Time Warping Intro & Applications In Underwater Acoustics

時間扭換簡介及其於水中聲學之應用

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Outline

I. Why Time Warping

- What is Warping?
- Single receiver (broadband) v.s. hydrophone array (spatial diversity)

II. What is Time Warping?

- Ideal Waveguide as theory based example
- Signal Processing & Mathematics: Time Frequency analysis
- Step-by-step to isolate and retrieve individual normal mode and its modal dispersion curve by a single receiver

III. Applications of Time Warping in shallow water environment

- Active sources- geoacoustic inversion, source localization, seabed attenuation
- Passively obtained signals – Noise Cross Correlation Function

Why Time Warping ?

Warp ?

U.S. to authorize COVID-19 vaccines in coming days

By ShareAmerica - Dec 11, 2020

President Trump speaks during the Operation Warp Speed Vaccine Summit at the White House on December 8. (© Evan Vucci/AP Images)

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Operation Warp Speed

From Wikipedia, the free encyclopedia

Operation Warp Speed (**OWS**) was a public–private partnership initiated by the United States government to facilitate and accelerate the development, manufacturing, and distribution of COVID-19 vaccines, therapeutics, and diagnostics.[1][2] The first news report of Operation Warp Speed was on April 29, 2020,[3][4][5] and the program was officially announced on May 15, 2020.[1] It was headed by Moncef Slaoui from May 2020 to January 2021 and by David A. Kessler from January to February 2021.[6] At the end of February 2021, Operation Warp Speed was transferred into the responsibilities of the White House COVID-19 Response Team.[7]

The program promoted mass production of multiple vaccines, and different types of vaccine technologies, based on preliminary evidence, allowing for faster distribution if clinical trials confirm one of the vaccines is safe and effective. The plan anticipated that some of these vaccines will not prove safe or effective, making the program more costly than typical vaccine development, but potentially leading to the availability of a viable vaccine several months earlier than typical timelines.[8]

Operation Warp Speed, initially funded with about $10 billion from the CARES Act (Coronavirus Aid, Relief, and Economic Security) passed by the United States Congress on March 27,[1] was an interagency program that includes components of the Department of Health and Human Services, including the Centers for Disease Control and Prevention, Food and Drug Administration, the National Institutes of Health, and the Biomedical Advanced Research and

Operation Warp Speed

Official seal of Operation Warp Speed

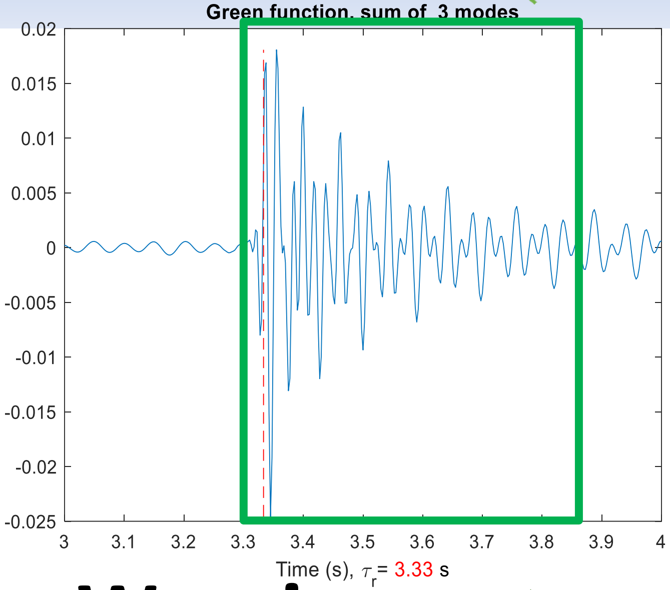
Active	May 15, 2020 – February 24, 2021 (285 days)
Disbanded	Transitioned to White House COVID-19 Response Team
Country	United States
Allegiance	United States
Part of	U.S. Department of Defense U.S. Department of Health and Human Services Other various government agencies
Engagements	Coronavirus disease 2019
Website	Coronavirus: Operation Warp Speed

Warping on Signals

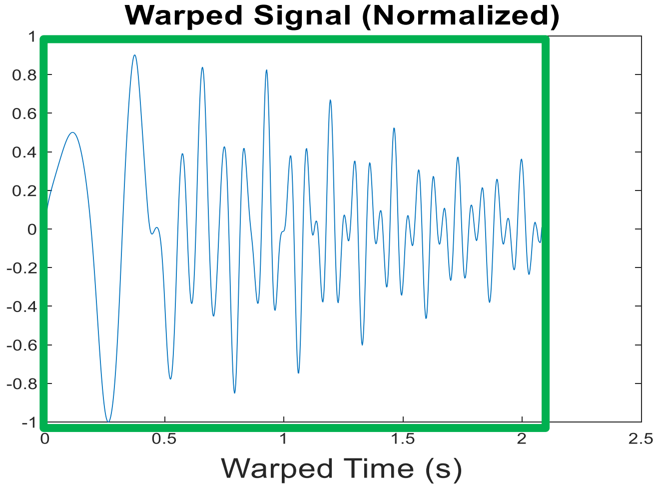
Disney

Warping

R. G. Baraniuk and D. L. Jones, "Unitary equivalence: A new twist on signal processing," *IEEE transactions on signal processing*, vol. 43, no. 10, pp. 2269-2282, 1995

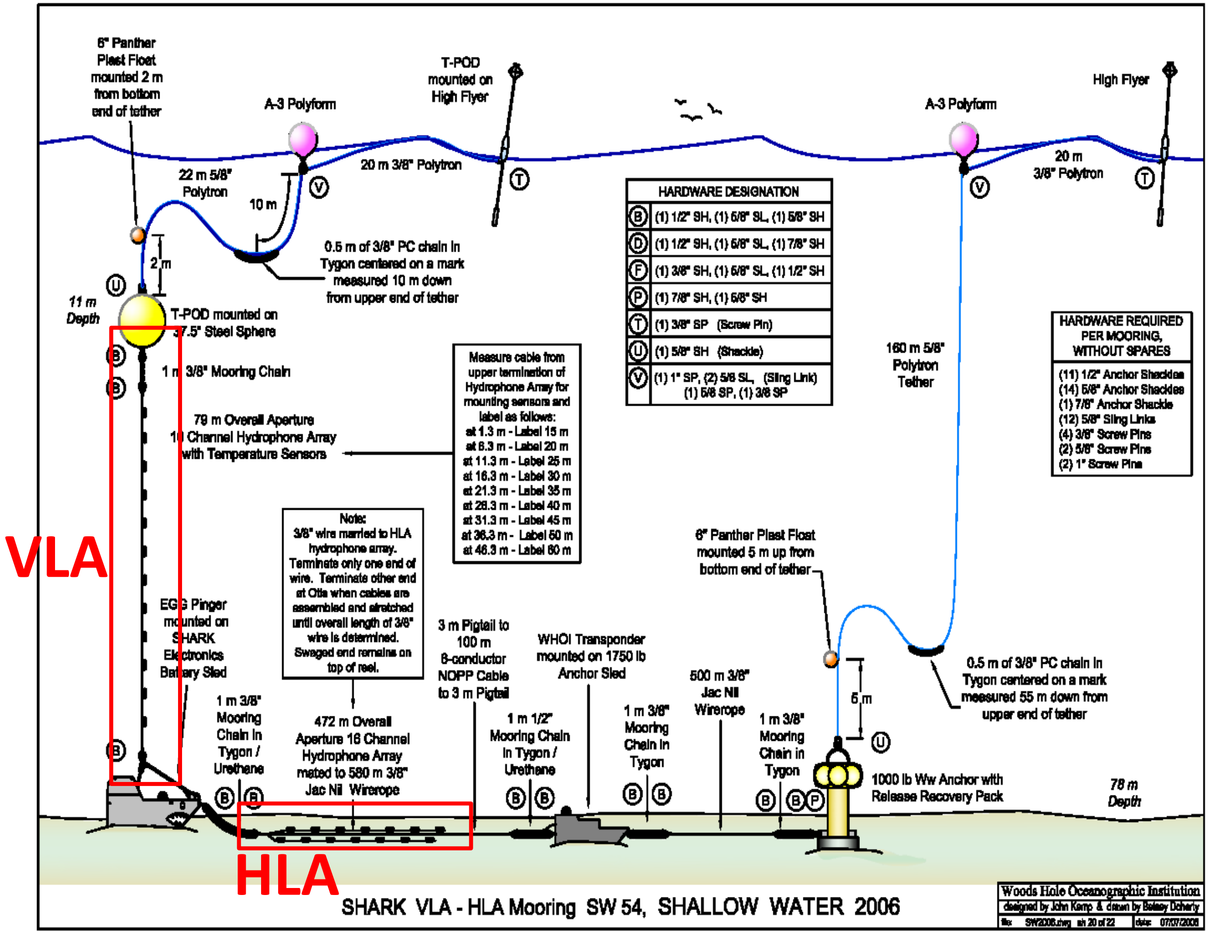


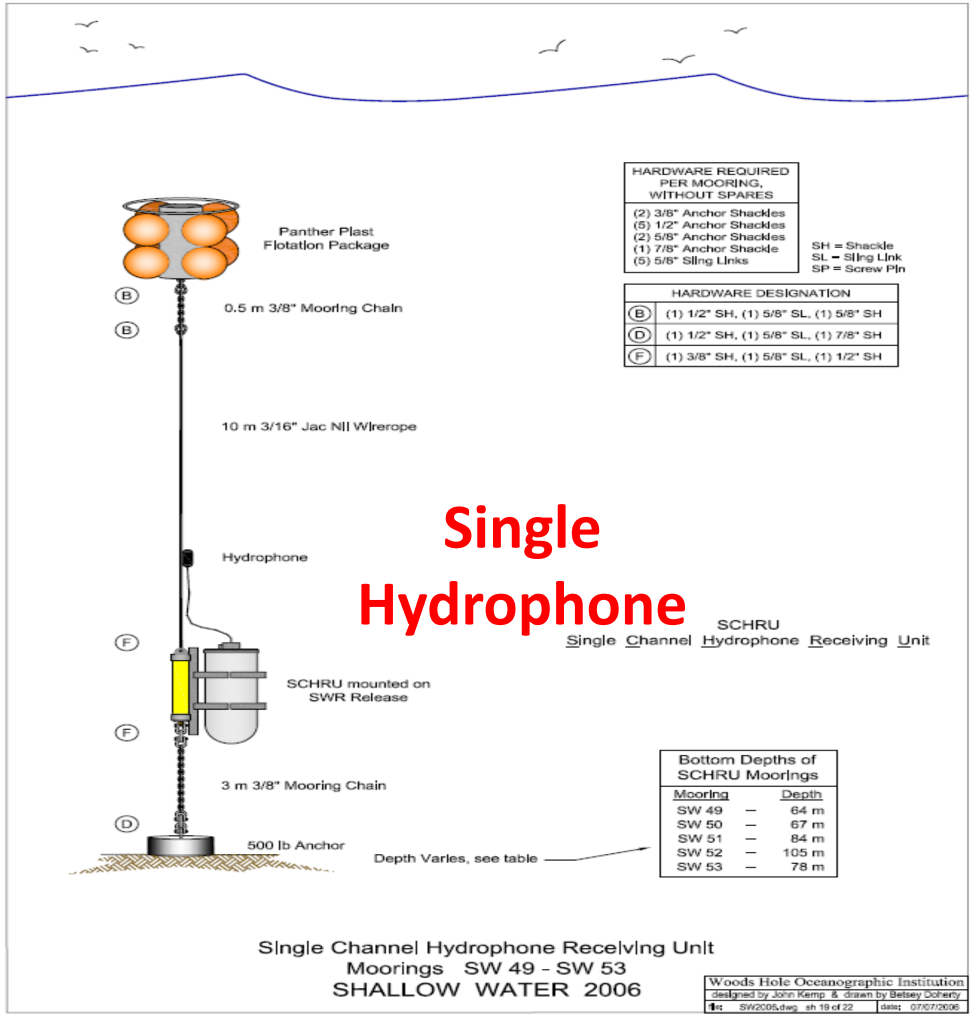
Warping



Why Time Warping in Underwater Acoustics?

Array (spatial diversity) VS Single Hydrophone (broadband frequency)





Arthur E. Newhall et al. "Acoustic and Oceanographic Observations and Configuration Information for the WHOI Moorings from the SW06 Experiment." May 2009 Technical Report

Time Warping : Math Background

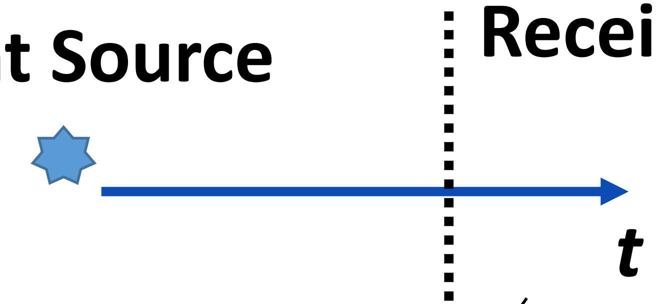
sound speed = *c*

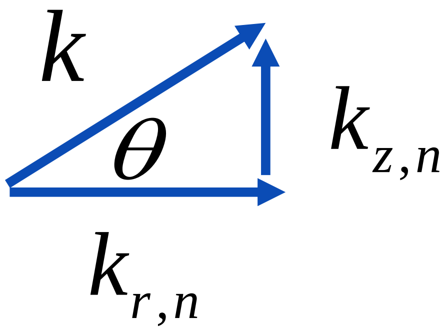
Phase

$$\phi_n(t) = \omega t - k_{r,n} r$$

Point Source

Received signal





$$t_r = r/c$$

$$k_{r,n} = k\cos\theta = k\frac{\sqrt{k^2 - k_{z,n}^{\;2}}}{k} = k\sqrt{1-\left(\frac{f_n}{f}\right)^2}$$

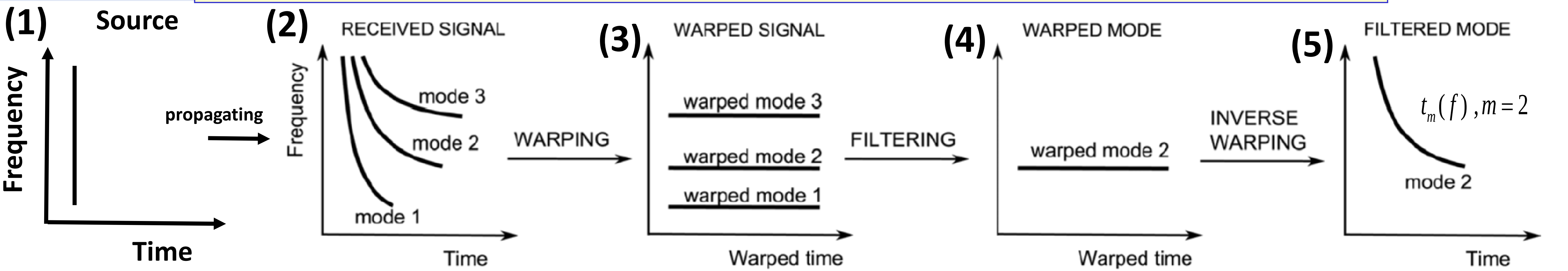
$$c_{g,n}(f) = c\cos\theta = c\sqrt{1-\left(\frac{f_n}{f}\right)^2} = \frac{r}{t}$$

$$\omega t - k_{r,n} r = \frac{2\pi f_n}{\sqrt{1-\left(\frac{r}{ct}\right)^2}}\left(t - \frac{r^2}{c^2 t}\right) = 2\pi f_n\sqrt{t^2 - t_r^2}$$

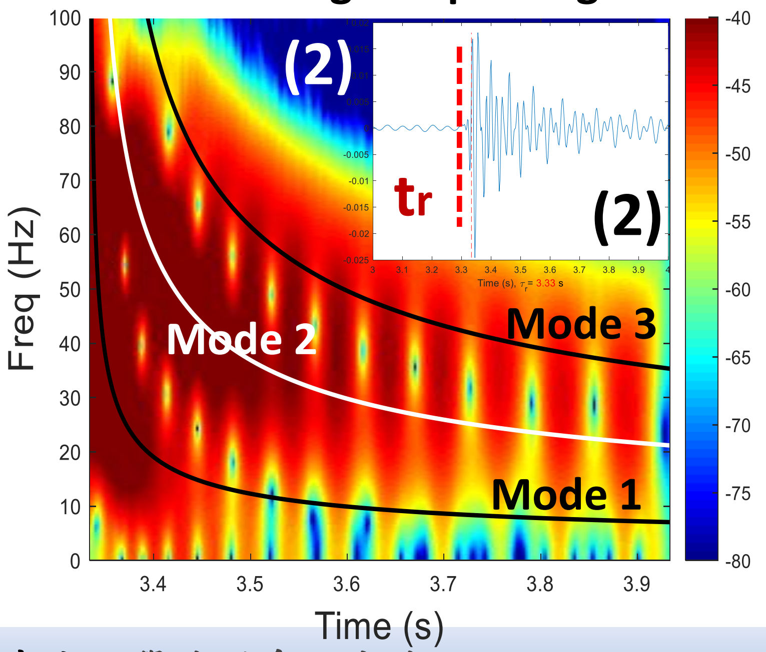
Linearize Phase in warped domain ➡ $w(t) = \sqrt{t^2 - t_r^2}$

Time Warping : Modal Filtering

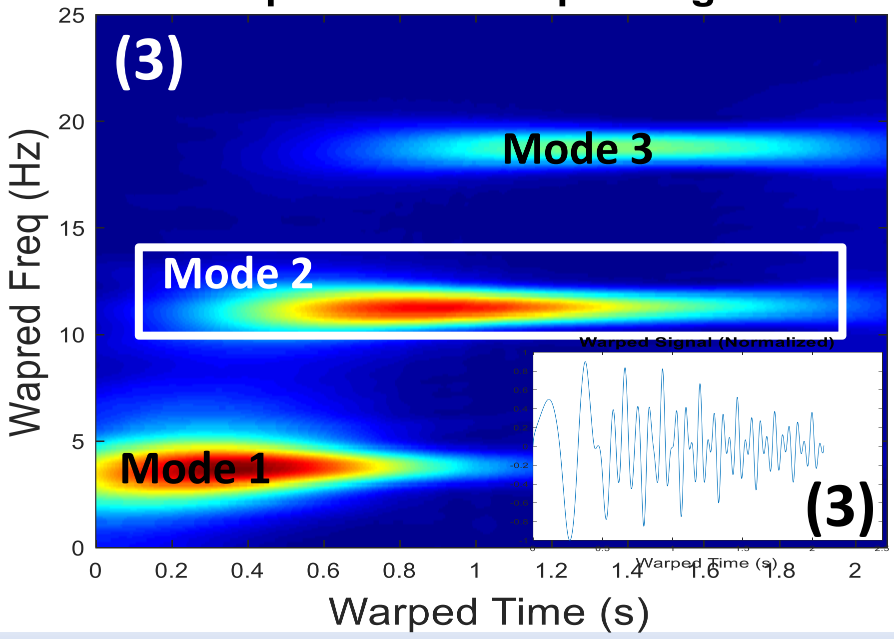
Julien Bonnel et al“Nonlinear time-warping made simple: A step-by-step tutorial on underwater acoustic modal separation with a single hydrophone” *J. Acoust. Soc. Am 147,1897 (2020)*



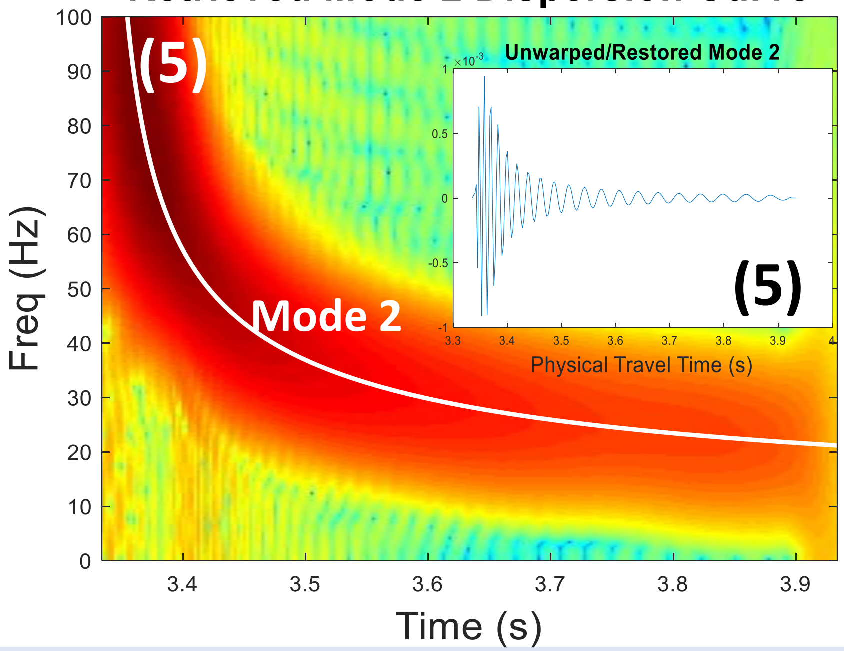
Received Signal Spectrogram



Warped Domain Spectrogram

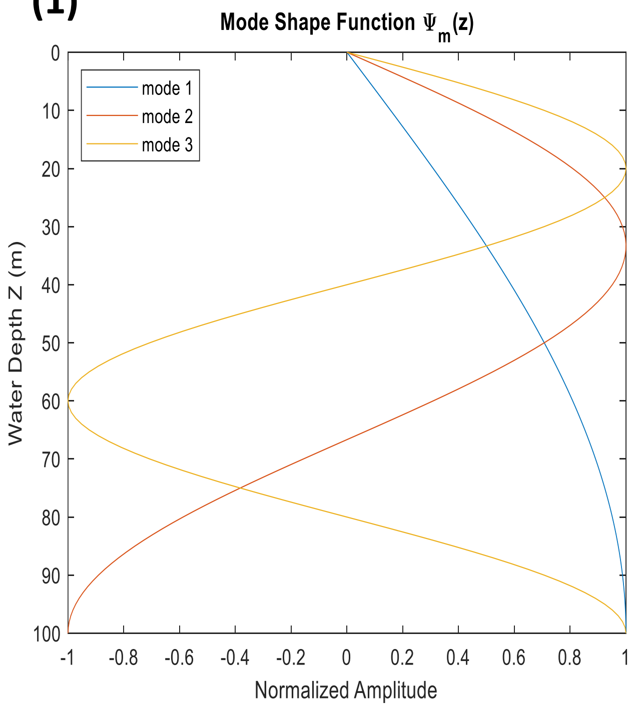


Retrieved Mode 2 Dispersion Curve



Generating Ideal Waveguide: Frequency Domain

(1)



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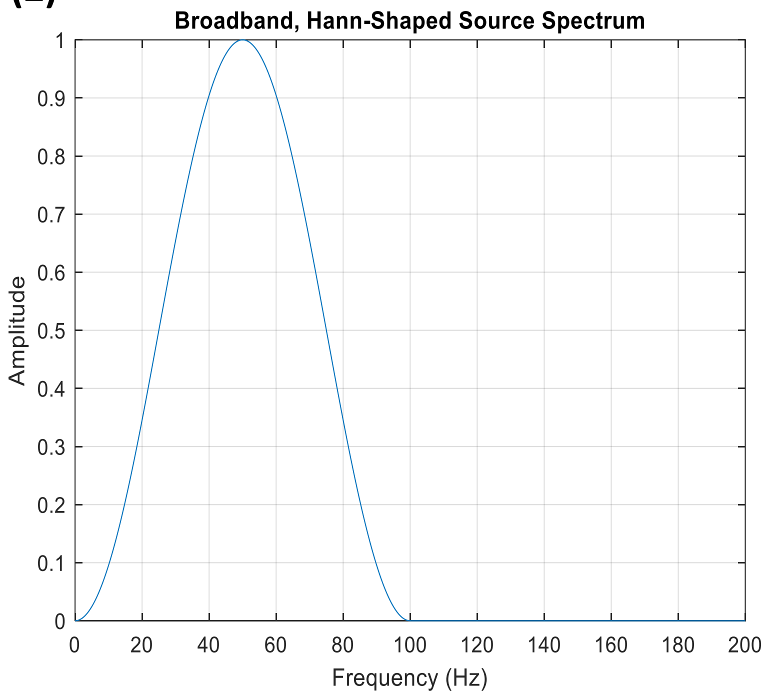

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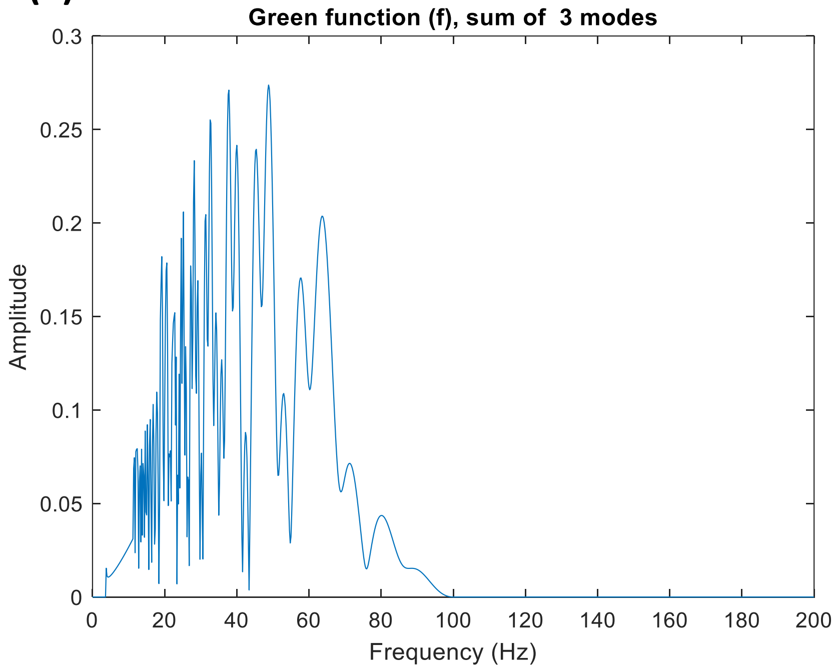


$$G(z_1, z_2, r, \omega) = \frac{-i}{4} \sum_m \psi_m(z_{source}) \psi_m(z_{receiver}) H_0^{(1)}(\xi_m r)$$

