



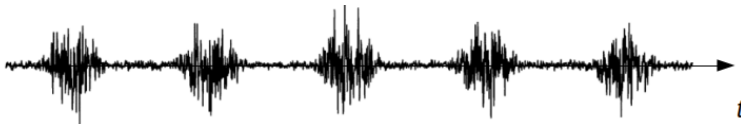
IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Effets des canaux acoustiques sous-marins sur les signaux cyclostationnaires

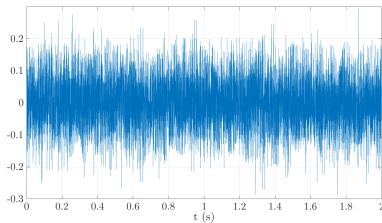
F.-X. Socheleau

SERENADE, Juin 2022

- Bruit d'hélices de navires

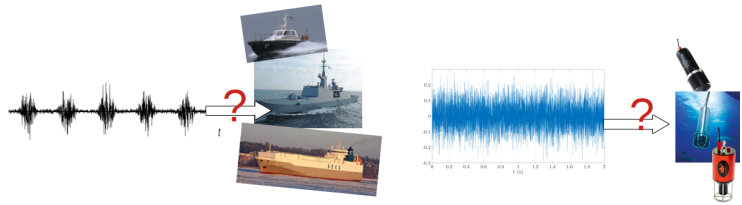


- Signaux de communications



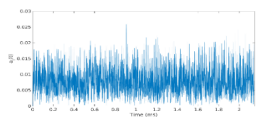
- Autres : biologiques

► Détection de signatures (navires, mammifères, communications)



[Antoni et al, 2012, Mahiout et al, 2020, ...]

► Reverse-engineering de signaux de communications



- **Systèmes** : X
- **Gamme de fréquence** : [val1,val2] kHz
- **Accès au canal** : FF/burst/EVF/DSS
- **Modulation** : PSK/QAM/OFDM FSK/CPM/ + paramètres
- **Code** : Convolutif/Turbo/RS...embrouilleur+entrelaceur...
- **Message** : « Hello world »

► Estimation de canal, vitesse relative, séparation de sources, etc.

INPUT CYCLOSTATIONARY FEATURES

UNDERWATER ACOUSTIC CHANNELS

CYCLOSTATIONARY ANALYSIS

APPLICATIONS

- Doppler scale estimation
- Signal signature detection
- Blind symbol-rate estimation

1. Cyclostationnarité du 2nd ordre

2. Canal multi-trajets multi-échelles

3. Canal Dispersif

► Fonction d'autocorrélation

$$R_x(t, u) = \mathbb{E}[x^*(t)x(t+u)]$$

Si cyclostationnaire au 2nd ordre : $R_x(t, u) = \sum_{\alpha \in \mathcal{A}} R_x^\alpha(u) e^{i2\pi\alpha t}$

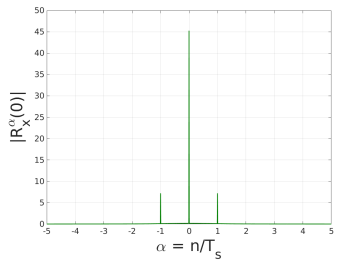
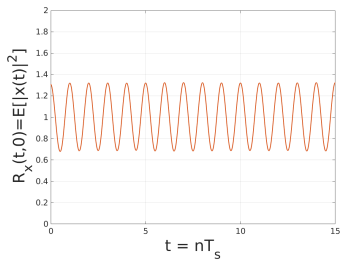
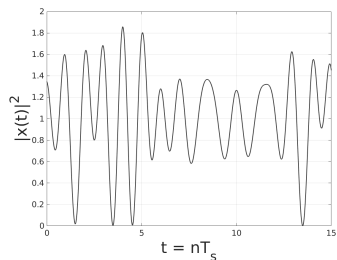
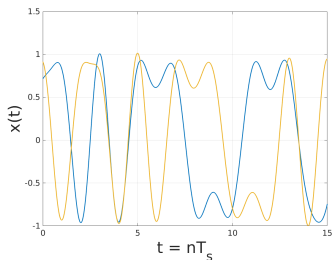
► Fonction d'autocorrélation cyclique

$$R_x^\alpha(u) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} R_x(t, u) e^{-i2\pi\alpha t} dt$$

