THE UNIVERSITY OF RHODE ISLAND

Acoustical Society of America
San Antonio– October 26-30, 2009

Time-frequency analysis techniques for long range sediment tomography

Gopu Potty and James H. Miller
University of Rhode Island, Narragansett, RI

Work supported by Office of Naval Research code 321OA

Outline

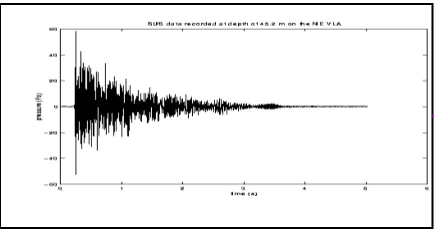
- Sediment tomography
- CSS data analysis using Dispersion Based STFT (D-STFT)
- Empirical Mode Decomposition – results
- Summary and Future work

THE UNIVERSITY OF RHODE ISLAND

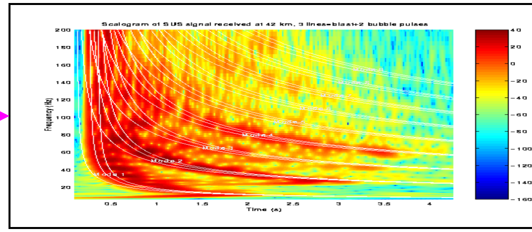
Inversion Scheme for Compressional Speeds

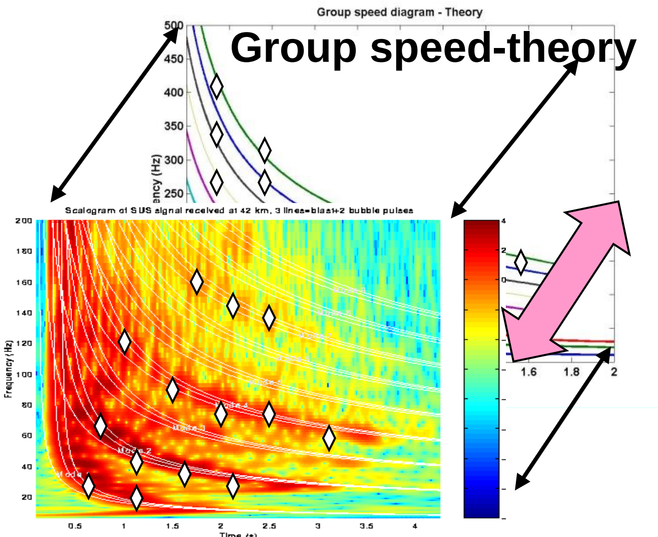
Group speed dispersion by Time-frequency analysis

Genetic Algorithm Optimization



Broadband data





Parameters for GA search

- EOF coefficients
- Sediment compressional speeds
- Bathymetry
- Source-receiver range

Objective Function for m^th parameter set

$$E(m) = ||w\,(d^{obs} - d^{pred})||_2$$

w – diagonal weight matrix
d^{obs} – observed data
d^{pred} – predictions of forward model

***A Posteriori* analysis**
mean, standard deviation

Levenberg-Marquardt
non-linear least squares method

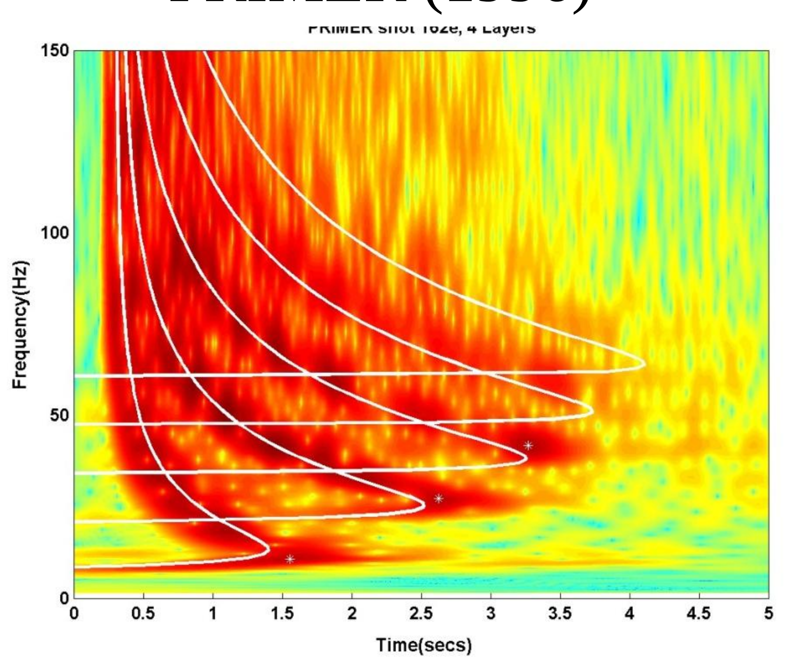
Potty, Miller, Lynch and Smith,``Tomographic mapping of sediments in shallow water, " J. Acoust. Soc. Am.,108(3), 973-986, (2000).

Broadband Sources

Range: 40 km
Water depth ≅ 100 m
Charge Weight: 0.8 kg
Source depth: 18 m

Arrival spread 4 s and 10- 150 Hz.

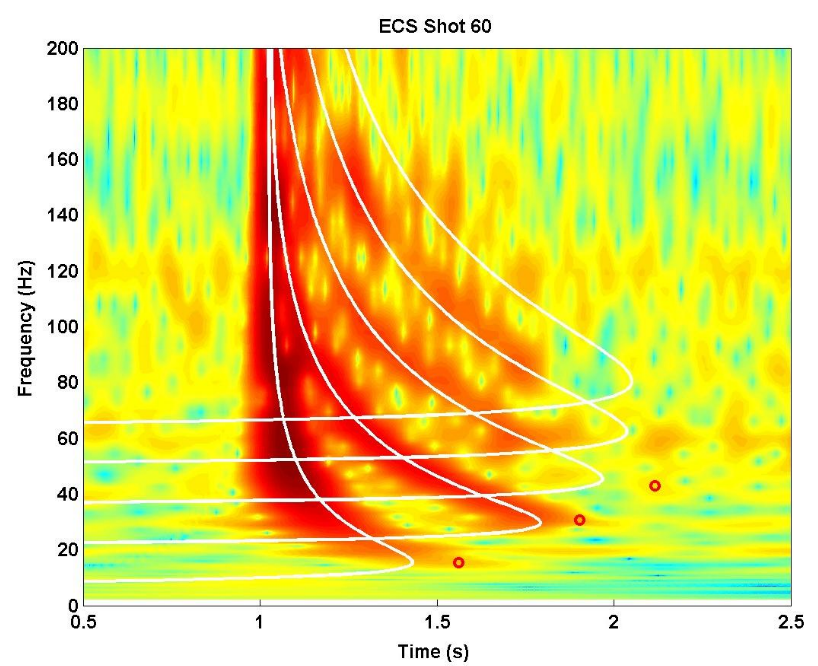
PRIMER (1996)