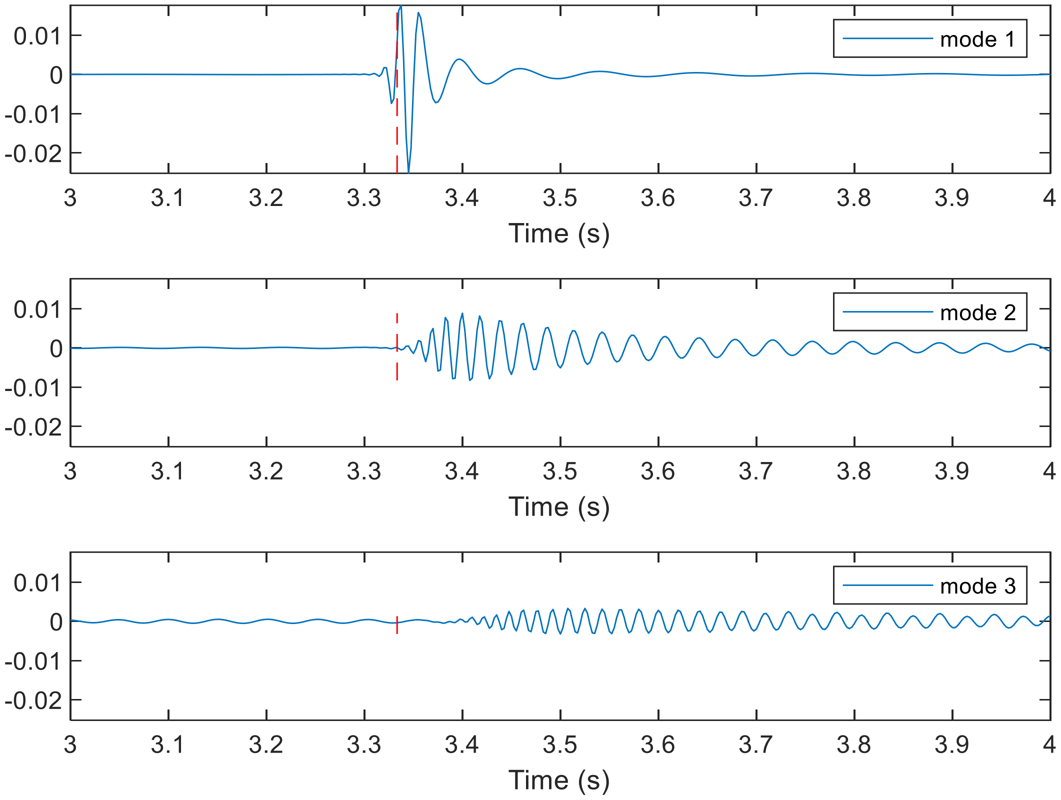
$$\psi_m(z) = \sqrt{\frac{2\rho_w}{H}} \sin\left(\frac{\pi z}{2H}(2m-1)\right)$$

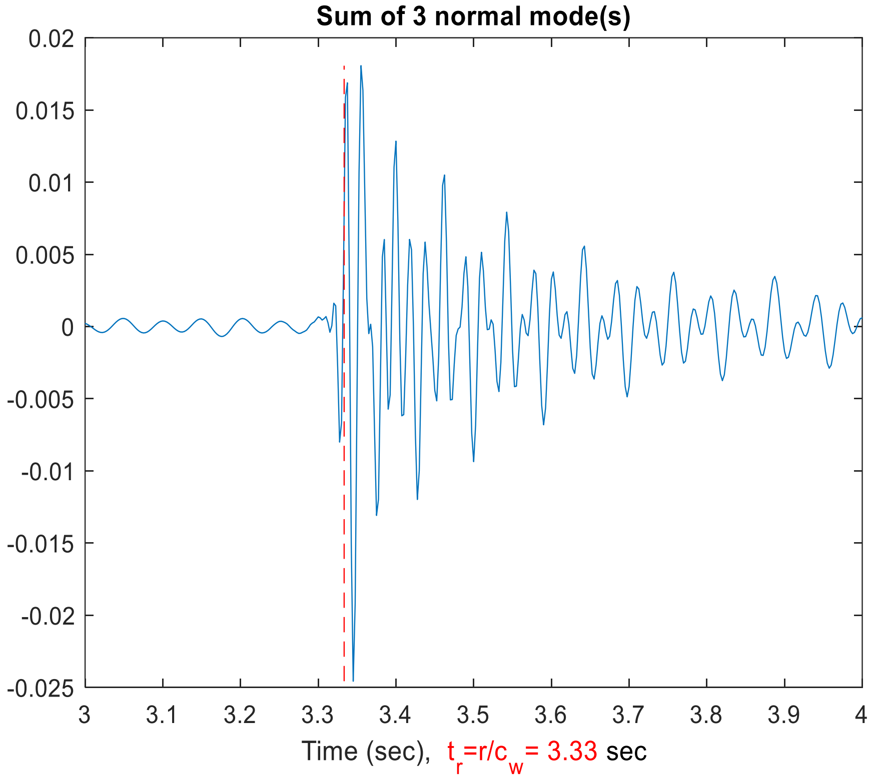
$$\xi_m = \sqrt{\frac{\omega^2}{c_w^2} - \frac{\pi^2 (2m-1)^2}{4H^2}}$$

$$H_0^{(1)}(\xi_m r) \approx \sqrt{\frac{2}{\pi \xi_m r}} \exp\left(i\xi_m r - \frac{i\pi}{4}\right)$$

Generating Ideal Waveguide: Time Domain

Time Warping begins at $t_r = r/c_w = 3.33$ (s)



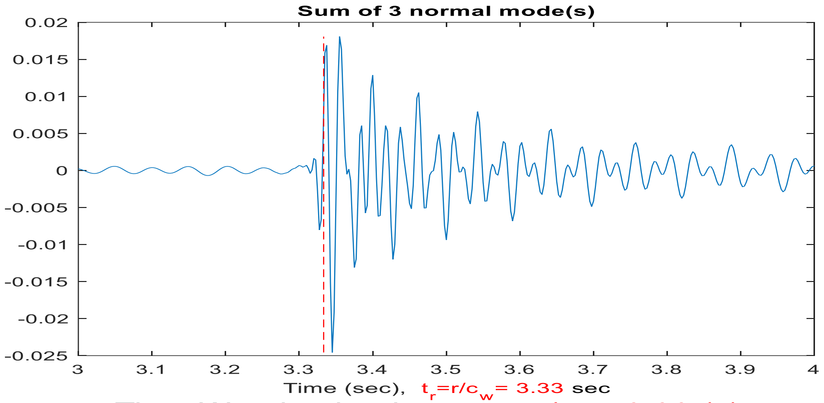


Inverse FT on $G(z_1, z_2, r; \omega) = \frac{-i}{4} \sum_m \psi_m(z_{source}) \psi_m(z_{receiver}) H_0^{(1)}(\xi_m r)$

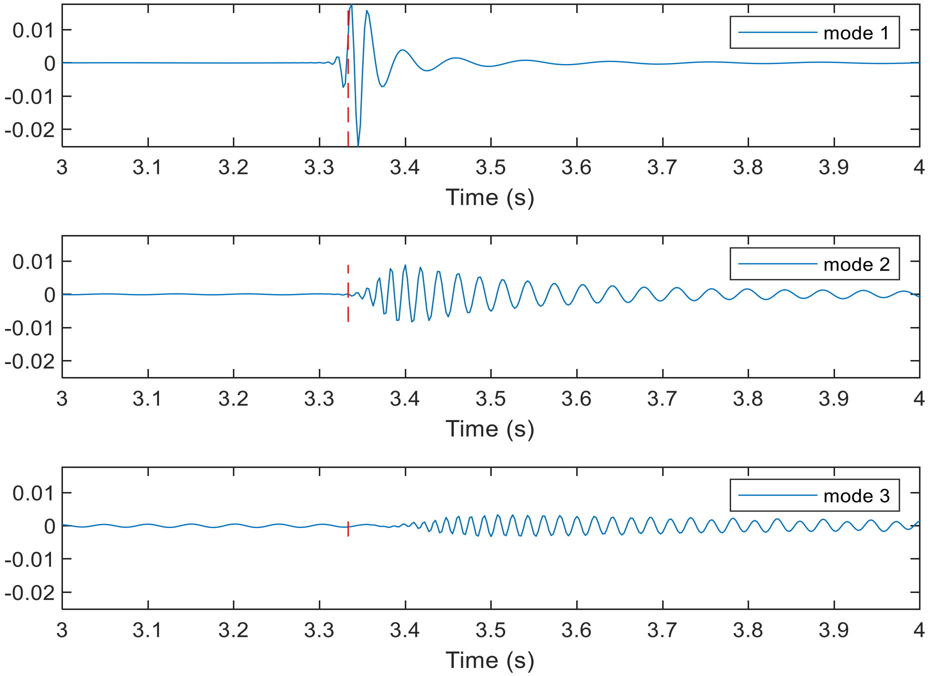
ROC Naval Academy

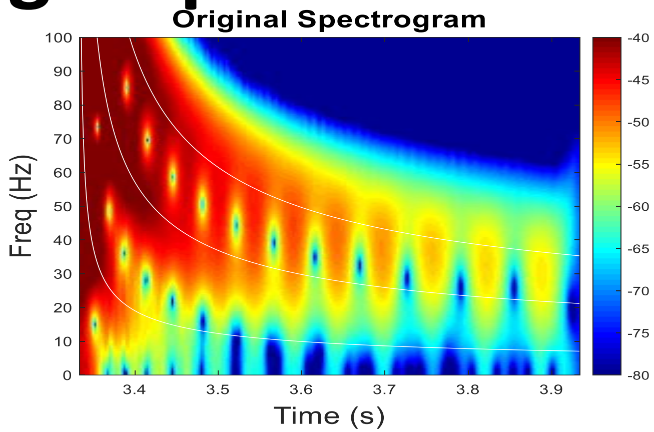
Building Spectrogram

~~measuring dispersion curves~~



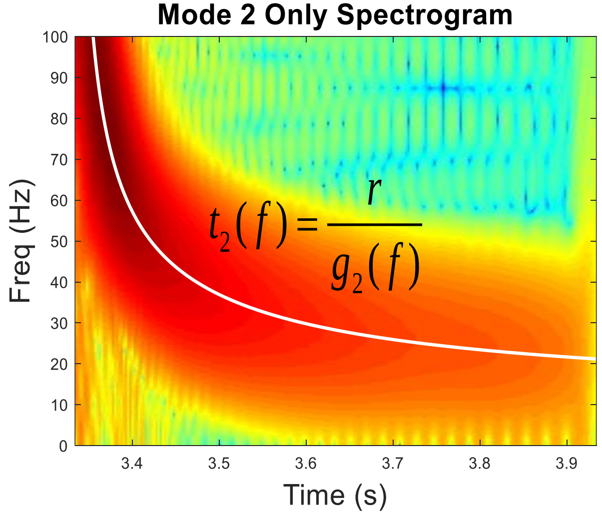
Time Warping begins at $t_r=r/c_w$= 3.33 (s)

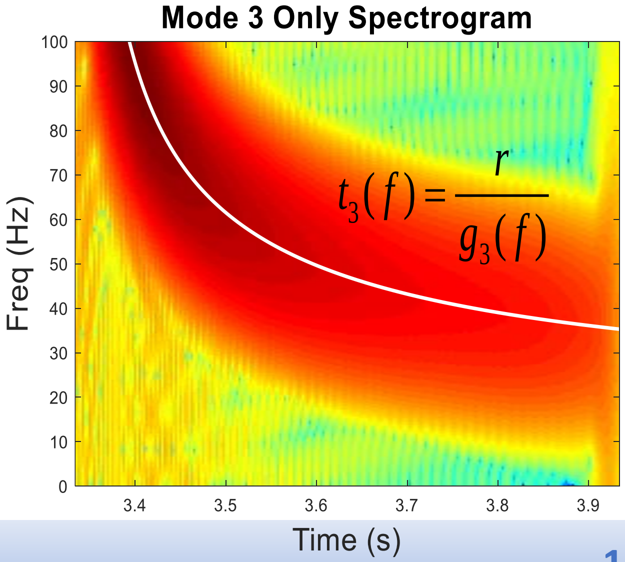




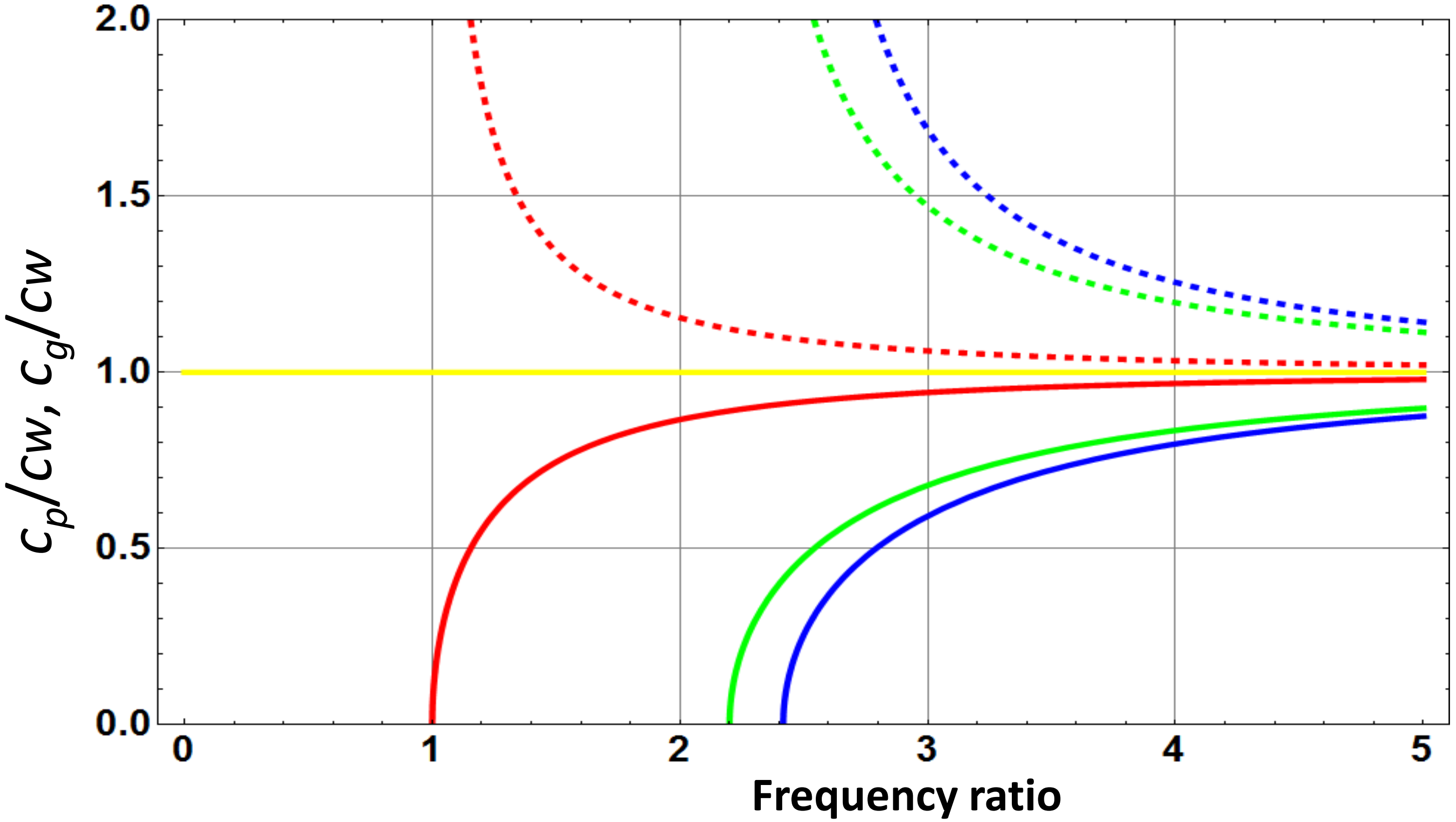
$$|\mathrm{STFT}_Y(t,f)|^2$$

$$\mathrm{STFT}_Y(t,f) = \int_{-\infty}^{\infty} y(\tau)h^*(\tau - t)e^{-i2\pi f\tau}d\tau.$$



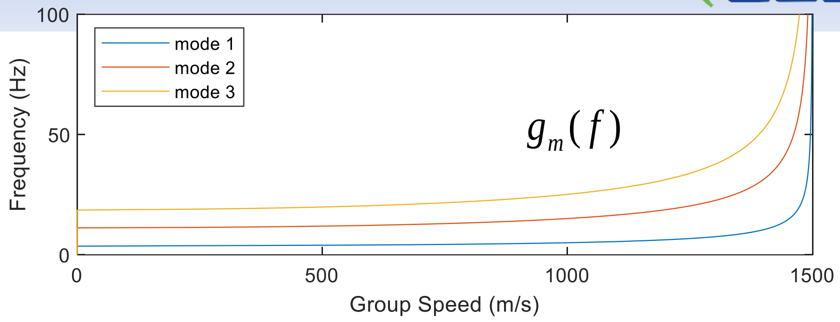


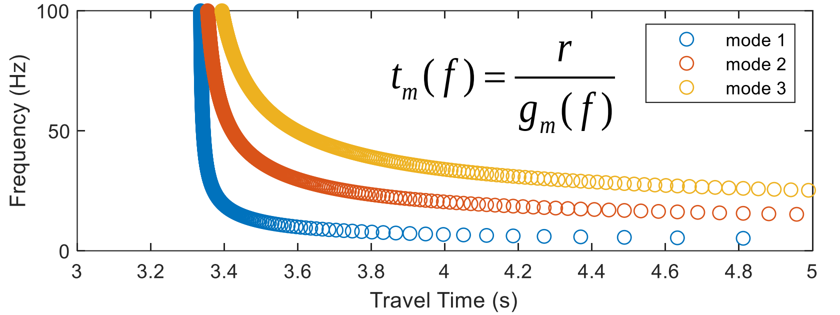
Time(Group Speed)-Frequency Analysis
Dispersion Curves

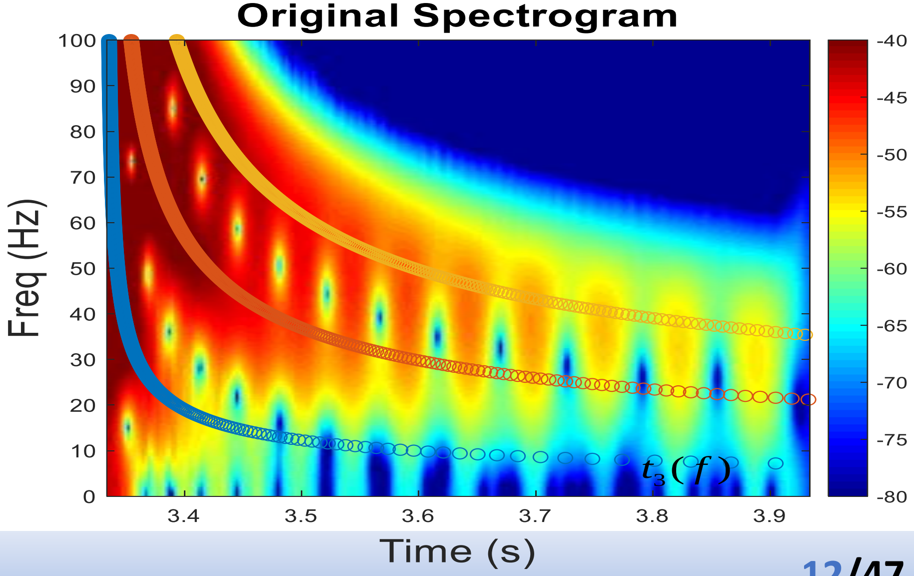


$$v_m(\omega)=\frac{\omega}{\xi_m}=c_w\left(1-\frac{\pi^2(2n-1)^2c_w^2}{4H^2\omega^2}\right)^{-1/2},\quad g_m(\omega)=\frac{\partial\omega}{\partial\xi_m}=c_w\left(1-\frac{\pi^2(2n-1)^2c_w^2}{4H^2\omega^2}\right)^{1/2}$$

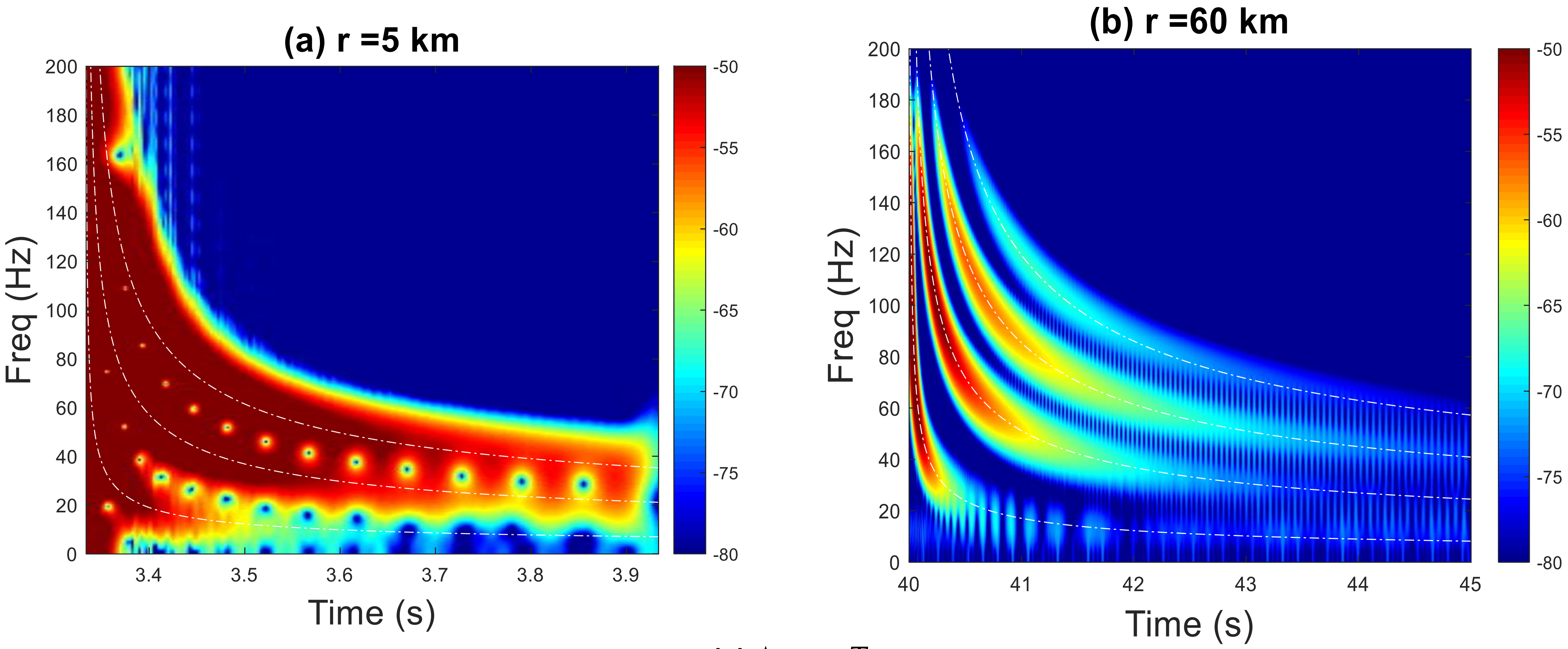
Group Speed g_m contains environmental information, H, C_w, including seabed properties in real environment







Modal Separation Restriction



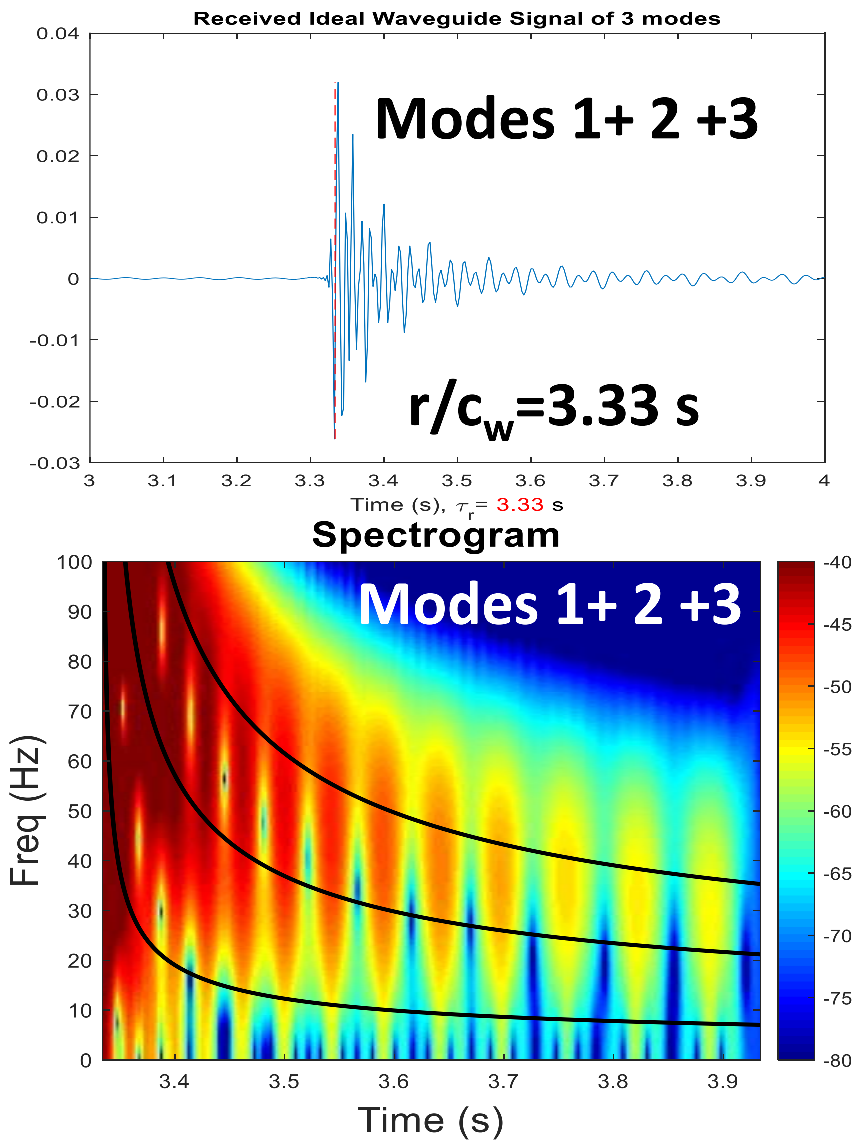
$$t_m(f) = \frac{r}{g_m(f)}$$

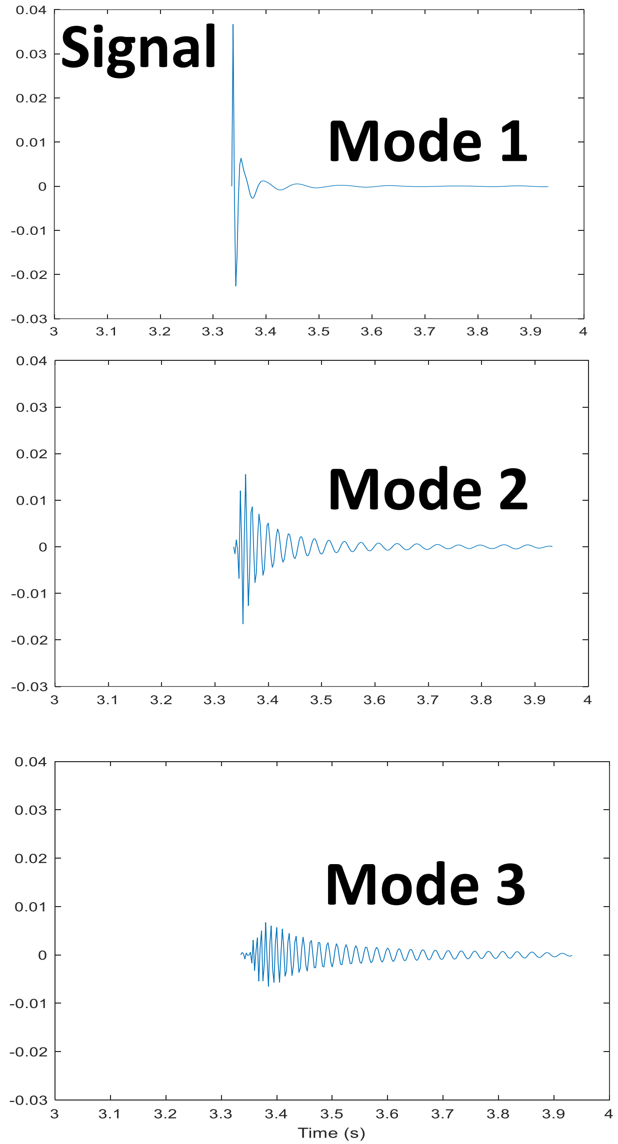
(1) $\Delta t_{\min} > T_h$

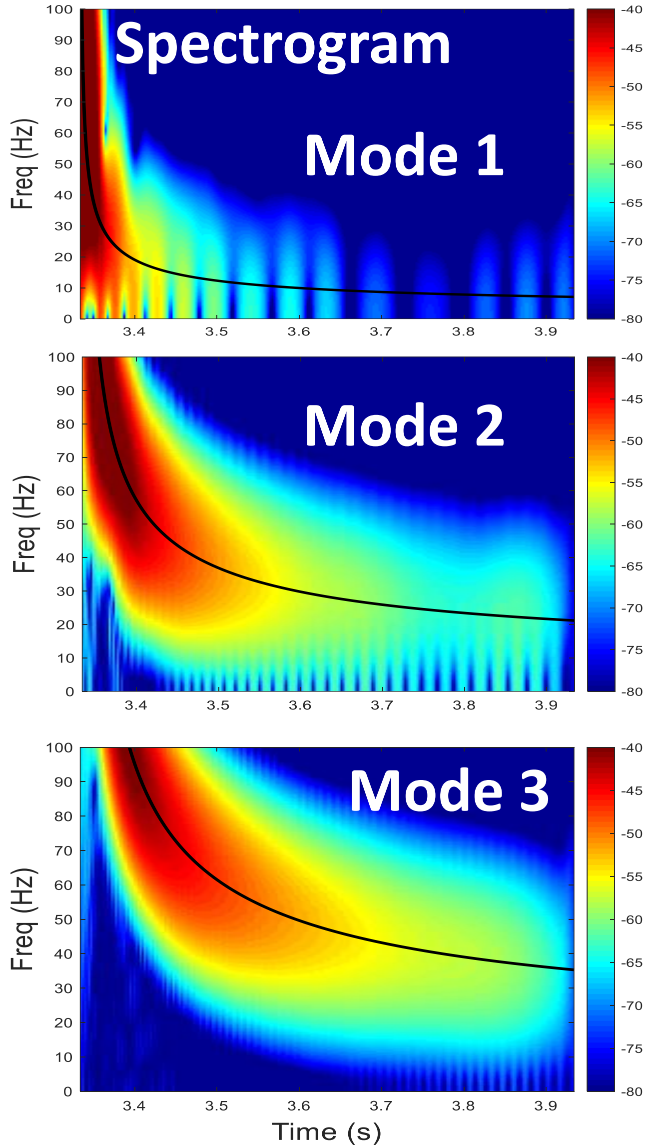
(2) $\Delta f_{\min} > \alpha / T_h,\ \alpha = 4$

