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Identification of normal modes in underwater acoustic propagation using convolutional neural networks

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Motivation

- Introduce a student into applications of Acoustical Oceanography
- **Background** : Mathematical Modeling, Acoustics, Inverse Problems
- **Problem** : Of practical interest

Given Problem

- **Concept** Use of modal dispersion as the characteristic feature of an acoustic signal to be exploited for inversions

- **Question** : How we can identify the dispersion characteristics of a measured signal in order for them to be used for inversion purposes

Objectives

- Suggest a scheme for an automatic identification of the dispersion characteristics (dispersion curves) for a limited number of modes.

- Test the scheme with synthetic data.

Theory

- Short time Fourier Transform

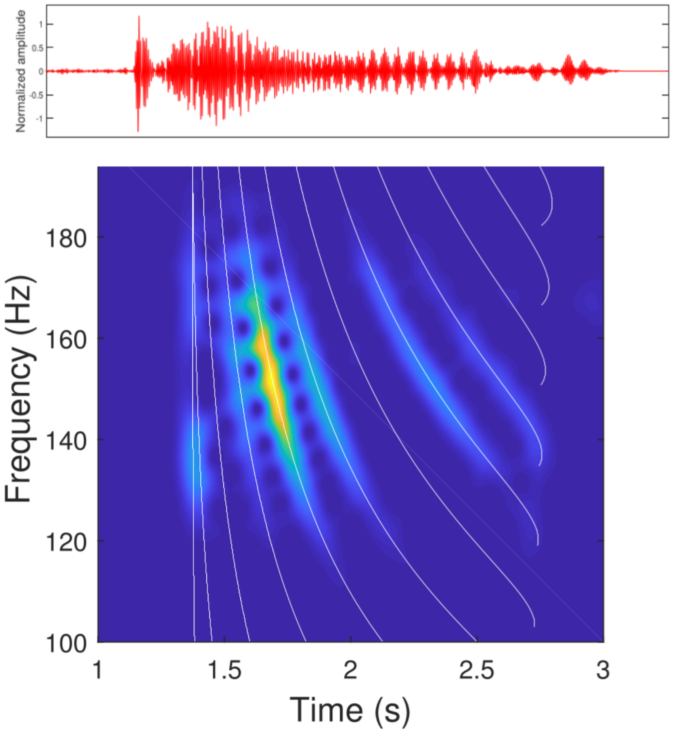
$$\mathrm{STFT}_h(s;\tau,f)=\int_{-\infty}^{\infty}s(t)h(t-\tau)e^{-i2\pi ft}dt$$

- Spectrogram

$$\mathrm{SP}_h(s;\tau,f)=\left|\mathrm{STFT}_h(\tau,f)\right|^2$$

- Dispersion curves :

$$t_n(f)=\frac{r}{v_{g,n}(f)},\quad v_{g,n}(f)=\left.\frac{\partial\omega}{\partial k_n}\right|_{\omega=2\pi f}$$



Solution

- Use Convolutional Neural Networks for the dispersion identification.
- Model the dispersion curves with an appropriate function.
- Train the CNN with a set of synthetic signals. (Training set)
- Evaluate the model with an independent set of signals. (Testing set)

Modelling the dispersion curves

- Polynomial of 5th order

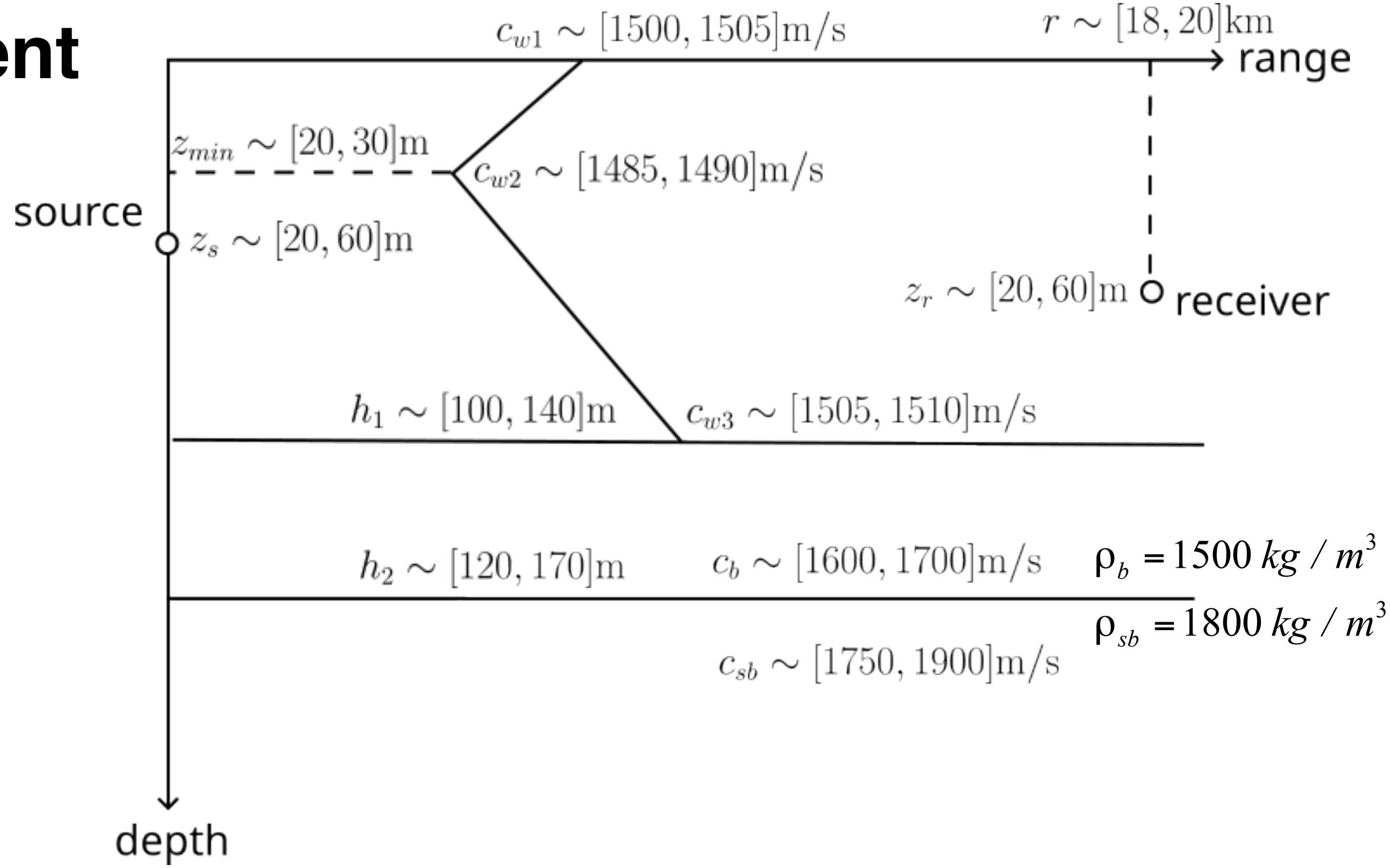
$$\hat{t}_n(f) = a_5^{(n)} f^5 + a_4^{(n)} f^4 + a_3^{(n)} f^3 + a_2^{(n)} f^2 + a_1^{(n)} f \ + a_0^{(n)}$$

