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When a ship is moving toward an acoustic receiver in an oceanic waveguide, the time-frequency representation of the recorded signal exhibits a striation pattern that can be useful in numerous applications such as ship localization or geoacoustic inversion. If there are many ships, the striation patterns add up and they must be separated if one wants to study them separately. In this paper, a physics-based filtering scheme for passive underwater acoustics has been developed. The algorithm allows separating the time-frequency striations of two different moving ships. The proposed method considers filtering the 2D Fourier transform of the received spectrogram. The filter design is based on the waveguide invariant principle and on some a priori knowledge on the oceanic waveguide. The noise nature on the spectrogram is taken into account by introducing a nonlinearity to the filtering scheme. The algorithm thus corresponds to a nonlinear homomorphic filter. The method is validated on both simulated data and experimental marine data. This filtering scheme offers good prospects for all applications using ship noise and a single receiver.

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INTRODUCTION

Ship noise is ubiquitous in the ocean [1]. Therefore, ship noise is widely studied in passive sonar applications. For instance, the harmonic signature of passing boats can be extracted [2] and analyzed to identify and classify them [3]. Besides, the broadband noise radiated by moving ship presents an interference pattern in the time-frequency domain which can be used to perform ship localization [4, 5] or geoacoustic inversion [6, 7]. However, problems can occur if more than one ship is moving in the vicinity of the receiver since the interference patterns add-up. This situation is very common, for instance one can notice that everyday more than one hundred ships pass on the Ouessant railway off the Brittany coast.

Within this paper, we present a physics-based filtering scheme in single receiver passive sonar configuration. The algorithm allows separating the time-frequency interference patterns of two different moving ships in a shallow water environment. The interference pattern properties, including waveguide invariant principle, and the spectral features of the spectrogram as a time-frequency representation of the ship noise are taken into account to design the filter.

Ship noise propagation modeling in shallow water is described below, followed by spectrogram modeling. Then the filtering method is described and finally practical results showing the good performance of the filter are presented.

SHIP NOISE PROPAGATION

In this paper, we focus on shallow water (< 300 m). It is a very common situation since areas of strategic interest are mainly located in coastal regions. We use normal mode propagation theory [8] which is the most convenient way to describe acoustic propagation in this context as well as to explain our filtering scheme.

Interference pattern

In a range-independent oceanic waveguide, the transfer function between a source and a receiver separated from a distance r can be expressed in terms of normal modes as [8]:

$$h(r, f) \propto \frac{1}{\sqrt{r}} \sum_{m=1}^N A_m e^{ik_{rm}(f)r}, \quad (1)$$

where N is the number of propagating modes, $k_{rm}(f)$ is the horizontal wavenumber of mode m , and A_m is the mode amplitude. A_m is a function of the source and receiver depths, and is slowly varying with respect to frequency compared to the exponential term so that its frequency dependence can be ignored. It should also be noticed that $k_{rm}(f)$ and A_m both depend on the environmental parameters (sound speed profile, seafloor properties ...).

For a broadband source of spectral density $\gamma_b(f)$, the acoustic intensity is given by [8]:

$$I(r, f) = |h(r, f)|^2 \gamma_b(f) \propto \frac{\gamma_b(f)}{r} \left[\sum_m A_m^2 + \sum_{m,n} A_m A_n \cos(\Delta k_{mn}(f)r) \right], \quad (2)$$

where $\Delta k_{mn}(f) = k_{rm}(f) - k_{rn}(f)$. Thus, one can see that the acoustic intensity is a sum of cosine terms resulting from the interference of two modes. These cosine terms are responsible for the interference pattern that appears in the range-frequency representation of the acoustic intensity (Figure 1).

Waveguide invariant

This interference pattern is also referred as striation pattern owing to the particular shape of the range-frequency representation (Figure 1). The slope of the striations depends on range, frequency and on the value of a scalar parameter β called the waveguide invariant [9]. The slope of the striations is given by:

$$\frac{\delta f}{\delta r} = \beta \cdot \frac{f}{r}. \quad (3)$$

This is an important property of acoustic propagation in oceanic waveguides used in many practical applications [4, 5, 7]. The waveguide invariant is only little dependent on the environmental parameters. In our shallow water environment context it can be assumed that $\beta \approx 1$ [8].