(3) $\Delta t_{\min} > \dfrac{\alpha}{\Delta f_{\min}},\ \alpha = 4$

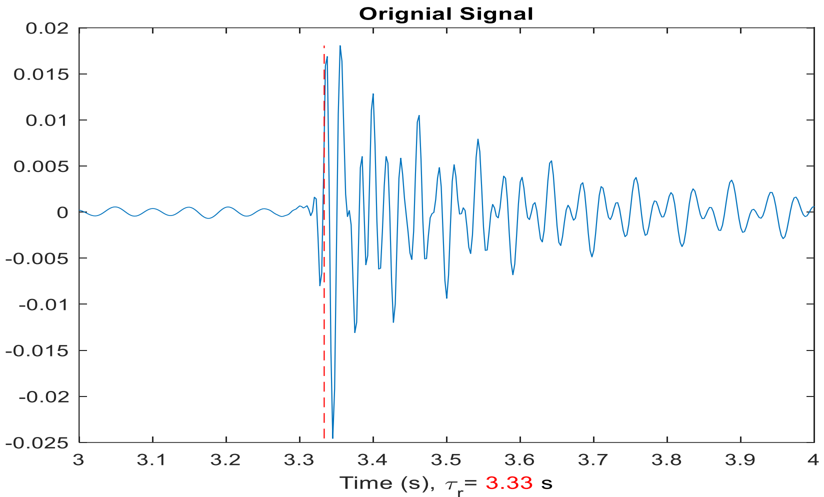
Objective of Time Warping





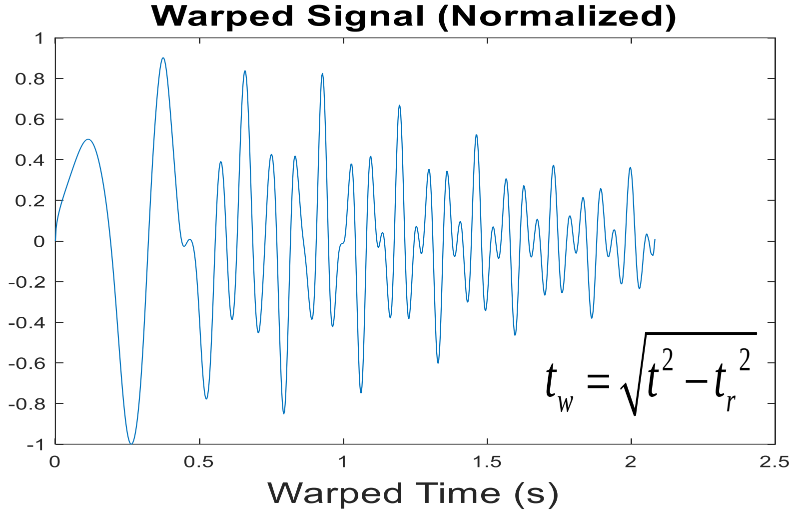


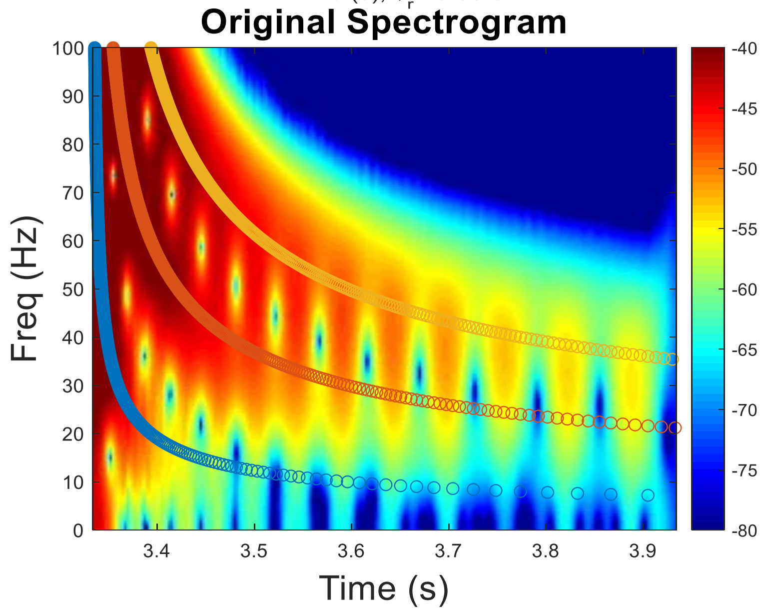
Time Warping: Quick View



$$w(t) = \sqrt{t^2 + t_r^2}$$

Time Warping



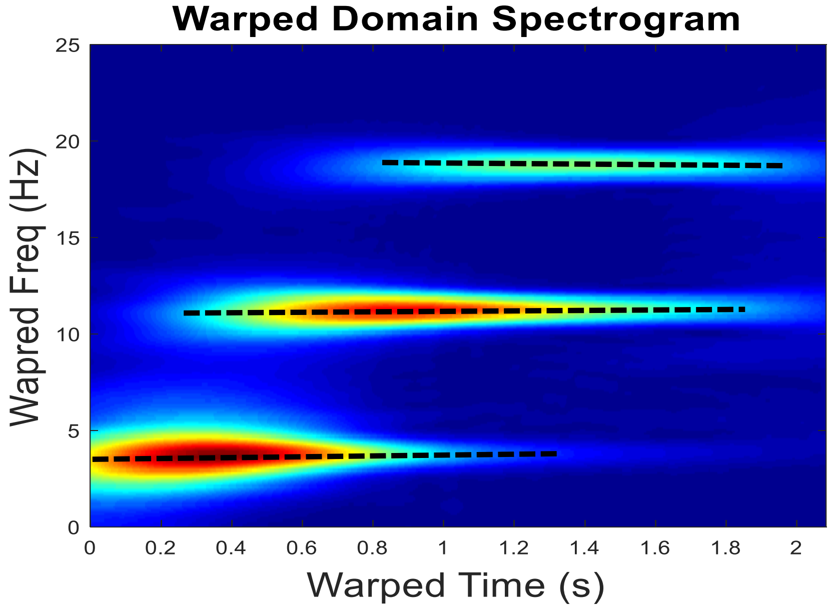


$$f_{w,m} = f_m(t)\sqrt{1 - \left(\frac{t_r}{t}\right)^2}$$

$$= F_m = \frac{2m-1}{4H} C_w$$

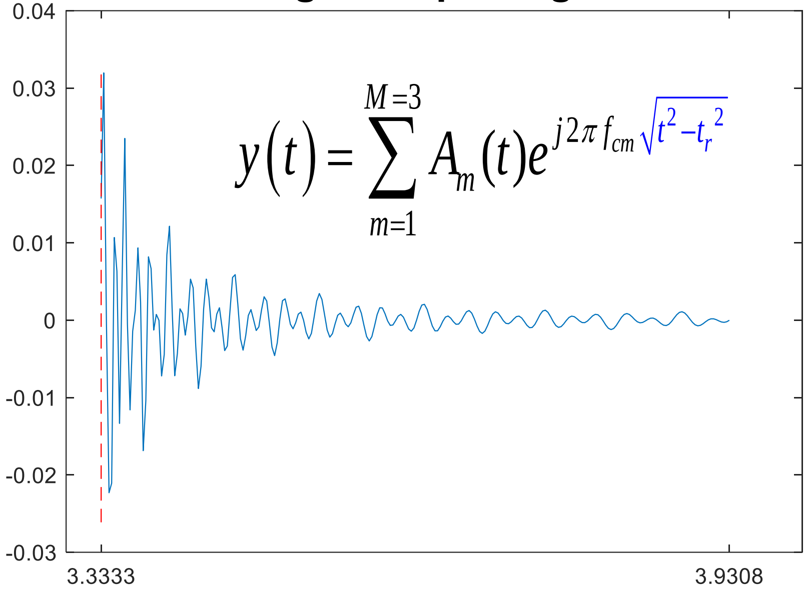
$$H = 100m; \ C_w = 1500m/s$$

$$F_1 = 3.75; \ F_2 = 12.5; \ \ F_3 = 18.75 \ Hz$$



II. Time Warping: Theory

Original Input Signal



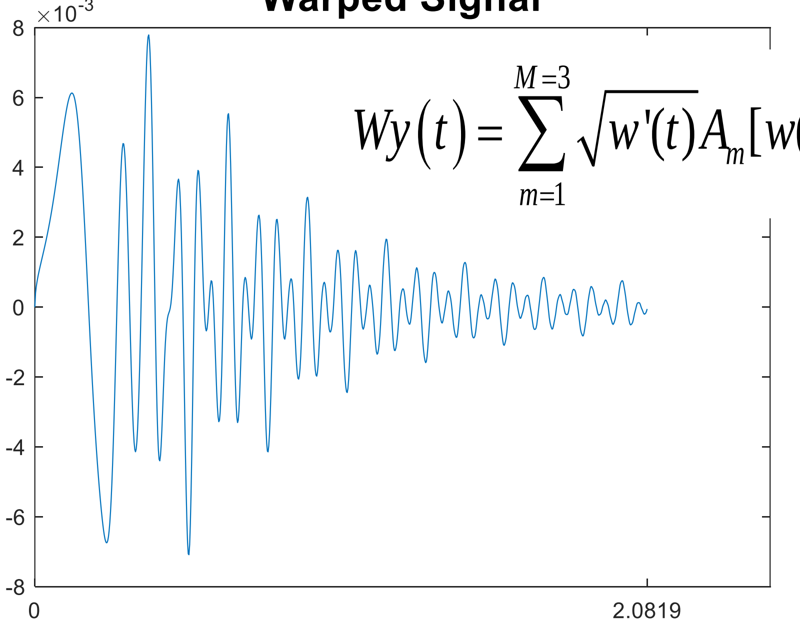
$$y(t)=\sum_{m=1}^{M=3} A_m(t)e^{j2\pi f_{cm}\sqrt{t^2-t_r^2}}$$

Time (s), t_r = 3.33 s

$$t_w=\sqrt{t^2-t_r^{\,2}}$$

$$Wy(t)=\sqrt{|w'(t)|}\,y\left[w(t)\right]$$

Warped Signal



$$Wy(t)=\sum_{m=1}^{M=3}\sqrt{w'(t)}A_m[w(t)]e^{j2\pi f_{cm}t_w}$$

Warped Time (s)

$$\Phi_m(t)=\zeta_{rm}(t)r \qquad \Phi^{id}{}_m(t)=2\pi f_{cm}\sqrt{t^2-t_r^{\,2}}$$

$$t_r=\frac{r}{c_w} \qquad \Phi^{id}{}_m(t)\rightarrow\Phi^{id}{}_m(t_w)=2\pi f_{cm}t_w$$

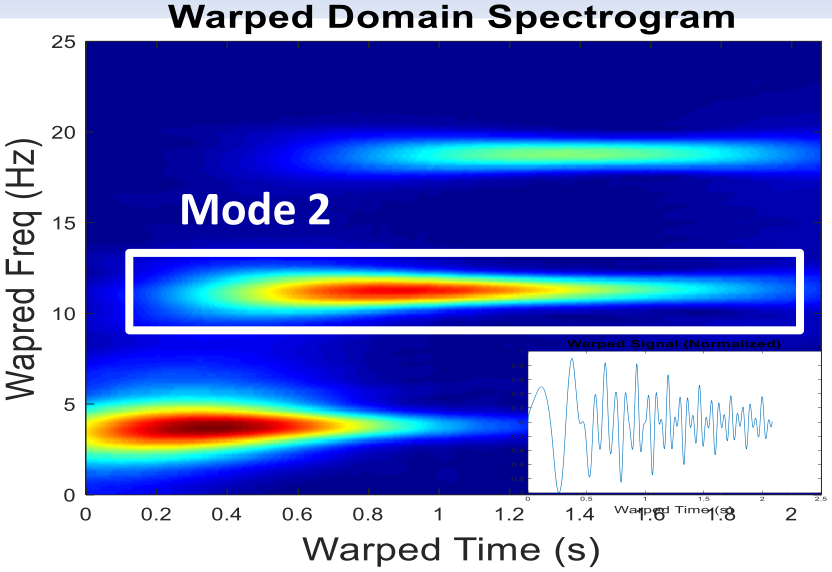
Warping Operator $w(t)=\sqrt{t^2+t_r^{\,2}}$

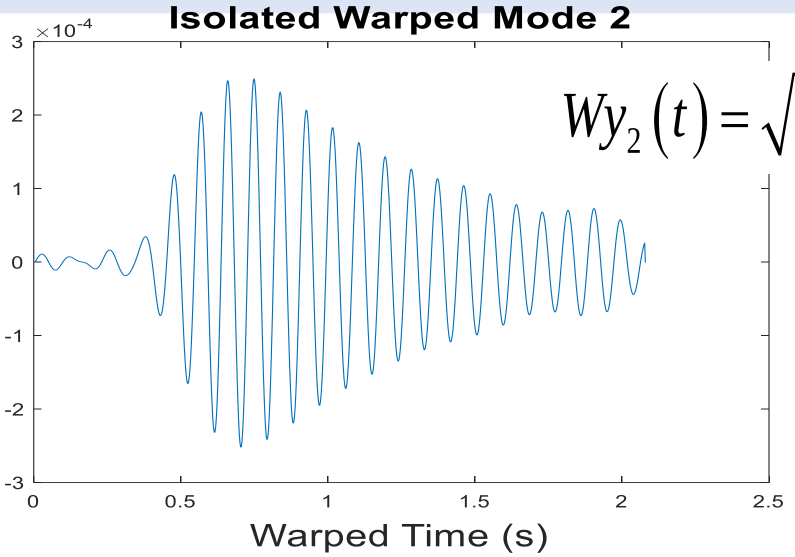
Unwarping Operator $w^{-1}(t)=\sqrt{t^2-t_r^{\,2}}$

$$W^{-1}Wy(t)=WW^{-1}y(t)=y(t)$$

Julien Bonnel, Barbara Nicolas, Jerome I. Mars and Shane C. Walker "Estimation of modal group velocities with a single receiver for geoacoustic inversion in shallow water" *J. Acoust. Soc. Am 128, 719-727(2010)*

II. Modal Separation by Time Warping

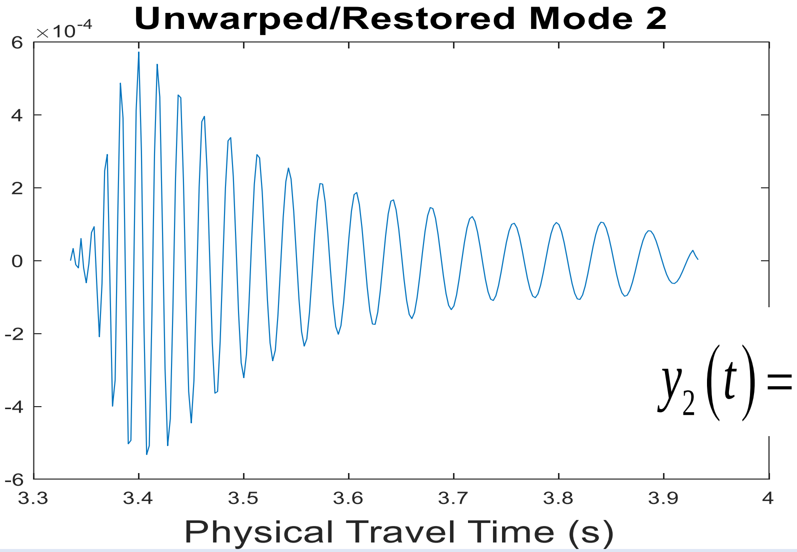




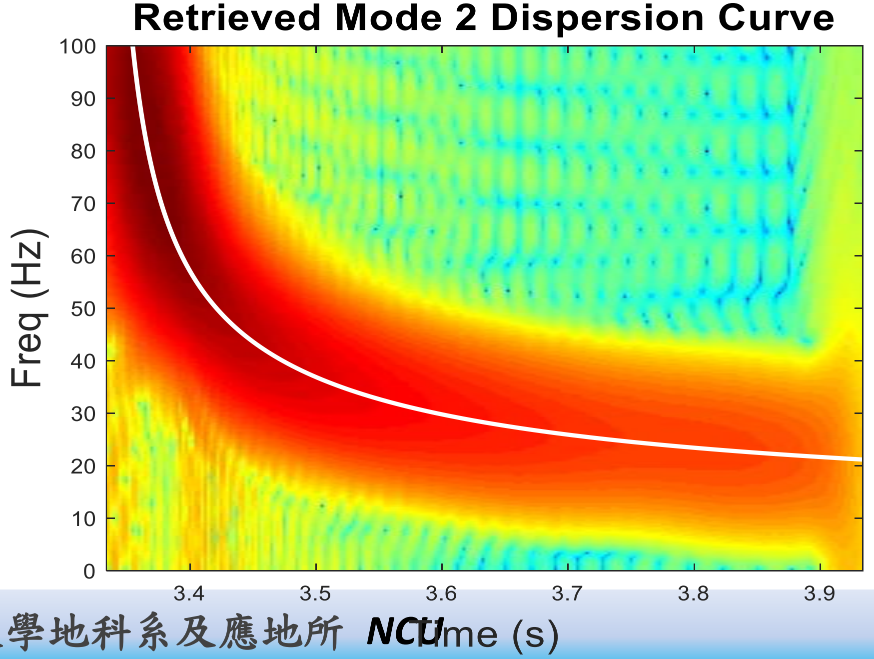
$$Wy_2(t) = \sqrt{w'(t)}A_2[w(t)]e^{j2\pi f_{c,2}t_w}$$

$$w^{-1}(t) = \sqrt{t^2 - t_r^2}$$

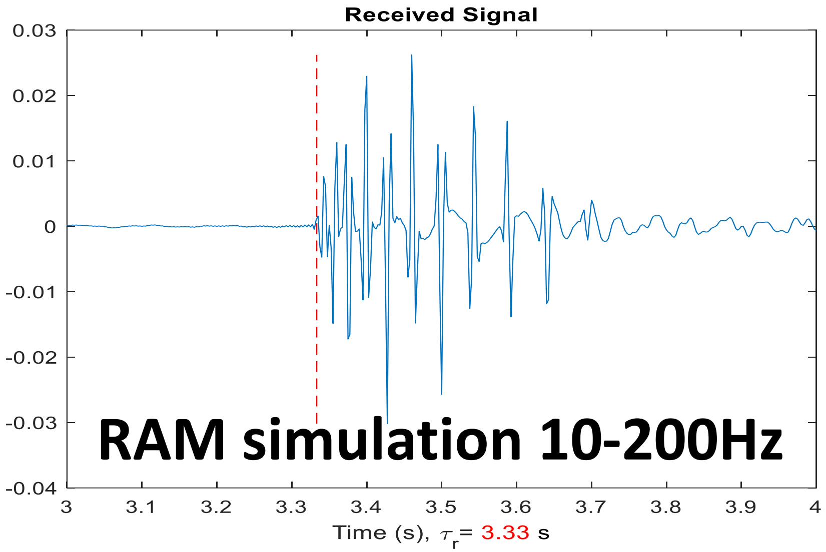
Unwarping Operator

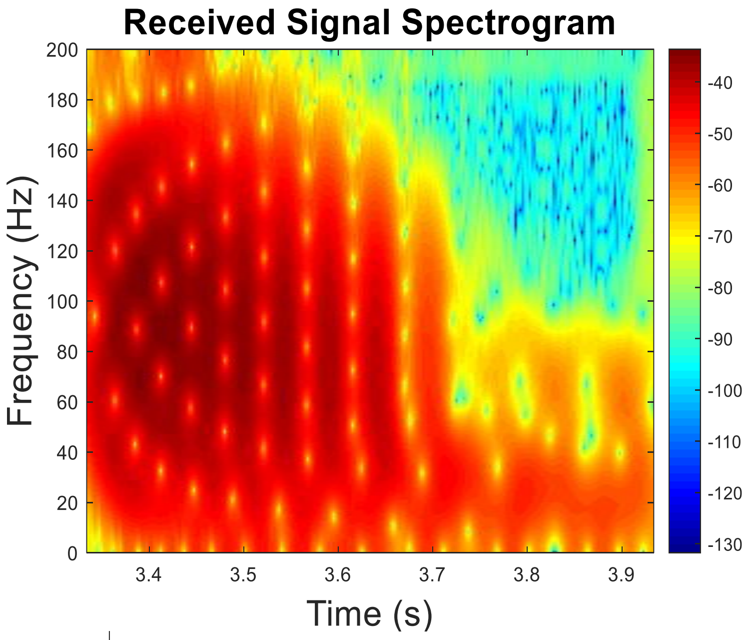


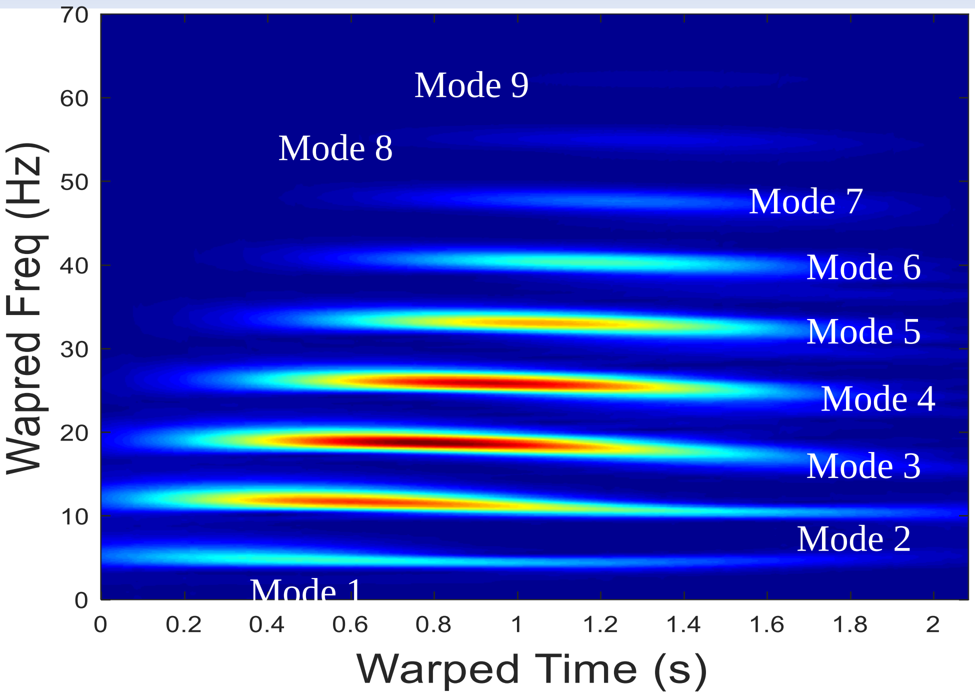
$$y_2(t) = A_2(t)e^{j2\pi f_{c,2}\sqrt{t^2 - t_r^2}}$$

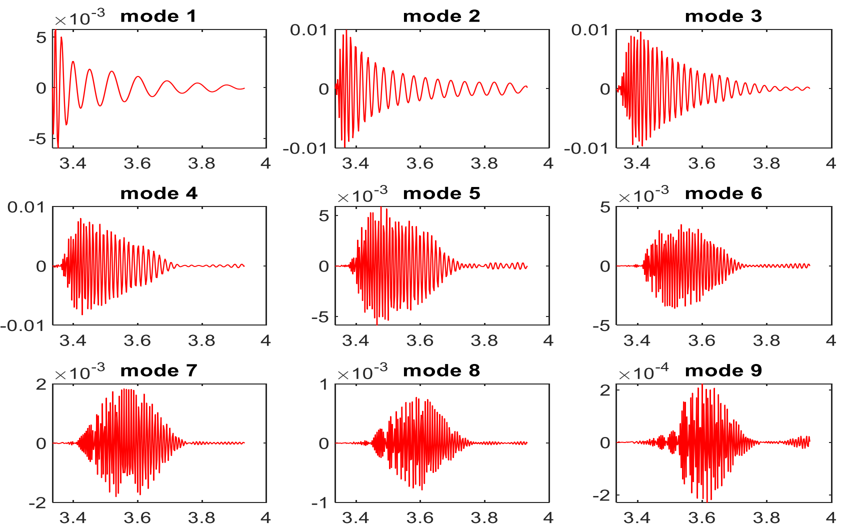


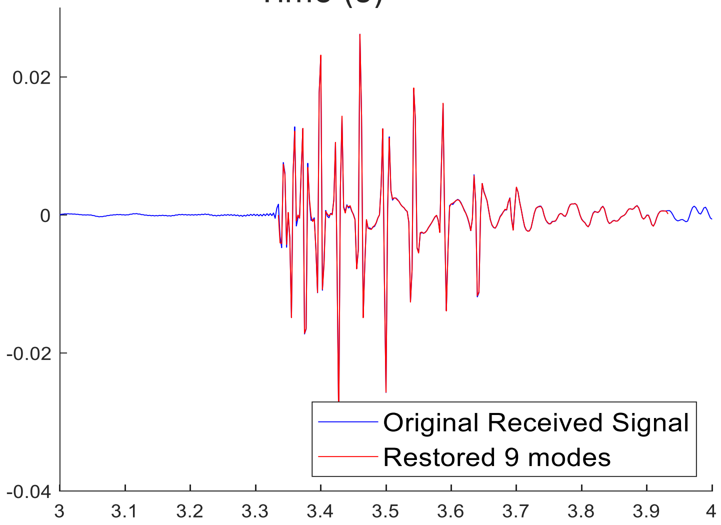
Time Warping + RAM (half-space Pekeris waveguide)