$$\hat{t}_n(f) = a_5^{(n)} f^5 + a_4^{(n)} f^4 + a_3^{(n)} f^3 + a_2^{(n)} f^2 + a_1^{(n)} f \ + \varepsilon\, a_0^{(n)}, \quad \varepsilon = 0.1$$

- The Neural Network should estimate the vector of the polynomial parameters for the three first orders of modes.

$$\mathbf{a}^{(n)} = \left(a_0^{(n)}, a_1^{(n)}, a_2^{(n)}, a_3^{(n)}, a_4^{(n)}, a_5^{(n)}\right)$$

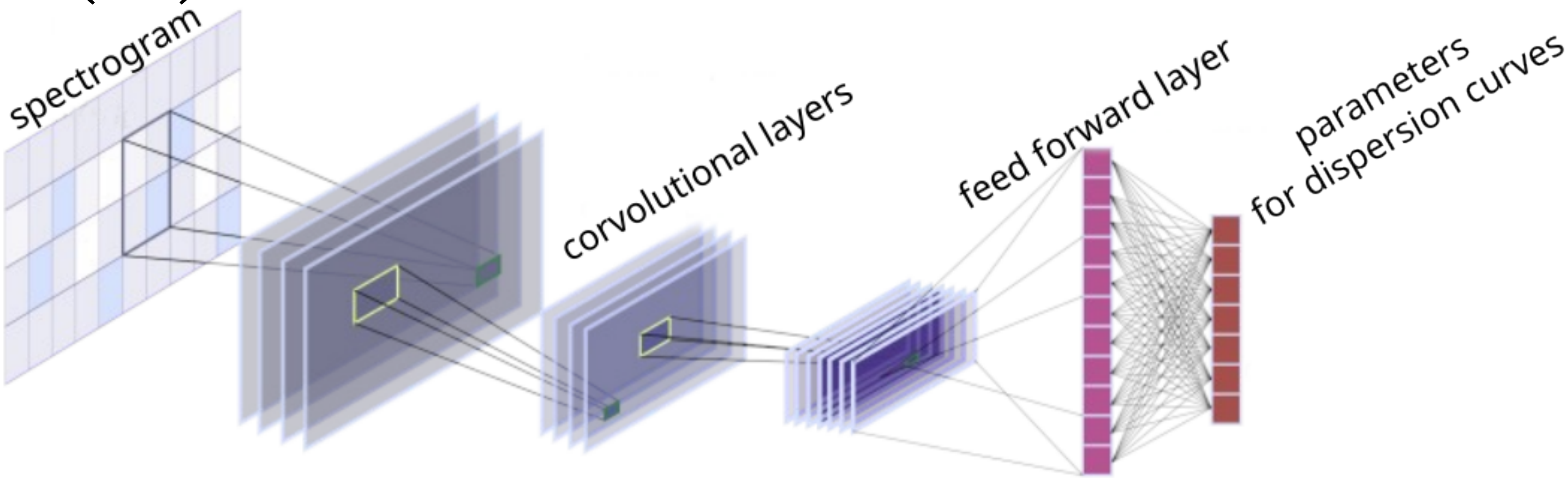
A simple environment