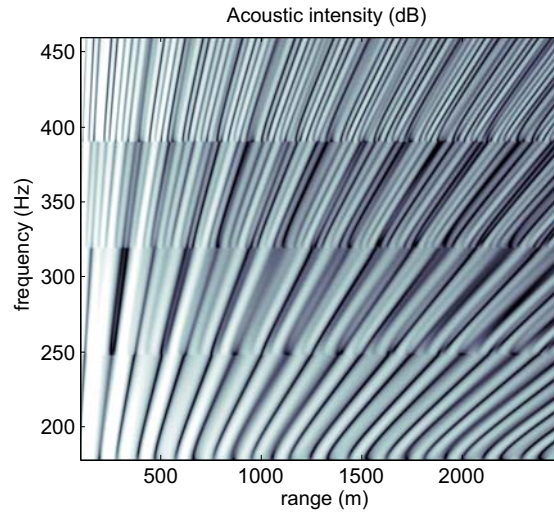


FIGURE 1: Acoustic intensity $I(r, f)$ of a broadband source in a Pekeris waveguide

SPECTROGRAM AND MULTIPLICATIVE NOISE

We showed that the acoustic intensity $I(r, f)$ caused by broadband ship noise presents striations in the range-frequency plan. Considering a ship moving toward a receiver, a time-frequency representation of the received signal exhibits the same striations since $I(t, f) = I(r(t), f)$. In underwater acoustics, time-frequency representations are usually obtained by computing the spectrogram of the received signal $s(t)$:

$$S(t, f) = \left| \int s(\tau) w(\tau - t) \exp(-j2\pi f \tau) d\tau \right|^2, \quad (4)$$

where, w is the windowing function. The spectrogram $S(t, f)$ can be seen as a sliding periodogram [10] of the analyzed signal, i.e. at time t the spectrogram is the periodogram of $s(\tau)w(\tau - t)$. Unfortunately, the periodogram is a bad spectral estimator in the case of highly random signals [10] as it is the case here (ship noise, ambient noise).

The periodogram of a random signal $x(t)$ is an estimator $\hat{\gamma}_x(f)$ of the power spectral density $\gamma_x(f)$ of $x(t)$. This estimator is unbiased but is also inconsistent. It can be considered that [11]:

$$\text{Var}(\hat{\gamma}_x(f)) = \gamma_x(f)^2, \quad (5)$$

which can be re-expressed as:

$$\hat{\gamma}_x(f) = \gamma_x(f) + b_{er}(f)\gamma_x(f), \quad (6)$$

where $b_{er}(f)$ is a noise with zero mean and variance one. This noise can be called estimation noise. When the ship is at a range r , the received signal $s(t)$ can be expressed as:

$$s(t) = b_b(t) * h(r, t) + b_a(t), \quad (7)$$

where $b_b(t)$ is the broadband ship noise, $*$ is the convolution operator, $h(r, t) = FT_f^{-1}\{h(r, f)\}$ is the waveguide impulse response, and $b_a(t)$ accounts for the ambient noise always presents in practical applications. Hence, the power spectral density $\gamma_s(f)$ of $s(t)$ is:

$$\gamma_s(f) = \gamma_b(f) \cdot |h(r, f)|^2 + \gamma_a(f) = I(r, f) + \gamma_a(f), \quad (8)$$

where $\gamma_a(f)$ is the ambient noise power spectral density. The periodogram $\hat{\gamma}_s(f)$ of the received signal can thus be written:

$$\hat{\gamma}_s(f) = I(r, f) + \gamma_a(f) + b_{er}(f) [I(r, f) + \gamma_a(f)], \quad (9)$$

where $b_{er}(f)$ is the periodogram estimation noise. If one considers that the ship is moving slowly so that $r(t)$ is almost constant in the window w , and if one neglects the time and frequency resolution problems, then the spectrogram can be expressed as:

$$S(t, f) \approx I(t, f) + b_{er}(t, f)I(t, f) + \gamma_a(f) + b_{er}(t, f)\gamma_a(f), \quad (10)$$

where $b_{er}(t, f)$ is the periodogram estimation noise at time t . Therefore, the spectrogram is made of the useful signal $I(t, f)$, of a signal dependent multiplicative noise $b_{er}(t, f)I(t, f)$, and of an additive noise $\gamma_a(f) + b_{er}(t, f)\gamma_a(f)$. It should be noticed that the multiplicative noise is always present even when there is no ambient noise since it is inherent to the ship noise periodogram.

FILTERING METHOD

Background and principle

The spectrogram of the signal radiated by a moving ship can be affected by the presence of another ship in the vicinity of the receiver. Then the striation patterns add-up (Figure 2) and they must be separated if one wants to study them one by one.

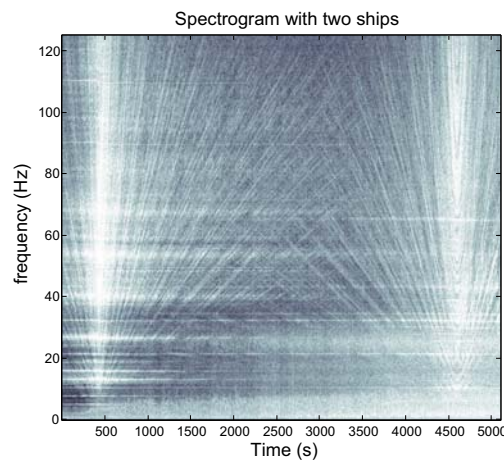


FIGURE 2: Example of a spectrogram with two ships, one can notice the interference patterns (striations) caused by each ship: the first one reaches the closest point of approach (CPA) at $t=400s$ and then goes away from the hydrophone, the second one moves toward the hydrophone and reaches the CPA at $t=4600s$

The spectrogram appears as a textured image with striations. In compliance with the waveguide invariant principle, these striations are characterized by their directionality. When a ship moves toward the receiver the slope of the striations is negative whereas when a ship goes away from the receiver the slope of the striations is positive. The proposed filtering scheme considers the 2D Fourier transform (2DFT) of the received spectrogram. In this domain, positive and negative striations spread in different regions which allows their separation. Separation will be achieved by applying a mask to the 2DFT in order to eliminate the needless regions in the 2DFT, and then by taking the inverse 2DFT. Besides, a nonlinearity will be introduced to the filtering scheme to take into account the multiplicative noise on the spectrogram.

2DFT filtering

In the 2DFT domain, the approaching boat's striations are in the upper right and lower left quadrants whereas the other boat's striations are in the upper left and lower right quadrants (Figure 3.(b)). Therefore, each boat's spectrogram can be obtained separately by eliminating the two needless quadrants and taking the inverse 2DFT. This is a rather rough filter since the useful signal can be localized more precisely on the 2DFT. To take things further, we derive bounds for the useful signal in the 2DFT domain knowing the range $r(t)$ of the desired boat and with little *a priori* knowledge on the oceanic waveguide. It provides an enhanced separation of the two ships along with a larger suppression of noise on the spectrogram. Hence, the proposed 2DFT filtering process consists of the following steps (Figure 3):

- Convert the time-frequency spectrogram $S(t, f)$ into a range-frequency $S(r, f)$ spectrogram and select the area $S_{win}(r, f)$ to filter
- Compute the 2DFT $S_{2DFT}(u, v)$ of $S_{win}(r, f)$ (u and v are respectively the frequency with respect to r and f)
- Design the filter and eliminate the needless regions in $S_{2DFT}(u, v)$ to obtain $\tilde{S}_{2DFT}(u, v)$
- Compute the inverse 2DFT of $\tilde{S}_{2DFT}(u, v)$ to obtain the filtered spectrogram $\tilde{S}_{win}(r, f)$

Filter parameters

The 2DFT $S_{2DFT}(u, v)$ can be seen as a bidimensional frequency-domain representation of $S_{win}(r, f)$. Therefore, if one knows the maximum oscillation frequency u_{max} and v_{max} of $I(r, f)$ towards r and f , then one knows the upper bounds of the useful signal in the 2DFT domain.