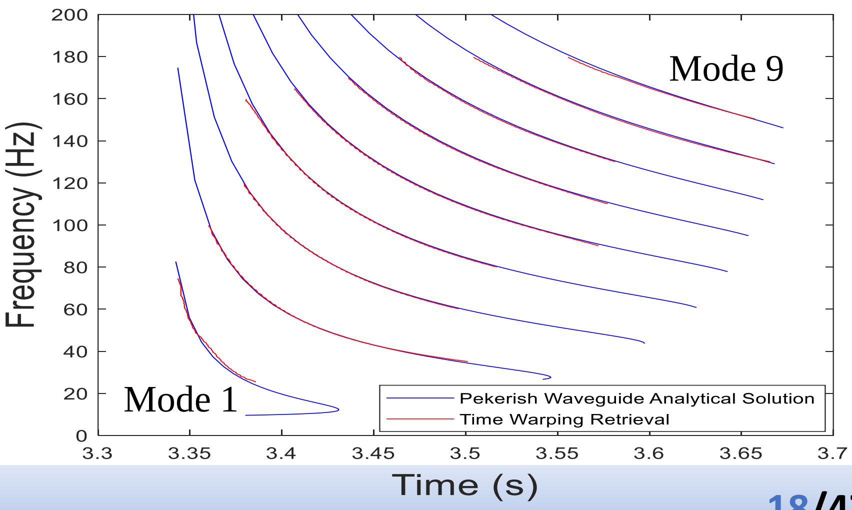






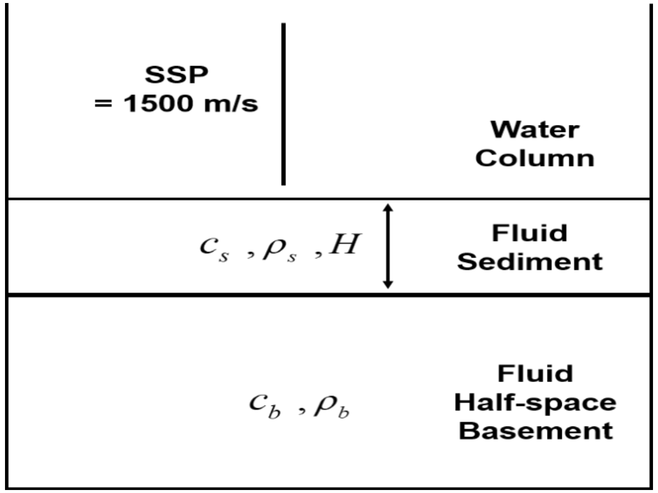


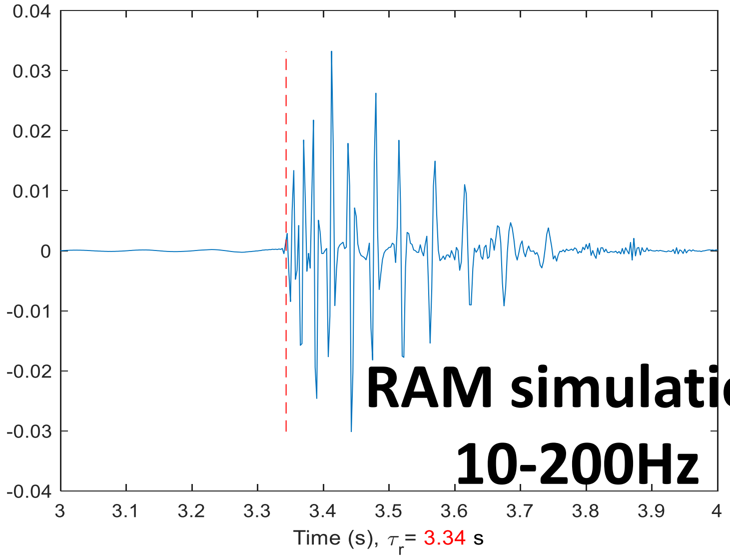




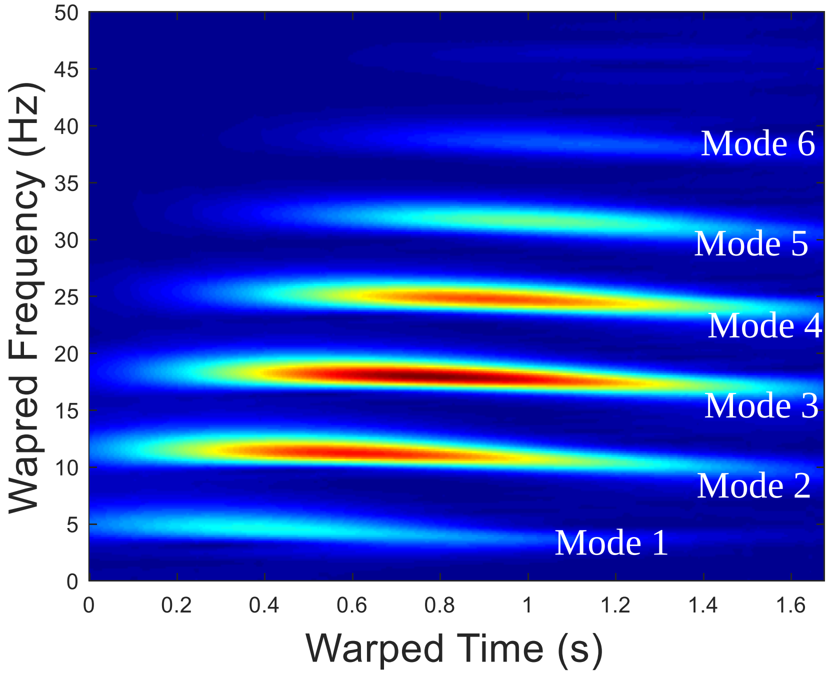
Time Warping + RAM + KRAKEN (sediment)

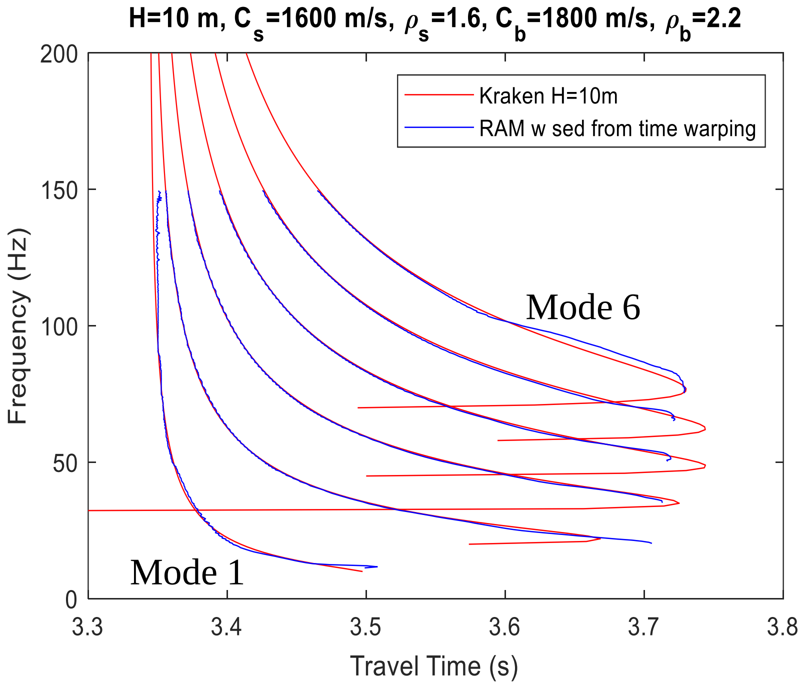
Geoacoustic Model





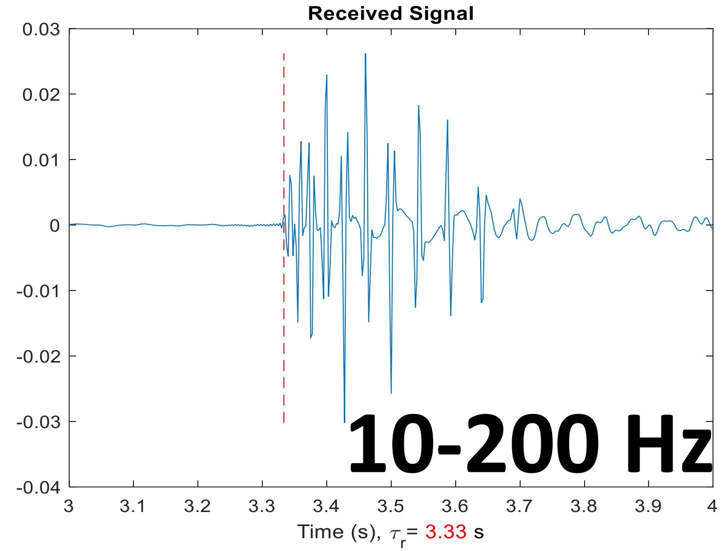
RAM simulation
10-200Hz

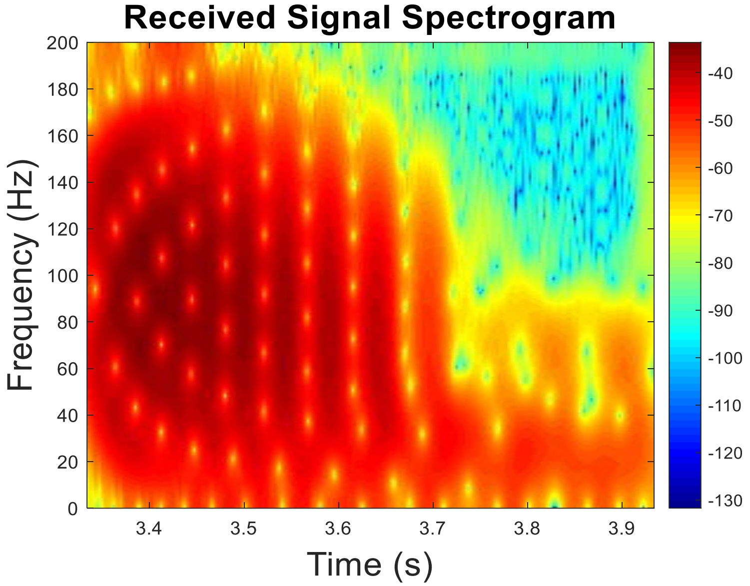


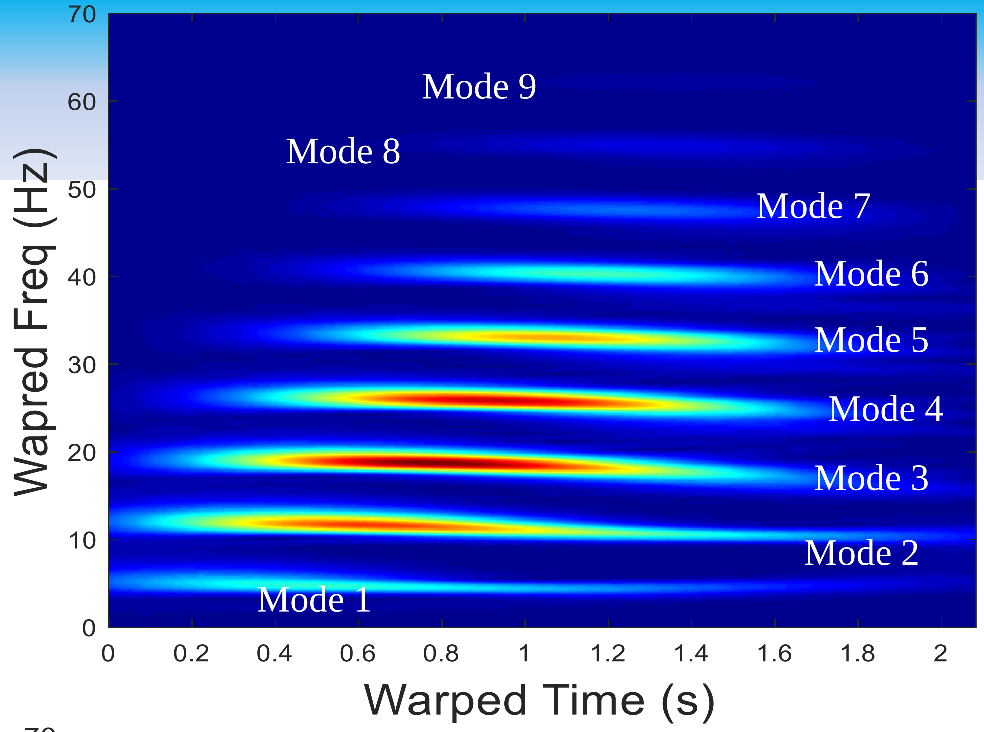


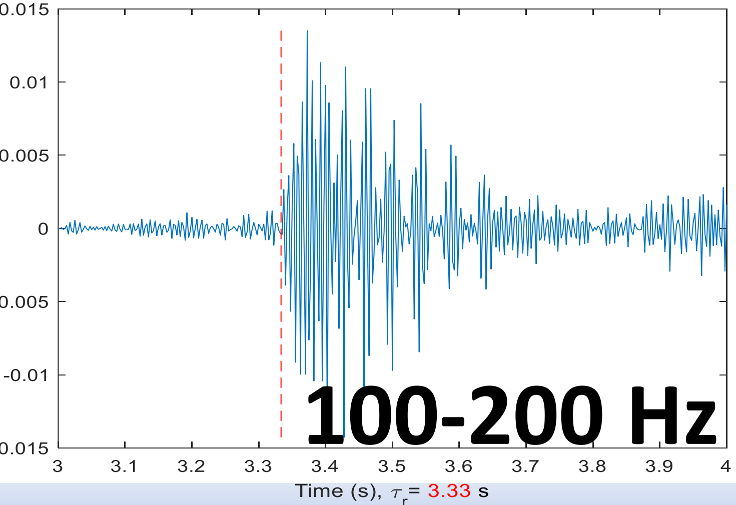
Kraken

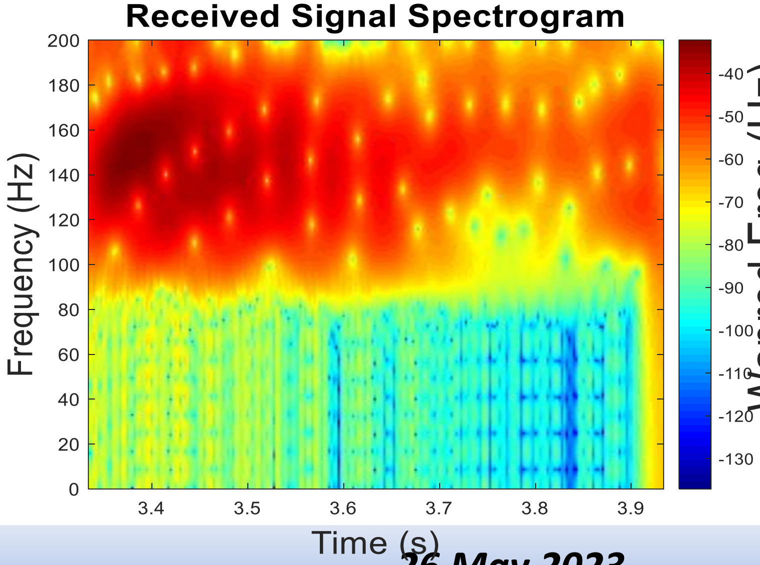
Time Warping Limitation

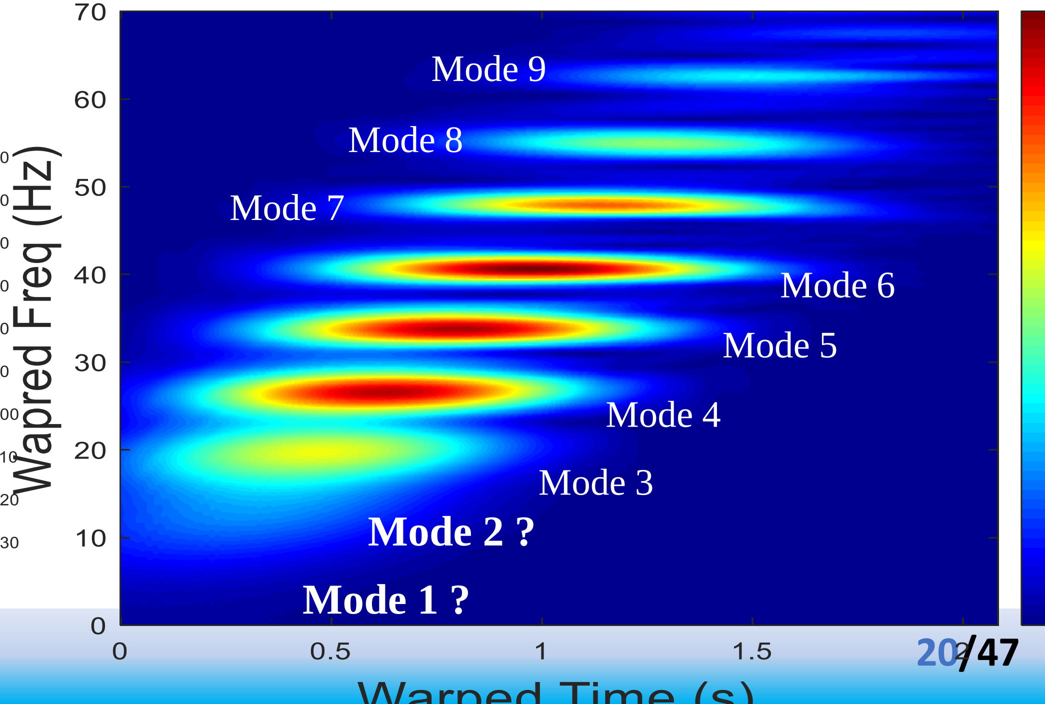












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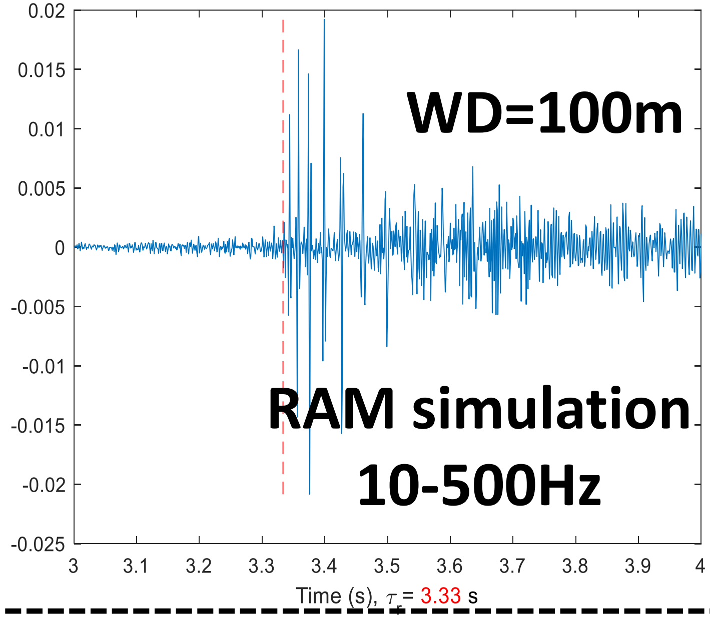
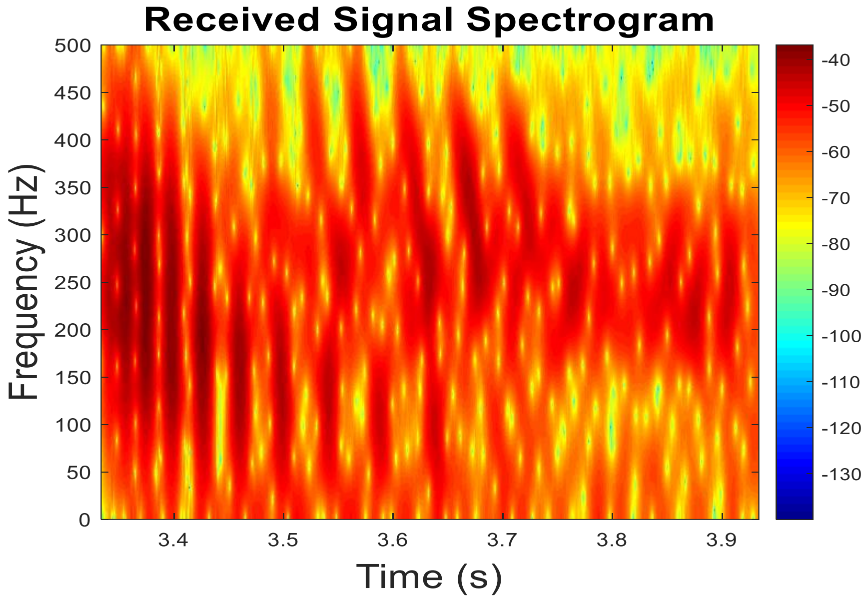
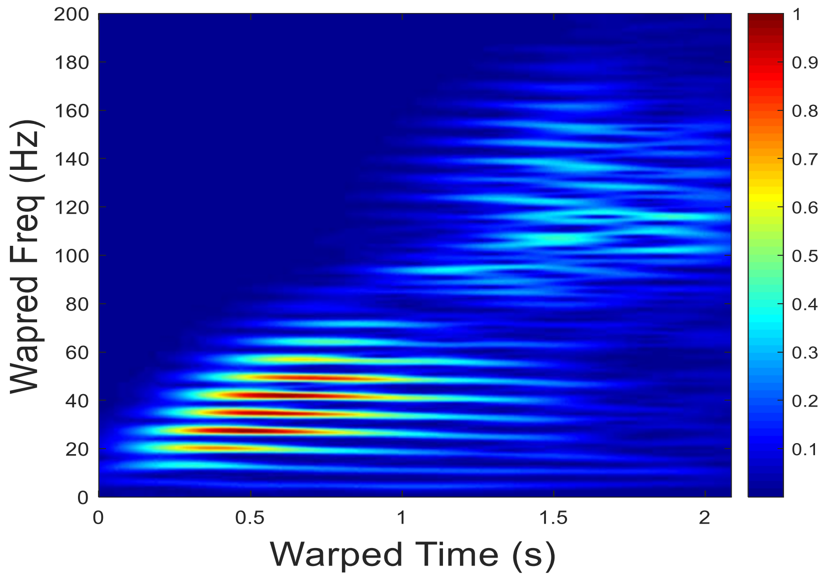
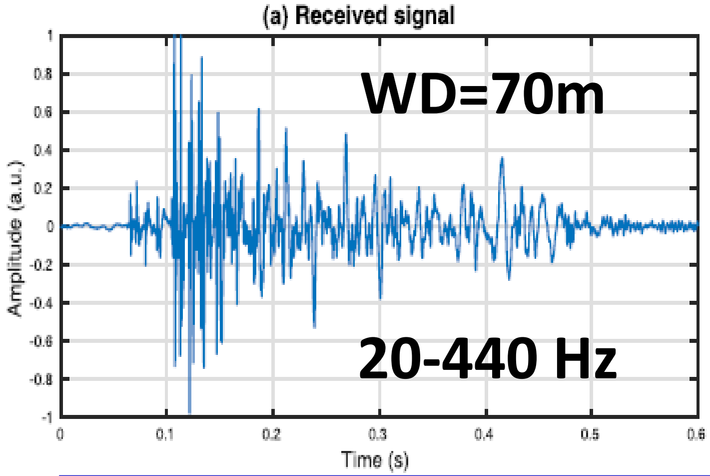
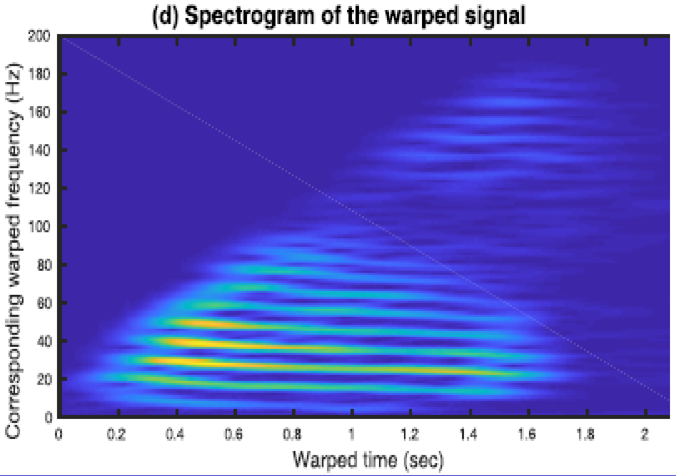
Time Warping Application to Higher Frequency