Range: 30km
Water depth ≅ 100 m
Charge Weight: 38 g;
Source depth: 50 m

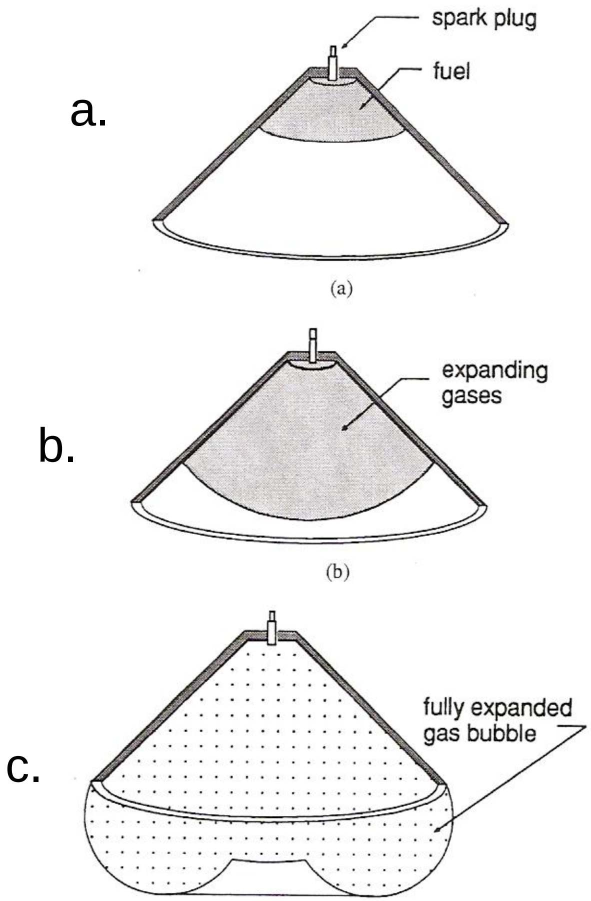
Arrival spread 1 s and 10- 200 Hz.

ASIAEX-ECS Shot 60



Combustive Sound Source (CSS) SW 06 (2006)

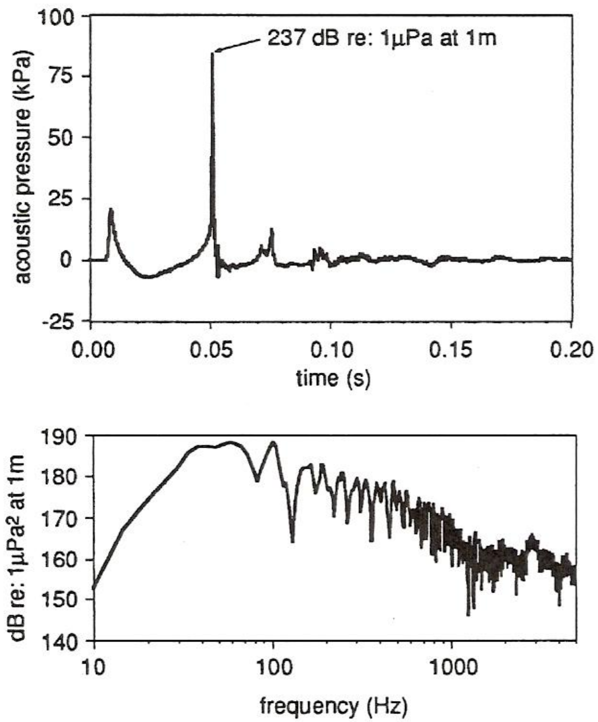
THE UNIVERSITY OF RHODE ISLAND



Cross section of CSS combustion Chamber

a. Unburnt gaseous fuel/oxygen mixture
b. Gases expand during combustion
c. Bubble assumes a toroidal shape upon full expansion

From: Wilson, P. S, Ellzey, J. L., and Muir, T. G., "Experimental Investigation of the Combustive Sound Source," IEEE J. Oceanic. Eng., 20(4), 1995.



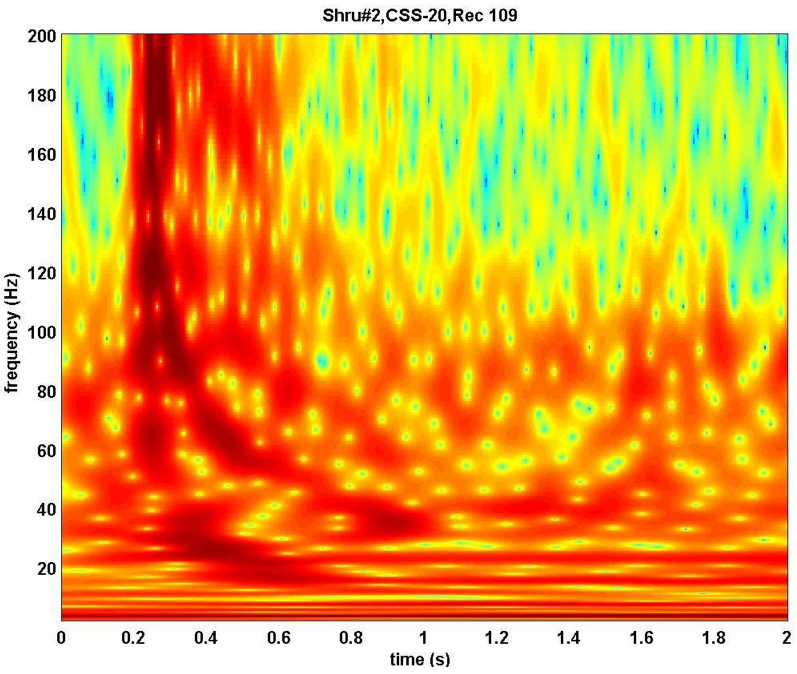
A typical CSS pressure signature (produced by the combustion of 5.0 l stoichiometric hydrogen and oxygen and the power spectrum

Combustive Sound Source (CSS) during SW-06

Range: 21.24 km
Water depth ≅ 90 m
Source depth: 26 m

Arrival spread 0.8 s and 10- 200 Hz.

CSS- SW06



The chamber we used in SW06 was a cylinder with a hemispherical cap. The bubble motion is not the same for the cylinder and the cone, although the radiated acoustic pulse is similar.

Time- Frequency Analysis Techniques

- **Over the years the source levels have become lower resulting in shorter ranges**

- **Less separation between mode arrivals and lower SNR**

- **CSS used in SW06 gave two to three modes; will provide properties of deeper sediments; lower depth resolution**

- **Need for high resolution time-frequency techniques**

- **Hong et al. developed an adaptive time-frequency analysis method, whose time-frequency tiling depends on the dispersion characteristics of the wave signal to be analyzed**

Jin-Chul Hong, Kyung Ho Sun, and Yoon Young Kim, "Dispersion-based short-time Fourier transform applied to dispersive wave analysis," J. Acoust. Soc. Am. **117** (5), May 2005

Short time Fourier Transform

$$Sf(u,\xi) = \int_{-\infty}^{\infty} f(t)\bar{g}_{(s,u,\xi)}dt$$

$$= \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{s}}g\left(\frac{t-u}{s}\right)e^{-i\xi t}dt$$

$$g_{(s,u,\xi)}(t) = \frac{1}{\sqrt{s}}g\left(\frac{t-u}{s}\right)e^{-i\xi t}$$

Window function g(t) is a Gaussian

$$\mathrm{g(t)} = \pi^{-1/4}e^{-\frac{t^2}{2}}$$

$$\left\{\begin{array}{l}\bar{g} \text{ denotes the complex conjugate of g} \\ \text{s determines the size of the window}\end{array}\right\}$$

