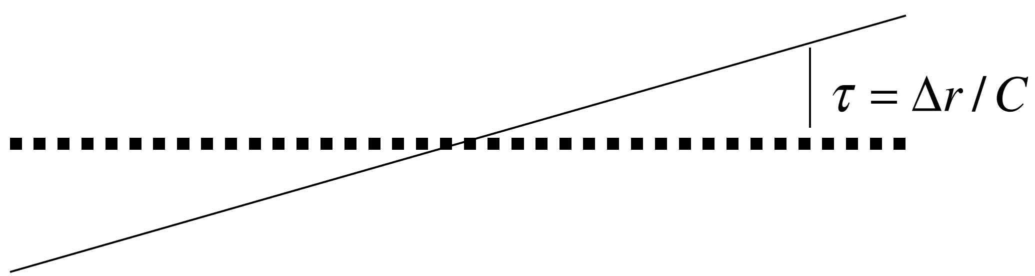
Steering the Array

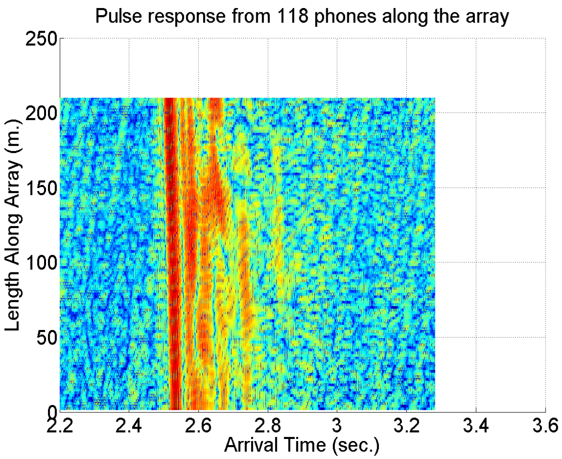
Small shifts in travel time without distortion of the waveform

