Noise-reduction process and useful signal interpretation on recorded passive acoustic signals using time-frequency representations

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Introduction (1/4)

- A major challenge in underwater communication:
  - Collect and distribute subsurface data from multiple distributed instruments in real time

- Problem: To achieve useful spatial coverage, the subsurface measurement involves multiple instruments deployed with separation of several kilometers
  - Seafloor wires and cables?
    - Deployment cost, Incompatible with bottom-fishing activities
  - Array of networked acoustic modems
    - Example: FRONT* Project

*Front-Resolving Observation Network with Telemetry, funded by the NOPP

Introduction (2/4)

- Networked acoustic modems:
  - Based on the use of repeater nodes
    - Individual acoustic modems
    - Use to relay the message
- Repeater node principle:
  - Decoding received data from the previous node
  - Encoding and sending data to the next one

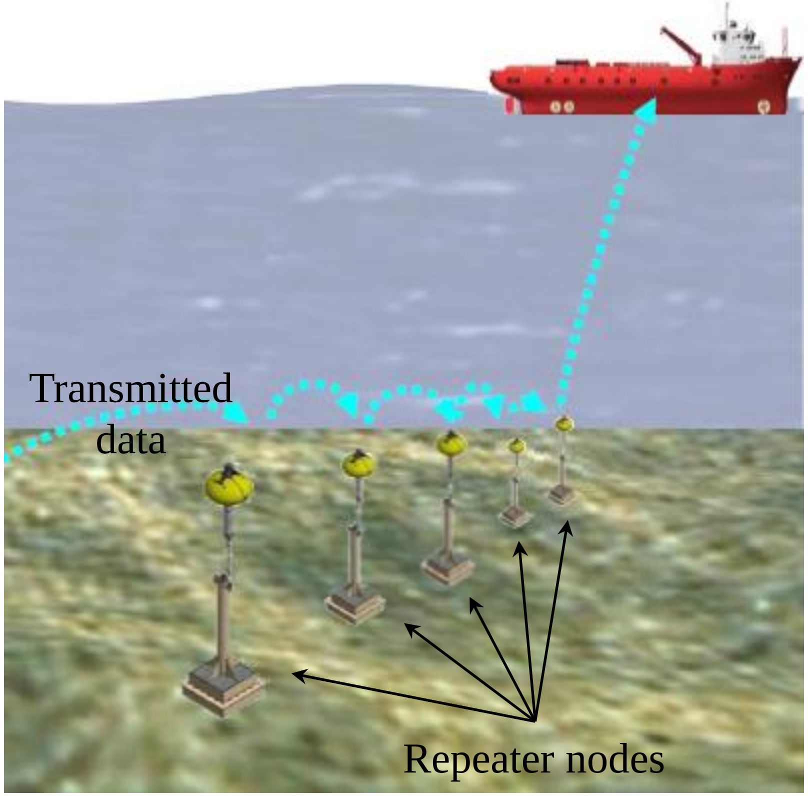


Image from Sonardyne International

- Problem: strong dependency with the modulation techniques
  - What happens in case of different systems on the same area?

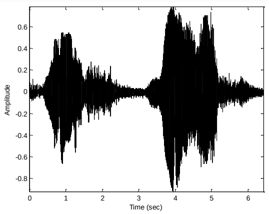
Introduction (3/4)

- Idea: Develop an acoustic repeater with no dependency on the type of modulation (blind system)
  - ↳ Universal repeater node ⇔ free access underwater wireless network
- Principle: Applied a denoising process on the received signal and amplified the resulting data before resending them
- Several denoising process based on:
  - ↳ Signal and/or noise statistics knowledge ⇔ lack of knowledge ?
  - ↳ Gaussian noise assumptions ⇔ disturbing signal = realization of a non-Gaussian process ?
  - ↳ Noise reduction in time domain ⇔ smoothing effect

Introduction (4/4)

➢ Proposition: take advantage of a time-frequency plane

Received acoustic signal → Time-frequency representation → Denoising → Useful signal reconstruction



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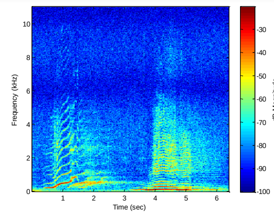

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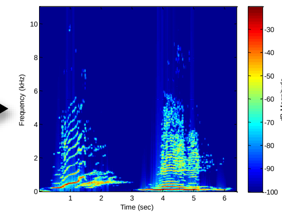

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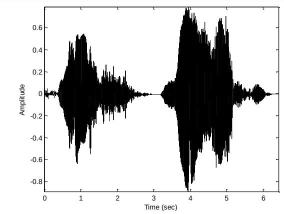


- Use of time-frequency plane ⇔ Gaussian properties
- Suited to non-stationary signals ⇔ time resolution preservation

➢ Which kind of time-frequency transformation ?