THE UNIVERSITY OF RHODE ISLAND

Dispersion based Short time Fourier transforms

D-STFT is defined using a basis function that include a new parameter d

$$Df(u,\xi) = \int_{-\infty}^{\infty} f(t)\bar{g}_{(s,u,\xi,d)}(t)dt$$

$$= \int_{-\infty}^{\infty} f(t)\left[\frac{1}{\sqrt{s}}g\left(\frac{t-u}{s}\right)\otimes(id)^{-1/2}e^{-i\left(\frac{t^2}{2d}\right)}\right]e^{-i\xi t}dt$$

$$g_{(s,u,\xi)}(t) = \left[\frac{1}{\sqrt{s}}g\left(\frac{t-u}{s}\right)\otimes(id)^{-1/2}e^{-i\left(\frac{t^2}{2d}\right)}\right]e^{-i\xi t}$$

Window function g(t) is a Gaussian

$$g(t) = \pi^{-1/4}e^{-\frac{t^2}{2}}$$

$$\begin{cases} \bar{g} \text{ denotes the complex conjugate of g} \\ \text{s determines the size of the window} \end{cases}$$

Group delay

The Fourier transform of g(t) is :

$$G(s,u,\xi,d) = \sqrt{s}G\left[s(\omega-\xi)\right]e^{-i\left[u(\omega-\xi)+\left(\frac{d}{2}\right)(\omega-\xi)^2\right]}$$

The group delay of the basis function is :

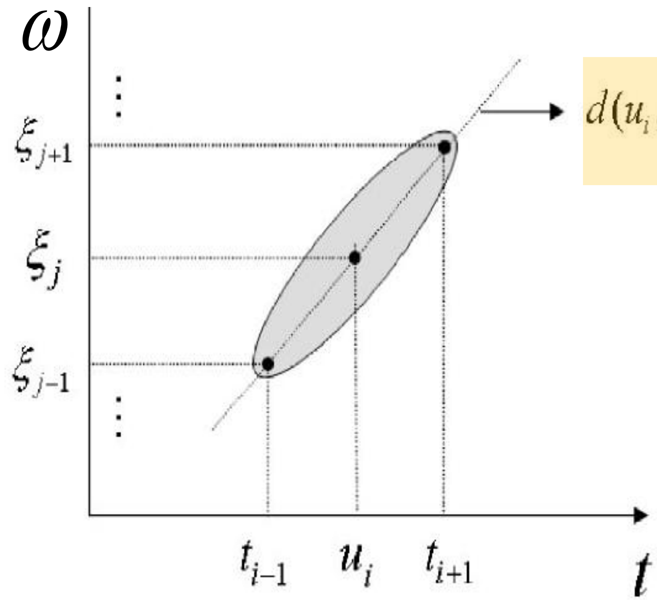
$$\tau(\omega) = \frac{\mathrm{d}}{\mathrm{d}\omega}\left[u(\omega-\xi)+\frac{d}{2}(\omega-\xi)^2\right]$$

$$\tau(\omega) = u + d(\omega-\xi)$$

Dispersion based Short time Fourier transforms

d determines the amount of rotation of the time - frequency box in (u, ξ)

$$d = d(u, \xi) = \frac{\Delta u}{\Delta \xi}$$



$$d(u_i, \xi_j) = \frac{t_{i+1} - t_{i-1}}{\xi_{i+1} - \xi_{i-1}}$$

The group delay is :

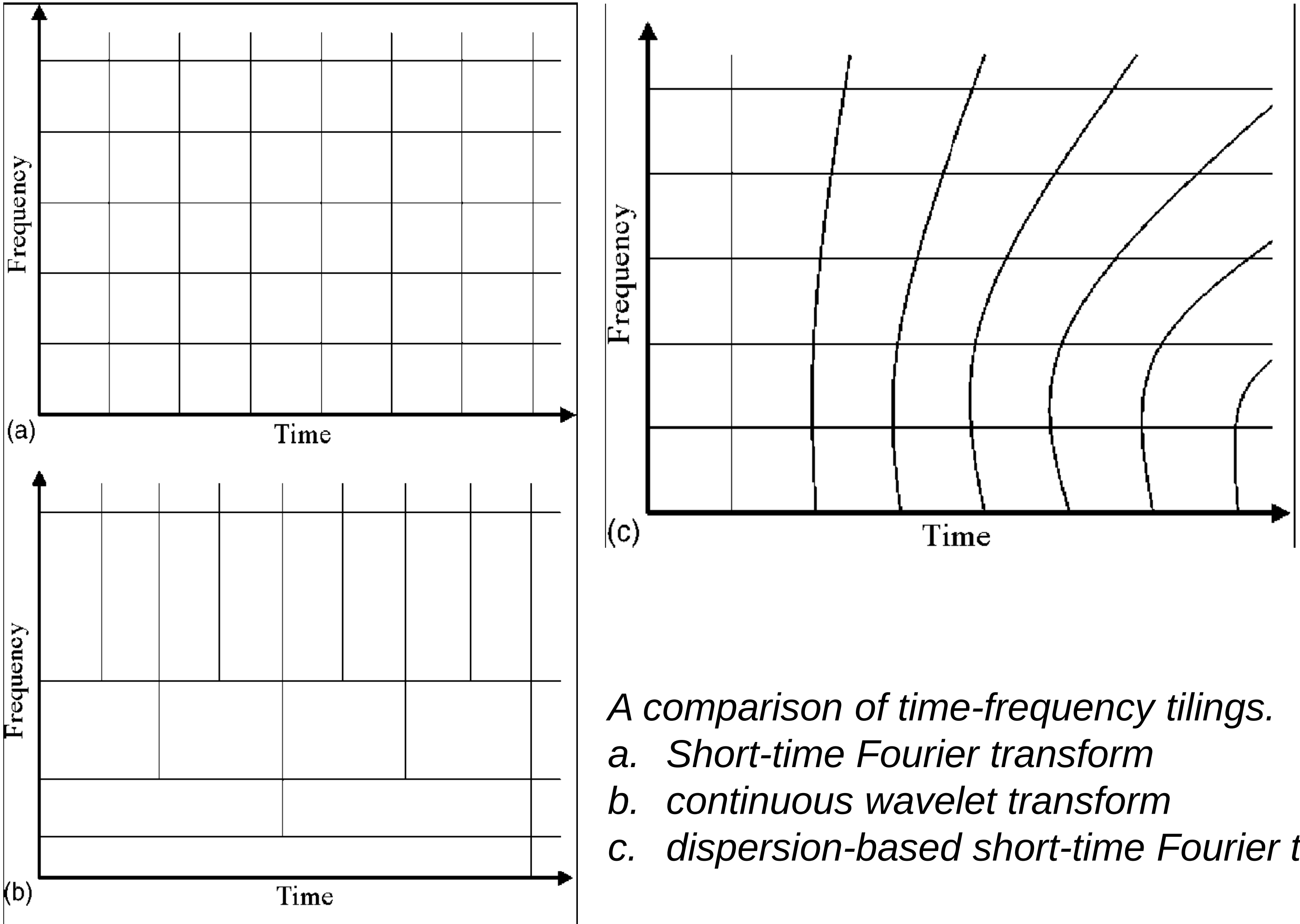
$$\tau(\omega) = u + d(\omega - \xi)$$

This implies that the time-frequency box in (u,ξ) can be obtained by rotating or shearing the time frequency box of standard STFT using the parameter d (u, ξ)

If d (u, ξ) is chosen based on the local wave dispersion, then the resulting time frequency tiling will correspond to the entire wave dispersion behavior.