These bounds can be derived from the work in [5]. According to expression (2), each cosine term oscillate at a frequency u_{mn} towards r such as:

$$u_{mn} = \frac{1}{2\pi} \frac{\delta(\Delta k_{mn}(f)r)}{\delta r} = \frac{1}{2\pi} \Delta k_{mn}(f), \quad (11)$$

and at a frequency v_{mn} towards f such as :

$$v_{mn} = \frac{1}{2\pi} \frac{\delta(\Delta k_{mn}(f)r)}{\delta f} = \frac{1}{2\pi} r \cdot \frac{\delta(\Delta k_{mn}(f))}{\delta f}. \quad (12)$$

For all oceanic waveguides, the horizontal wavenumbers $k_{rm}(f)$ are bounded by $[\frac{2\pi f}{c_{max}}, \frac{2\pi f}{c_{min}}]$ [8], where c_{max} et c_{min} are the maximum and minimum sound speeds in the waveguide. Furthermore, the group slowness $\frac{\delta(k_{rm}(f))}{\delta f}$ is linked to the phase slowness $\frac{k_{rm}(f)}{f}$ through the waveguide invariant [9] whose value is assumed to be one here. As a result

$$u_{max} = f_{max} \left(\frac{1}{c_{min}} - \frac{1}{c_{max}} \right), \quad (13)$$

$$v_{max} = r_{max} \left(\frac{1}{c_{min}} - \frac{1}{c_{max}} \right). \quad (14)$$

where, f_{max} and r_{max} are the maximum frequency and range in $S_{win}(r, f)$. The useful signal can therefore be bounded in the 2DFT domain if one has an *a priori* knowledge on the parameters c_{min} and c_{max} of the waveguide (see Figure 3.(b)).

The 2DFT also displays the orientation of the textures in a signal: there is a difference of 90 degrees between the space directions and the frequency directions. The maximum and minimum slope α_{max} and α_{min} of the striations in $S_{win}(r, f)$ can be deduced from the waveguide invariant principle. In the 2DFT, the signal can be bounded by the slope p_{max} and p_{min} (see Figure 3.(b)) such as:

$$p_{max} = \frac{-1}{\alpha_{min}} = \frac{-r_{min}}{\beta \cdot f_{max}}, \quad (15)$$

$$p_{min} = \frac{-1}{\alpha_{max}} = \frac{-r_{max}}{\beta \cdot f_{min}}. \quad (16)$$

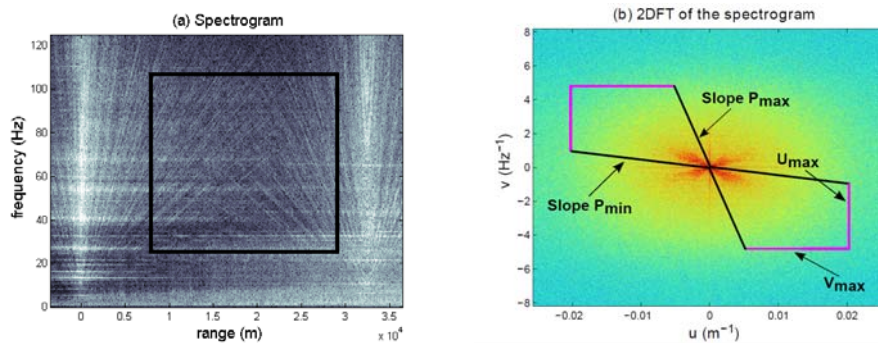


FIGURE 3: Filtering method: (a) spectrogram with two ships and selected window (b) 2DFT of the window and filter parameters

Non linear filtering

A nonlinearity is introduced in the filtering scheme in order to take into account the nature of the noise in the spectrogram. The idea is to apply the previous filtering on the logarithm of the spectrogram. The algorithm thus corresponds to a nonlinear homomorphic filter [12].