- Time and frequency resolutions ⇔ Heisenberg principle
- Narrow frequency resolution ⇔ high amount of computations
- Must make possible the time domain reconstruction

Contents

The *Hearingogram* (1/3)

➢ Main idea

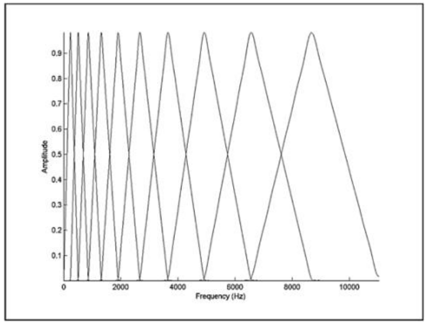
- Solve three main problems:
  - ⇨ Time-frequency approaches ⇔ resolution problems or interferences
  - ⇨ Narrow frequency resolution ⇔ memory problems and high computing time
  - ⇨ Invertible process:

- Take into account the human physiology

The *Hearingogram* (2/3)

➢ The Mel's filters

- Human ear = filters concentrated only on certain frequency components
- Mel's filters non-uniformly spaced on the frequency axis



⇨ Triangular shaped filters bank in accordance with the Mel's scale:

$$mel(\nu) = 2595 \log_{10}\left(1 + \frac{\nu}{700}\right)$$

- Mel's filter characteristics

Bandwidth

$$B(m) = \begin{cases} \nu_2 - mel(\nu_{min}), & m = 1 \\ \nu_{m+1} - \nu_{m-1}, & m = 2, \dots, M-1 \\ mel(\nu_{\max}) - \nu_{M-1}, & m = M \end{cases}$$

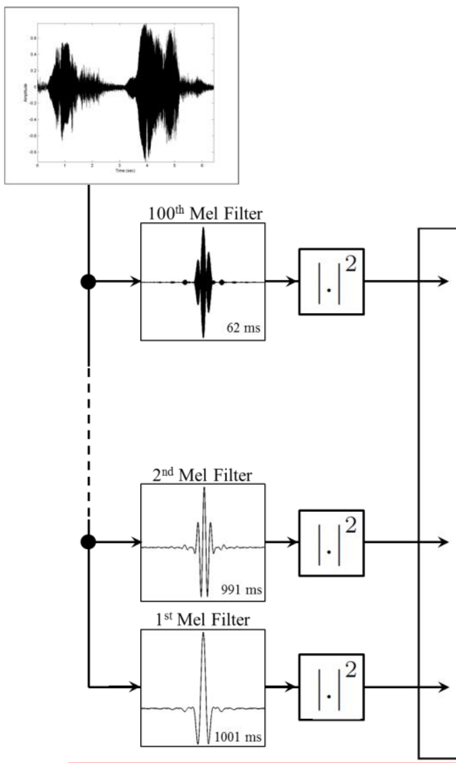
Center frequencies

$$\nu_m = 700\left(10^{\frac{mel(\nu_m)}{2595}} - 1\right)$$

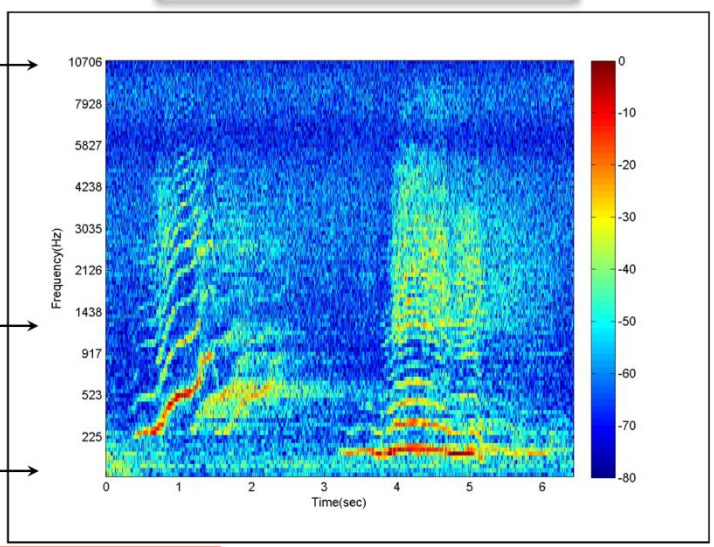
with: $mel(\nu_m) = \frac{m}{M+1}\left(mel(\nu_{max}) - mel(\nu_{min})\right)$