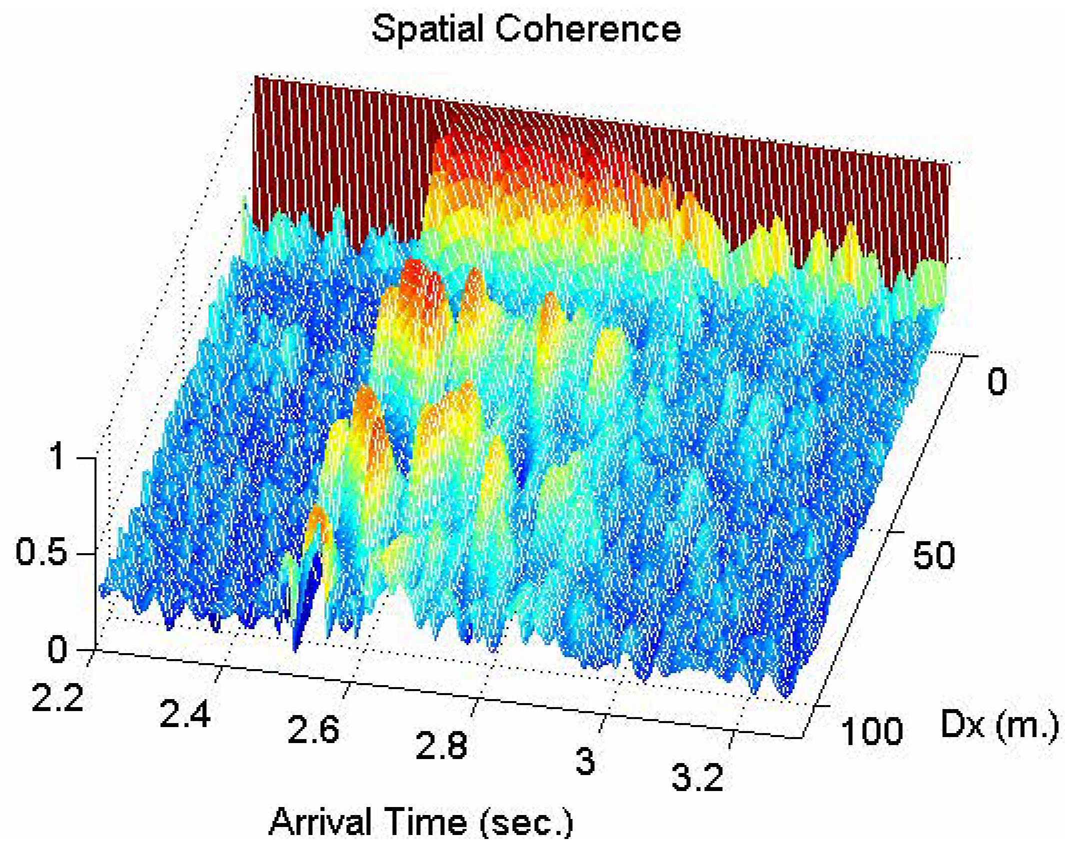
→ Fourier Time Shifting Theorem ←

$$p(t) \quad \Rightarrow FT \Rightarrow \quad F(\omega)$$

$$F(\omega)e^{i\omega\tau} \quad \Rightarrow IFT \Rightarrow \quad p(t-\tau)$$

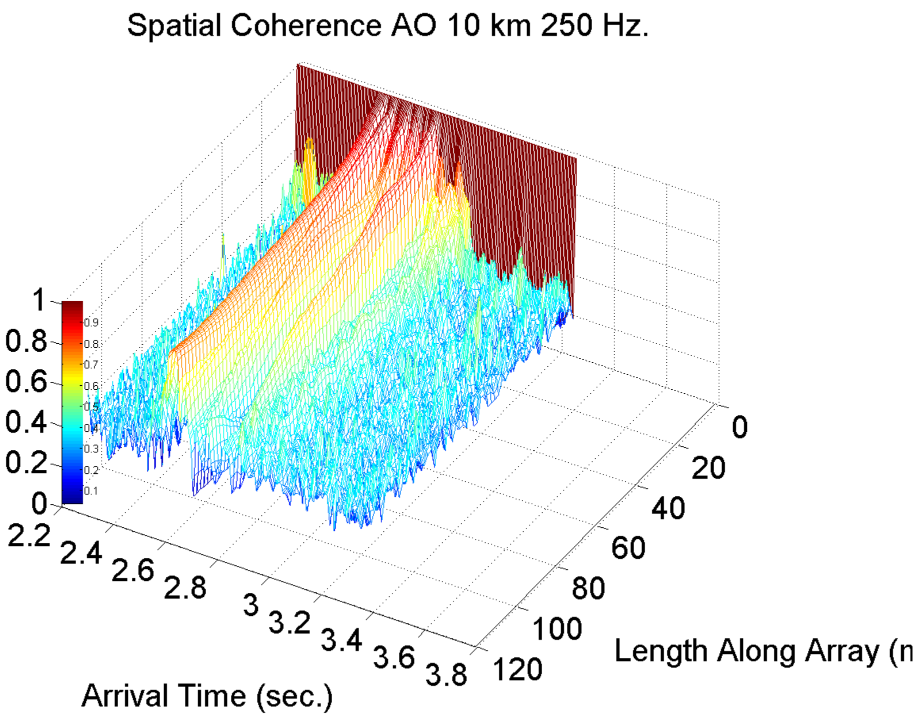


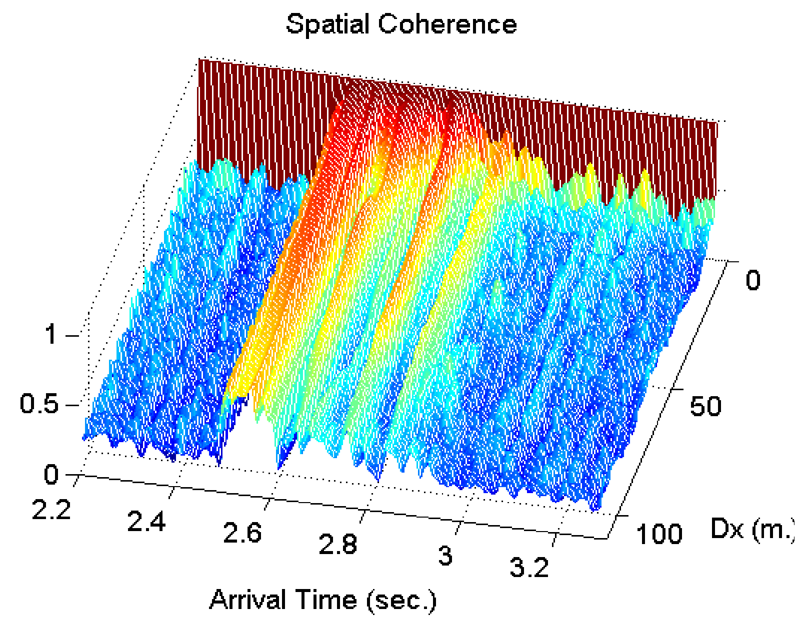




Not aligned with wavefront

Phase changing along the array causing the coherence calculation to cycle.