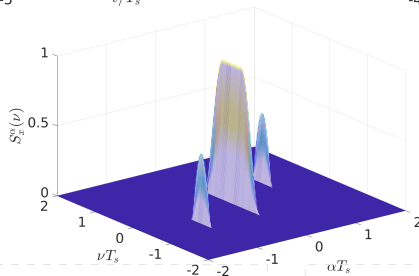
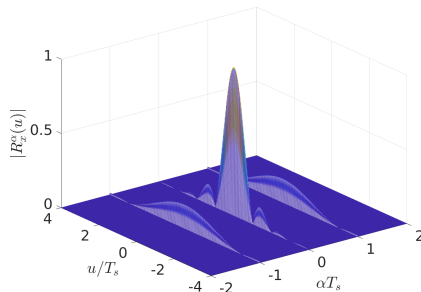
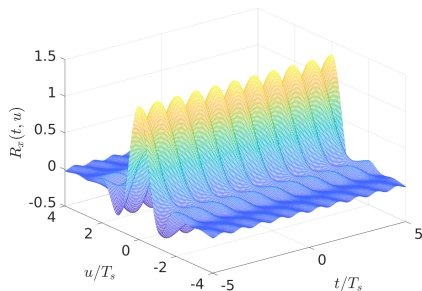
► Spectre cyclique

$$S_x^\alpha(\nu) = \int_{\mathbb{R}} R_x^\alpha(u) e^{-i2\pi u \nu} du$$

QPSK

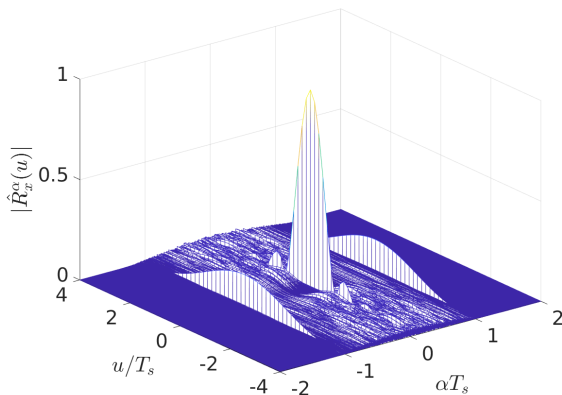


QPSK



Réalisation unique

$$\hat{R}_X^\alpha(u) = \frac{1}{T_{\text{obs}}} \int_0^{T_{\text{obs}}} x^*(t)x(t+u)e^{-i2\pi\alpha t} dt$$

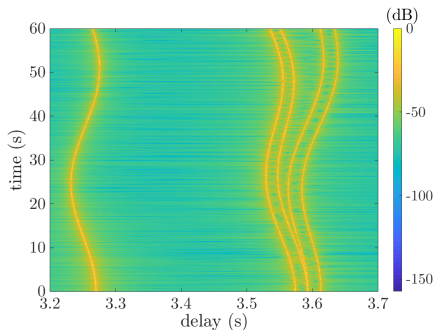


1. Cyclostationnarité du 2nd ordre

2. Canal multi-trajets multi-échelles

3. Canal Dispersif

► Exemple



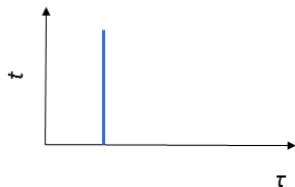
► Signal émis : $x(t)$, signal reçu

$$r(t) = \sum_{\ell=1}^L \lambda_{\ell}(t) y_{\ell}(t) + w(t), \text{ avec } y_{\ell}(t) = x(t - \tau_{\ell} - \phi_{\ell}(t)) e^{-i2\pi f_c(\tau_{\ell} + \phi_{\ell}(t))}.$$