Time and Frequency Resolution

Time-frequency tiling in D-STFT is performed by adaptively rotating each of the analysis atoms with respect to the dispersion relationship



A comparison of time-frequency tilings.

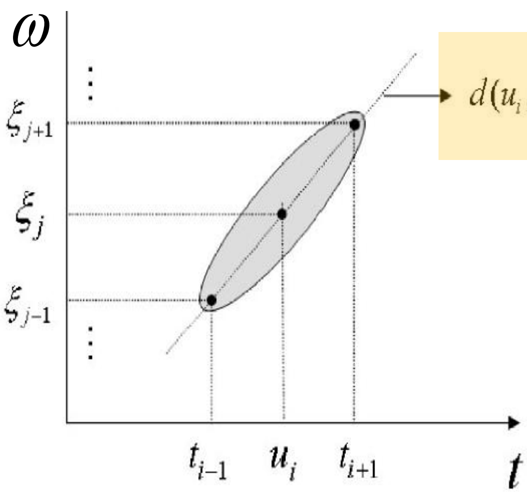
a. Short-time Fourier transform

b. continuous wavelet transform

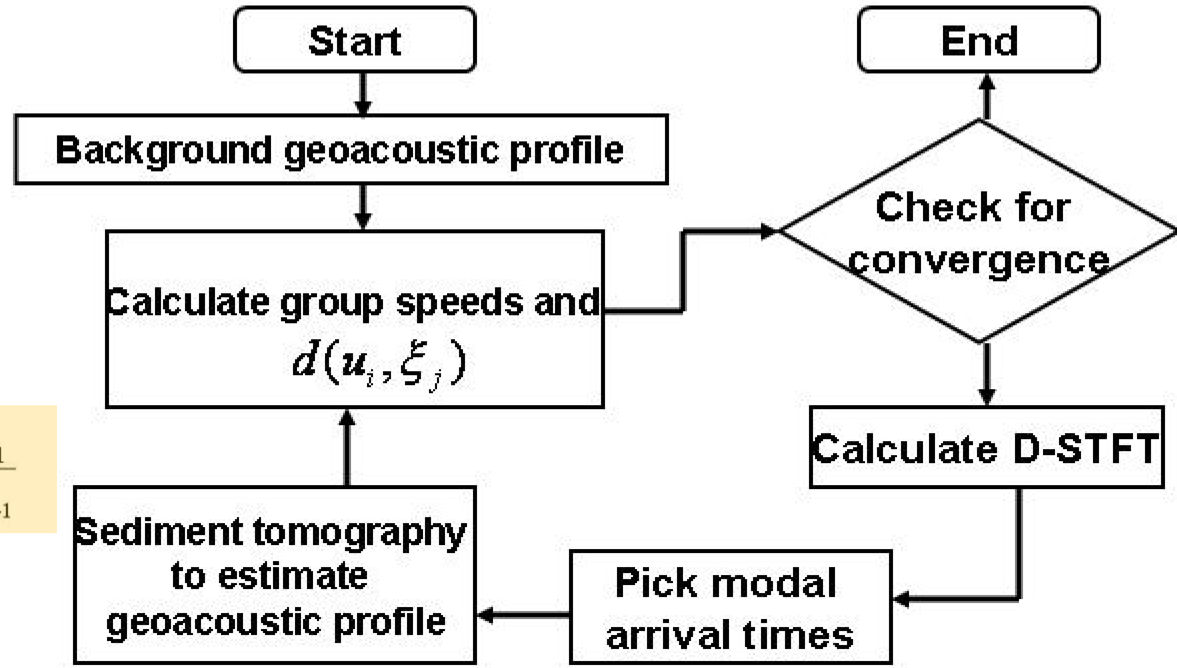
c. dispersion-based short-time Fourier transform.

Iterative Scheme for estimating modal group speeds

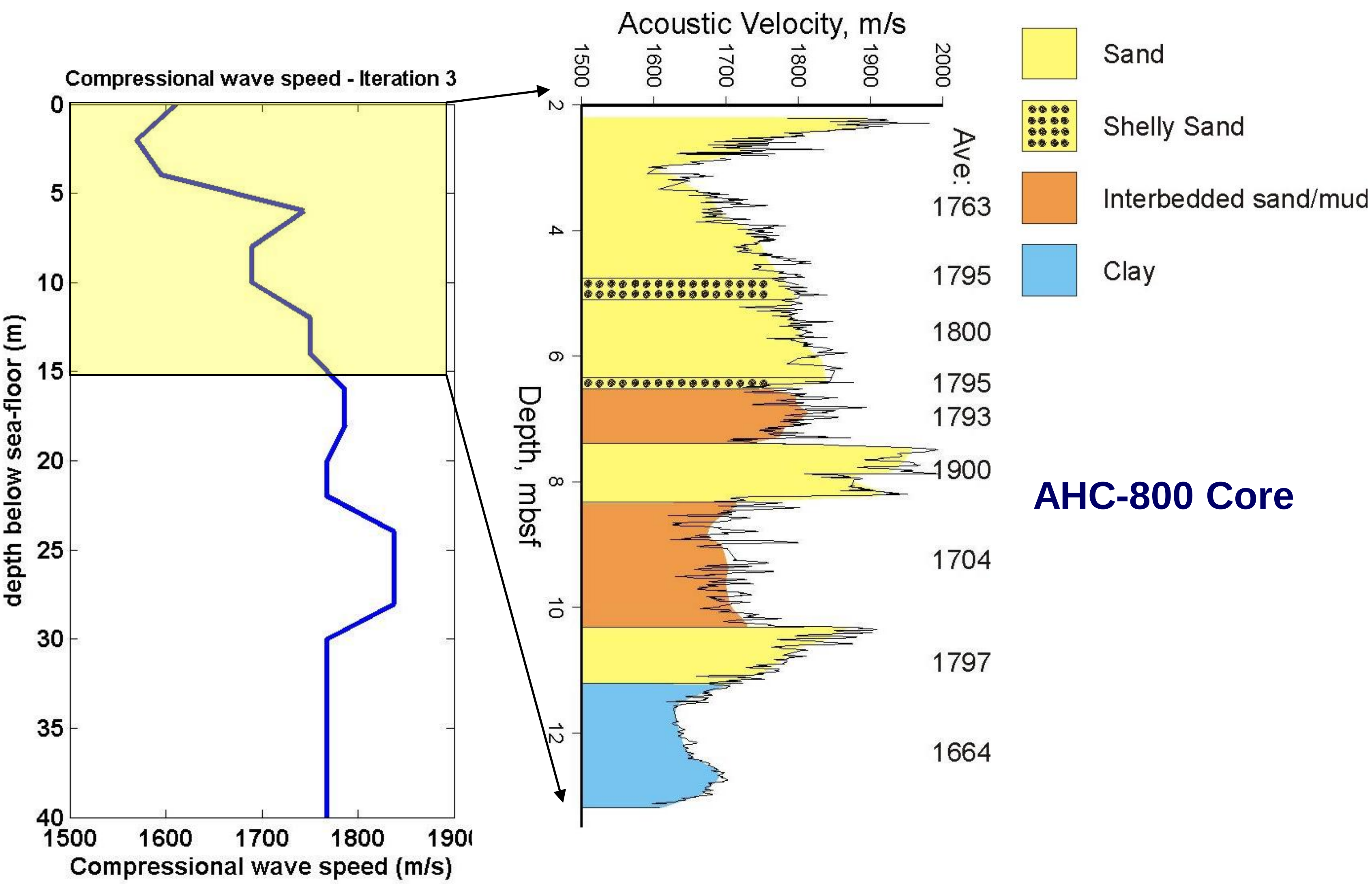
The key step in the algorithm is to connect each of the rotation parameters d(u,ξ) to the actual dispersion relationship