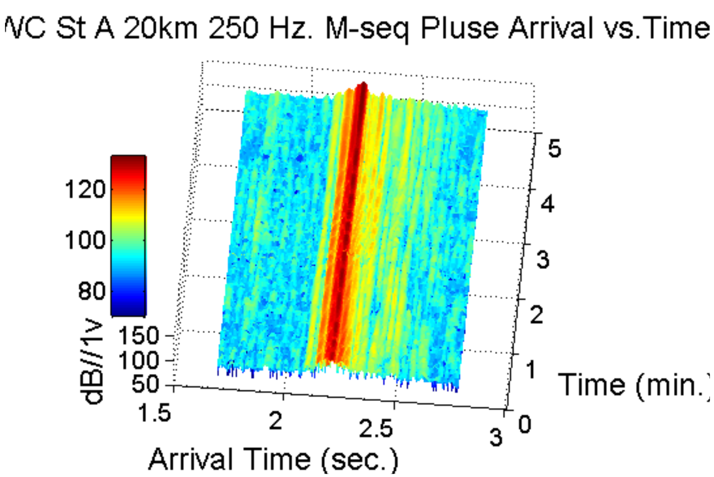




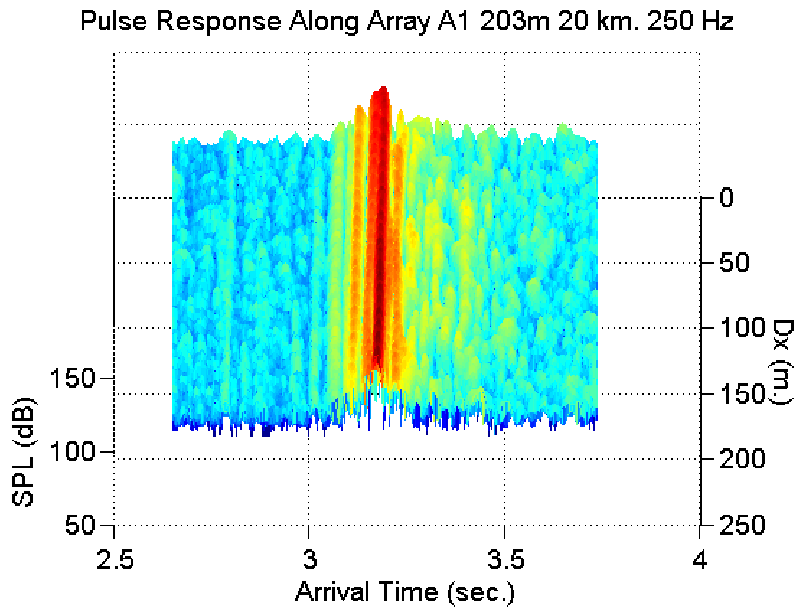
1. Lower order modes are more spatially coherent than higher order modes
2. All modes have ***same*** angle of arrival