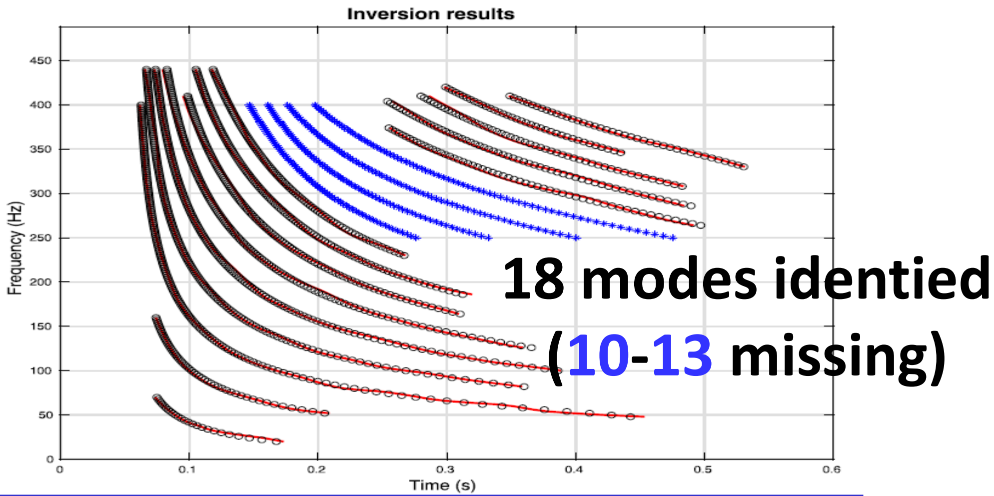








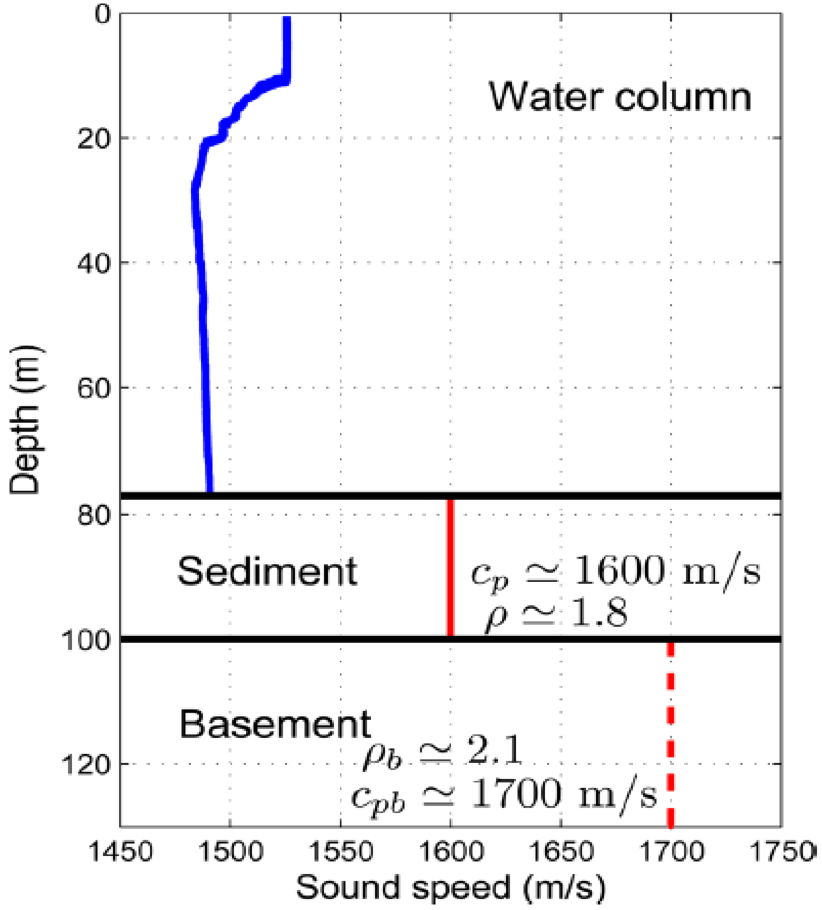


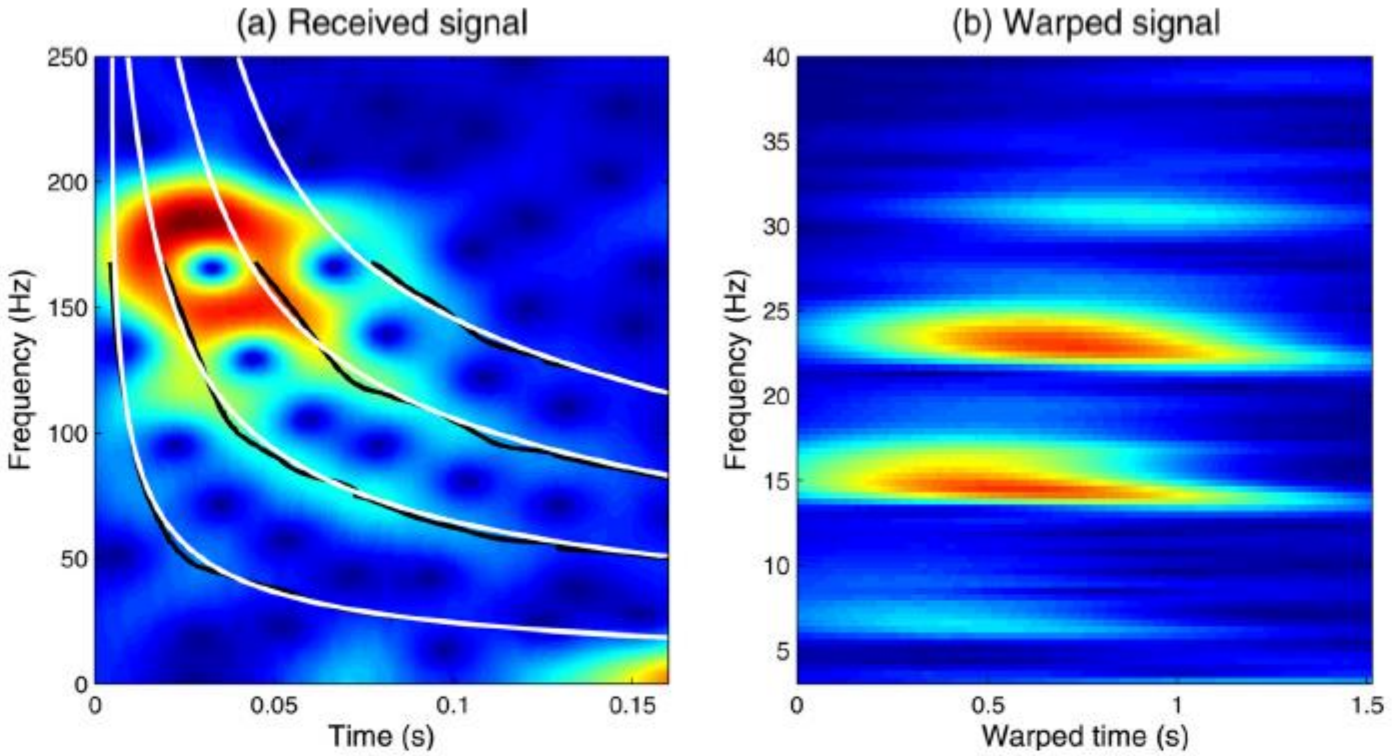


J. Bonnel et al"Geoacoustic inversion on the New England Mud Patch using warping and dispersion curves of high-order modes" *J. Acoust. Soc. Am 143(5), EL405-EL411(2018)*

Time Warping Applications in Underwater Acoustics (Active Scheme)

Time Warping Application - Geoacoustic Inversion





$$\left[\hat{A}, \hat{dt}\right] = \min_{A,dt}\left\{\sum_{m,n=1}^{M,N}\left[\hat{t}_m(f_n) - dt - t_m(f_n, A)\right]^2\right\}$$

Bonnel, Julien, and N. Ross Chapman. "Geoacoustic inversion in a dispersive waveguide using warping operators." The Journal of the Acoustical Society of America 130.2 (2011): EL101-EL107.

Time Warping Application- Seabed Attenuation

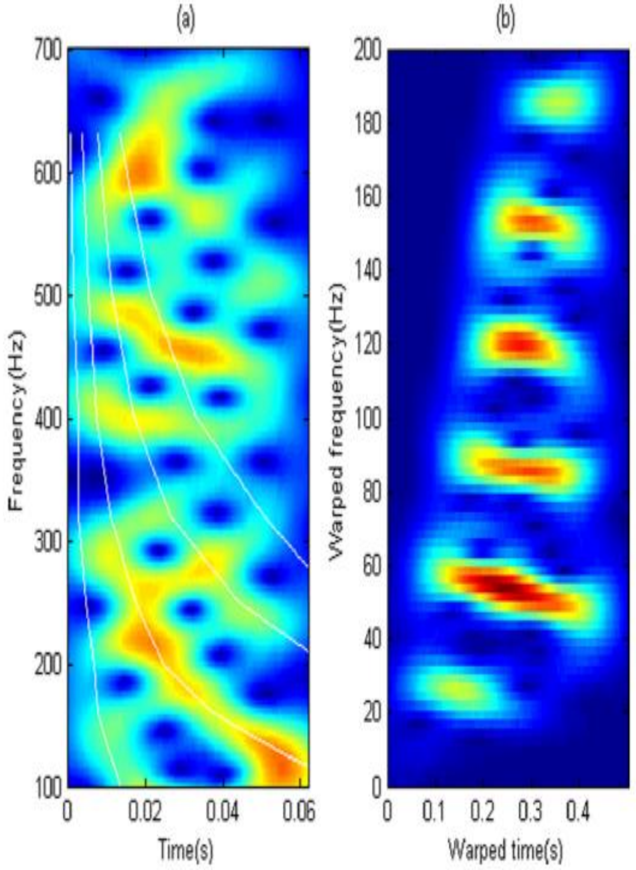


Fig. 1. (Color online) (a) Spectrogram of the original signal and the extracted dispersion curves for the first four modes, indicated by the white lines. (b) Spectrogram of the warped signal (100–700 Hz)

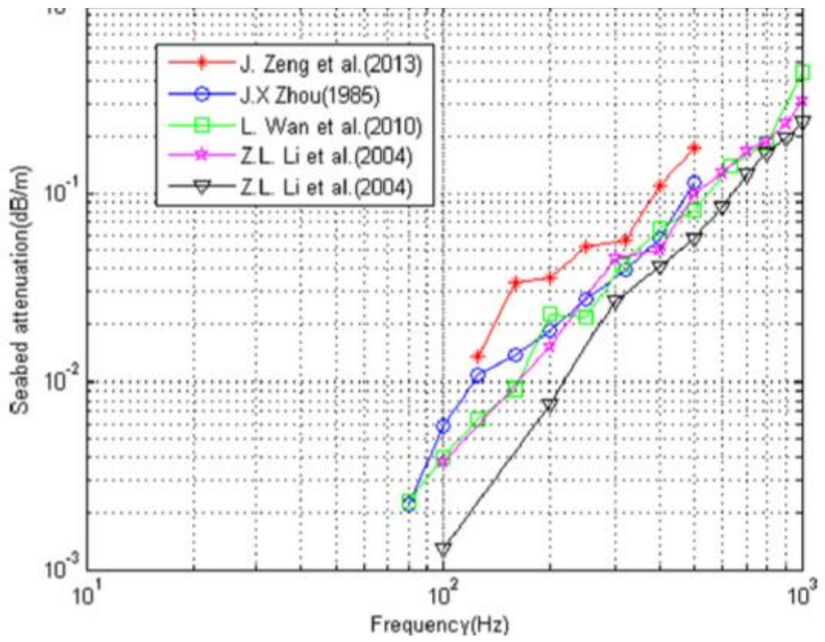
Zeng, J., Chapman, N.R. and Bonnel, J., 2013. Inversion of seabed attenuation using time-warping of close range data. The Journal of the Acoustical Society of America, 134(5), pp.EL394-EL399.

$$P(\omega, z_r) \approx BS(\omega)\sum_{m=1}^{M}\psi_m(\omega, z_s)\psi_m(\omega, z_r)\frac{e^{jk_m(\omega)r-\beta_m(\omega)r}}{\sqrt{k_m(\omega)r}}$$

$$A0_m = \sqrt{\sum_{\omega_w=\omega_w^m-\Delta\omega_w}^{\omega_w^m+\Delta\omega_w} |F_w(\omega_w)|^2},$$

$$A_m(\omega) = [\psi_m(z_s)\psi_m(z_r)/k_m]e^{-\beta_m r}\Bigg/\sqrt{\sum_{m0=1}^{M}\left|\frac{\psi_{m0}(z_s)\psi_{m0}(z_r)}{k_{m0}}e^{-\beta_{m0}r}\right|^2}.$$

$$A_m = A0_m\Bigg/\sqrt{\sum_{m=1}^{M}A0_m^2}.$$



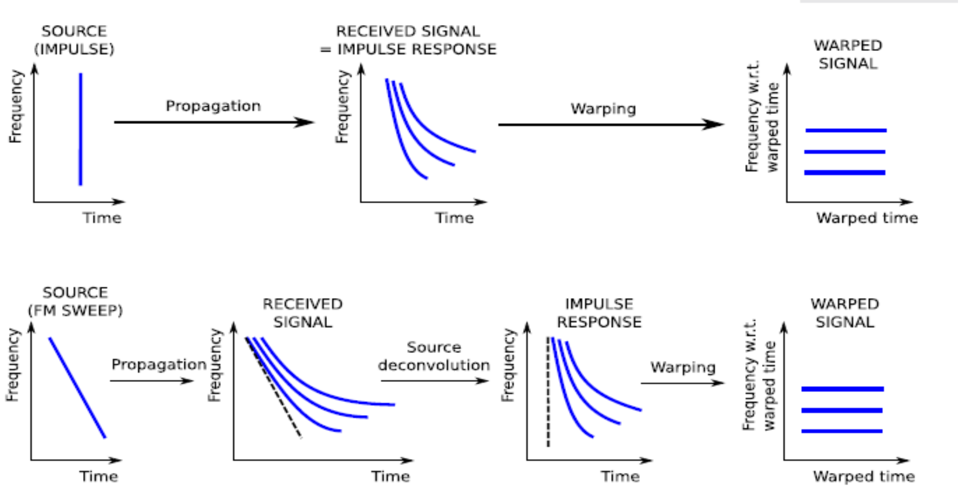
$$\hat{\alpha}_b = \min_{\alpha_b}\left\{\sum_{m=1}^{M}[\hat{A}_m(\omega) - A_m(\omega, \alpha_b)]^2\right\}.$$

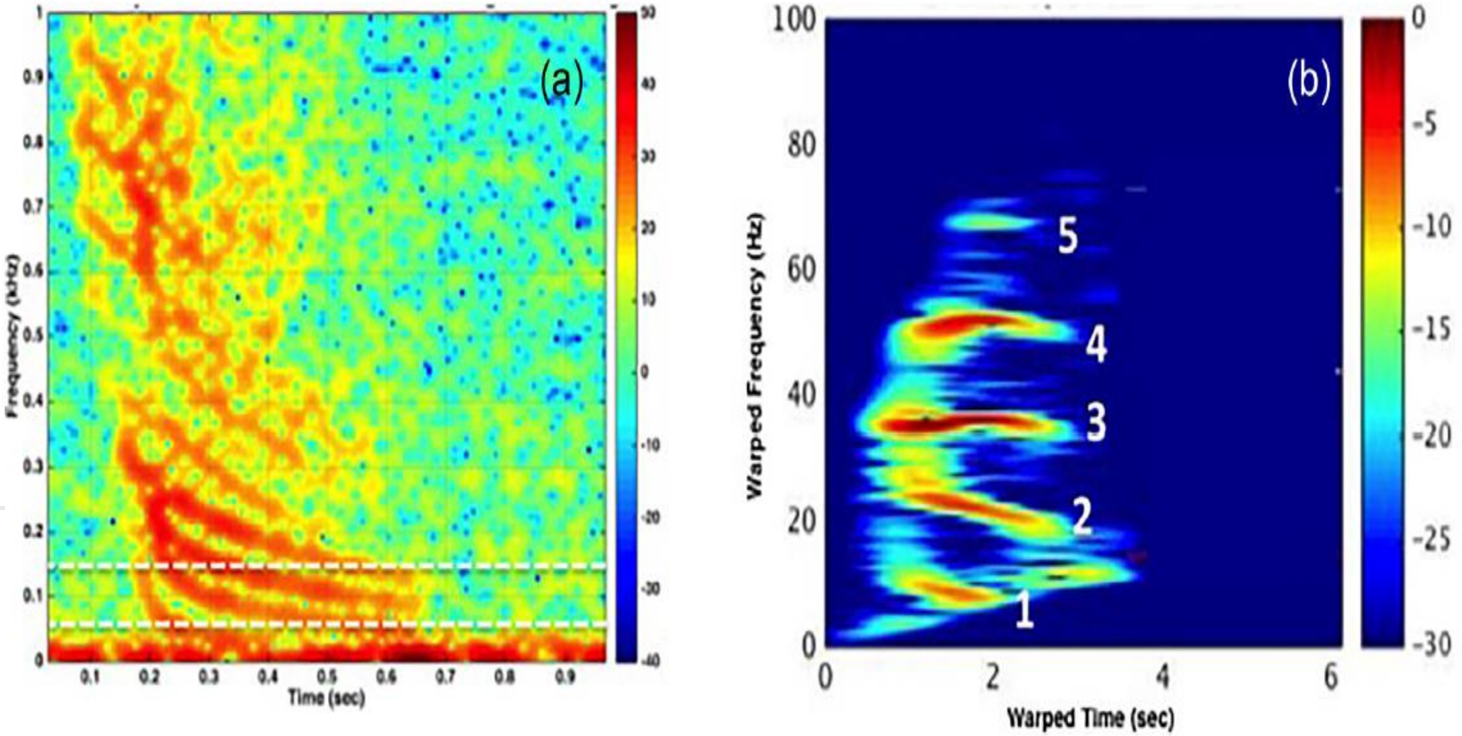
Table 2. Estimates of the seabed attenuation.

Frequency (Hz)	125	160	200	250	320	400	500
Attenuation (dB/m)	0.0134	0.0334	0.0352	0.0522	0.0567	0.109	0.174

Time Warping Application – Source Vocalization

北太平洋露脊鯨
(North Pacific right whale)

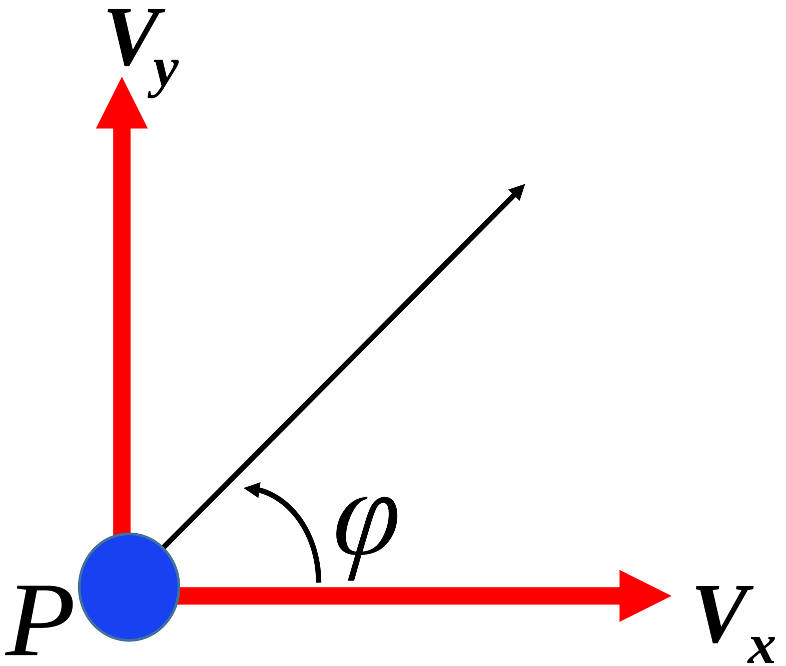




Thode, Aaron, et al. "Using nonlinear time warping to estimate North Pacific right whale calling depths in the Bering Sea." The Journal of the Acoustical Society of America 141.5 (2017): 3059-3069.

Bonnel, J., Thode, A., Blackwell, S., Kim, K., and Macrander, A. (2014).“Range estimation of bowhead whale (Balaena mysticetus) calls in thearctic using a single hydrophone,” J. Acoust. Soc. Am. 136(1), 145–155

Time Warping Application – Vector Sensor



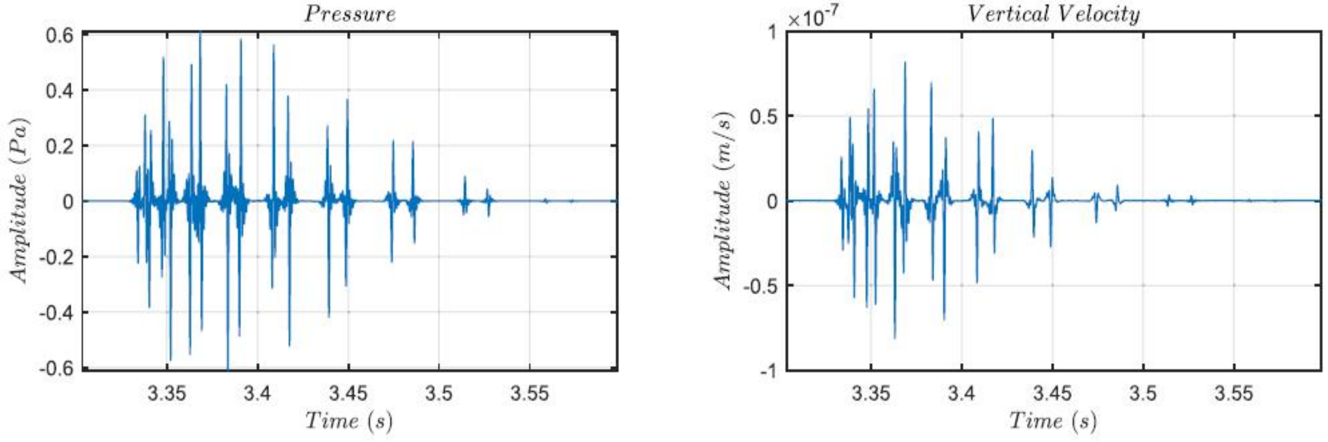
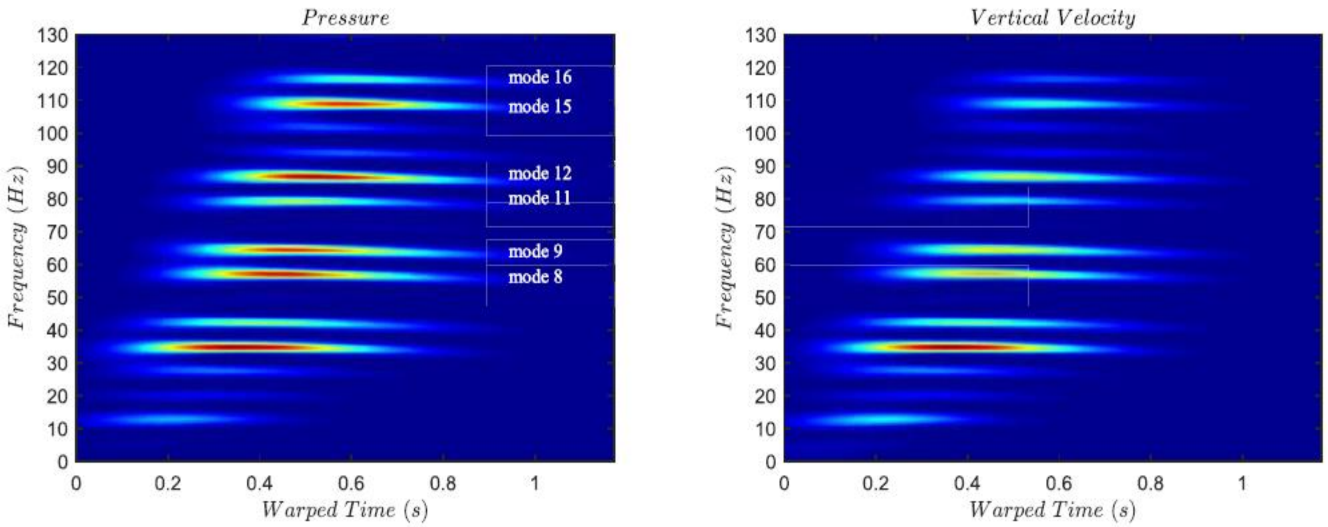


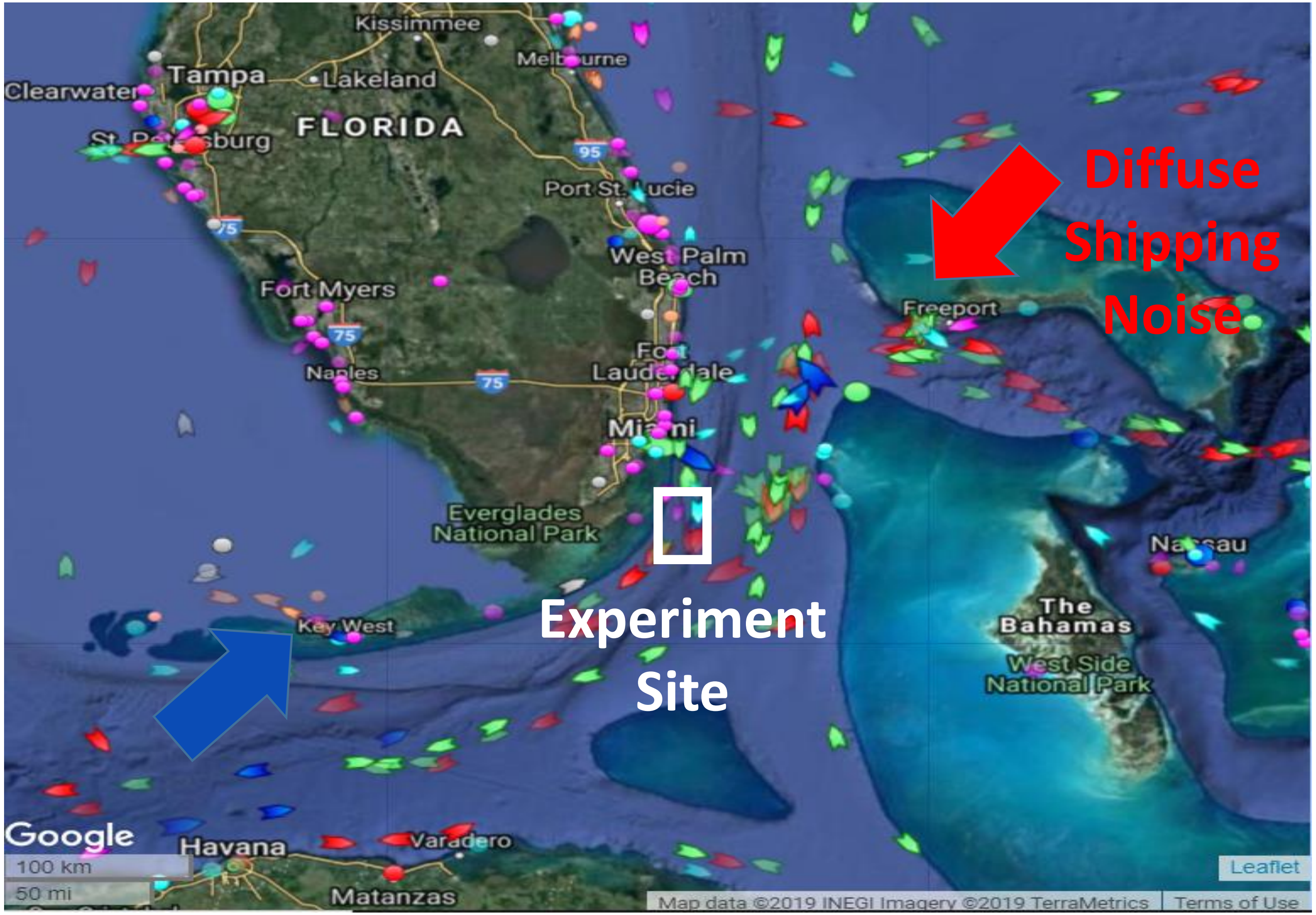
Fig. 11. Theoretical pressure and vertical velocity signals at the vector sensor.



Guarino, A. L., Smith, K. B., & Godin, O. A. (2022). Bottom attenuation coefficient inversion based on the modal phase difference between pressure and vertical velocity from a single vector sensor. Journal of Theoretical and Computational Acoustics, 30(02), 2150008.