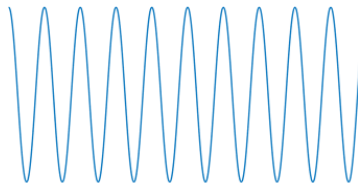
► Compression-dilatation Doppler

$$\phi_{\ell}(t) = \frac{v_{\ell}}{c} t + \frac{a_{\ell}}{2c} t^2 + o(t^2)$$

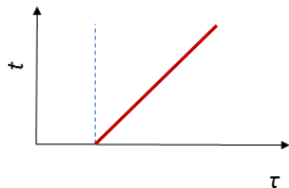
QPSK



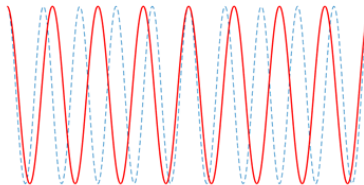
$$R_r(t, 0) = \mathbb{E}[|r(t)|^2]$$



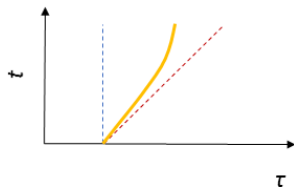
QPSK



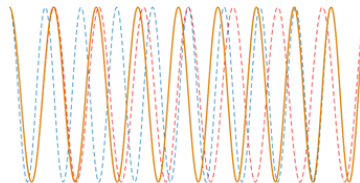
$$R_r(t, 0) = \mathbb{E}[|r(t)|^2]$$



QPSK

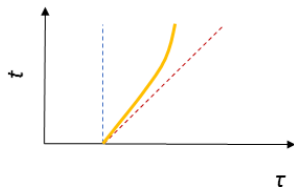


$$R_r(t, 0) = \mathbb{E}[|r(t)|^2]$$

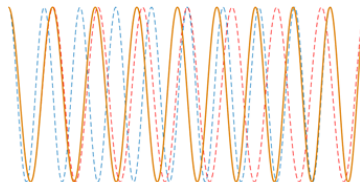


⇒ warping temporel

QPSK



$$R_r(t, 0) = \mathbb{E}[|r(t)|^2]$$



► Canal MTME

$$r(t) = \sum_{\ell=1}^L \lambda_{\ell}(t) y_{\ell}(t) + w(t),$$

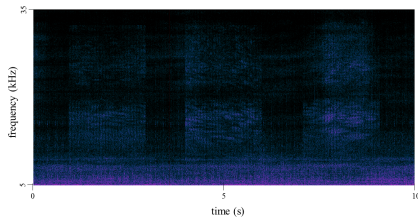
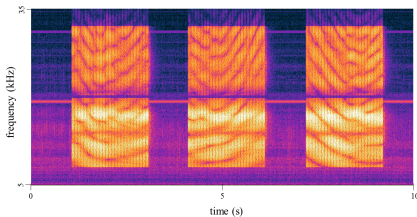
with

$$y_{\ell}(t) = x(t - \tau_{\ell} - \phi_{\ell}(t)) e^{-i2\pi f_c(\tau_{\ell} + \phi_{\ell}(t))}, \quad \phi_{\ell}(t) = \frac{v_{\ell}}{c} t + \frac{a_{\ell}}{2c} t^2 + o(t^2)$$

$\Rightarrow R_r(t, u) =$ combinaison linéaire de chirps

1. Estimation de la compression-dilatation Doppler

► Signaux OFDM (Pierres noires)