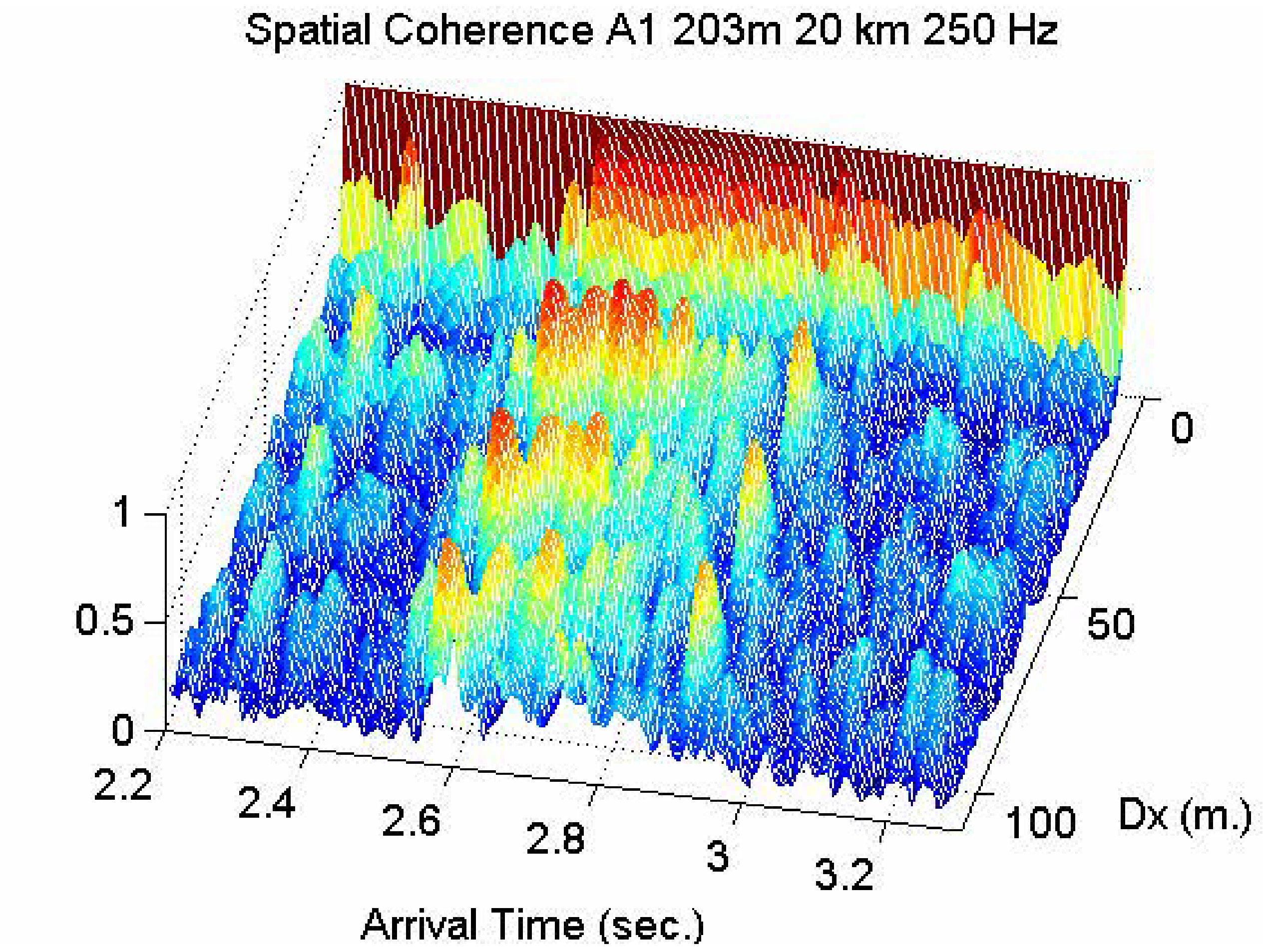
Winter CALOPS 20 km 302 m Source Depth

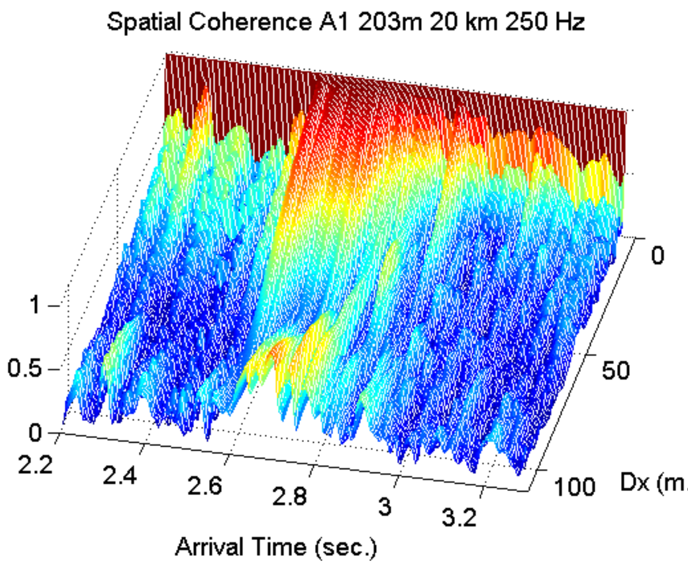
Time

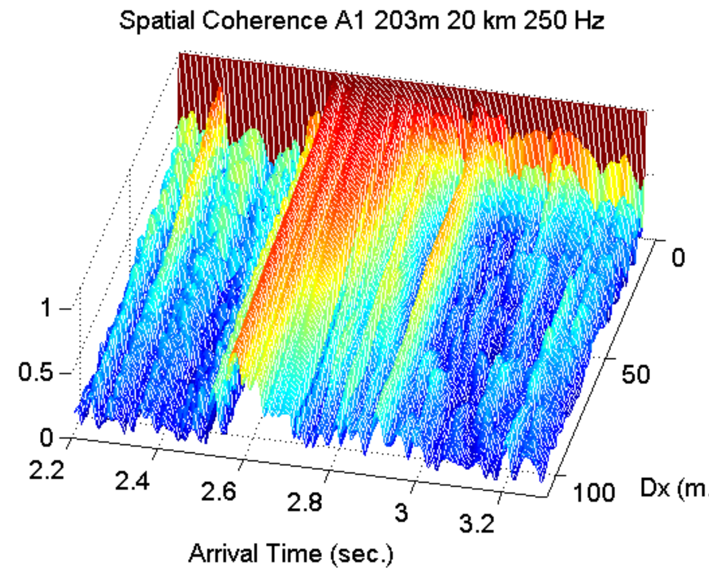