$$d(u_i,\xi_j)=\frac{t_{i+1}-t_{i-1}}{\xi_{i+1}-\xi_{i-1}}$$

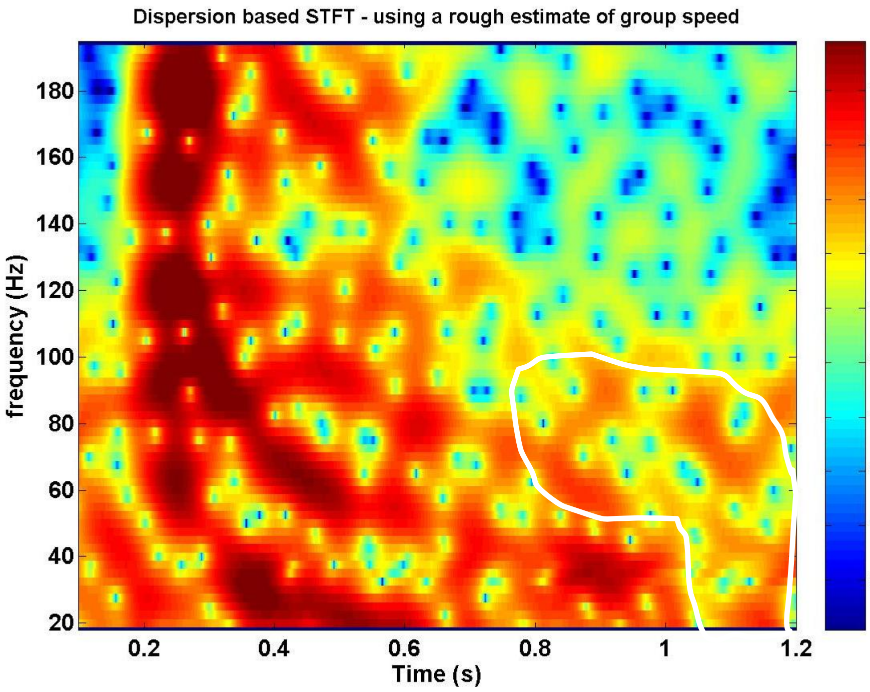


D-STFT- Iteration: 3

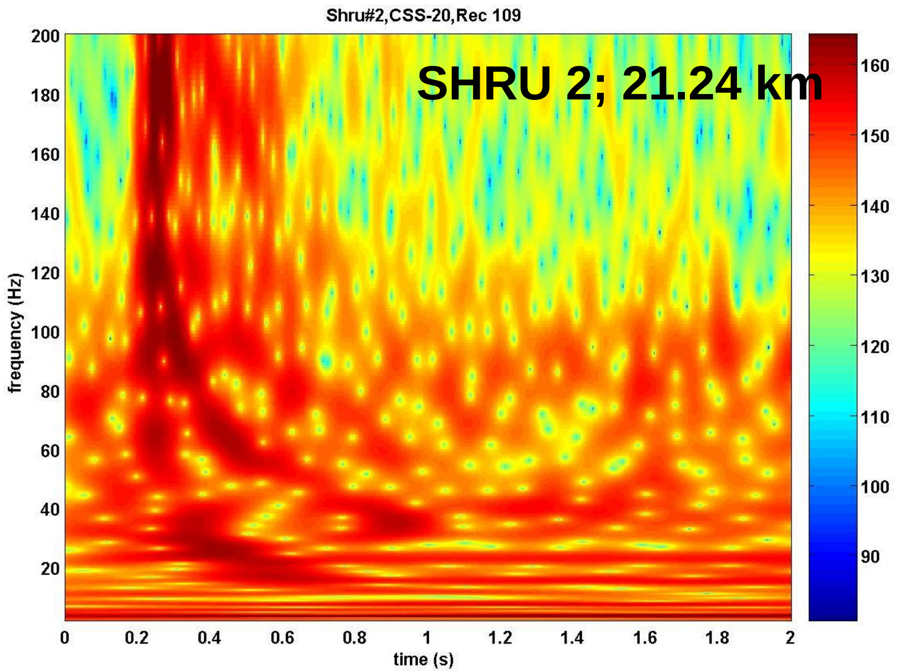


Comparison – D-STFT Vs Wavelet Scalogram

Modes 1, 2 and 3 D-STFT produces similar information
Mode 4 – possibly on a null
Mode 5 – D- STFT offers some promise as opposed to Scalogram



D-STFT



Wavelet Scalogram

Empirical Mode Decomposition

Empirical mode decomposition (EMD), is used to generate a set of intrinsic mode functions (IMF). EMD is a method of breaking down a signal without leaving the time domain.

The objective of the EMD is to empirically separate a signal into several subsignals of varying, and possibly overlapping, frequency content.

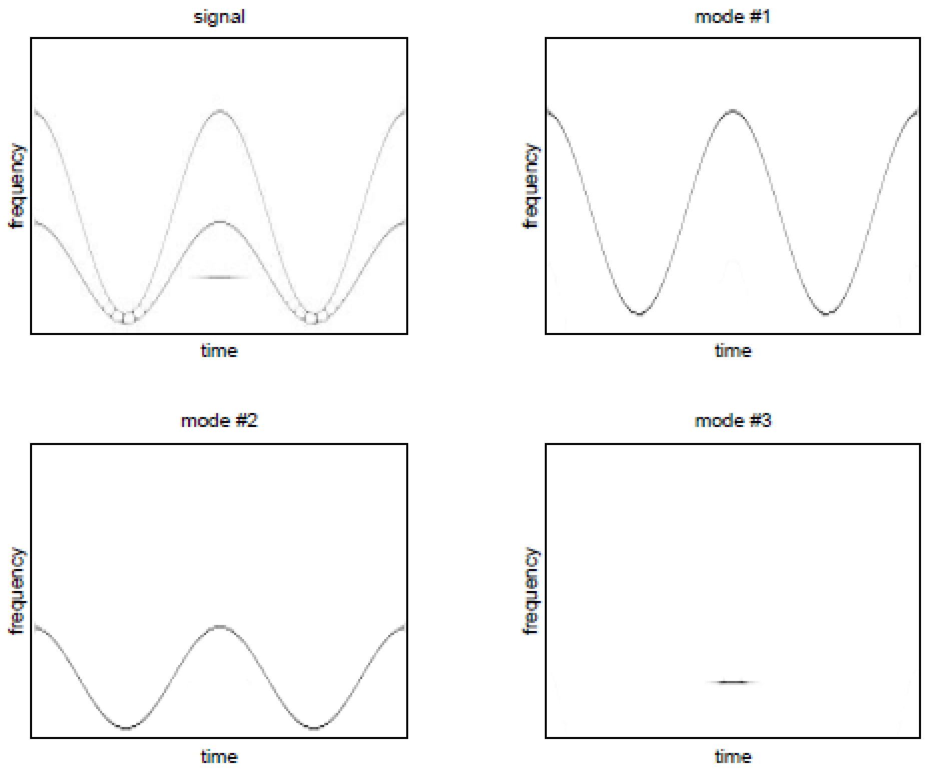
Each of the sub-signals is referred to as an intrinsic mode function because it is empirically derived from the data i.e., there are no user-specified filters.