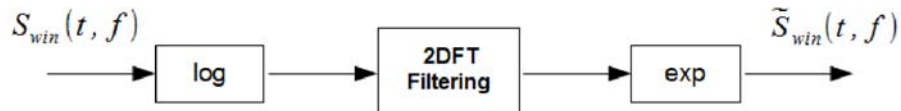


FIGURE 4: The nonlinear homomorphic filter

This nonlinearity turns to be essential. In fact, without the logarithm, the multiplicative noise $b_{er}(r, f)I(r, f)$ in expression (10) appears as a convolution in the 2DFT:

$$b_{er}(r, f)I(r, f) \xrightarrow{2DFT} FT_{2D}\{b_{er}(r, f)\} * FT_{2D}\{I(r, f)\}. \quad (17)$$

This convolution spreads $2DFT\{I(r, f)\}$ wherever the noise $2DFT\{b_{er}(r, f)\}$ is present. The contribution of each vessel thus invades the 2DFT through the multiplicative noise making it impossible to completely separate the two ships when 2DFT filtering since ships contributions are not fully localized. The logarithm solves this problem by turning the convolution of expression (17) into an addition:

$$\log[b_{er}(r, f)I(r, f)] = \log[b_{er}(r, f)] + \log[I(r, f)] \xrightarrow{2DFT} FT_{2D}\{b_{er}(r, f)\} + FT_{2D}\{I(r, f)\}. \quad (18)$$

RESULTS

Application to simulated data

The separation scheme is applied on simulated data. To model acoustic propagation we consider a Pekeris waveguide [13] which is a rather realistic waveguide for shallow waters. The Pekeris waveguide is chosen with the following parameters: depth of the water column $D = 20 \text{ m}$, sound speed in the water $c_w = 1500 \text{ m/s}$, density in the water $\rho_w = 1000 \text{ kg/m}^3$, sound speed in the semi-infinite fluid halfspace $c_b = 1800 \text{ m/s}$, density in the semi-infinite fluid halfspace $\rho_b = 1850 \text{ kg/m}^3$. To define the filter parameters we presume that the water sound speed is known with an uncertainty of $\pm 100 \text{ m/s}$ and that the bottom sound speed is known with an uncertainty of $\pm 200 \text{ m/s}$. It is a rather weak *a priori* on the medium properties. Hence, for a window $r = [200 \text{ m}, 2.5 \text{ km}]$ and $f = [180 \text{ Hz}, 460 \text{ Hz}]$, the filter parameters are $u_{max} \approx 0.10 \text{ m}^{-1}$, $v_{max} \approx 0.56 \text{ Hz}^{-1}$, $p_{min} \approx -0.43 \text{ m.s}$ et $p_{max} \approx -13.9 \text{ m.s}$.

The filter performance is evaluated in terms of gain in signal to noise ratio (SNR). The gain in SNR is defined as the difference between the SNR after filtering and the SNR before filtering where the second ship is considered as a noise. Two parameters have to be considered in order to assess the filter quality: the level of ambient noise and the power ratio between the first and the second ship. Hence, the filter performance is evaluated for various level of SNR on the spectrogram with first ship and ambient noise alone, and for various power ratios between the first and the second ship. In the simulation, ship noise and ambient noise are set white and Gaussian. Results are presented below on figure 5.

It should be noticed that the initial SNR is never high in our simulation because, as stated before, a big part of the noise is due to the bad spectral performance of the spectrogram in the case of highly random signals ¹. We can see that the gain in SNR is high and that it increases when the second ship power ratio increases which testifies of proper elimination of the second ship.