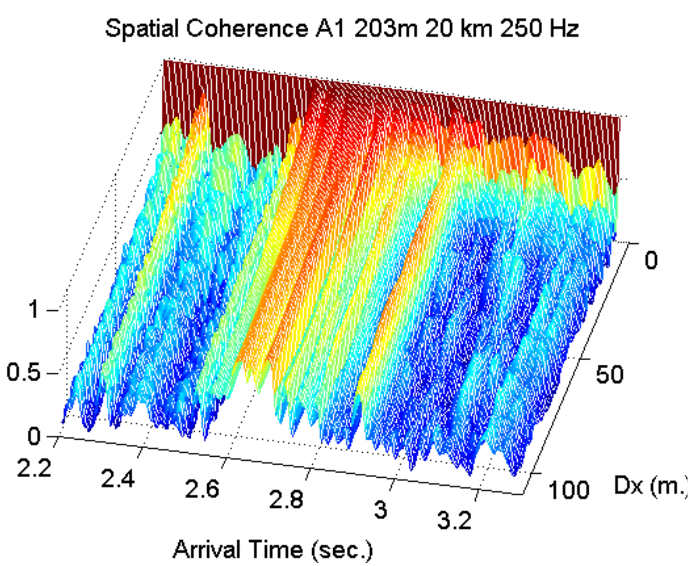
Dx Along array

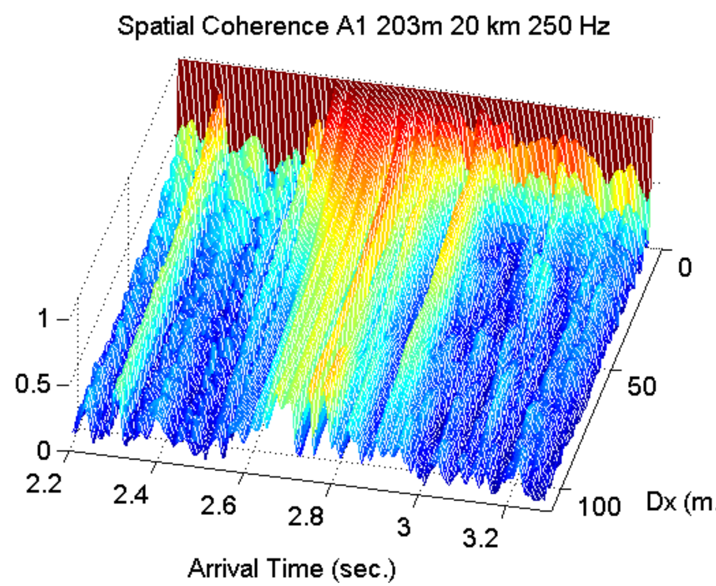



Spatial Coherence A1 203m 20 km 250 Hz
1
0.5
0
2.2
2.4
2.6
2.8
3
3.2
Arrival Time (sec.)
0
50
100
Dx (m.)