The *Hearingogram* (3/3)

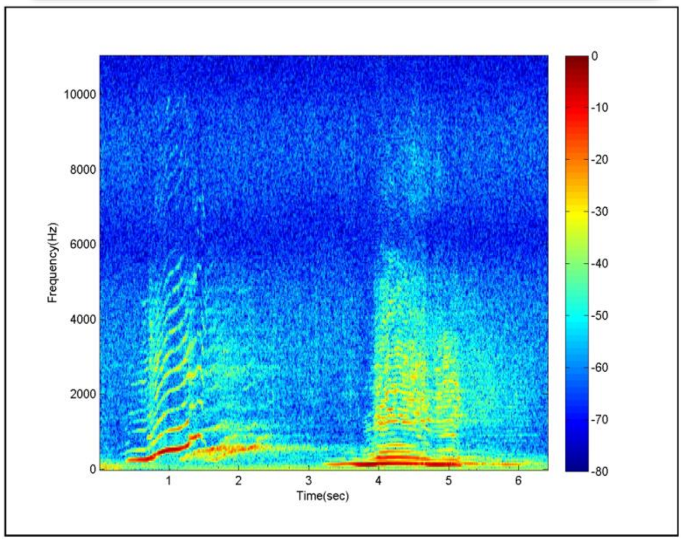
➢ The *Hearingogram* principle



Hearingogram
(100 Mel's filters)



Short-Time Fourier Transform
(4096 rows)



Number of samples to describe h_m

$$\Theta_Z[n,m] = \left(\sum_{k=1}^{M_{h_m}} Z[n-k]h_m[k]\right)^2$$

Impulse response associated to the m[th] Mel's filter

The denoised *Hearingogram* (1/2)

➢ Principle

- Statistical properties: the disturbing terms in the received signal become Gaussian, before the square magnitude, in $\Theta_Z[n,m]$

$$\boldsymbol{N}_{\boldsymbol{h_m}} \hookrightarrow \mathcal{N}\left(0, \sigma^2_{N_{h_m}}\right)$$

- Gaussian noise ⇔ wavelet based denoising method
  - ⇨ Discrete Wavelet Transform (DWT) following the Mallat multiresolution algorithm
  - ⇨ Wavelet coefficients thresholding setting to zero the coefficients lower than the *universal* threshold:

$$\lambda_m[p] = \alpha \sigma_{N_{h_m}} \sigma_\eta^m[p] \sqrt{2 \ln M_Z}$$

Scale level (p)

Parameter used to reinforce the noise reduction (α)