The convolutional neural network

Input : $log\left(SP+1\right)$

Output : $\left(a_i^{(n)}\right)$, $i=1,\ldots,6$ $n=1,2,3$

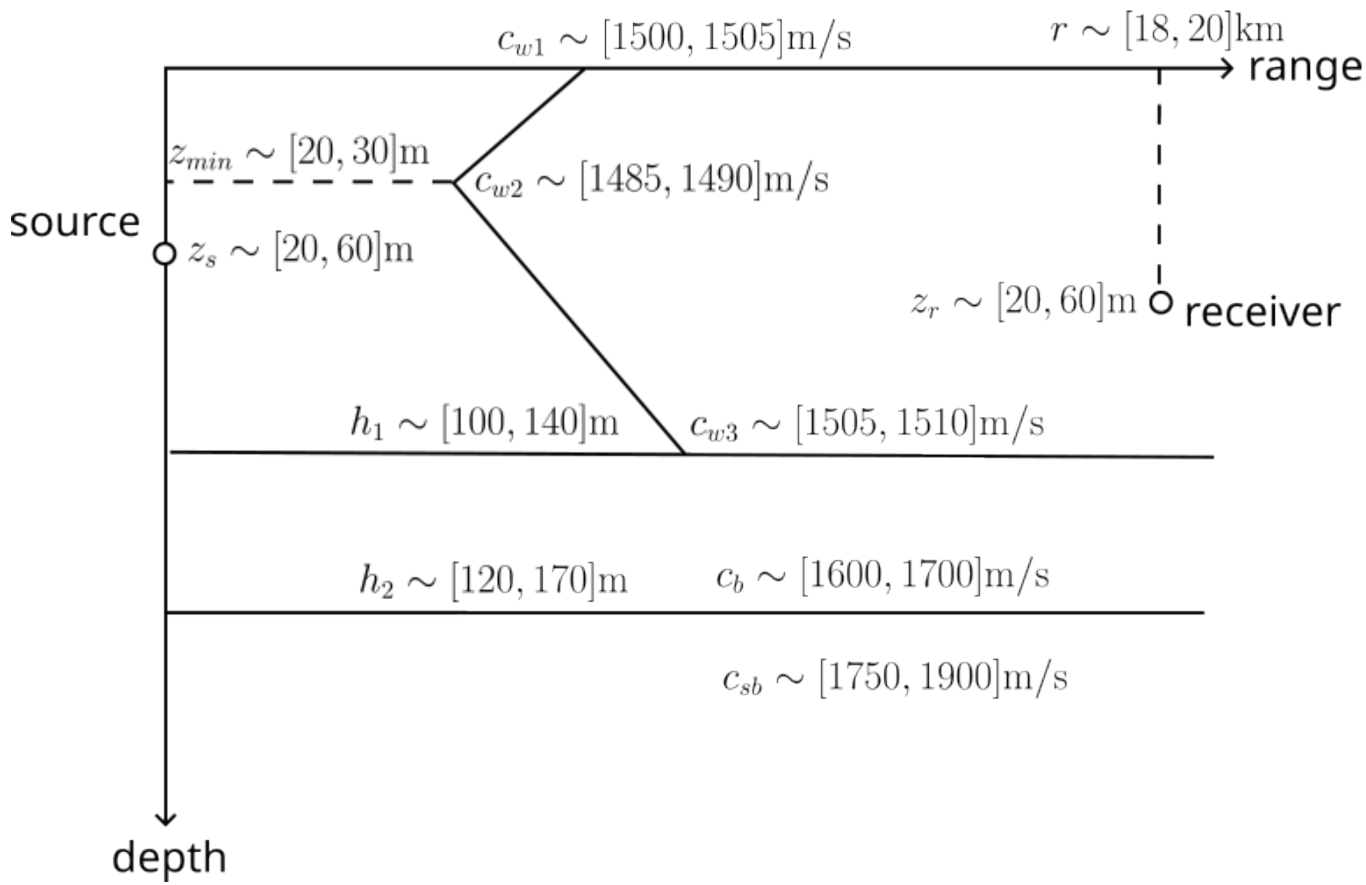


Implementation

4096 random samples

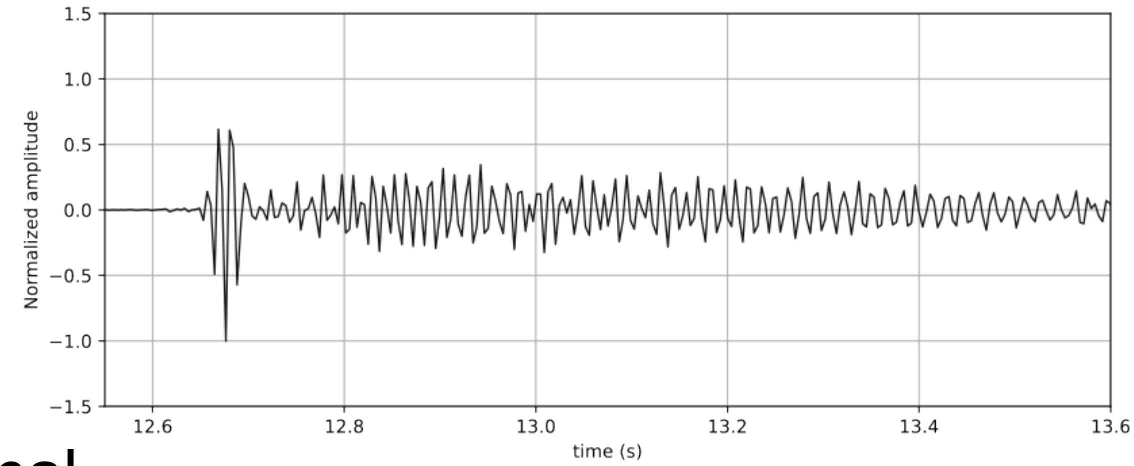
80% training set

20% testing set



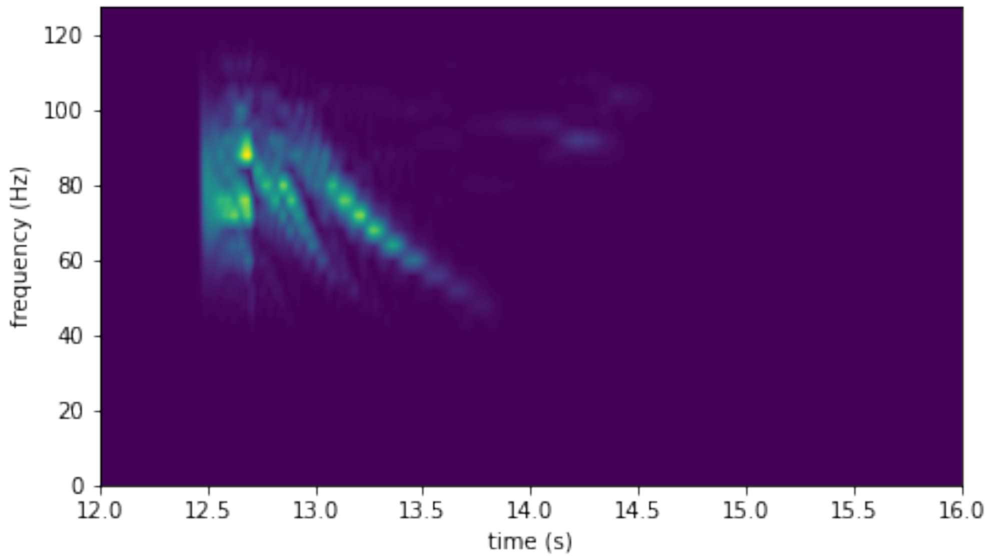
Implementation

A signal is chosen among the testing set to be used as the reference (measured) signal