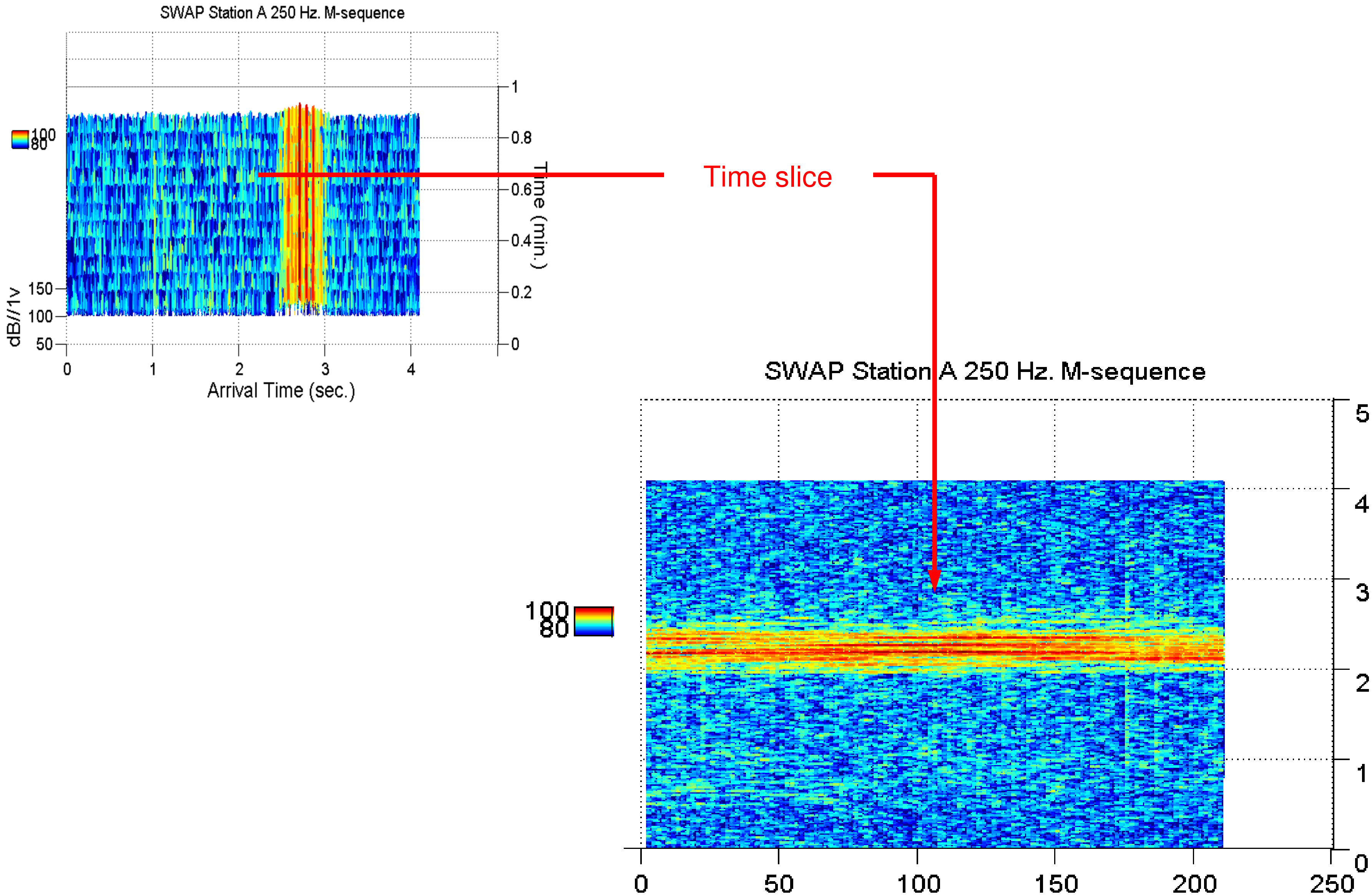

Spatial Coherence A1 203m 20 km 250 Hz
0
0.5
1
2.2
2.4
2.6
2.8
3
3.2
Arrival Time (sec.)
0
50
100
Dx (m.


Spatial Coherence A1 203m 20 km 250 Hz
0
0.5
1
2.2
2.4
2.6
2.8
3
3.2
Arrival Time (sec.)
0
50
100
Dx (m.)

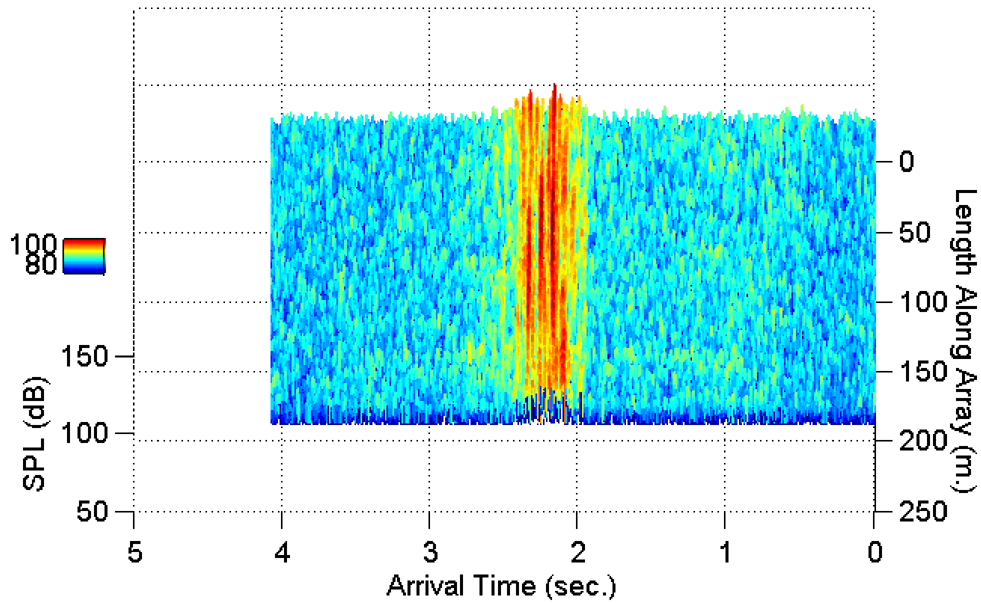

Spatial Coherence A1 203m 20 km 250 Hz
0
0.5
1
2.2
2.4
2.6
2.8
3
3.2
Arrival Time (sec.)
0
50
100
Dx (m.)


Spatial Coherence A1 203m 20 km 250 Hz
0
0.5
1
2.2
2.4
2.6
2.8
3
3.2
Arrival Time (sec.)
0
50
100
Dx (m.)