$\sigma_{N_{h_m}} = MAD(\boldsymbol{Z}_{\boldsymbol{h_m}})/0.6745$

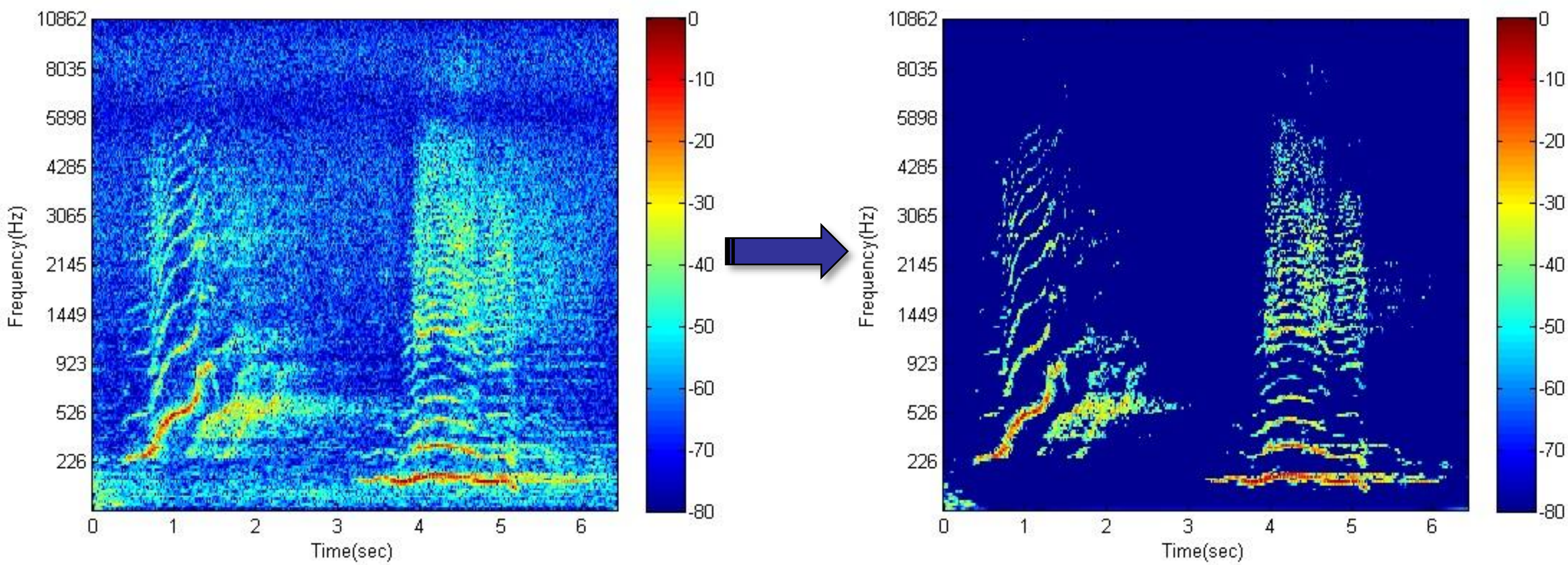
Standard deviation at scale level p of the response of the m[th] Mel's filter to a white Gaussian noise ($\sigma_\eta^m[p]$)

The denoised *Hearingogram* (2/2)

Flowgraph

Z_{h_m} → DWT → Thresholding → DWT^{-1} → $\tilde{S}_{h_m}$

➢ Example



Denoised useful signal reconstruction (1/2)

➢ Principle

↳ Whole Mel's filters bank = band-pass filter

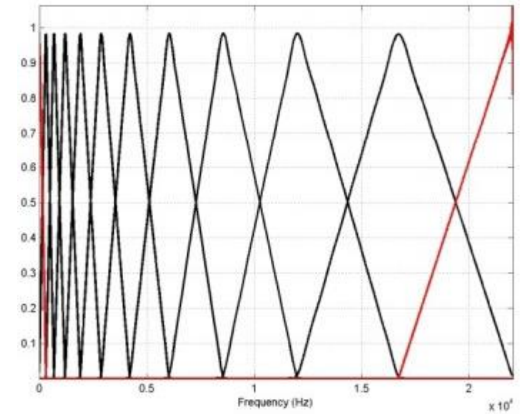
$$H^{Mel}(\nu) = \sum_{m=1}^{M} H_m(\nu) = 1, \forall \nu \in [\nu_1; \nu_M]$$

with $[mel(\nu_{min}); \nu_1[$ and $]\nu_M; mel(\nu_{max})]$ as transition widths