No noise is added

Its spectrogram



Implementation

The spectrogram is given in discrete sets of time and frequency

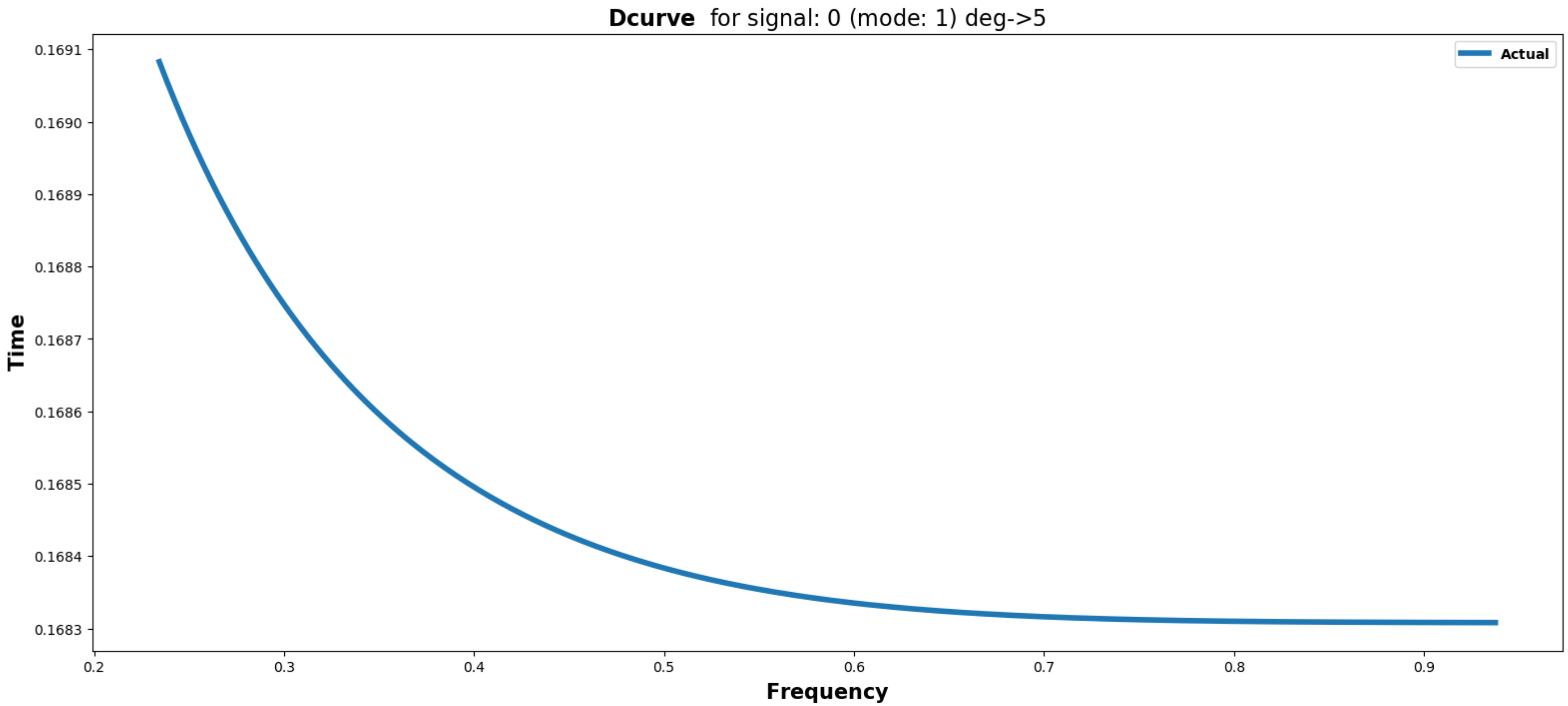
Determination of the CNN output

$$a_*^{(n)} = \arg\min \sum_i \left(\hat{t}^{(n)}(f_i) - t^{(n)}(f_i) \right)^2$$