The EMD produces a bank of IMFs whose sum yields the original signal.

The first IMFs produced contain the highest frequency components of a signal while the latter contain the lowest frequency components.

N.E. Huang, Z. Shen, S.R. Long, M.L. Wu, H.H. Shih, Q. Zheng, N.C. Yen, C.C. Tung and H.H. Liu, "The empirical mode decomposition and Hilbert spectrum for nonlinear and nonstationary time series analysis," ***Proc. Roy. Soc. London A, Vol. 454, pp. 903–995, 1998.***

EMD – Example (Rilling et al.)



EMD of a 3-component signal. ***The analyzed signal is the sum of 2 sinusoidal FM components and 1 Gaussian wavepacket. The time frequency analysis of the total signal (top left) reveals 3 time-frequency signatures which overlap in both time and frequency. The time-frequency signatures of the first 3 IMF's extracted by EMD evidence that these modes efficiently capture the 3-component structure of the analyzed signal.***

Hilbert – Huang spectrum

X_n : bank of IMFs

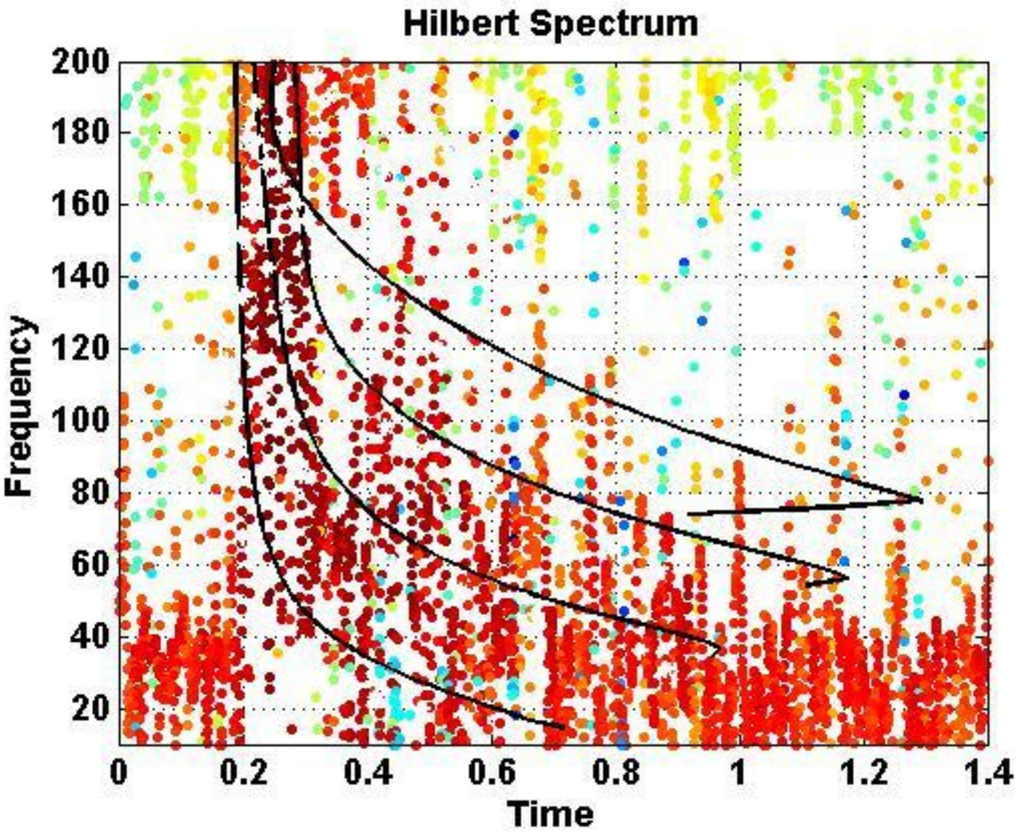
Y_n : bank of their Hilbert transforms

$$\text{Amplitude } a_n(t) = \sqrt{X_n(t)^2 + Y_n(t)^2}$$

$$\text{Phase } \phi_n(t) = \tan^{-1}\left(\frac{Y_n(t)}{X_n(t)}\right)$$

Instantaneous frequency :