Time Warping on
Noise Cross-Correlation Function (NCCF)
Retrieved from Florida Straits 2012 Experiment

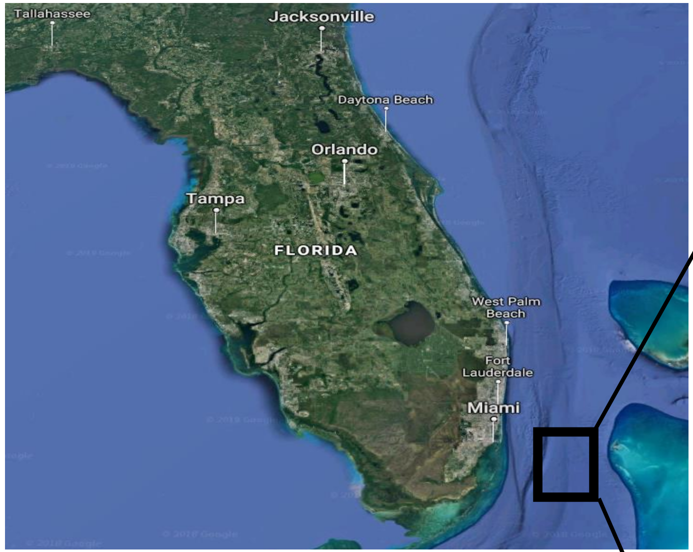
FL Straits Shipping Lanes

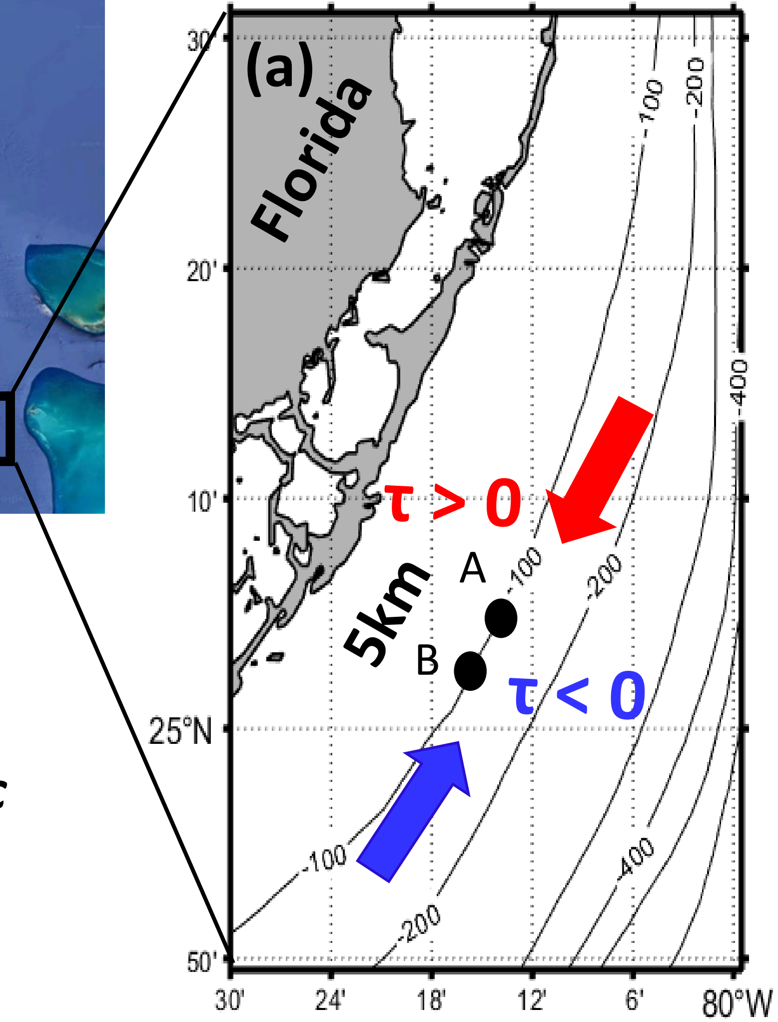


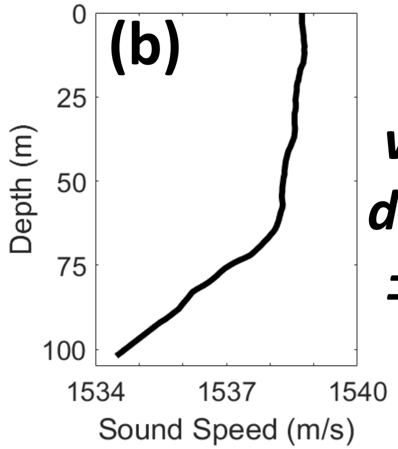
Diffuse Shipping Noise

http://www.shiptraffic.net

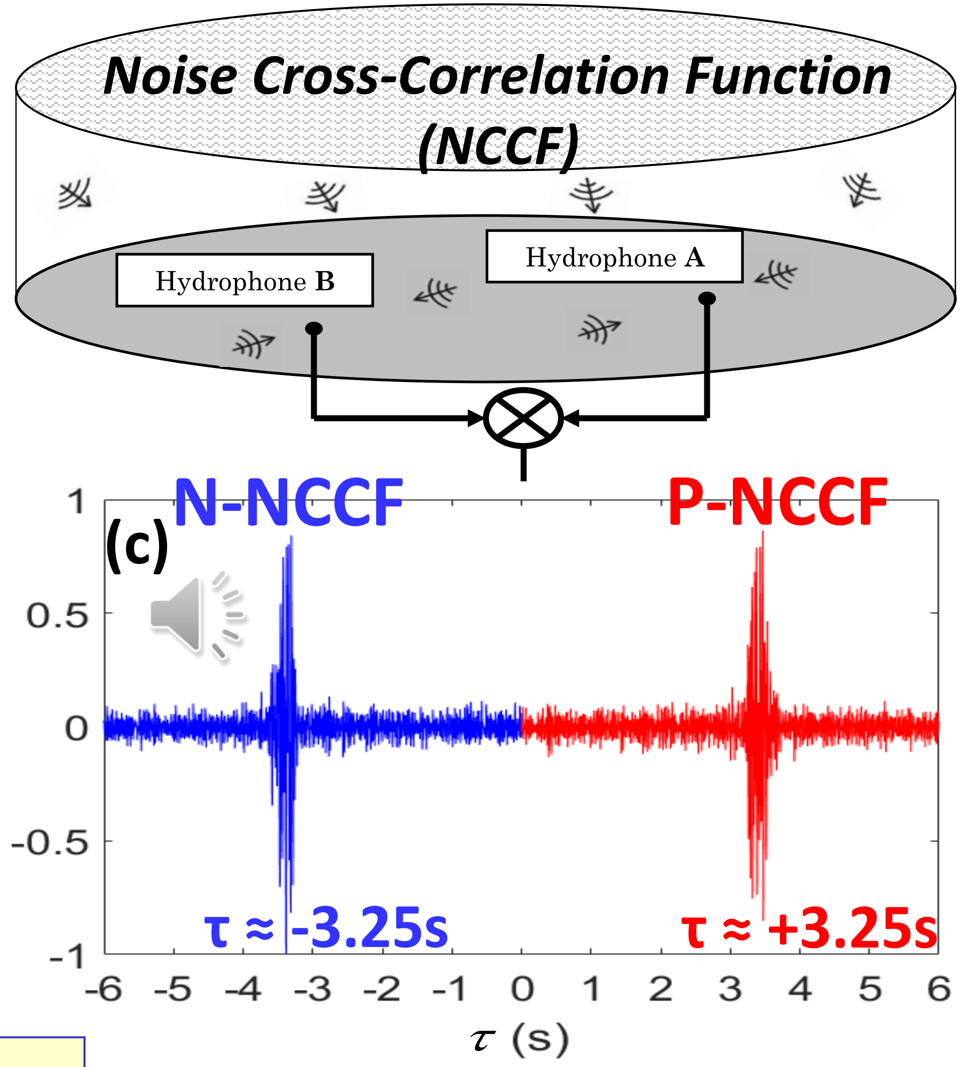
Florida Straits 2012 NI Experiment & NCCF





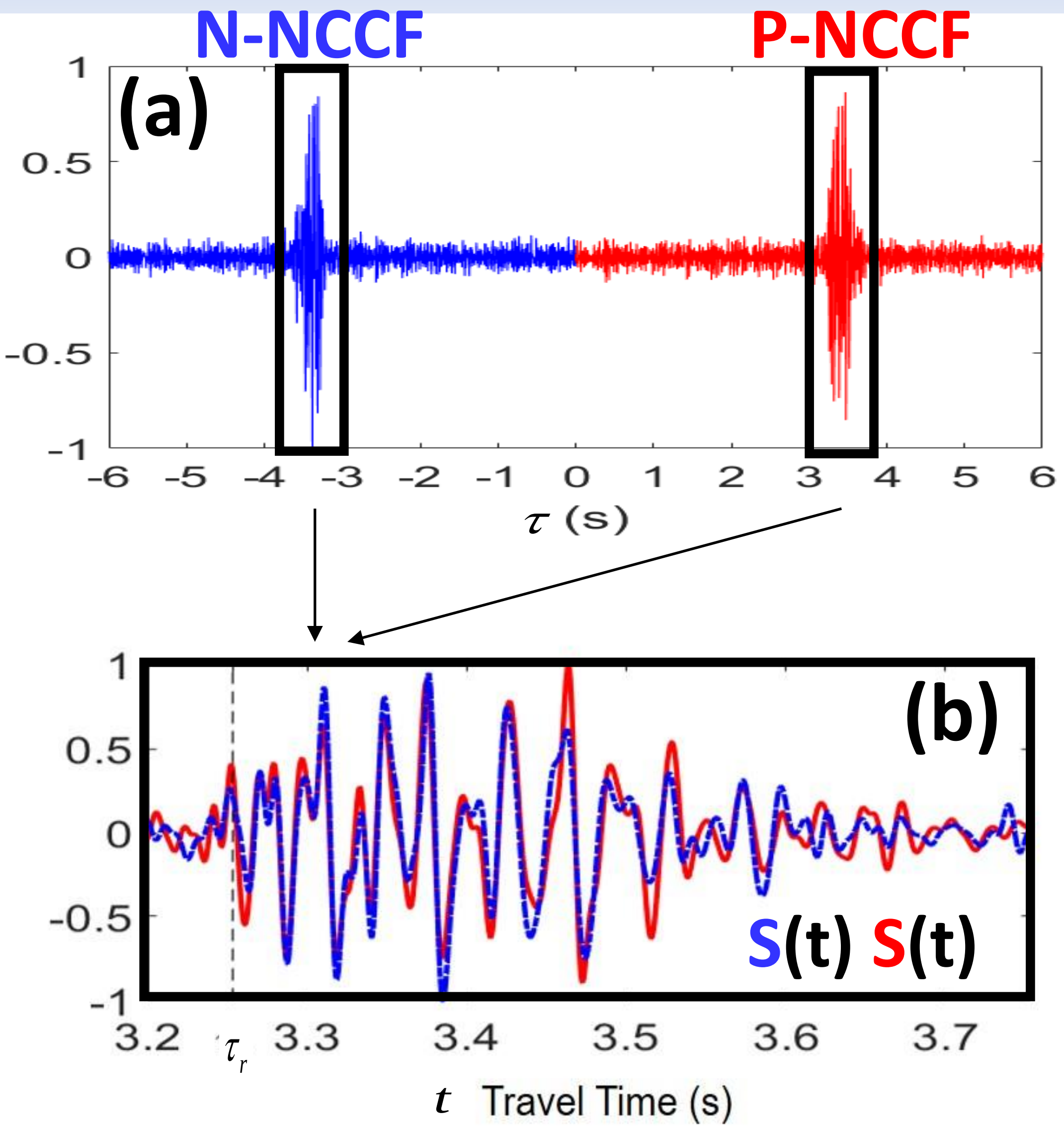


SSP weakly dynamic ±2 m/s



T. Tan, O.A. Godin, M.G. Brown, and N.A. Zabotin, "Characterizing the seabed in the Straits of Florida by using acoustic noise interferometry and time warping ," J. Acoust. Soc. Am. 146(4), 2321-2334 (2019)

Time Warping on Noise Cross Correlation Function (NCCF)



NCCF as Approximated Green's function

$$\frac{d}{dt}C_{AB}(\tau) \cong \left[G(\mathbf{r}_B,\mathbf{r}_A,-\tau) - G(\mathbf{r}_A,\mathbf{r}_B,\tau)\right]$$

Warping/Unwarping Function

$w(t)=\sqrt{t^2-\tau_r^{\ 2}}$ $w^{-1}(t)=\sqrt{t^2+\tau_r^{\ 2}}$

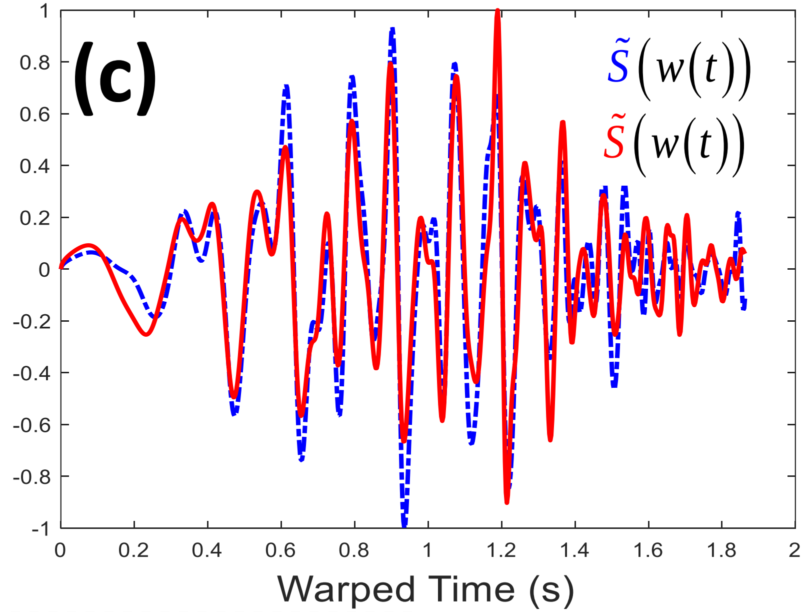
(b) Warping (c)

$$|w'(t)|^{-1/2} S(t) = \tilde{S}(w(t))$$

$$|w'(t)|^{-1/2} S(t) = \tilde{S}(w(t))$$

(b) Unwarping (c)

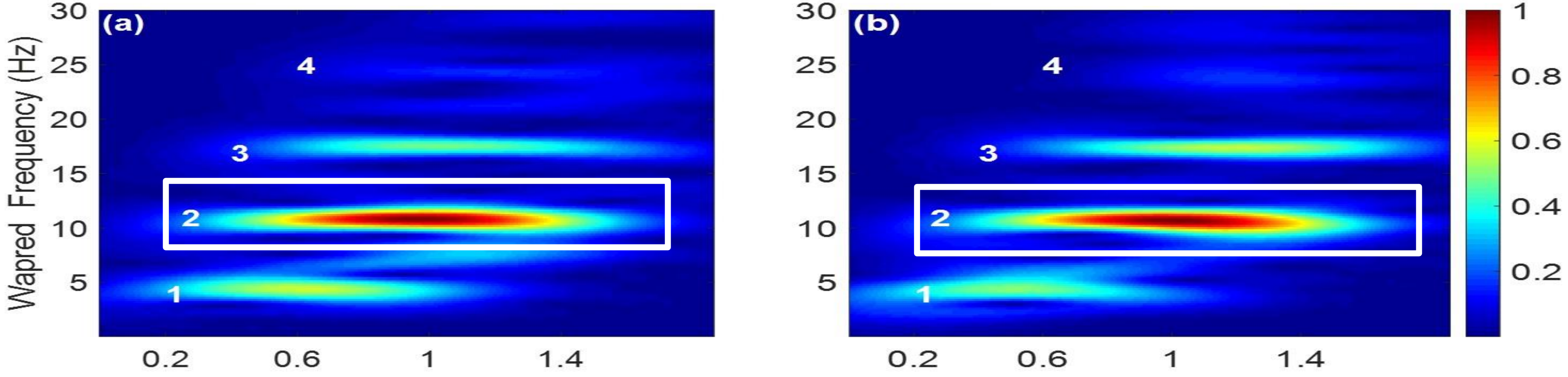
$w^{-1}\left[\tilde{S}(w(t))\right] = S(t)$

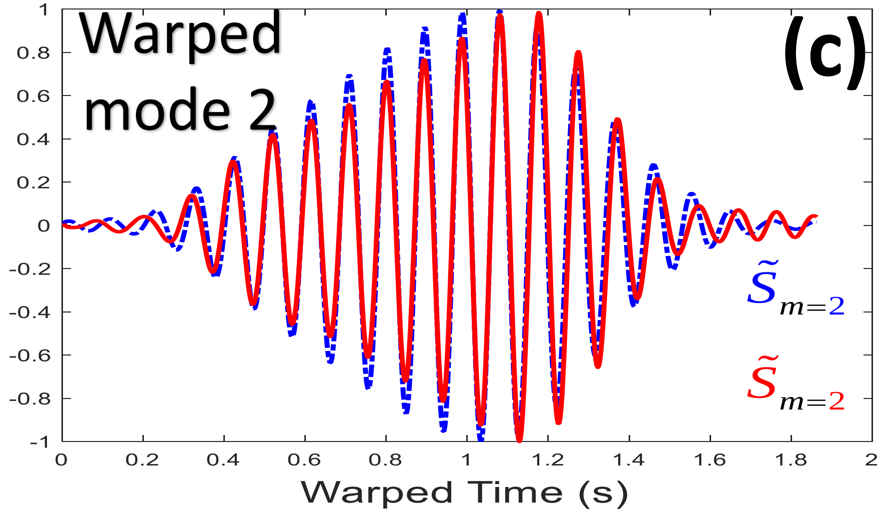


N-NCCF & P-NCCF mode restoration

$$\tilde{S}\left(w(t)\right)=\sum_{m=1}^{4}\tilde{S}_m\left(w(t)\right)$$

$$\tilde{S}\left(w(t)\right)=\sum_{m=1}^{4}\tilde{S}_m\left(w(t)\right)$$

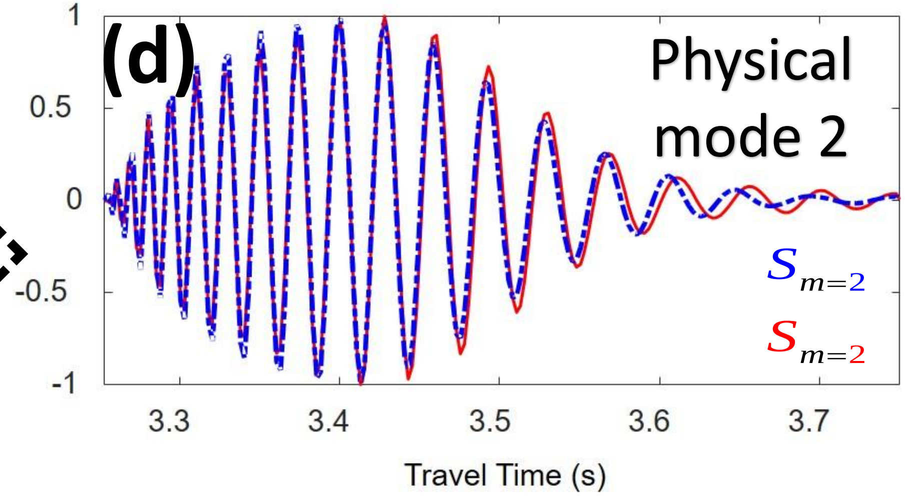




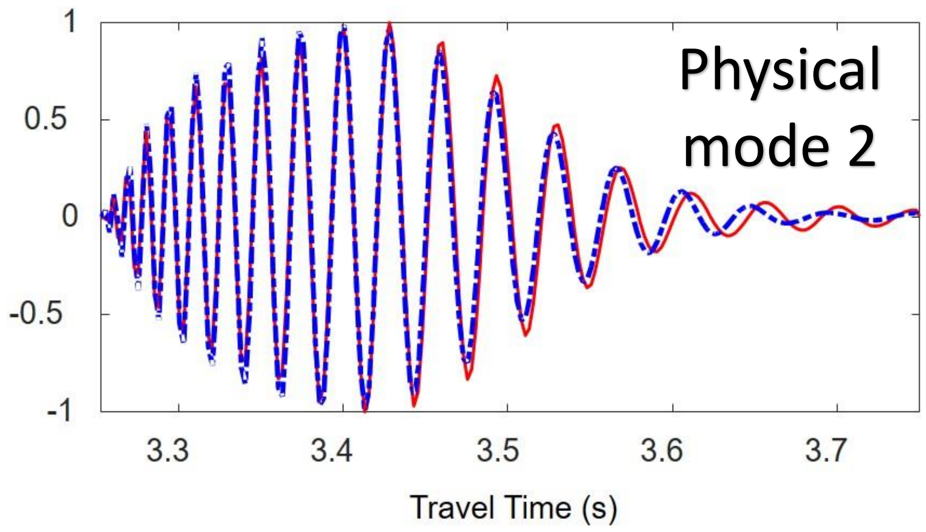
$$w^{-1}(t)=\sqrt{t^2+\tau_r^{\,2}}$$

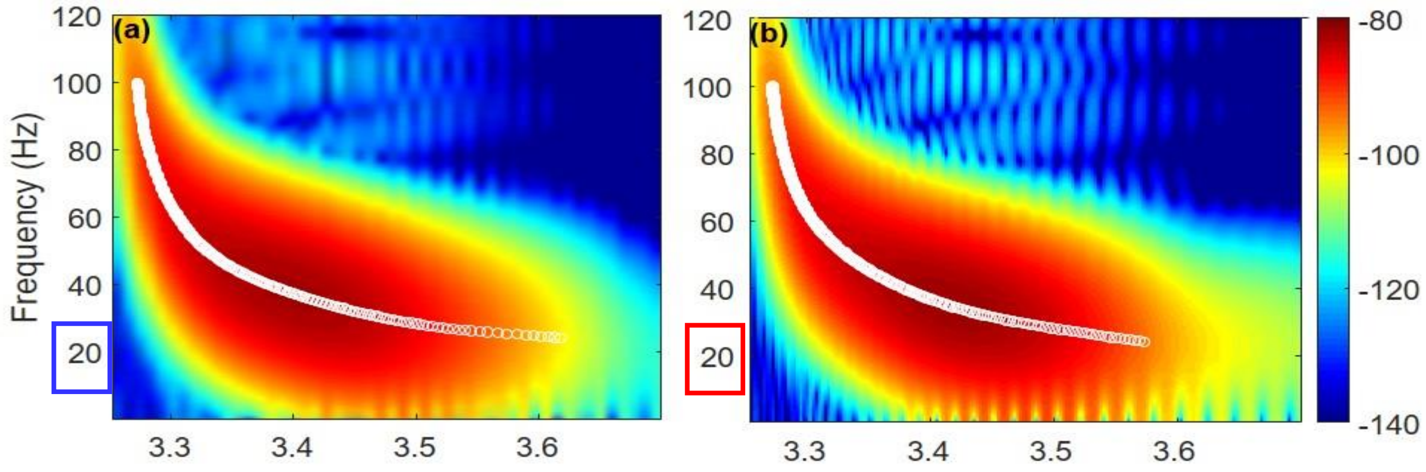
(c) Unwarping (d)

$$w^{-1}\left[\tilde{S}_m\left(w(t)\right)\right]=S_m(t),\, m=2$$



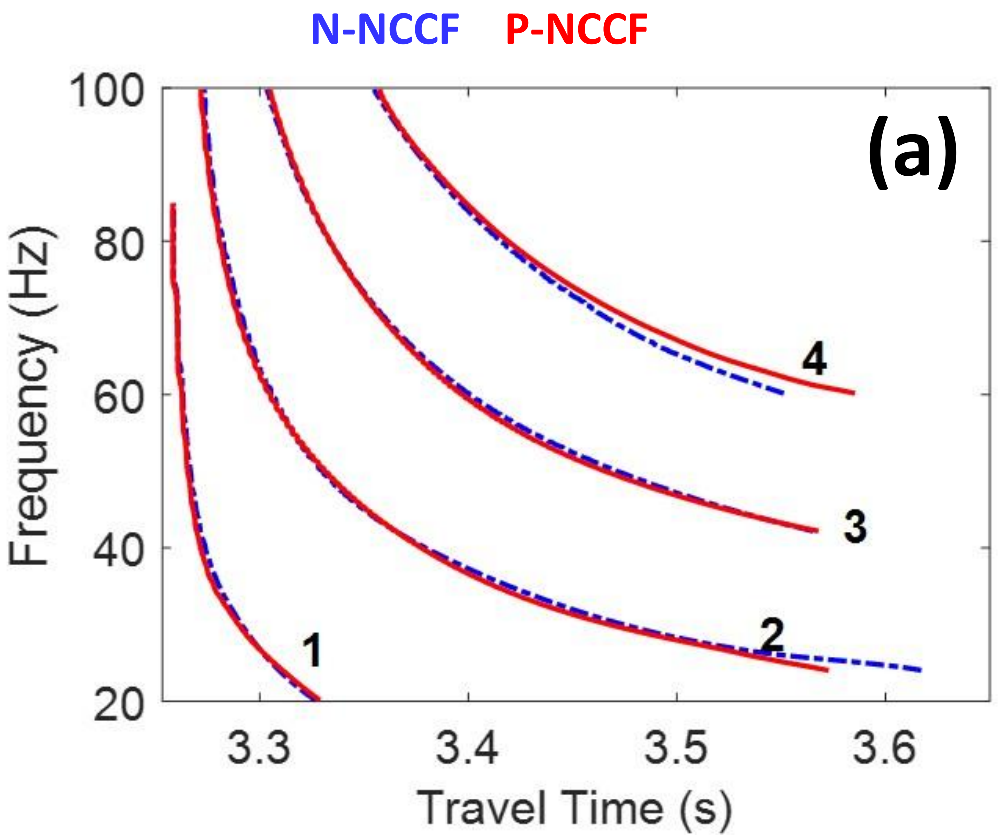
Retrieving N-NCCF & P-NCCF mode dispersion curve