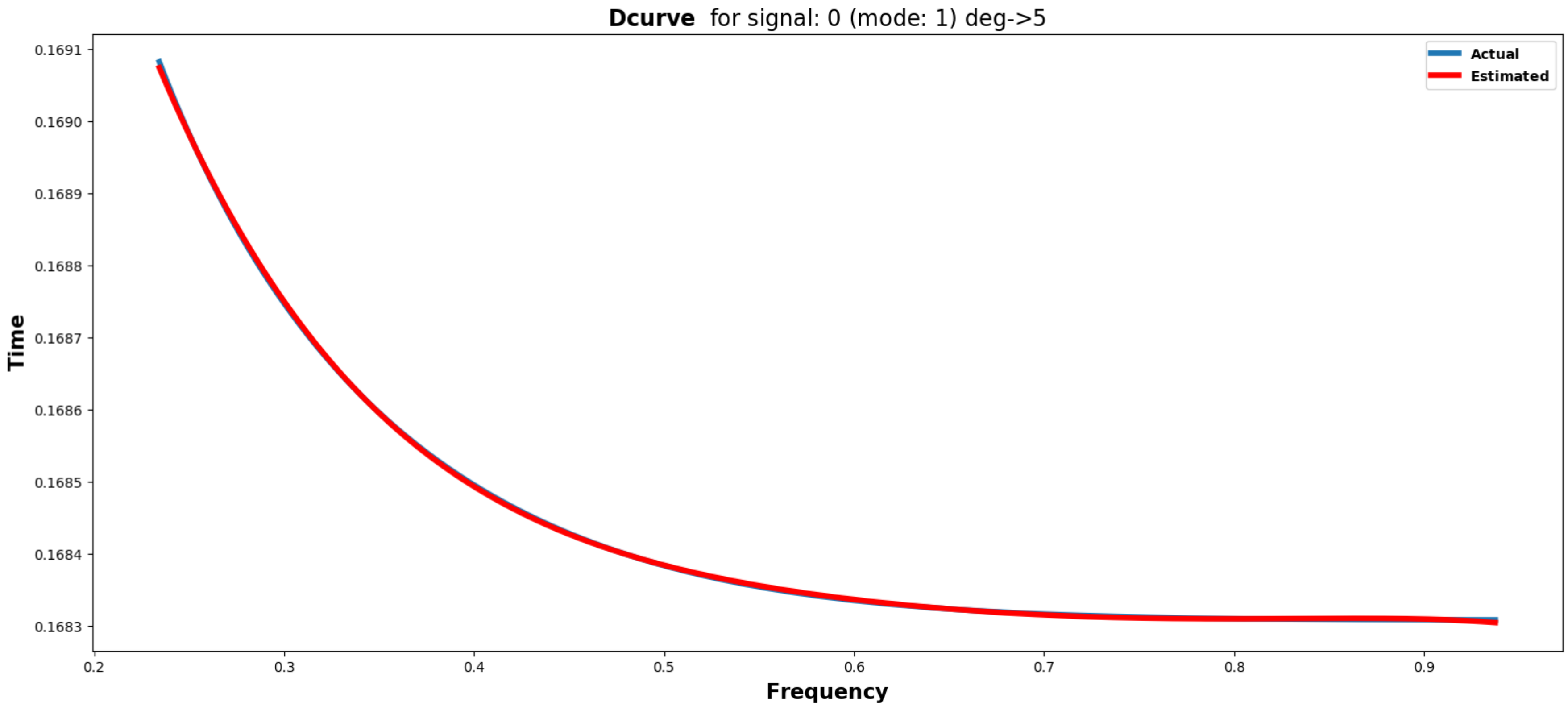
Results

Mode	a_0	a_1	a_2	a_3	a_4	a_5	
1	0.1925,	-0.0279,	0.0731,	-0.1039,	0.0727,	-0.0201	
2	0.3702,	-1.1324,	3.1526,	-4.5516,	3.3233,	-0.9606	“Measured”
3	0.3857,	-0.8043,	1.6648,	-1.9313,	1.1617,	-0.2713	
1	0.1725,	-0.0277,	0.0753,	-0.1055,	0.0752,	-0.0215	
2	0.3739,	-1.3339,	3.7522,	-5.4873,	4.0550,	-1.1950	“Estimated”
3	0.4067,	-1.1110,	2.5854,	-3.3142,	2.2223,	-0.6082	