► Fonction de coût

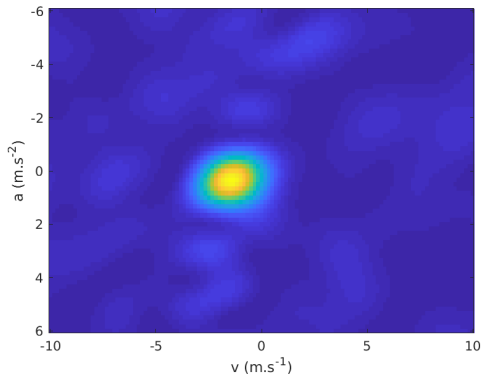
$$J(v, a) = \frac{1}{T_{\text{obs}}} \sum_{(u, \alpha) \in \mathcal{S}} \left| \int_0^{T_{\text{obs}}} r^*(t) r\left(t + \phi_{v,a}^{-1}(u)\right) e^{-i2\pi\left(\alpha\phi_{v,a}(t) - \frac{a}{c} u f_c t\right)} dt \right|^2.$$

$\mathcal{S} \subseteq \mathcal{C}$, où $\mathcal{C} = \{(u, \alpha) : R_x^\alpha(u) \neq 0\}$

⇒ Projection de la corrélation estimée sur une base de chirps

1. Estimation de la compression-dilatation Doppler

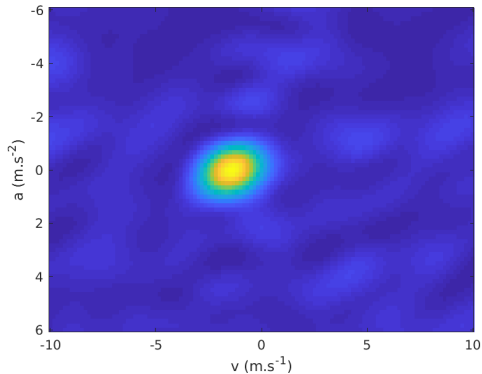
- Mer agitée, D =qqques dizaines de mètres, B =[20-32] kHz, $T_{obs} = 0.5$ s



$t = 0$ s

1. Estimation de la compression-dilatation Doppler

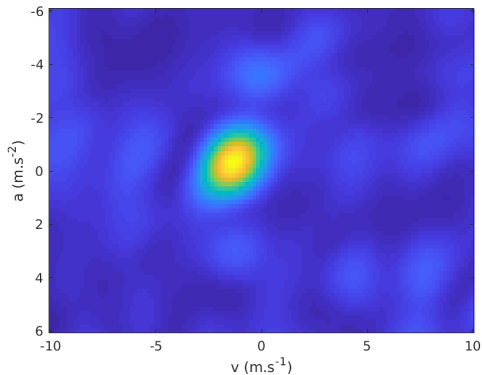
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 0.1$ s

1. Estimation de la compression-dilatation Doppler

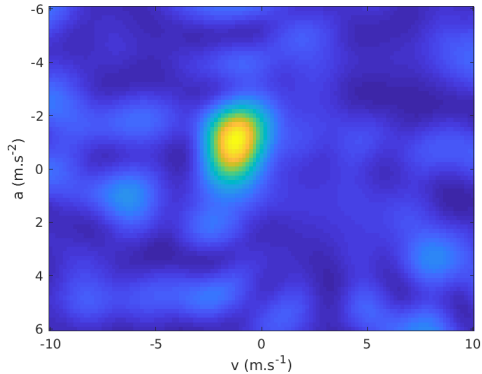
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 0.2$ s

1. Estimation de la compression-dilatation Doppler

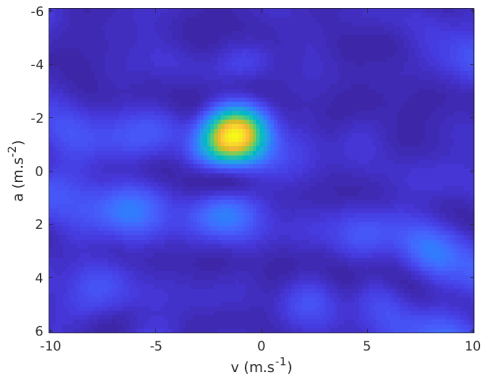
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 0.3$ s