↳ Energy conservation ⇔ add two filters

$$H(\nu) = H_0(\nu) + H_{M+1}(\nu) + H^{Mel}(\nu) = 1,$$

$$\forall \nu \in [0; F_s/2]$$



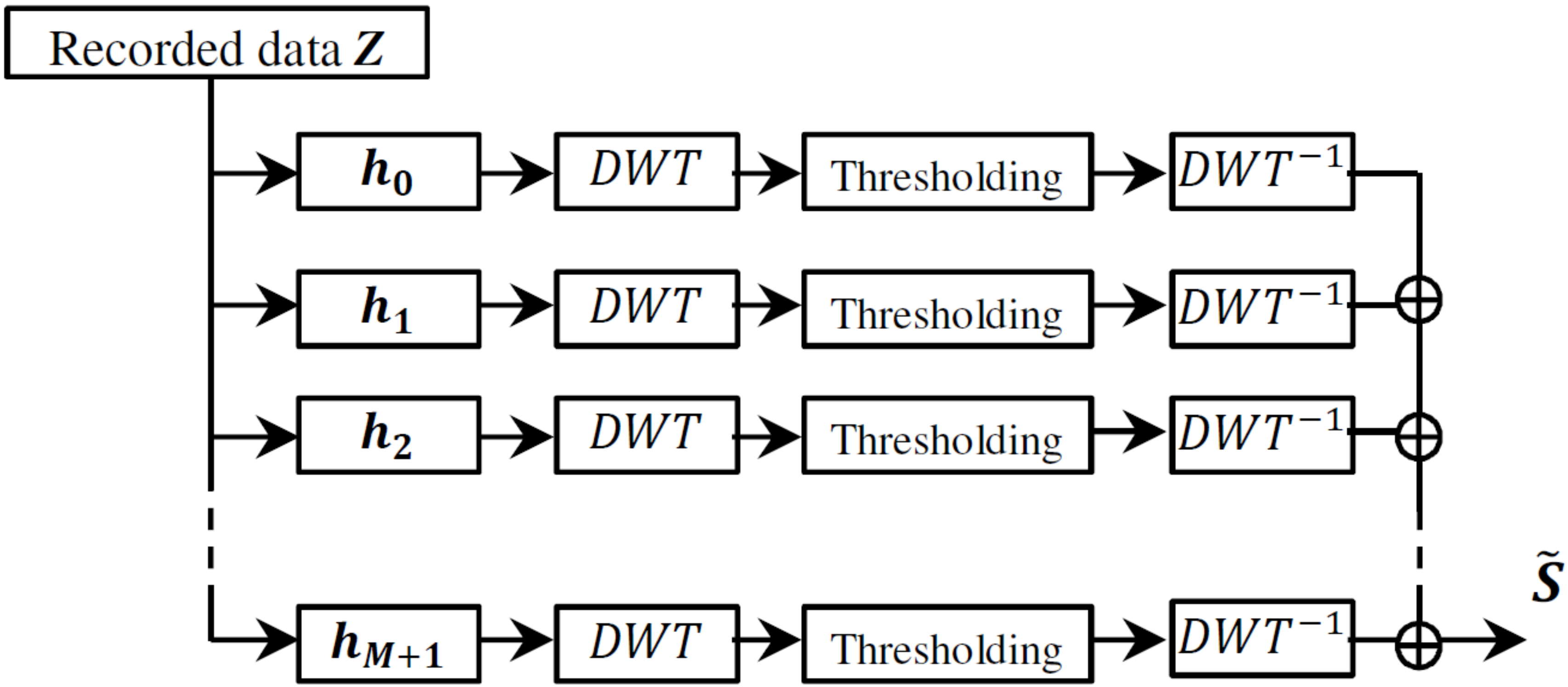
↳ Associated impulse response

$$\boldsymbol{h} = TF^{-1}[H(\nu)] \cong \delta$$

⇒ Approximation of the useful signal: $\tilde{s} = \sum_{m=0}^{M+1} \tilde{s}_{h_m}$

Denoised useful signal reconstruction (2/2)