$$f_n(t) = \frac{1}{2\pi}\frac{d\phi_n}{dt}$$

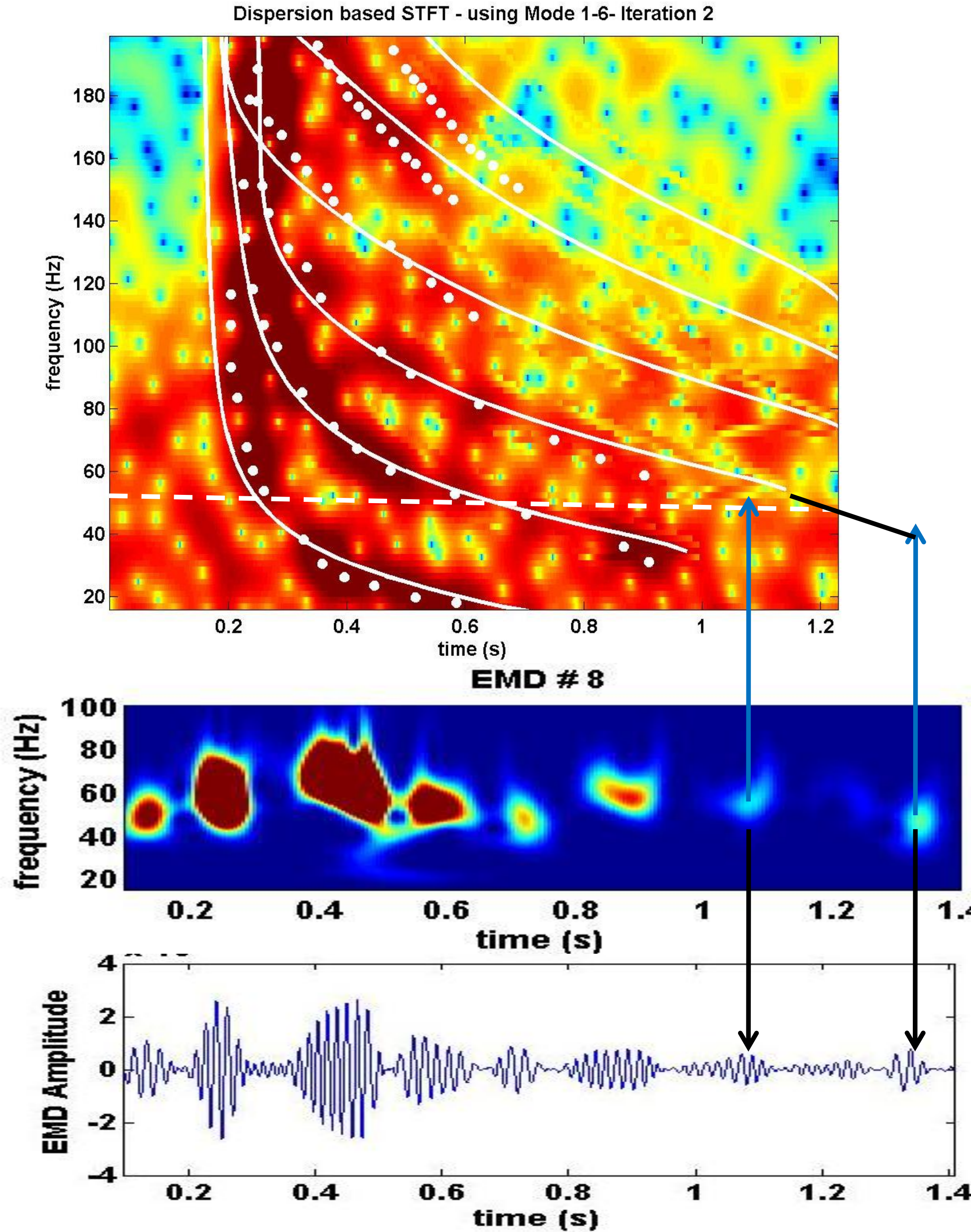


Amplitude, phase and frequency can be time-sorted and displayed in a time-frequency fashion.

Time – frequency structure not clear !!!!!

THE UNIVERSITY OF RHODE ISLAND

Intrinsic Mode Function (IMF) # 8



IMF # 8 – 40 to 60 Hz

Mode 1 and 2 dominant (0.4 and 0.6 sec respectively)

Mode 3 energy at 1.1 sec (~50 Hz) and 1.35 sec (~ 40 Hz)

Arrivals before mode 1 (50 Hz)

THE UNIVERSITY OF RHODE ISLAND

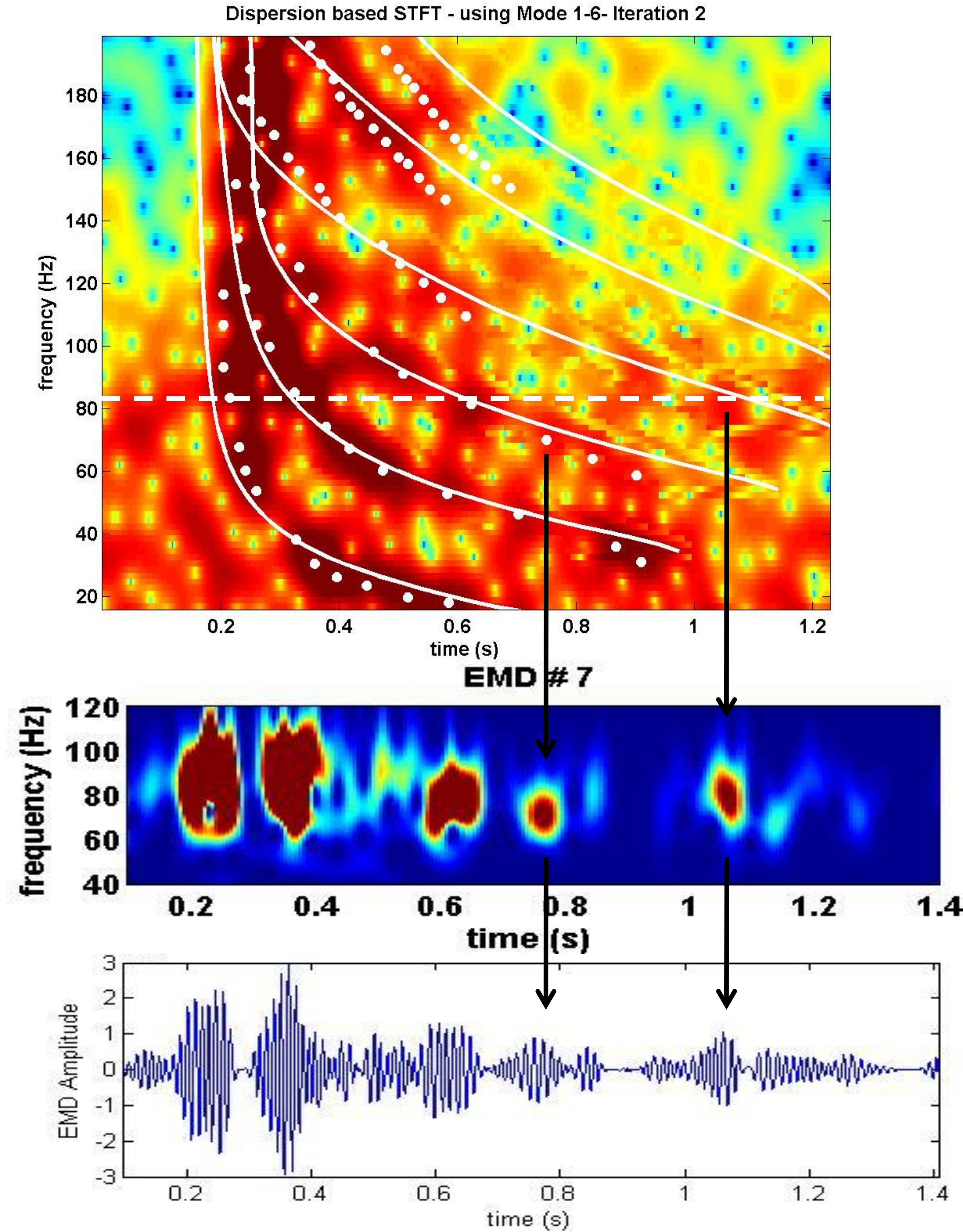
Intrinsic Mode Function (IMF) # 7

IMF # 7 – 60 to 100 Hz

Mode 1 and 2 dominant (0.2 and 0.4 sec respectively)

Mode 3 energy at 0.6 sec (~80 Hz) and 0.8 sec (~ 65 Hz)

Mode 4 energy at 1.05 sec (75 Hz)