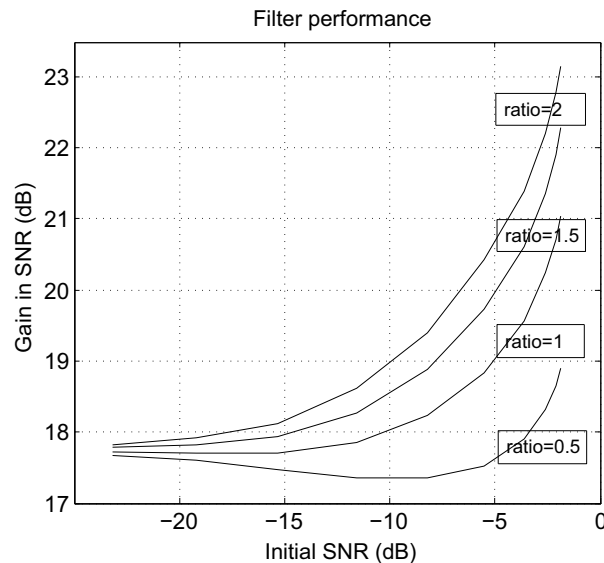


FIGURE 5: Filter performance (100 runs for each point): each curve describes the increase in SNR performed by the filter for a particular power ratio between the first ship and the second ship. The initial SNR is the SNR on the spectrogram when there is only the first ship and the ambient noise

¹Noise inherent to the periodogram spectral estimation is linked to the random signal power through the relation (5), consequently $\text{SNR}=0 \text{ dB}$ when there is only ship noise and no ambient noise ($\gamma_a(f) = 0$)

Application to real data

The experimental data presented here come from data collected during the MATANE experiment. This experiment conducted off the Quebec coasts enabled to obtain acoustic radials of several ships in a channel with a depth of approximately 300m. To test our filter we take data for which two ships are moving in the vicinity of the hydrophone. The range $r(t)$ of the desired ship is achieved via target motion analysis but could also be obtained from the Automatic Identification System (AIS). To design the filter, we assume a little *a priori* on the waveguide sound speeds: we presume that the water sound speed is bounded by [1400 m/s, 1550 m/s], and that the bottom sound speed is bounded by [1500 m/s, 2000 m/s]. For a window $r = [8 \text{ km}, 26 \text{ km}]$ and $f = [35 \text{ Hz}, 110 \text{ Hz}]$, the filter parameters are $u_{max} \approx 0.025 \text{ m}^{-1}$, $v_{max} \approx 5.56 \text{ Hz}^{-1}$, $p_{min} \approx -73 \text{ m.s}$ and $p_{max} \approx -742 \text{ m.s}$. The filtering results are presented bellow on figure 6. The filter seems to be working very well: the striations of the second ship are totally eliminated and the striations of the first ship are more visible.

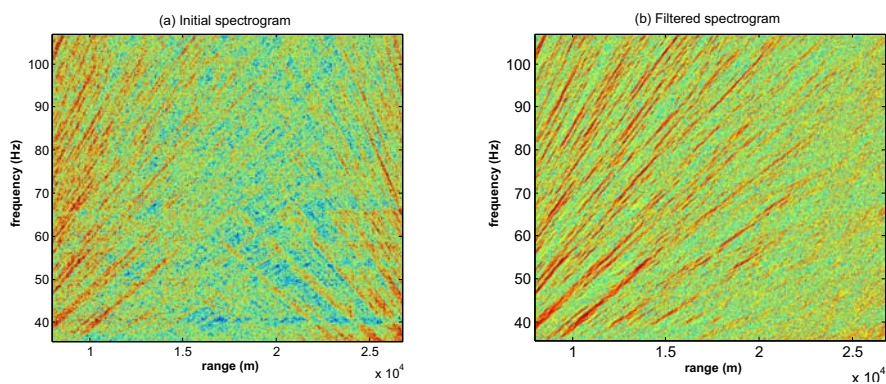


FIGURE 6: Separation on real data: (a) initial spectrogram (b) filtered spectrogram

CONCLUSION

This paper presents a method that allows to separate the striations of two moving ships. The striations have different directions for an approaching ship than for a moving away ship. This particularity and a little *a priori* knowledge on the oceanic environment are used in the 2DFT domain to separate the striation patterns of the two ships. The multiplicative noise, always present on the spectrogram, prevents the 2DFT filtering to work alone. Its effect is mitigated by introducing a nonlinearity in the filtering scheme. The method is validated on both simulated and experimental marine data. It offers good prospects for all applications using ship noise and a single receiver.

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