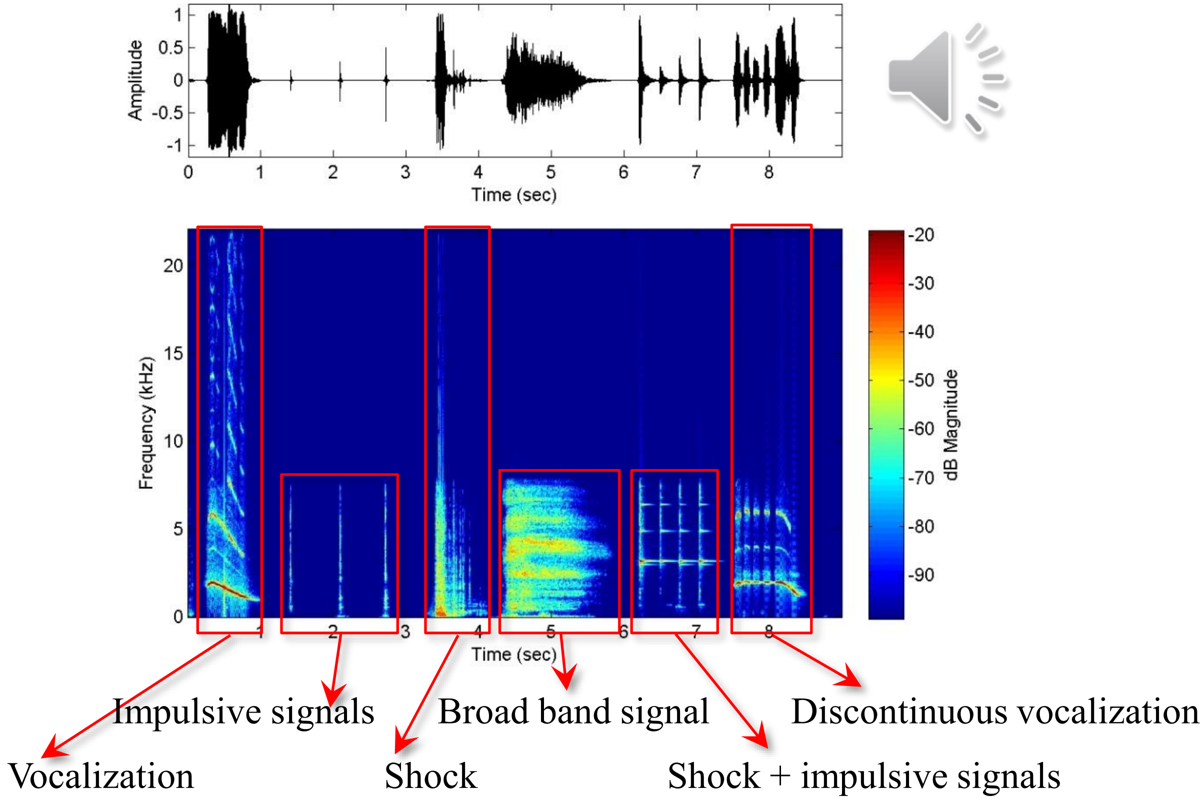
- Flowgraph



Experiments (1/5)

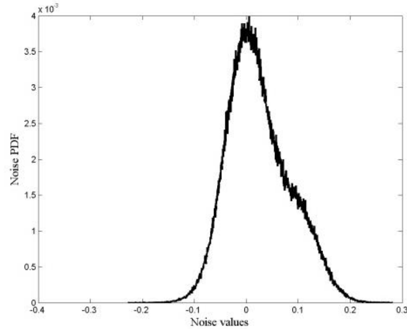
➢ Simulated data

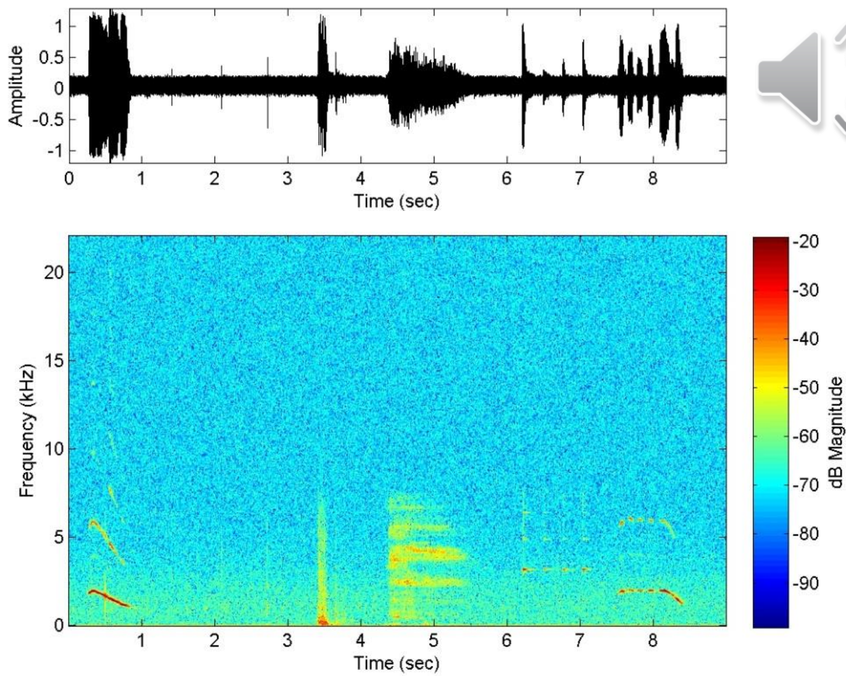
↳ Test signal (sampling frequency: 44 100 Hz)