THE UNIVERSITY OF RHODE ISLAND

Intrinsic Mode Function - (IMF) # 6

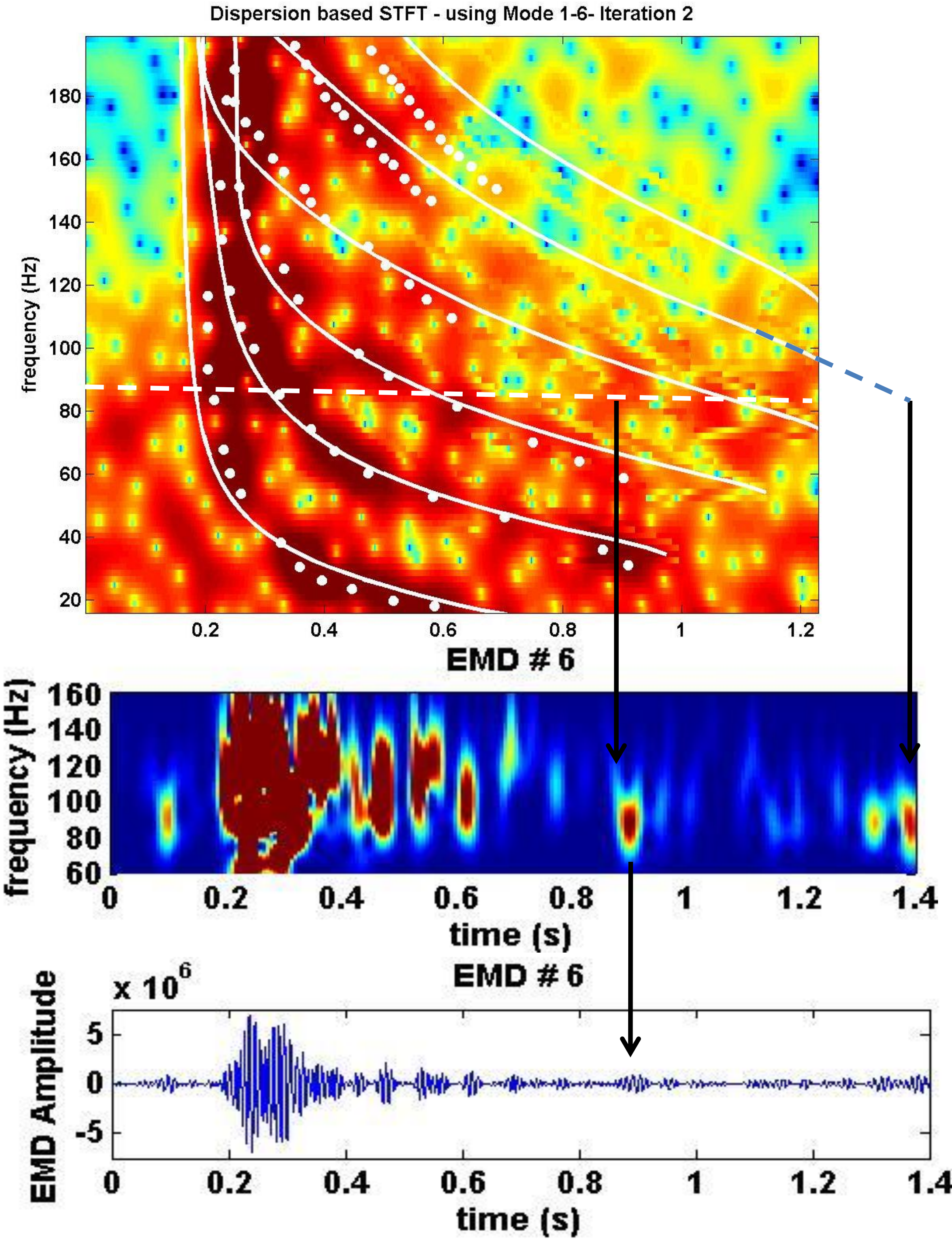
IMF # 7 – 60 to 160 Hz

Mode 1 and 2 dominant (0.2 and 0.3 sec respectively)

Mode 3 energy smeared between 0.4 and 0.6 sec

Mode 4 energy at 0.9 sec (80 Hz)

Mode 5 energy at 1.4 sec (80 Hz)



THE UNIVERSITY OF RHODE ISLAND

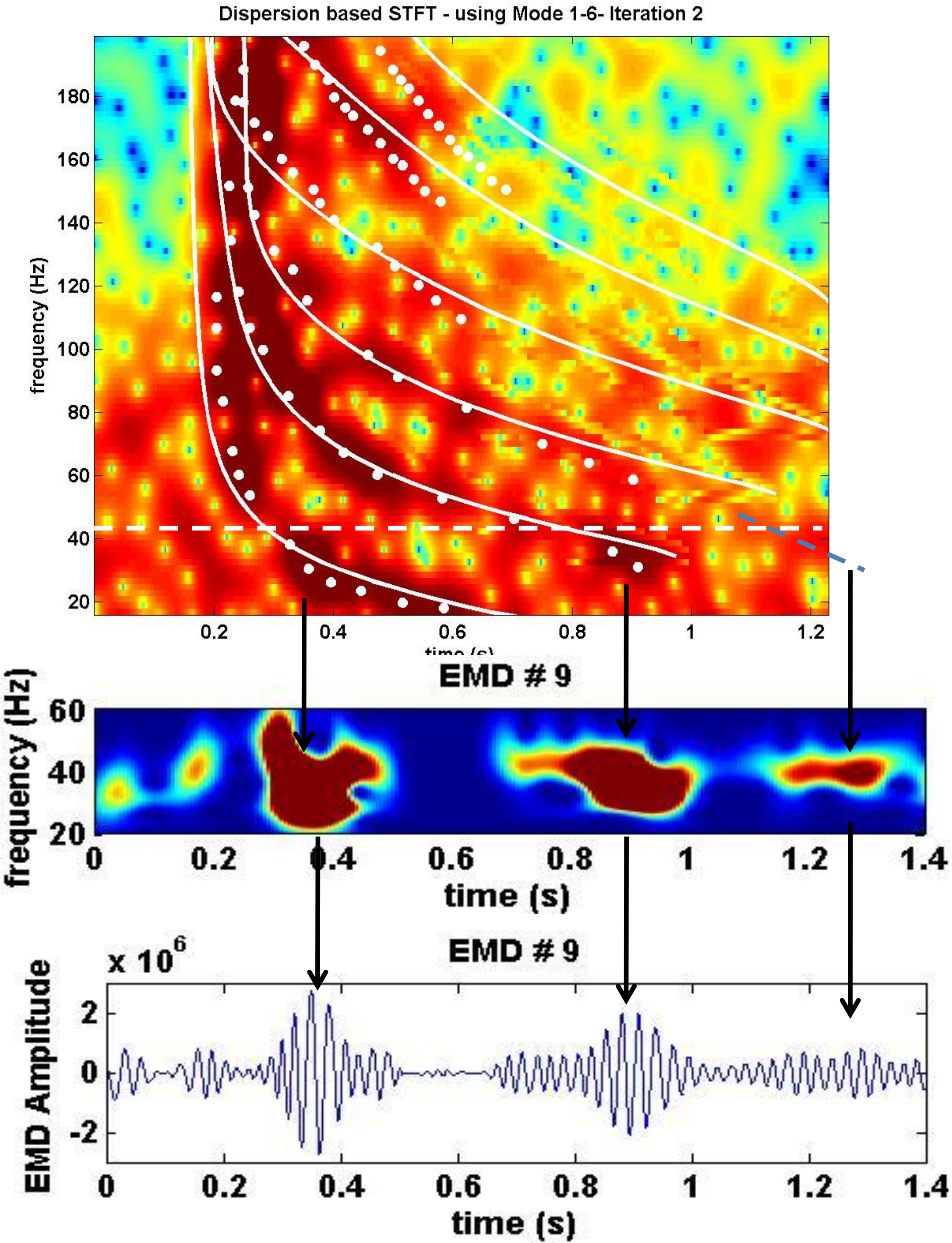
Intrinsic Mode Function (IMF) # 9

IMF # 9 – 60 to 160 Hz

Mode 1 energy(0.35 sec)

Mode 2 energy at 0.9 sec (40 Hz)

Mode 3 energy at 1.3 sec (40 Hz)



THE UNIVERSITY OF RHODE ISLAND

Summary and Future Work

- **D-STFT was applied to CSS data to improve the performance of time-frequency data.**
- **Individual EMFs provide insights into the modal arrivals at specific frequency bands.**
- **EMFs can improve the D-STFT (or wavelet) dispersion information by identifying or confirming mode arrival information especially at low frequency region.**

Questions ??