1. Estimation de la compression-dilatation Doppler

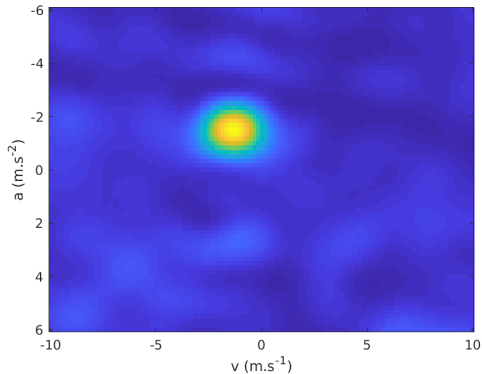
- Mer agitée, D =qqques dizaines de mètres, B =[20-32] kHz, $T_{obs} = 0.5$ s



$t = 0.4$ s

1. Estimation de la compression-dilatation Doppler

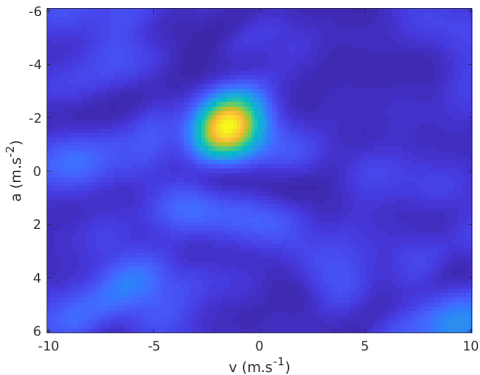
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 0.5$ s

1. Estimation de la compression-dilatation Doppler

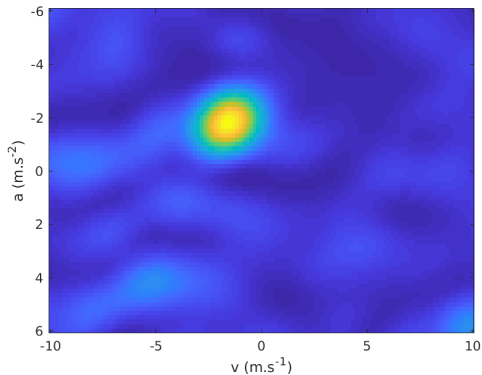
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 0.6$ s

1. Estimation de la compression-dilatation Doppler

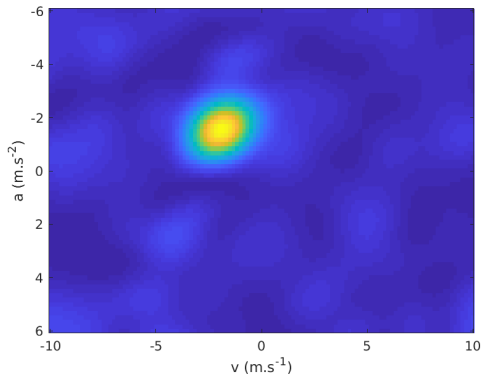
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 0.7$ s

1. Estimation de la compression-dilatation Doppler

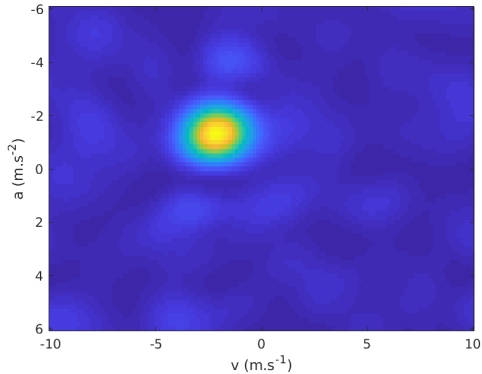
- Mer agitée, D =qqques dizaines de mètres, B =[20-32] kHz, $T_{obs} = 0.5$ s



