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

P. Courmontagne, Senior IEEE
IM2NP / ISEN-Toulon
France

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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
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

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

- 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
- The denoised Hearingogram
- Useful signal reconstruction
- Experiments
  - Simulated signal
  - Real underwater records
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

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Center frequencies</th>
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| \[ B(m) = \begin{cases} 
\nu_2 - mel(\nu_{min}), & m = 1 \\
\nu_{m+1} - \nu_{m-1}, & m = 2, ..., M - 1 \\
mel(\nu_{max}) - \nu_{M-1}, & m = M 
\end{cases} \] |
| \[ \nu_m = 700 \left( 10^{\frac{mel(\nu_m)}{2595}} - 1 \right) \] with: \[ mel(\nu_m) = \frac{m}{M + 1} (mel(\nu_{max}) - mel(\nu_{min})) \] |
The Hearingogram principle

**Hearingogram** (100 Mel’s filters)

**Short-Time Fourier Transform** (4096 rows)

Number of samples to describe $h_m$

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

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 $\Theta_Z[n, m]$

$$N_{hm} \sim \mathcal{N}(0, \sigma_{N_{hm}}^2)$$

*Gaussian noise $\iff$ 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:*

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

- **Scale level**
- **Parameter used to reinforce the noise reduction**
- **Standard deviation at scale level** $p$ of the response of the $m^{th}$ Mel’s filter to a white Gaussian noise
  $$\sigma_{N_{hm}} = \text{MAD}(Z_{hm})/0.6745$$
The denoised *Hearingogram* (2/2)

**Flowgraph**

\[ Z_{hm} \rightarrow \text{DWT} \rightarrow \text{Thresholding} \rightarrow \text{DWT}^{-1} \rightarrow \hat{S}_{hm} \]

**Example**

![Denoised Hearingogram Example](image)
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 \([mel(\nu_{\text{min}}); \nu_1[ \text{ and } ]\nu_M; mel(\nu_{\text{max}})]\) 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**

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

⇒ Approximation of the useful signal: \( \tilde{s} = \sum_{m=0}^{M+1} \tilde{s}_{hm} \)
Denoised useful signal reconstruction (2/2)

Flowgraph

Recorded data $Z$

$h_0 \rightarrow DWT \rightarrow$ Thresholding $\rightarrow DWT^{-1}$

$h_1 \rightarrow DWT \rightarrow$ Thresholding $\rightarrow DWT^{-1}$

$h_2 \rightarrow DWT \rightarrow$ Thresholding $\rightarrow DWT^{-1}$

$h_{M+1} \rightarrow DWT \rightarrow$ Thresholding $\rightarrow DWT^{-1}$

$\tilde{S}$
Experiments (1/5)

- **Simulated data**

  - **Test signal** (sampling frequency: 44 100 Hz)

  ![Waveform and spectrogram example]

  - Impulsive signals
  - Vocalization
  - Broad band signal
  - Shock
  - Discontinuous vocalization
  - Shock + impulsive signals
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Experiments (2/5)

 Gazette: 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)
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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.