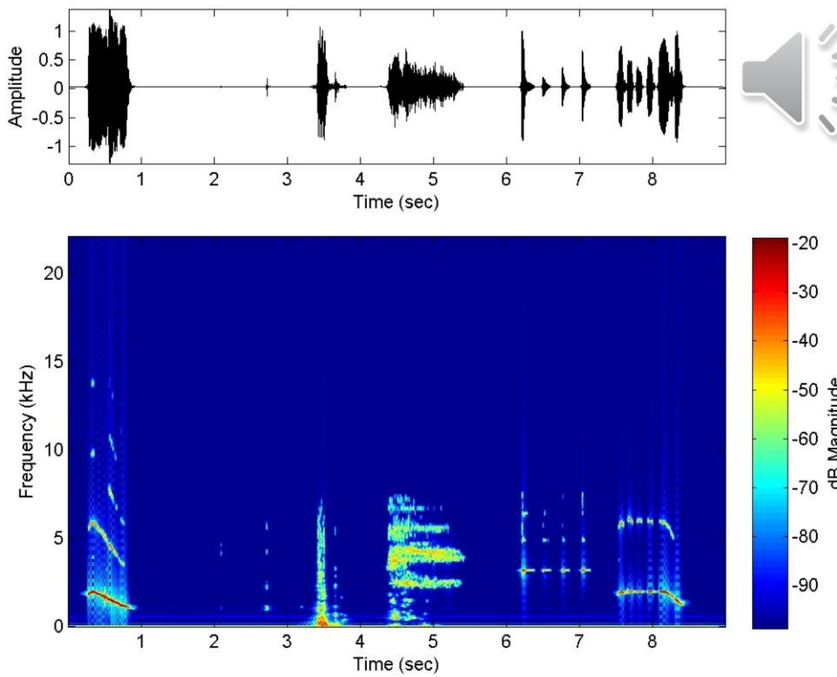


Experiments (2/5)

- Simulated noisy received signal
  - Disturbing terms: Gaussian-Gaussian mixture
  - Denoising: 200 Mel's filters, 4th order Daubechies wavelet, $\alpha=1$