$t = 0.8$ s

1. Estimation de la compression-dilatation Doppler

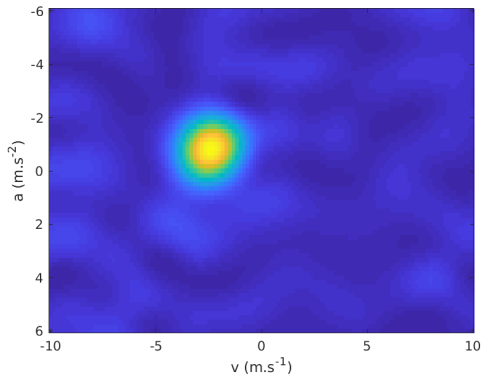
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 0.9$ s

1. Estimation de la compression-dilatation Doppler

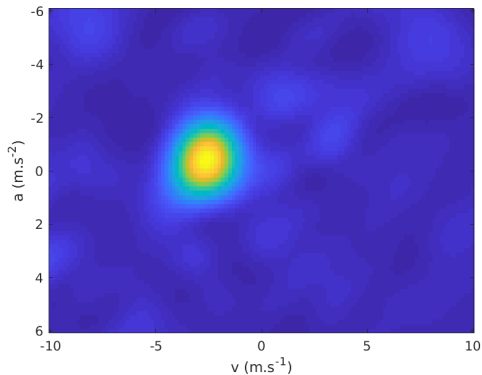
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 1$ s

1. Estimation de la compression-dilatation Doppler

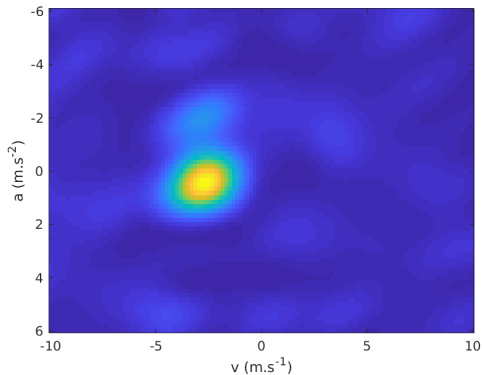
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 1.1$ s

1. Estimation de la compression-dilatation Doppler

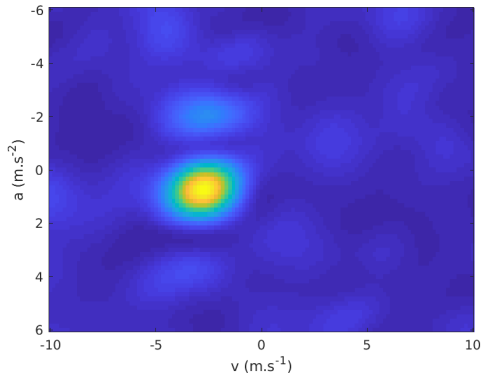
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 1.2$ s

1. Estimation de la compression-dilatation Doppler

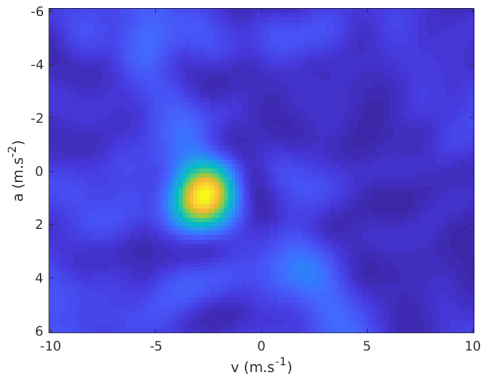
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 1.3$ s