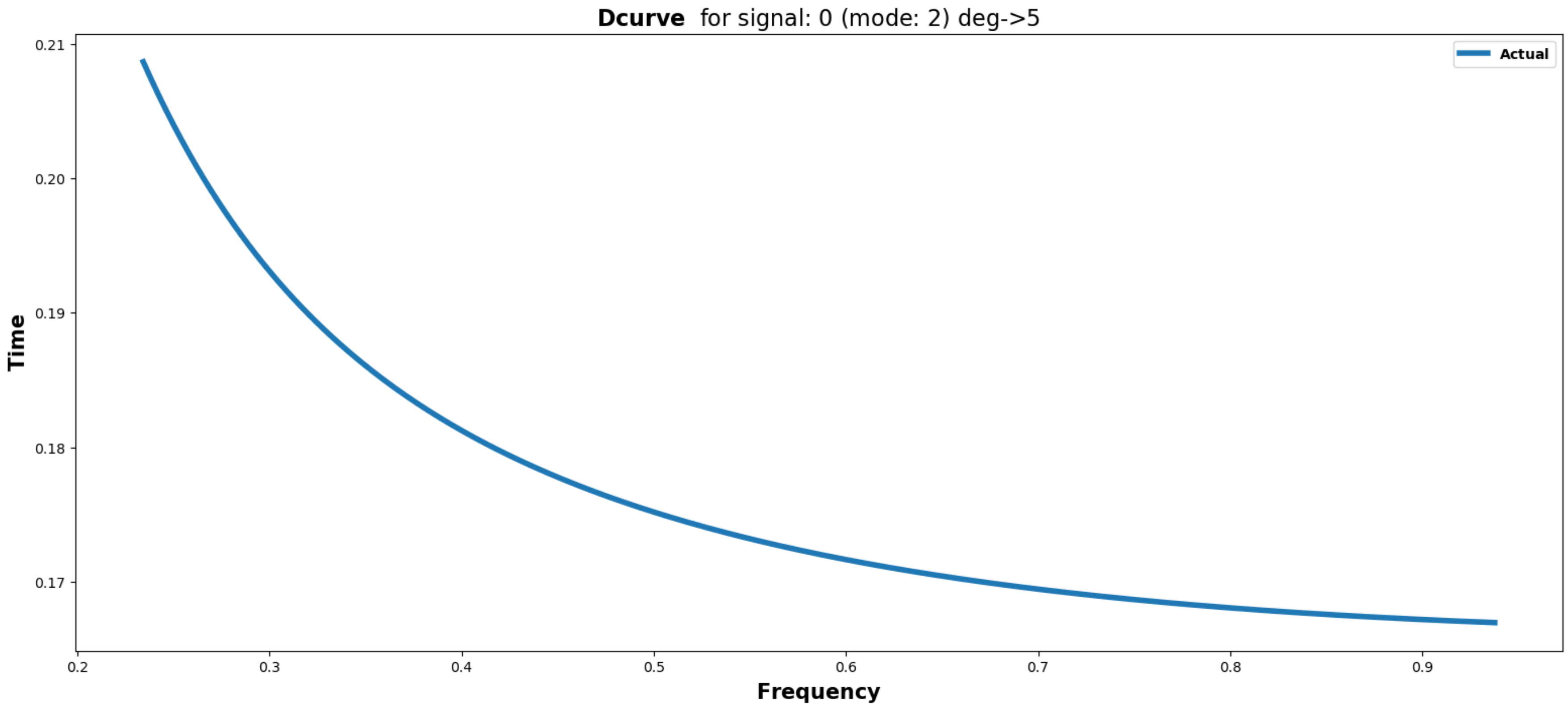
Mode 1


Dcurve for signal: 0 (mode: 1) deg->5
Actual
Time
Frequency
0.1691
0.1690
0.1689
0.1688
0.1687
0.1686
0.1685
0.1684
0.1683
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Mode 1

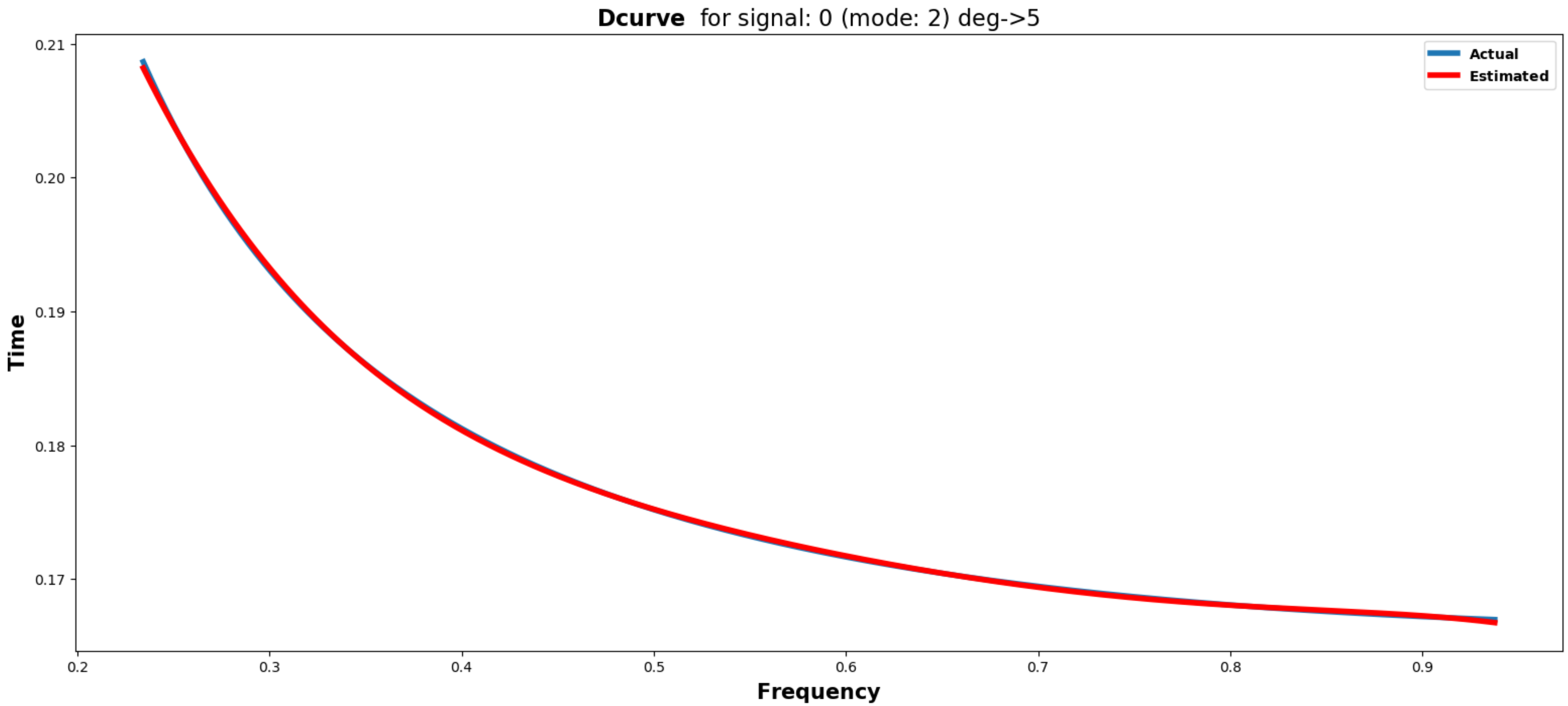

Dcurve for signal: 0 (mode: 1) deg->5
Actual
Estimated
Time
Frequency
0.1691
0.1690
0.1689
0.1688
0.1687
0.1686
0.1685
0.1684
0.1683
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Mode 2