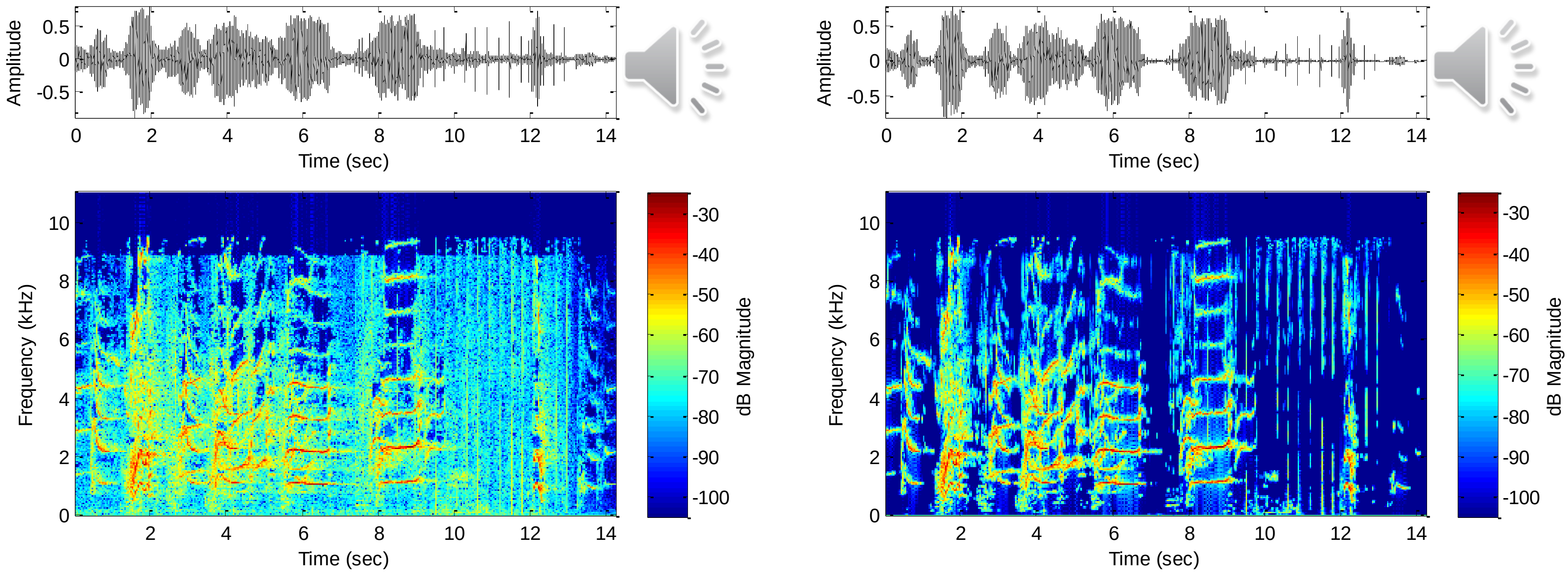






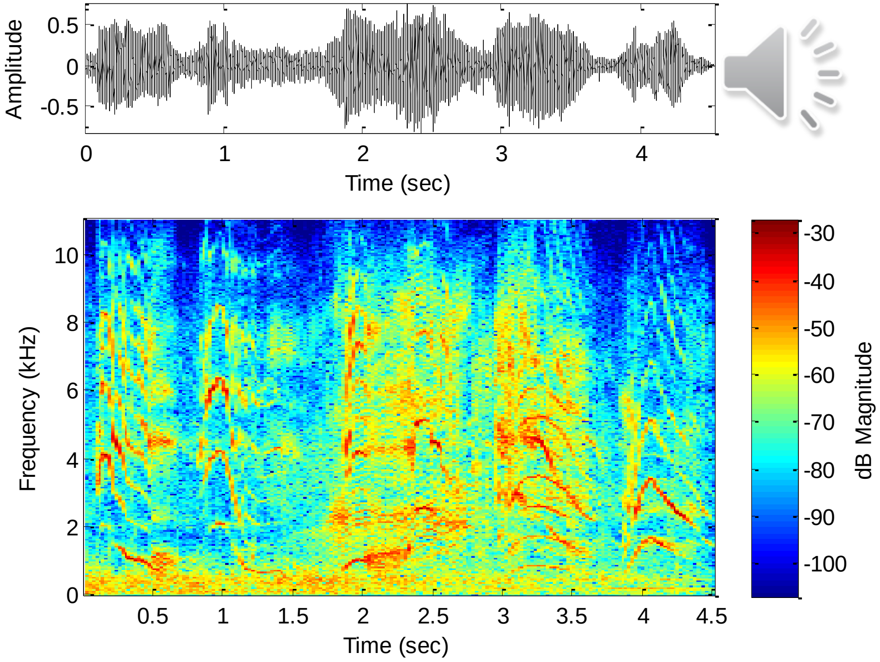
Experiments (4/5)

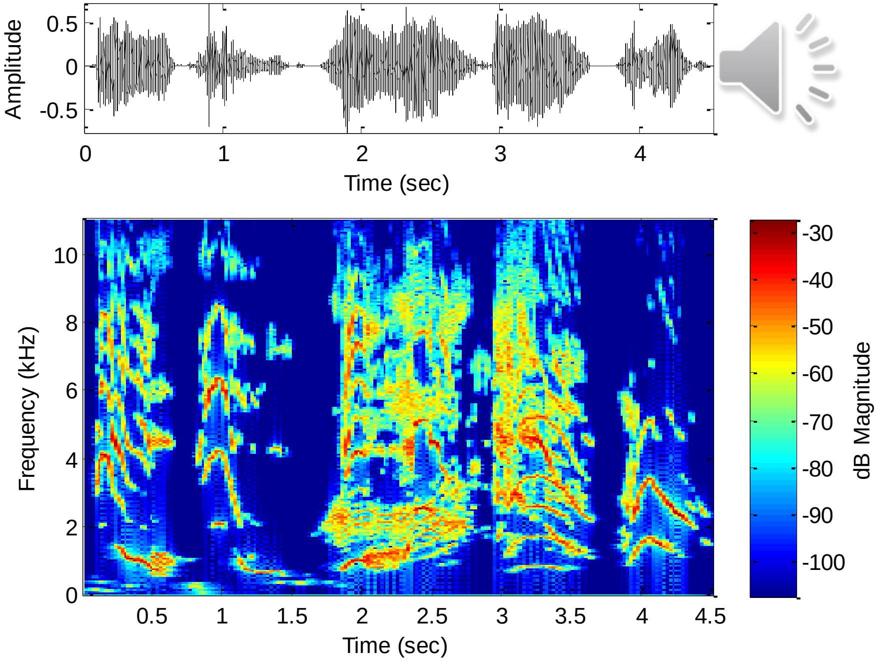
- Real underwater records
  - Killer whale vocalization (sampling frequency: 22 050 Hz)



Experiments (5/5)

- Dolphin sounds
  (sampling frequency: 22 050 Hz)





Concluding remarks

- Results obtained on real and simulated data reveal the efficiency of the denoising process
- Method can be easily parallelized ⇔ Real-time compatibility
- Noise reduction
  - No assumption or information about the useful signal and noise
  - Blind process fully automatic (key point in fully automatic and operational systems)
- Next step: sea trials in a context of wireless underwater communications

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