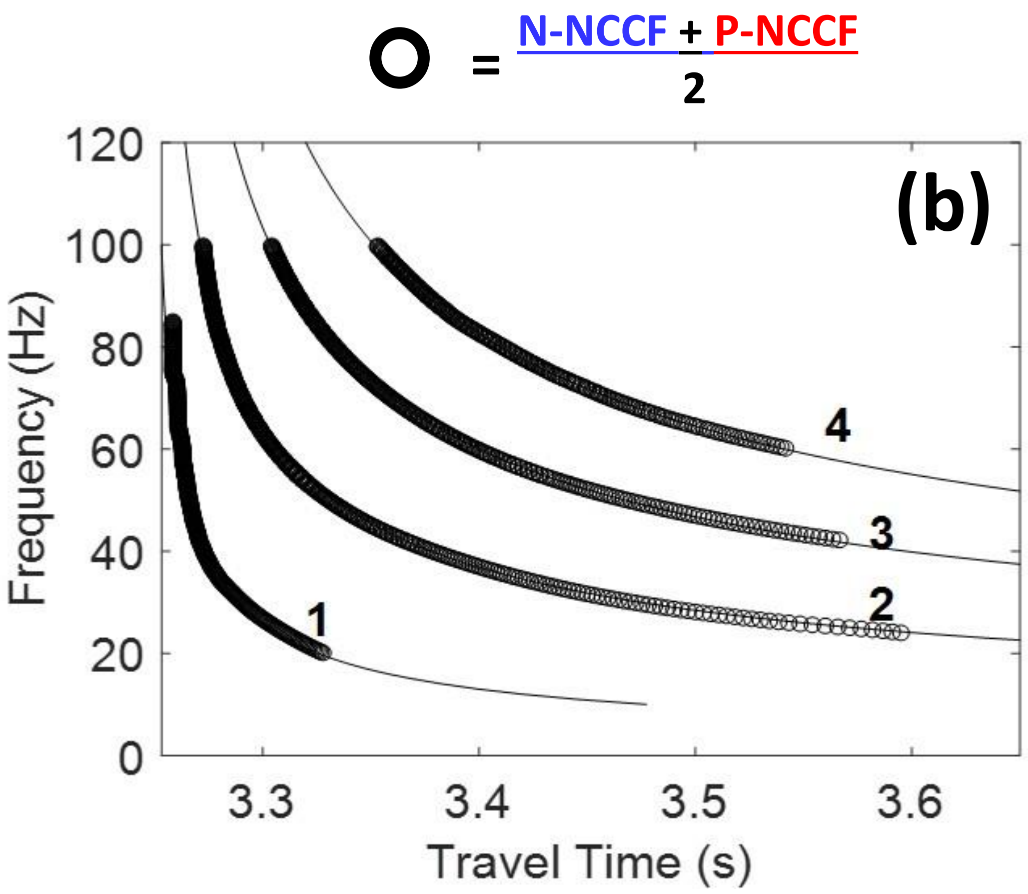




$t_m(f), m=2$ $t_m(f), m=2$

Inverse problem

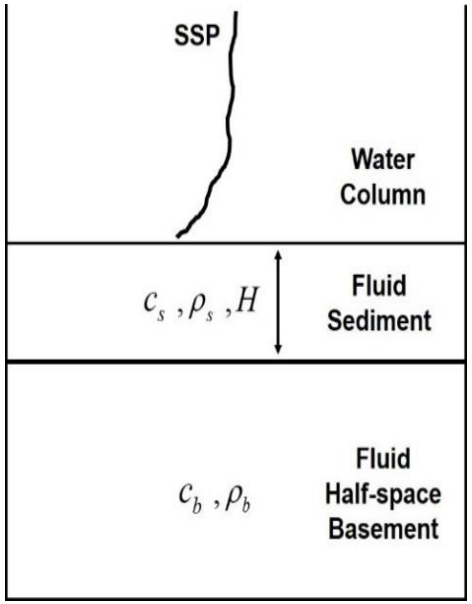




Cost function: $K(\mathbf{U}) = \frac{1}{M} \sum_{m,n=1}^{M=4,N} \left[\frac{t_m(f_n) - \hat{t}_m(f_n, \mathbf{U})}{N} \right]^2$

1-D Sensitivity Animation

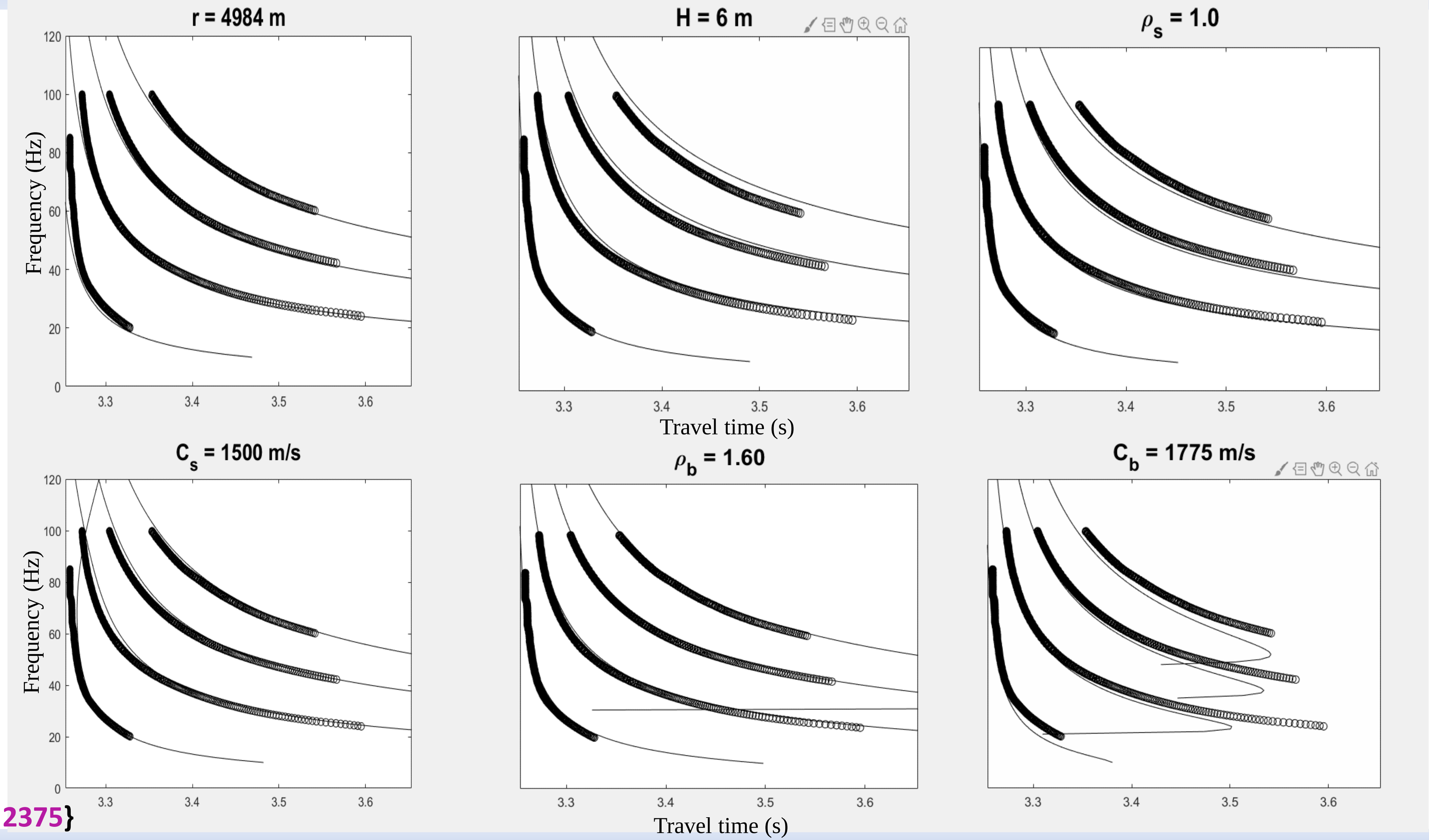
Geoacoustic model



r : distance btw receivers
H : sediment thickness
ρ_s: sediment density
C_s: sediment sound speed
ρ_b: basement density
C_b: basement sound speed

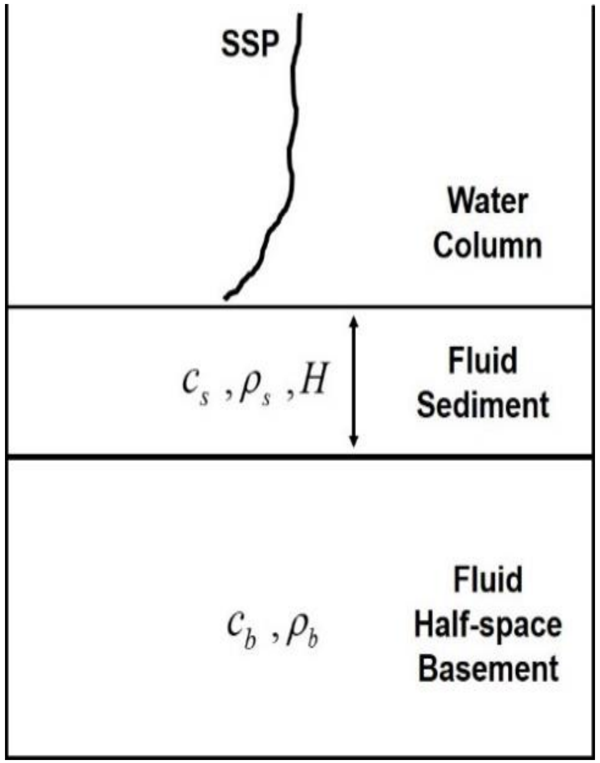
U={r, *H*, ρ_s, C_s, ρ_b, C_b}

U ={4994, 14, 1.4, 1550, 2.35, 2375}



Inverse problem

(a) Geoacoustic model

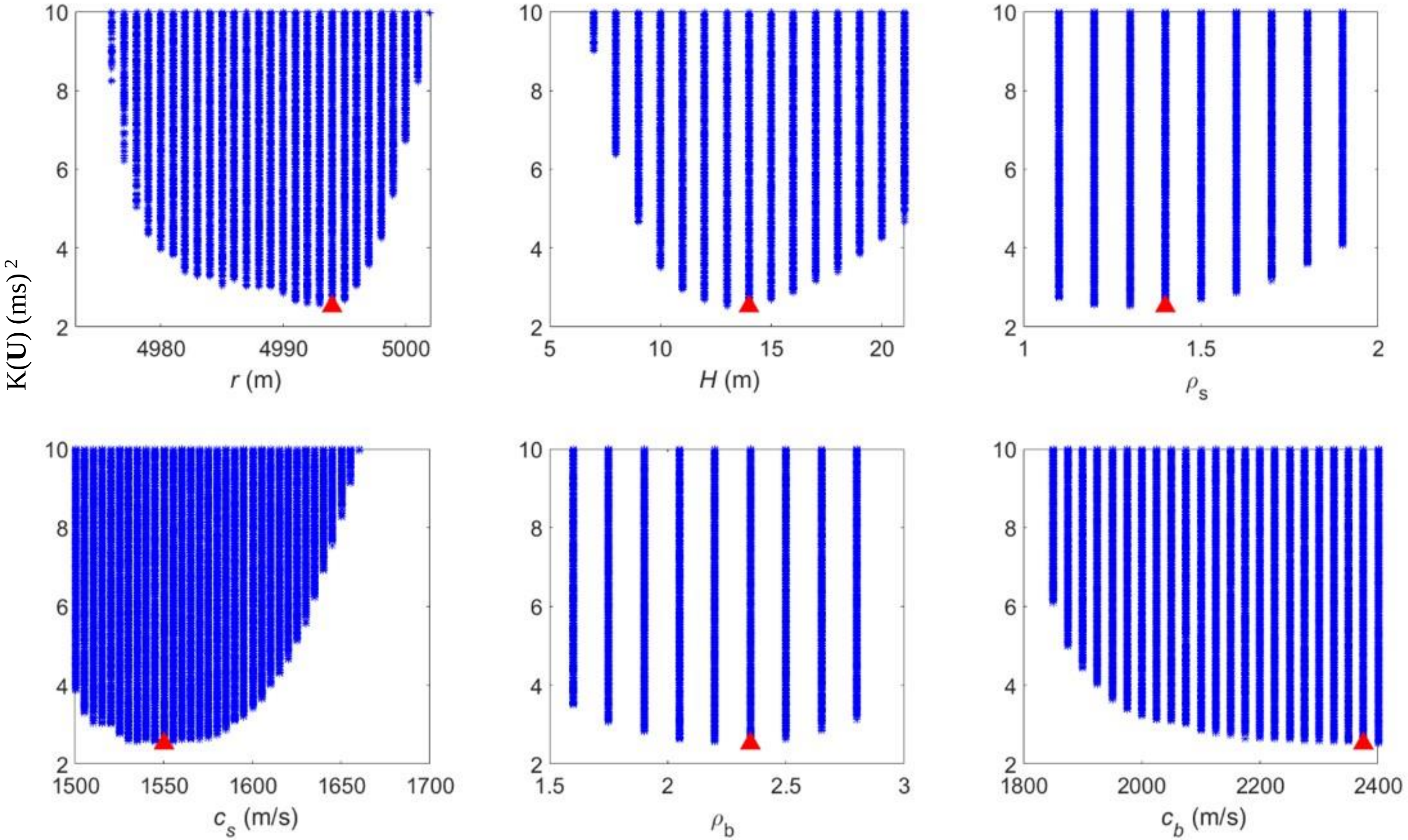


$$K(\mathbf{U}) = \frac{1}{M}\sum_{m,n=1}^{M=4,N}\left[\frac{t_m(f_n)-\hat{t}_m(f_n,\mathbf{U})}{N}\right]^2$$

U = {r, H, c_s, c_b, ρ_s, ρ_b}

(b) Sensitivity Analysis

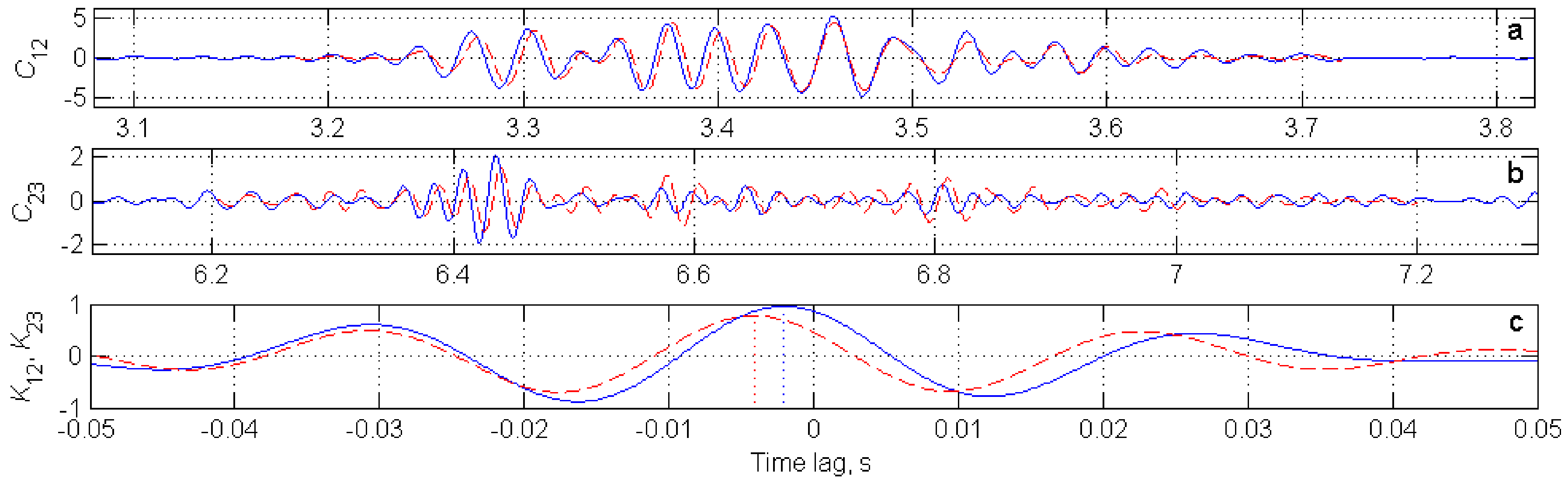
▲ $= K(\hat{\mathbf{U}}) \approx 2.52\ (ms)^2$

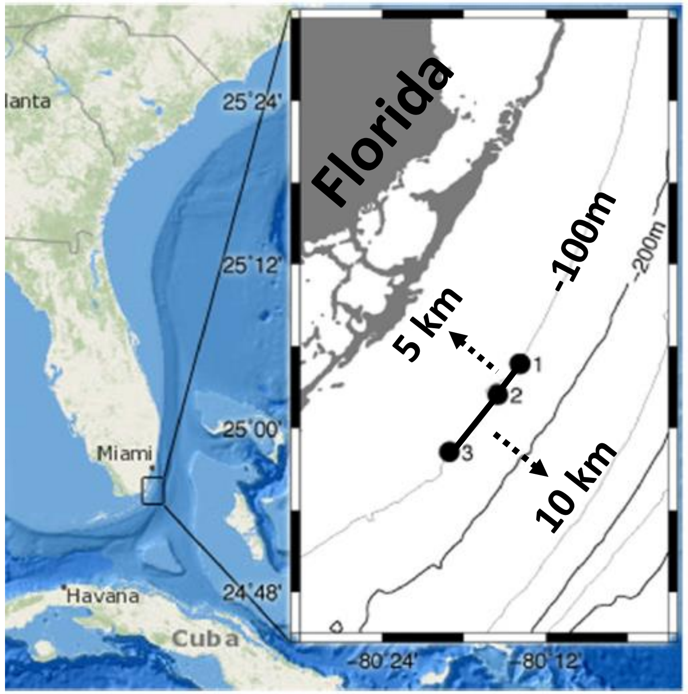


T. Tan, O.A. Godin, M.G. Brown, and N.A. Zabotin, "**Characterizing the seabed** in the Straits of Florida by using acoustic noise interferometry and time warping ," *J. Acoust. Soc. Am. 146(6), 2321-2334* (2019).

FL Straits Experiment Future Work

Nonreciprocity of N-NCCF & P-NCCF to estimate depth-averaged flow velocity





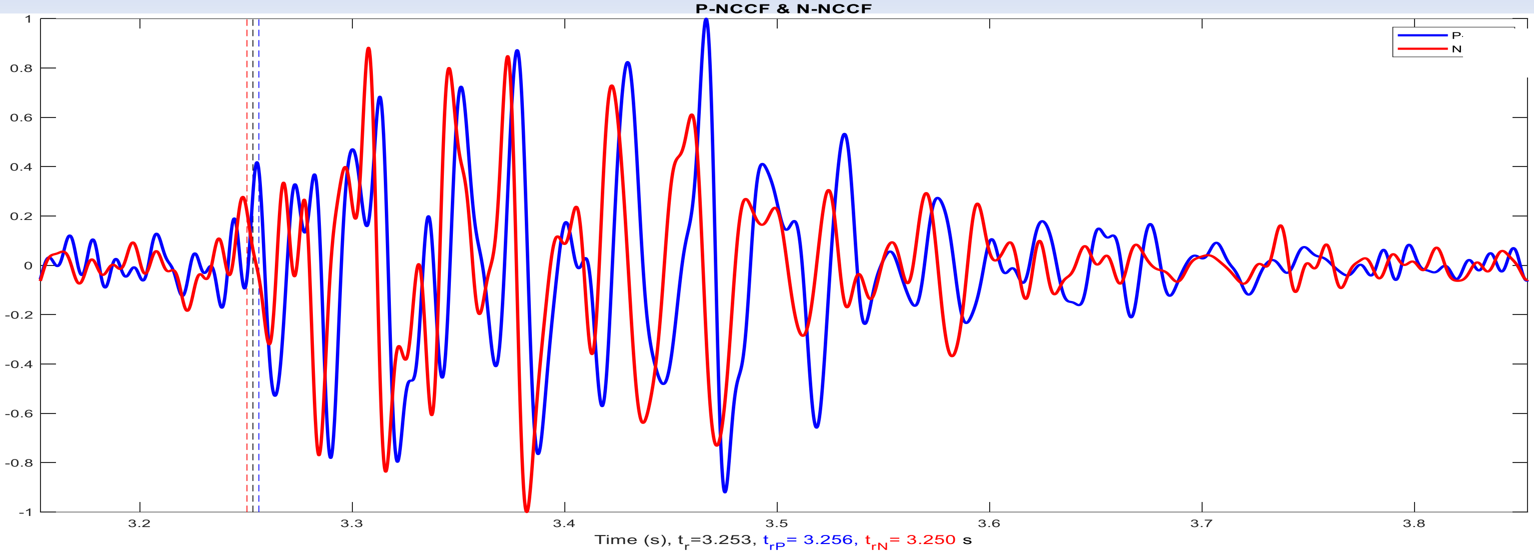
(a) The noise cross-correlation function C_{12} is shown for P-NCCF (solid line) and N-NCCF (dashed line) after removal of the relative drift of system clocks. The entire available data set is used for noise averaging. (b) Same as (a) but for C_{23}. (c) Correlation between the positive- and negative-time-delay parts of the cross-correlation functions C_{12} (solid line) and C_{23} (dashed line). The position of the peak of the correlation of correlations determines the nonreciprocity of travel times induced by currents at sound propagation between the respective pair of instruments.

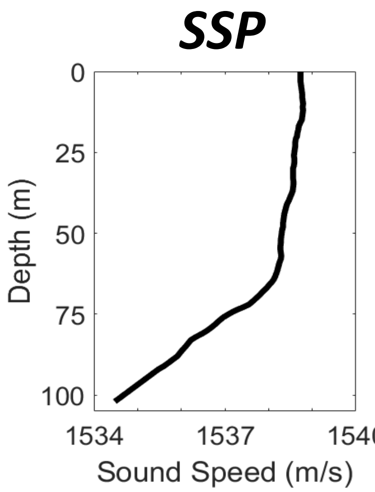
Travel time nonreciprocity: $\delta t = 2c^{-2} rU,\ U = H^{-1}\int_0^H u_x(z)\,dz$

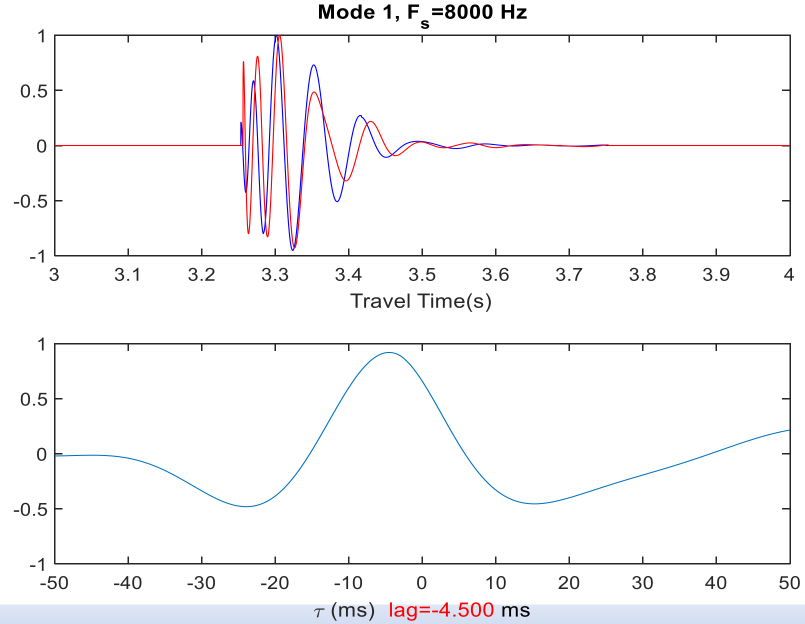
Measured current velocity: $U_{12} = -0.47$ m/s ± 7%, $U_{23} = -0.49$ m/s

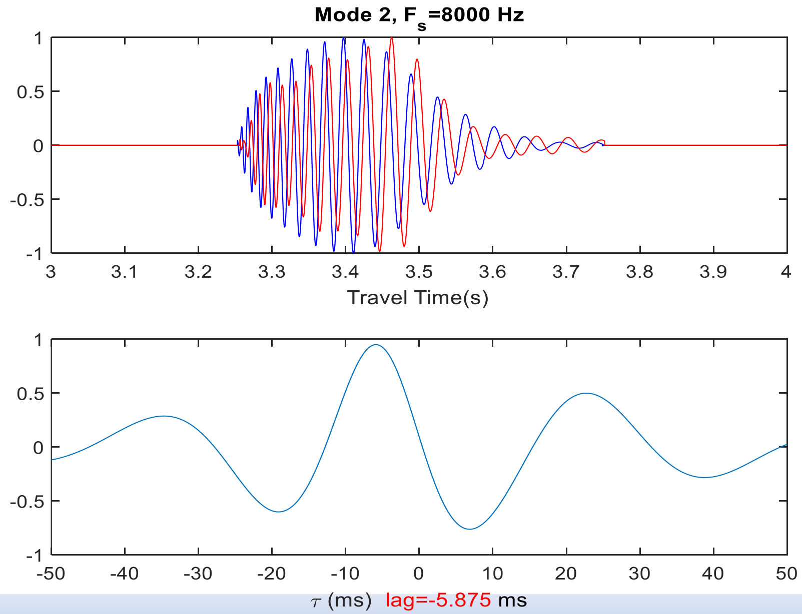
O. A. Godin, M. G. Brown, N. A. Zabotin, L. Zabotina, and N. J. Williams, Passive acoustic measurement of **flow velocity** in the Straits of Florida, Geoscience Lett. 1, Art. 16 (2014)

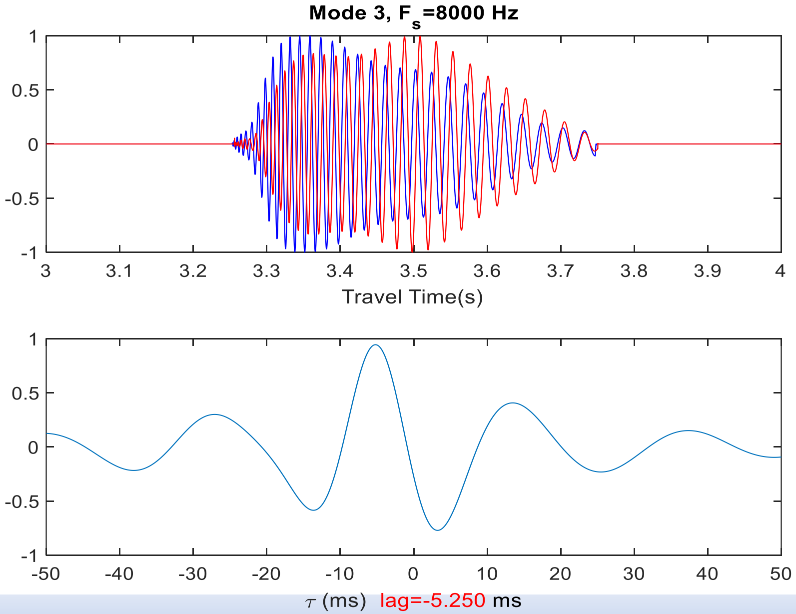
FL Future work: Passively quantifying current