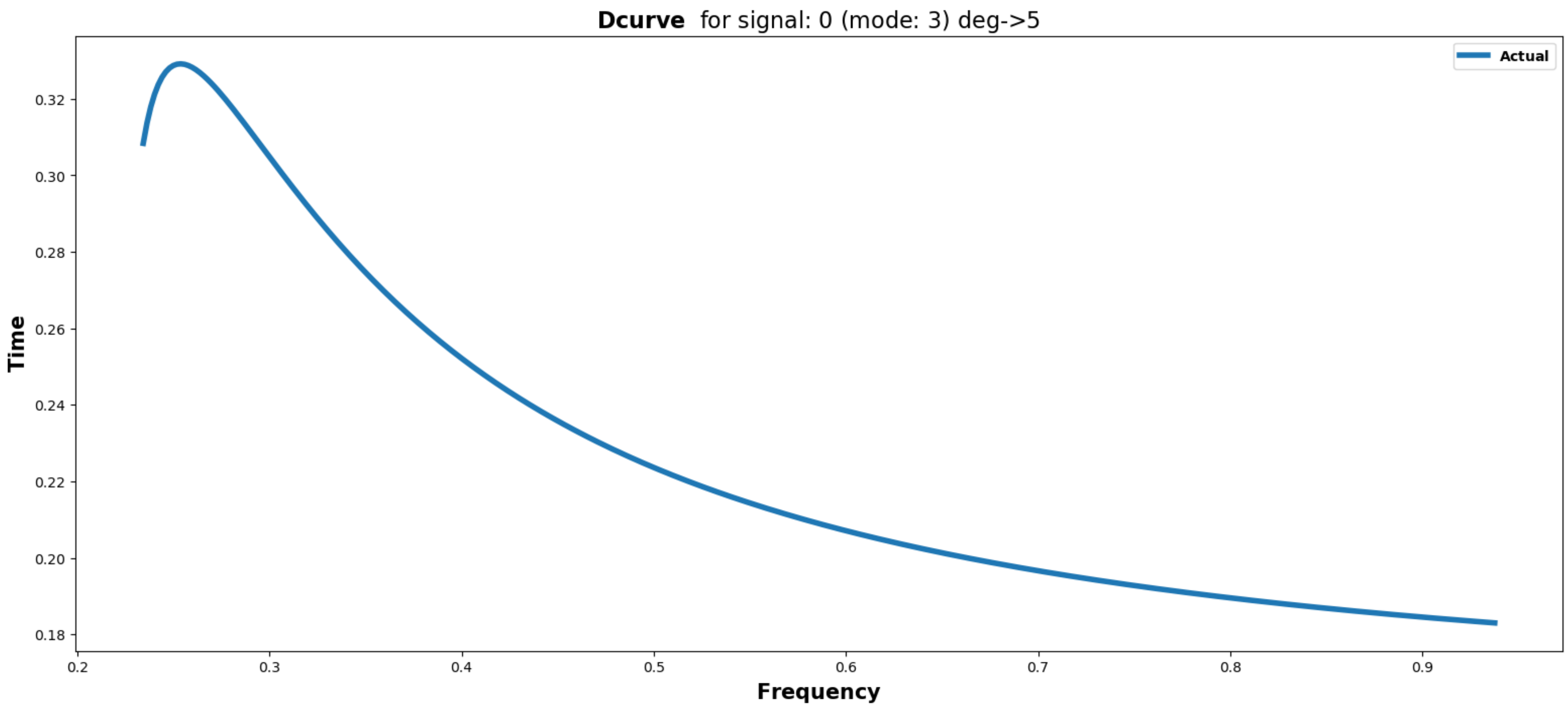


Dcurve for signal: 0 (mode: 2) deg->5
Actual
Time
Frequency
0.21
0.20
0.19
0.18
0.17
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