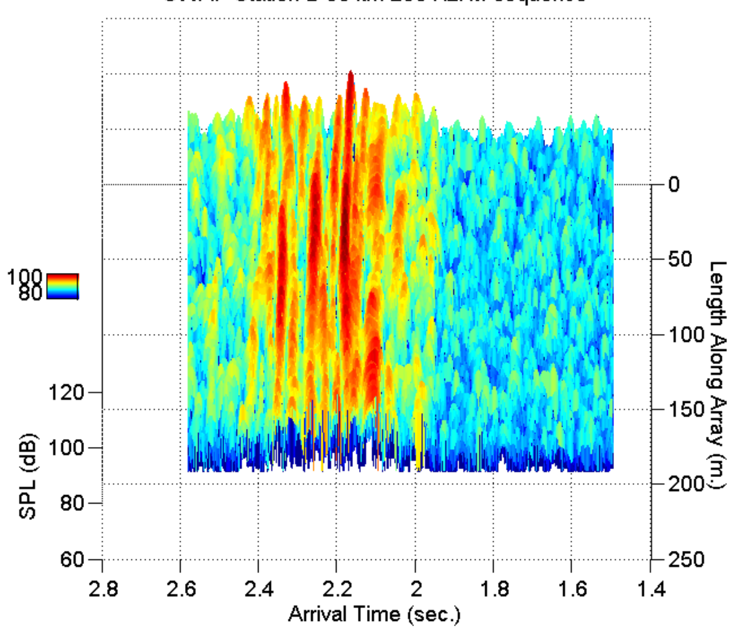
80 km m-sequence reception

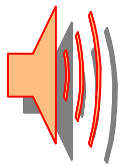


SWAP Station A 250 Hz. M-sequence

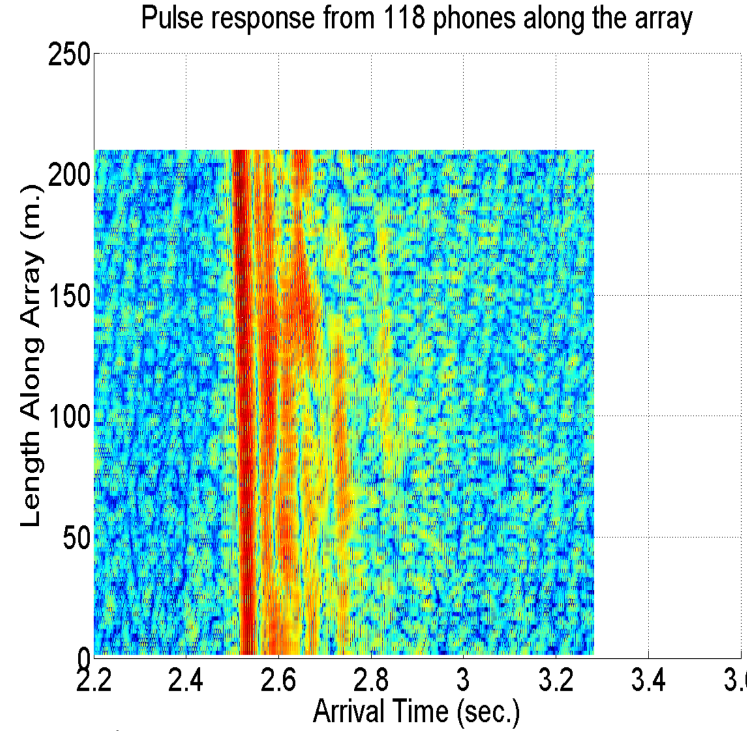


SWAP Station B 80 km 250 Hz. M-sequence

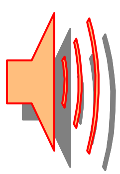




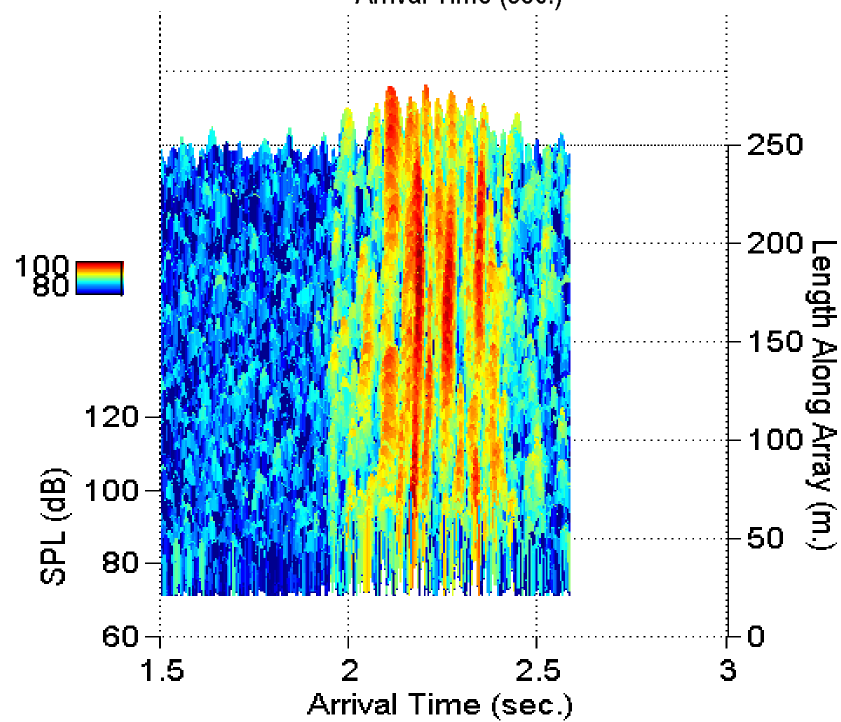
10 km



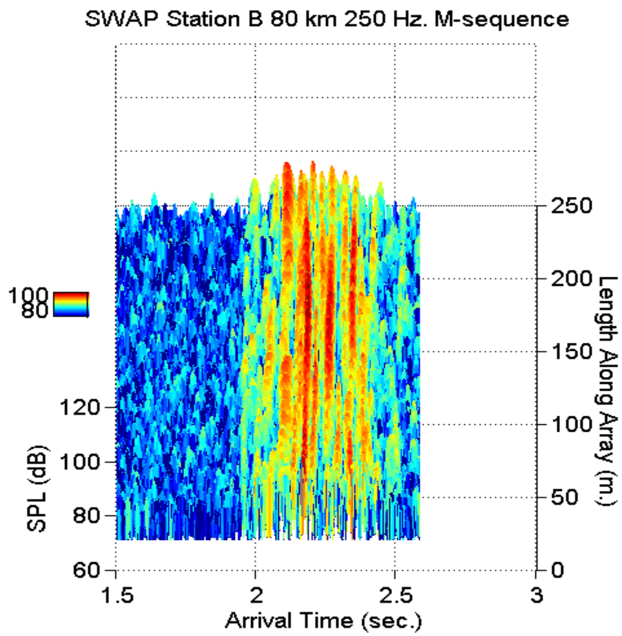
Pulse response from 118 phones along the array
Length Along Array (m.)
250
200
150
100
50
0
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
Arrival Time (sec.)

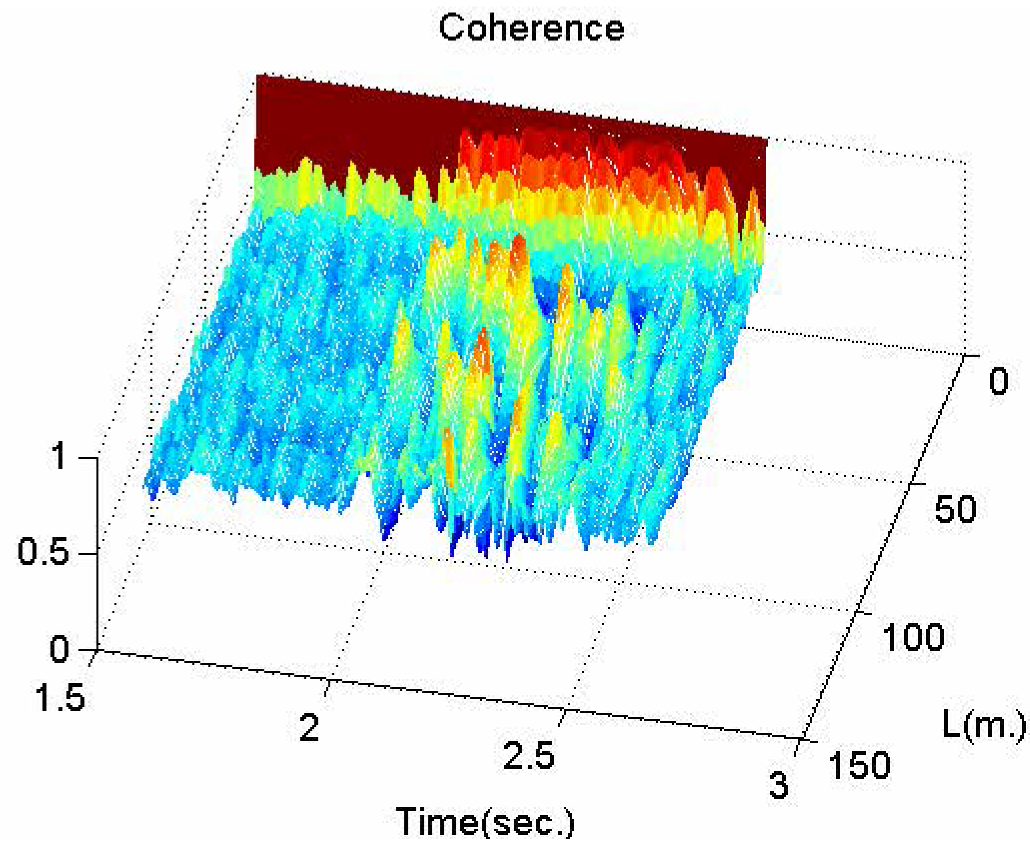


80 km



100
80
SPL (dB)
120
100
80
60
1.5
2
2.5
3
Arrival Time (sec.)
250
200
150
100
50
0
Length Along Array (m.)





1. No recognizable modal structure
2. Burst of micro-paths
3. Different angles of arrival

Spatial Coherence

Higher order modes less coherent than lower order

Modes have varying arrival angles (horizontal)

Angular spread (horizontal) depends on range

<1 deg. @ 10 km

< 2 deg. 20 km

< 4-6 deg. 80 km

Publications

1. Observations of Low-Frequency Temporal and Spatial Coherence in Shallow water. DeFerrari.

   Topic -- FSPE and AO data analysis of spatial and temporal coherence

   Status – Submitted

5. Temporal Coherence of Mode Arrivals. DeFerrari, Lynch, Newhall.

   Topic -- MSM to SHRU's transmission data analysis - temporal coherence

   Status – Submitted

9. Spatial Coherence of Mode arrivals. DeFerrari, Colis, Duda, Newhall

   Topic -- MSM to Shark - Coherence of mode arrivals.

   Status – Early draft.

13. Acoustic Propagation on Shallow Shelves Inside of Retrograde and Progade Fronts.

    Topic -- Comparison of internal wave fields and effects of propagation for two types of environments.

5. Limitations of Horizontal Coherence in Shallow Water.