1. Estimation de la compression-dilatation Doppler

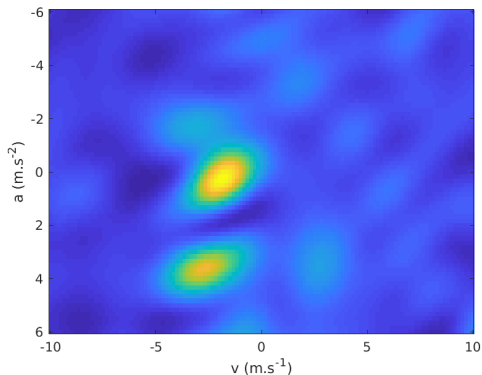
- Mer agitée, D =qqques dizaines de mètres, $B=[20-32]$ kHz, $T_{obs} = 0.5$ s



$t = 1.4$ s

1. Estimation de la compression-dilatation Doppler

- Mer agitée, D =qqques dizaines de mètres, B =[20-32] kHz, $T_{obs} = 0.5$ s



Doppler multi-échelle

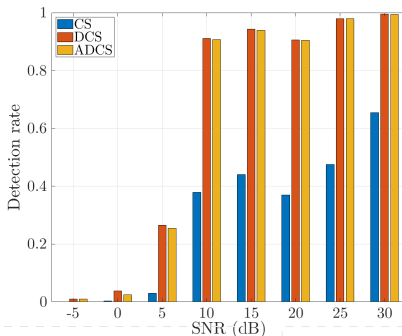
2. Détection de signatures cycliques

- Hypothèses à tester

$$\begin{cases} \mathcal{H}_0 : R_x^\alpha(u) = 0, \forall (u, \alpha) \in \mathcal{S} \\ \mathcal{H}_1 : R_x^\alpha(u) \neq 0, \forall (u, \alpha) \in \mathcal{S}. \end{cases} \quad (1)$$

$\mathcal{S} \subseteq \mathcal{C}$, où $\mathcal{C} = \{(u, \alpha) : R_x^\alpha(u) \neq 0\}$

- Détecteur : $\max_{v,a} J(v,a) \underset{H_0}{\overset{H_1}{\geq}} \Lambda$
- Résultats sur les signaux précédents (PFA = 10^{-6})



1. Cyclostationnarité du 2nd ordre

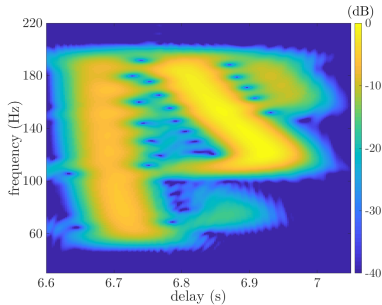
2. Canal multi-trajets multi-échelles

3. Canal Dispersif

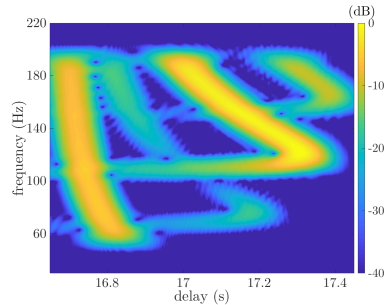
► Réponse fréquentielle

$$H(\nu) = \sum_{m=1}^M A_m(\nu) e^{i\theta_m(\nu)}$$

► Exemple (guide de Pekeris, hauteur d'eau = 50 m)