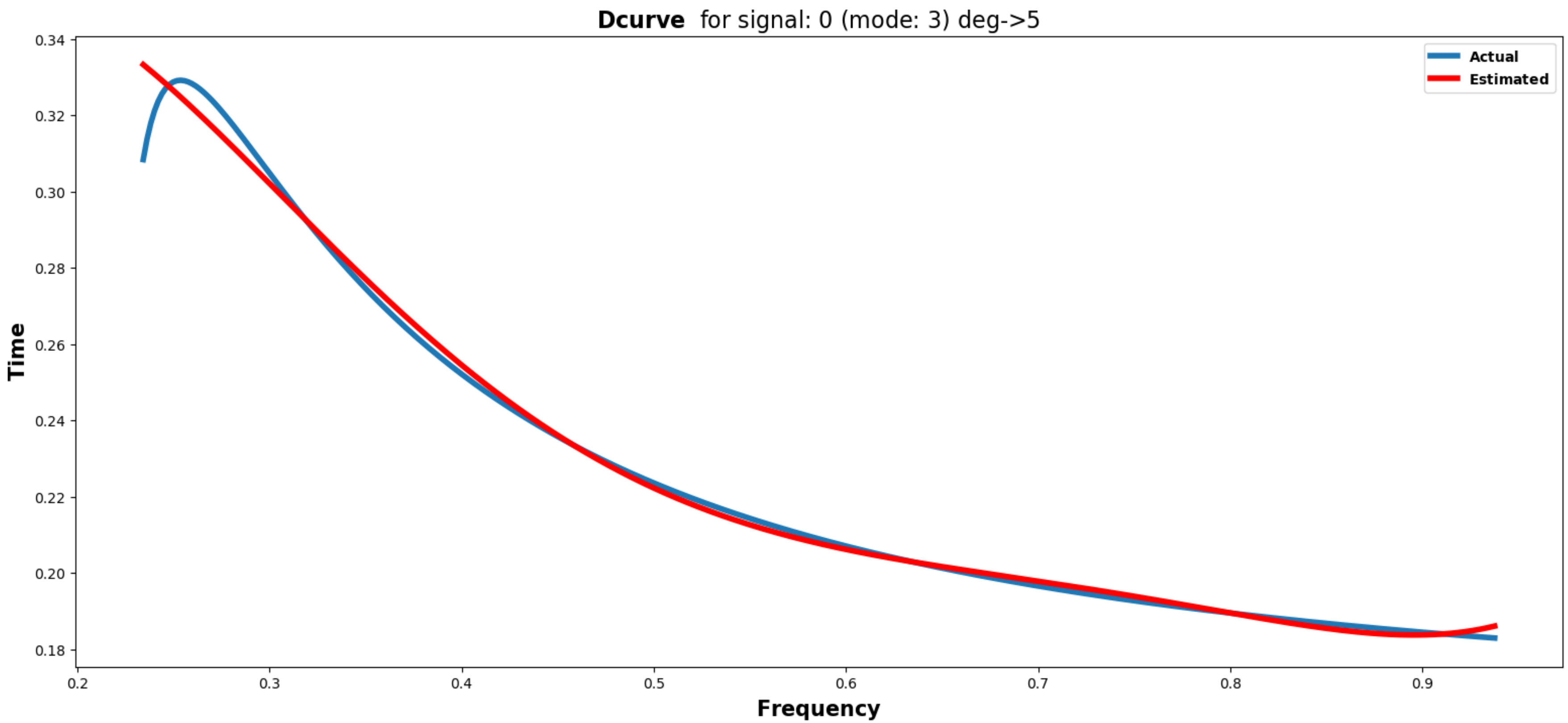
Mode 2


Dcurve for signal: 0 (mode: 2) deg->5
Actual
Estimated
Time
Frequency
0.21
0.20
0.19
0.18
0.17
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Mode 3


Dcurve for signal: 0 (mode: 3) deg->5
Actual
Time
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
Frequency
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Mode 3

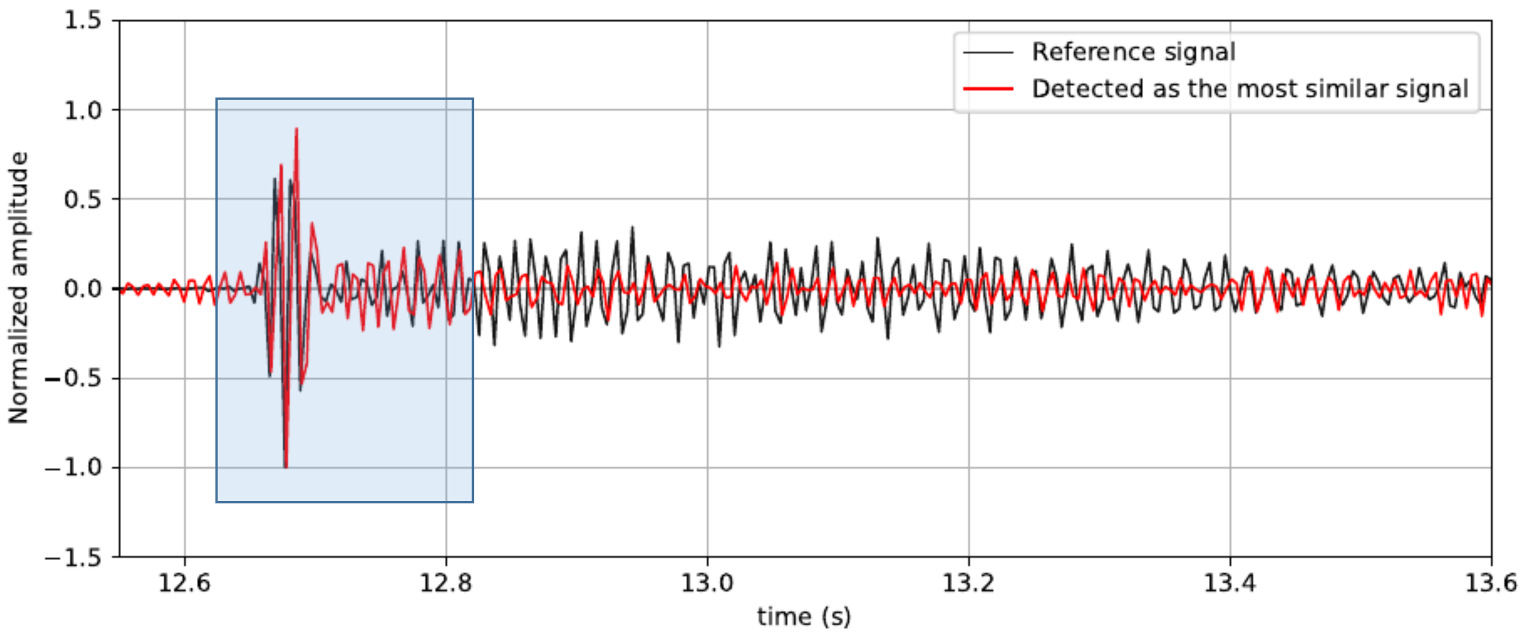

Dcurve for signal: 0 (mode: 3) deg->5
Actual
Estimated
Time
Frequency
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

An attempt to use the estimated dispersion curves for environmental parameters estimation

Discretize the curves and compare them with those associated with the signals of the data sets.

Use a simple least square norm of their distance to determine the closest (most similar) signal.

Signal associated with estimated dispersion curves



Among signals of the NN sets

Naive inversion

Comparison between the environmental/operational parameters associated with the "measured" signal and the "closest" signal

Parameter	Reference	Closest signal
$r\ (km)$	18.834	18.994
$c_{w1}\ (m/s)$	1500	1503
$c_{w2}\ (m/s)$	1485	1488
$c_{w3}\ (m/s)$	1506	1505
$z_{min}\ (m)$	23	24
$h_1\ (m)$	112	105
$h_2\ (m)$	133	126
$z_s\ (m)$	48	43
$z_r\ (m)$	20	31
$c_b\ (m/s)$	1653	1659
$c_{sb}\ (m/s)$	1812	1780

Conclusions

- The students under appropriate supervision can produce interesting results to be used as the basis of further research.

- The identification of the modal packets of an underwater acoustic signal in the time-frequency domain using Artificial Neural Network seems feasible.

Future projects

- For realistic applications there is a need to increase the training set.
- Application in inverse problems of ocean acoustic tomography or geoacoustic inversion, based on the identification of the dispersion characteristics of the propagating modes.
- We need to identify higher order modal packets.
- Try splines instead of polynomials

Thank you for your attention

Ευχαριστώ για την προσοχή σας

관심을 가져주셔서 감사합니다.