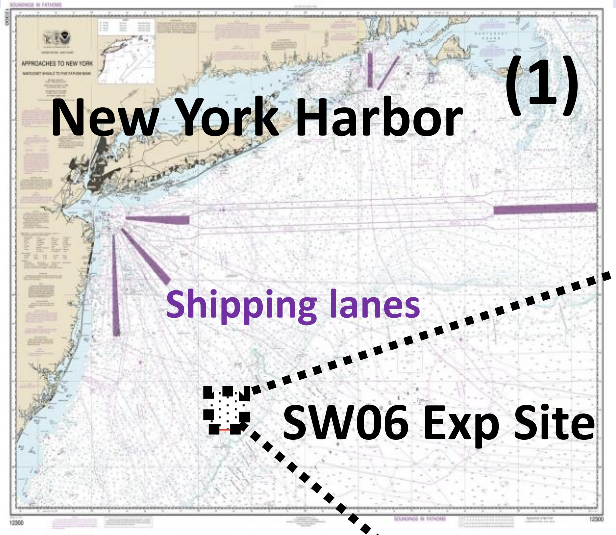




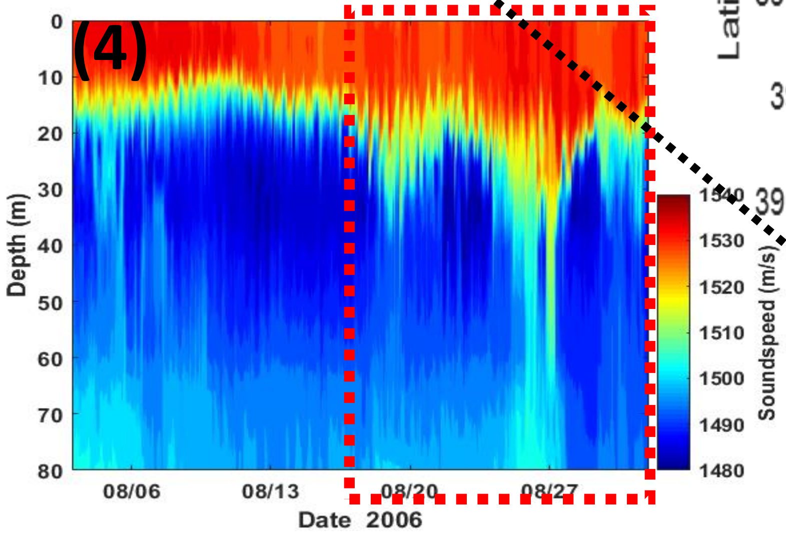


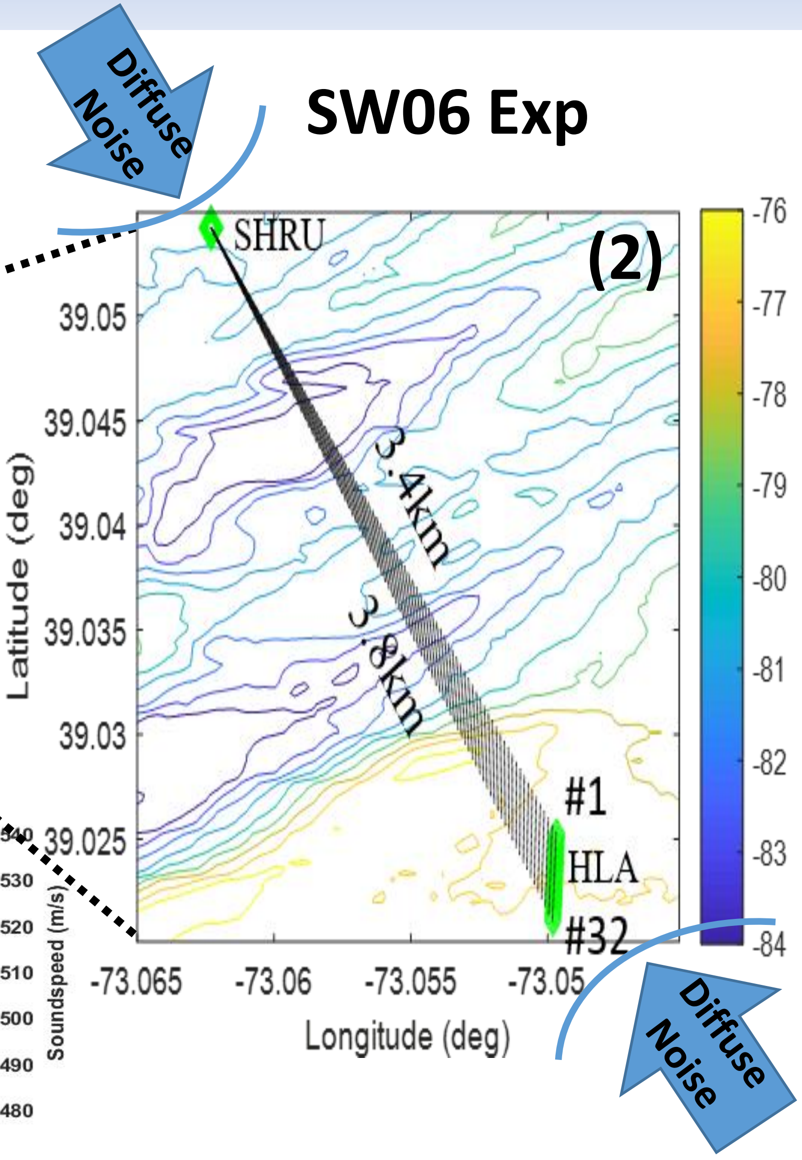
Time Warping on Empirical Green's Functions (EGFs) from Shallow Water 2006 Experiment (SW06)

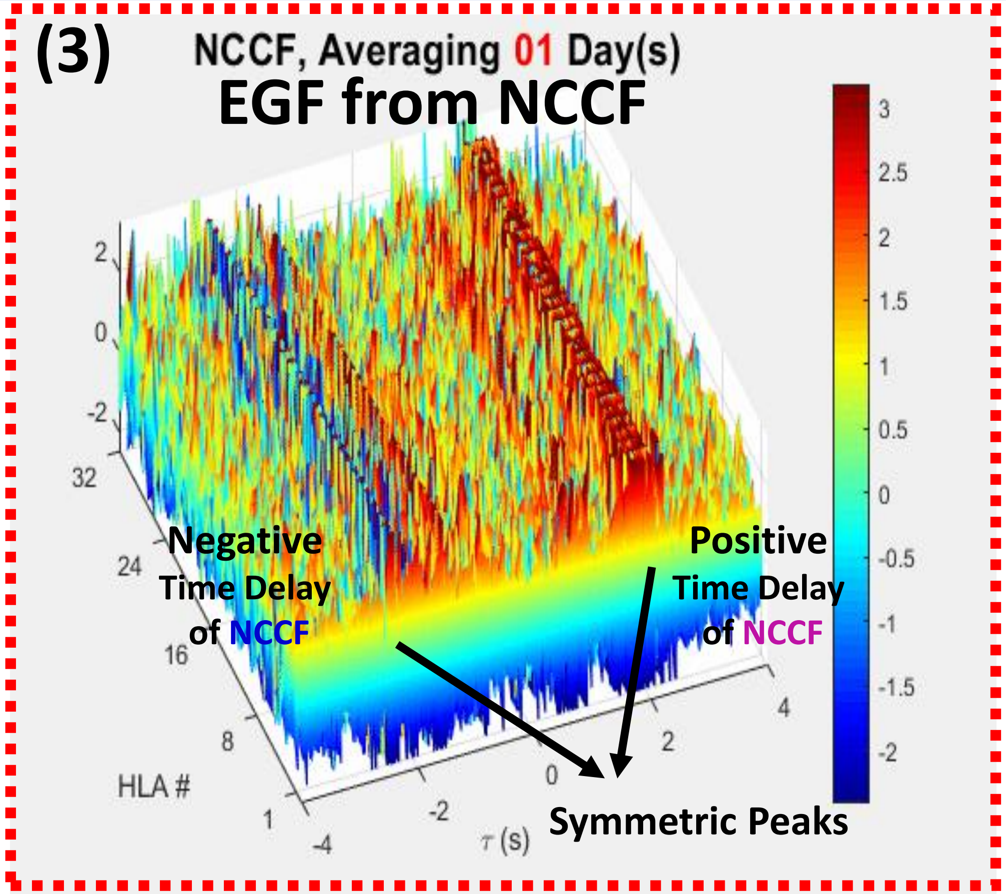
Noise Cross Correlation Functions (NCCFs) : 15-day Avg



SW06 location in the chart "Approaches of New-York"





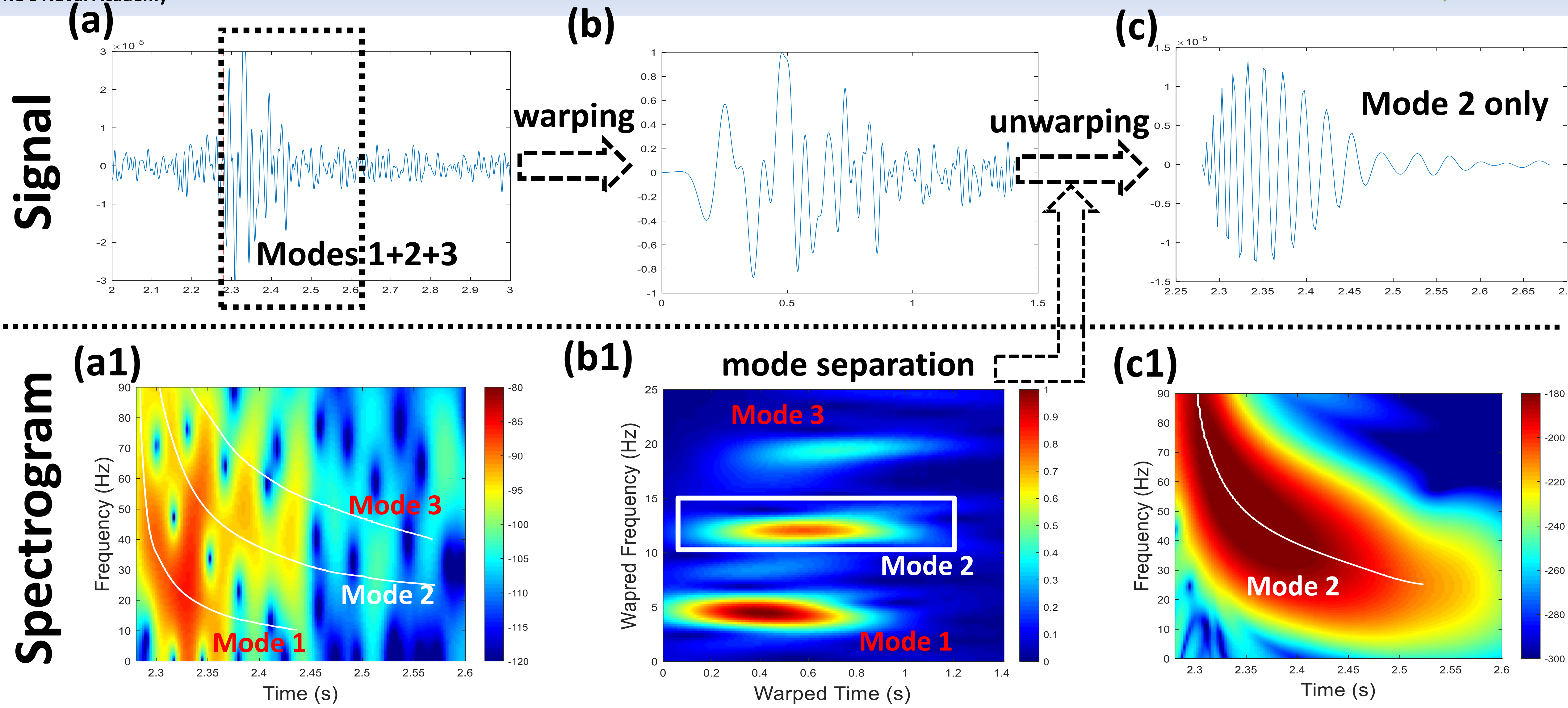


$$\hat{C}_i(f) = \frac{1}{N}\sum_{n=1}^{N} \frac{P_{SHRU}^{(n)}(f) P_{HLA,i}^{(n)}(f)^*}{\left| P_{SHRU}^{(n)}(f) P_{HLA,i}^{(n)}(f)^* \right|}, \quad i = 1, 2, \ldots, 32$$

$$\frac{d}{dt} C_i(t) = D(t) * \left[G\left(\mathbf{r}_{HLA,i}, \mathbf{r}_{SHRU}, -t\right) - G\left(\mathbf{r}_{SHRU}, \mathbf{r}_{HLA,i}, t\right) \right]$$

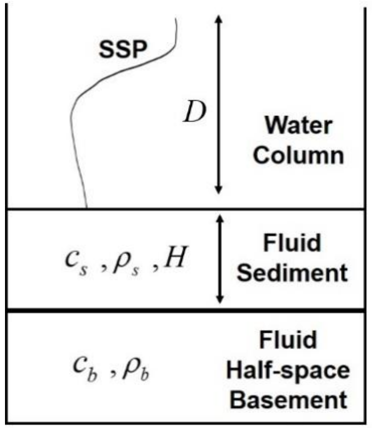
Time Warping on NCCF (15-day avg)

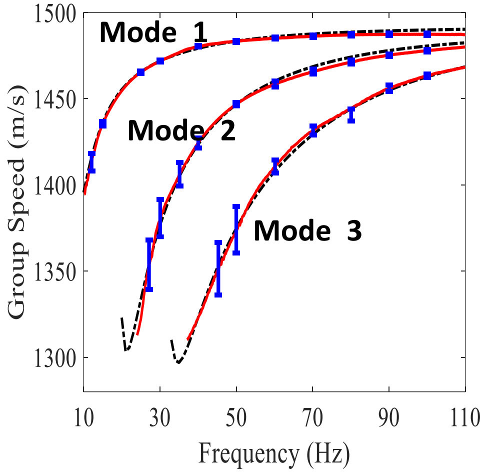
ROC Naval Academy

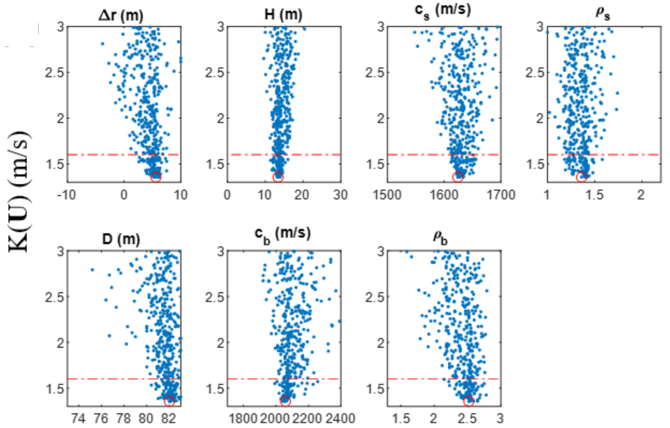


Ocean Characterization by EGFs of Sub-Seasonal Sound Speed Variations : 15-day Avg

ROC Naval Academy



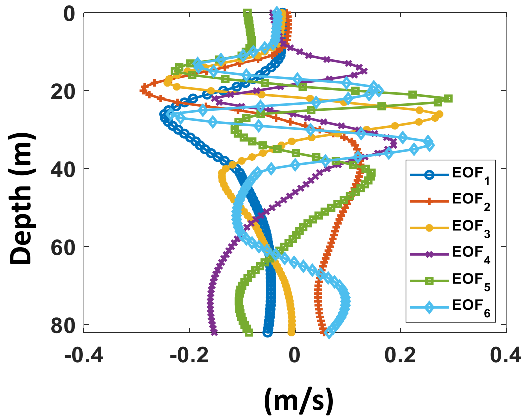


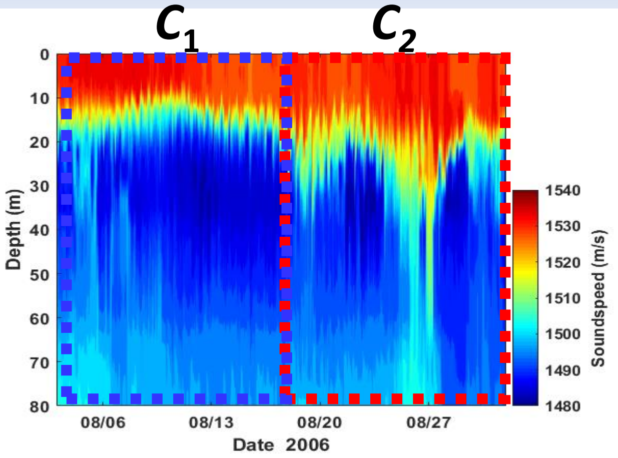


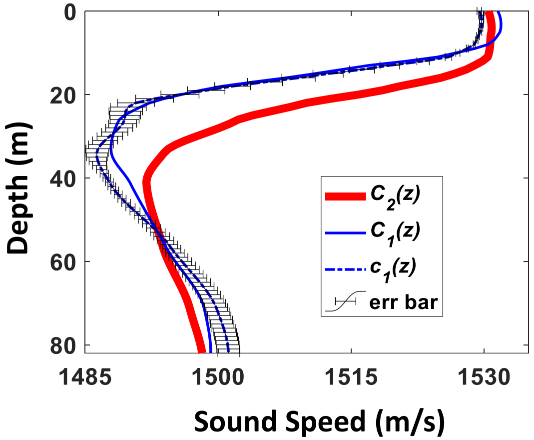
$$K(\mathrm{U}) = \sqrt{\sum_{m=1}^{M} \frac{1}{M N_m} \sum_{n=1}^{N_m} \left[\bar{g}_m(f_n) - \hat{g}_m(f_n, \mathrm{U}) \right]^2}$$

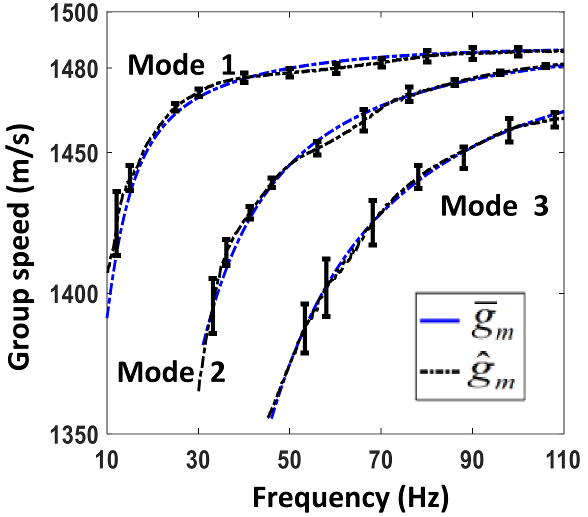
Geoacoustic Inv

Seabed









SSP Inv $c_1 \approx C_1$

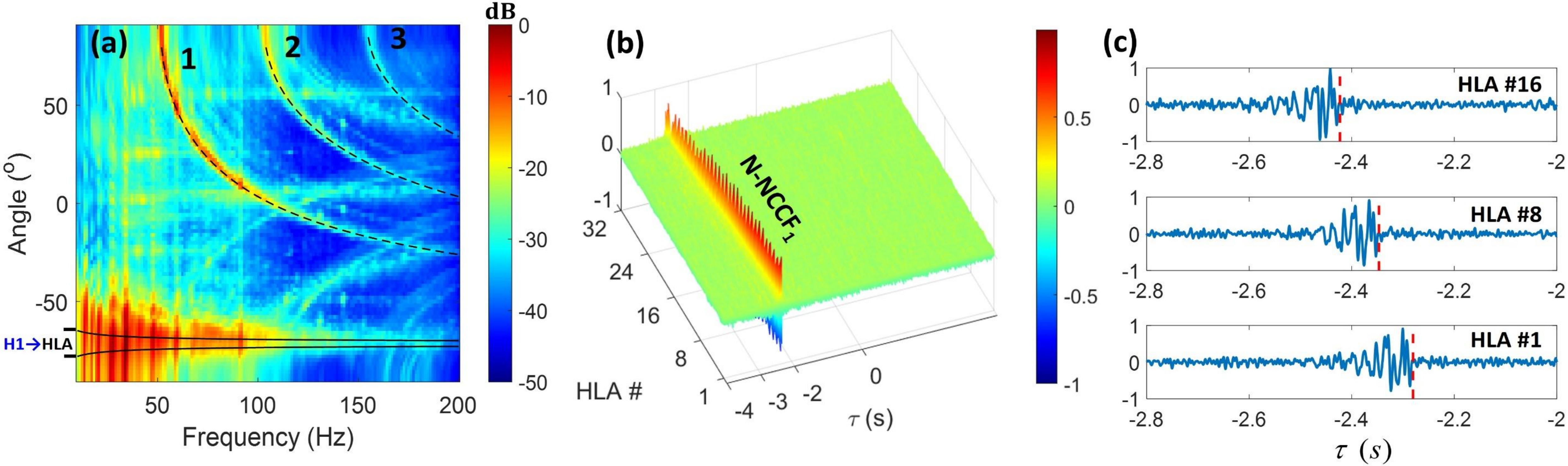
T. Tan, O.A. Godin, B.G. Katsnelson, and M. Yarina **(2020)** , "Passive **geoacoustic inversion** in a dynamic environment on a continental shelf ," *J. Acoust. Soc. Am. 147, EL453-459*

T. Tan and O. A. Godin **(2021)** , "Passive acoustic characterization of **sub-seasonal sound speed variations** in a coastal ocean," *J. Acoust. Soc. Am.* 150.4 2717-2737.

Rapid Emergence of N-NCCF (64 sec)

$$w_m(\varphi) = e^{-ikd_m \sin(\varphi)}$$

$$B(\varphi_s) = \mathbf{w}^{?}\mathbf{p}\left(\mathbf{w}\ \mathbf{p}\right)^{\dagger} = \mathbf{w}^{?}(\varphi_s)\mathbf{K}(\varphi)\mathbf{w}(\varphi_s)$$

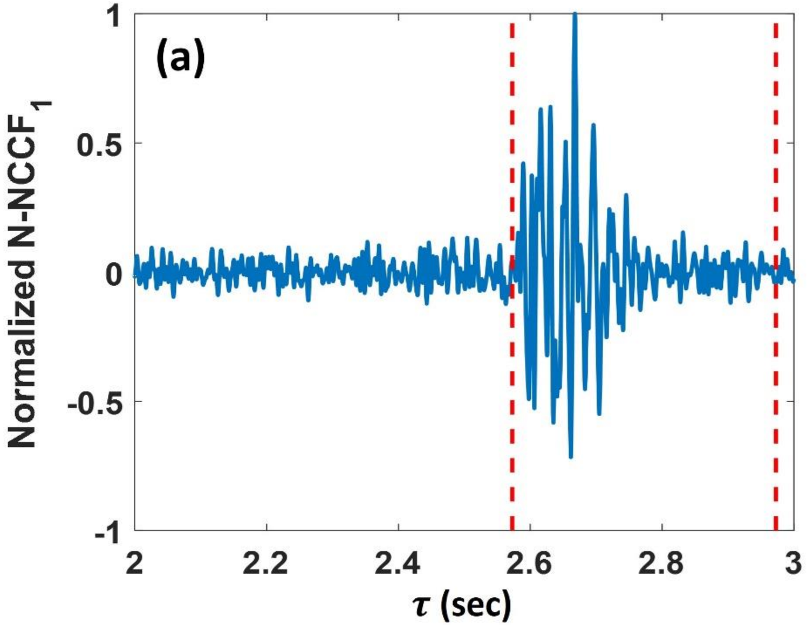


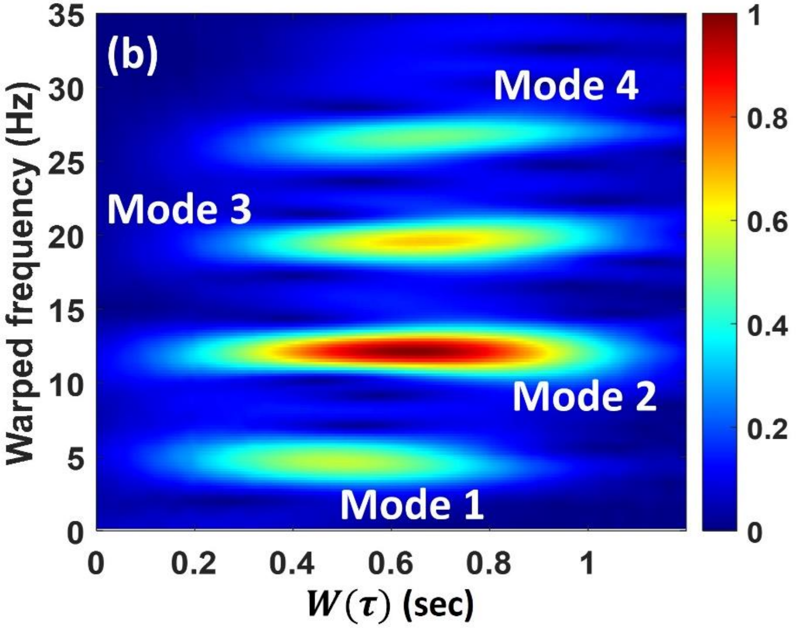
Beamforming on HLA

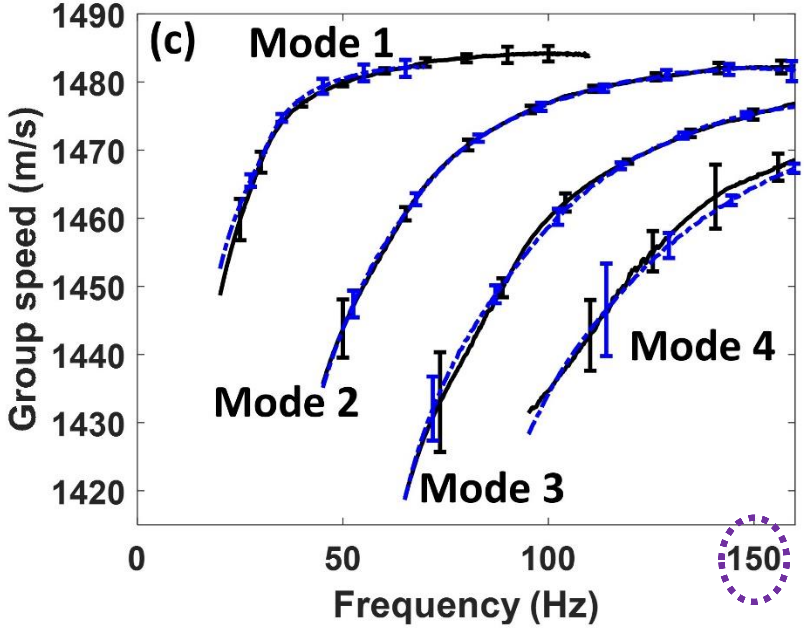
Rapid N-NCCF: Broader Frequency

Extra Higher Mode

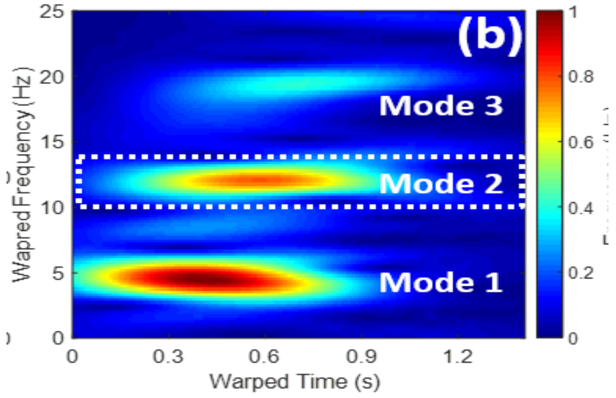
Broader Frequency Band

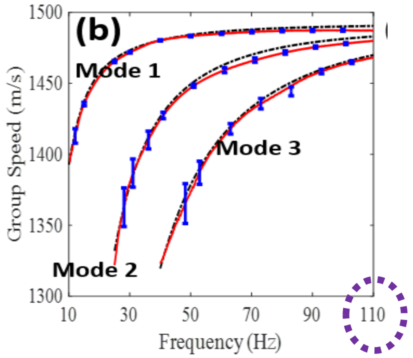






Previous 15-day NCCF





Conclusion on Time Warping in Underwater Acoustics Applications

Time Warping in Underwater Acoustics Applications

- **Time Warping suitable to analyze the modal components of low-frequency (<500 Hz) acoustic Green's functions in shallow water (water depth <200 m) after propagation several kilometers (>1 km)**
- **Applications: Geoacoustic Inversion, Source Localizations, Marine Mammals Vocalizaitons, Tomography, Vector sensor, Noise Cross-Correlation Function….**

Thank You!
Q & A