$r_s = 10 \text{ km}$



$r_s = 25 \text{ km}$

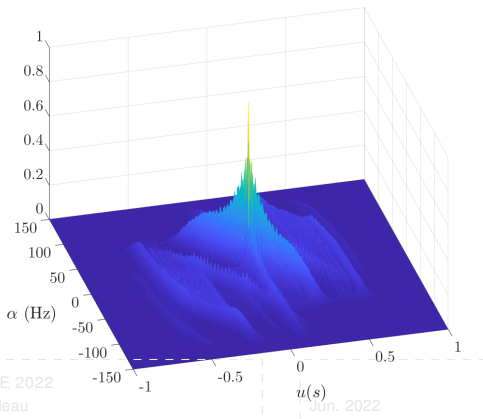
- ▶ Canal = opérateur linéaire

$$R_r^\alpha(u) = R_x^\alpha(u) \circledast_u A_h^\alpha(u) + R_w(u),$$

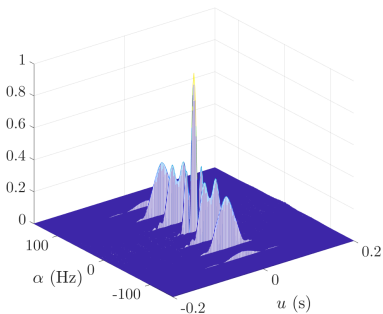
avec

$$A_h^\alpha(u) = \int h^*(t)h(t+u)e^{-i2\pi\alpha t}dt$$

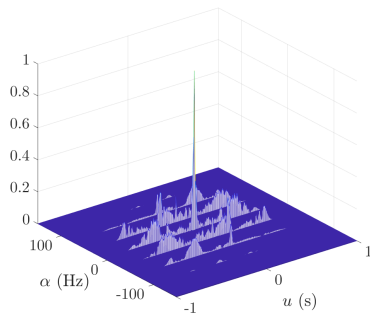
- ▶ Exemple



► Signal DSSS



$$R_x^\alpha(u)$$



$$R_r^\alpha(u) \text{ (sans bruit)}$$

⇒ Atténue, étale et retarde l'énergie cyclique

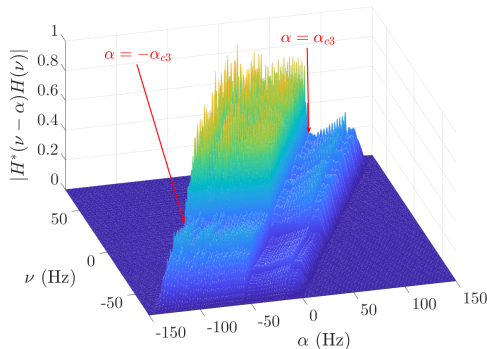
- ▶ Canal = opérateur linéaire

$$S_r^\alpha(\nu) = S_x^\alpha(\nu) S_H(\nu - \alpha, \nu) + S_w^0(\nu)$$

avec

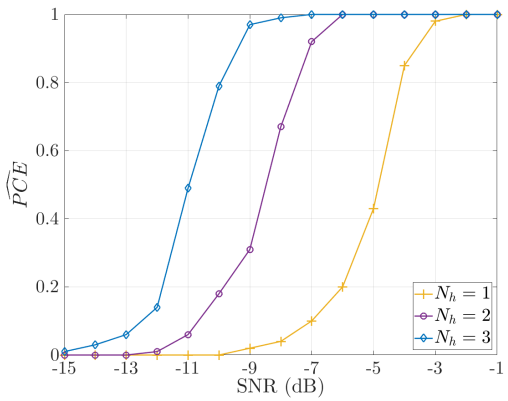
$$S_H(\nu_1, \nu_2) = H^*(\nu_1) H(\nu_2)$$

- ▶ Exemple



► Estimation aveugle de la période symbole (signal DSSS)

$$PCE = \mathbb{P} \left(\left| \frac{\hat{T}_s - T_s}{T_s} \right| \leq 10^{-2} \right)$$



Conclusions

- ▶ Potentiel de la cyclostationnarité sous exploité en ASM
- ▶ Nécessite de prendre en compte les particularités du milieu
- ▶ Complexité *raisonnable* (implémentation FFT)
- ▶ Adaptable aux bruits impulsifs
- ▶ Aide à la conception de communications furtives
- ▶ Plus de détails :
F.X. Socheleau, Cyclostationarity of Communication Signals in Underwater Acoustic Channels, IEEE JOE (soumis)

Merci