The Kravchuk transform

A novel covariant representation for discrete signals amenable to zero-based detection tests

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Séminaire Signal Image

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Outline of the presentation

- Context and notations
- Time-frequency analysis: the Short-Time Fourier Transform

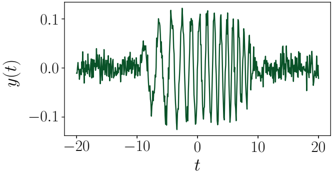
. . . .

- Signal detection based on spectrogram zeros - I
- Covariance principle and stationary point processes

. . . .

- The Kravchuk transform and its zeros
- Signal detection based on spectrogram zeros - II

Finite energy signal $y \in L^2_{\mathbb{C}}(\mathbb{R})$: function of time t.



- electrical cardiac activity,
- audio recording,
- seismic activity,
- light intensity on a photosensor
- ...

Information of interest:

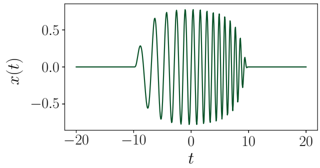
- time events, e.g., an earthquake and its replica
- frequency content, e.g., monitoring of the heart beating rate

time
ever-changing world
marker of events and evolutions

frequency
waves, oscillations, rhythms
intrinsic mechanisms

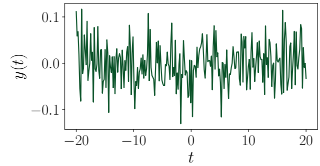
E.g., chirp: transient waveform modulated in amplitude and frequency:

$$x(t) = A_\nu(t) \sin\left(2\pi \left(f_1 + (f_2 - f_1)\frac{t+\nu}{2\nu}\right) t\right)$$



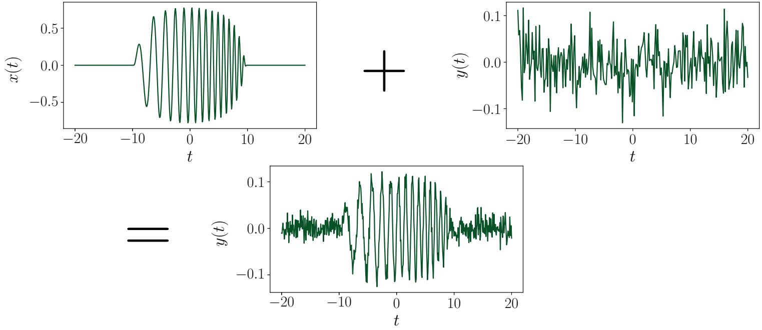
White noise: random process $\xi(t)$ such that

$$\mathbb{E}[\xi(t)] = 0 \quad \text{and} \quad \mathbb{E}[\overline{\xi(t)}\xi(t')] = \delta(t - t')$$



P. Flandrin: 'A signal is characterized by a structured organization.'

Noisy observations $y(t) = \mathrm{snr} \times x(t) + \xi(t)$



Classical tasks: given an observation $y(t)$

- detection decides whether $y(t) = \mathrm{snr} \times x(t) + \xi(t)$, $\mathrm{snr} > 0$ or $y(t) = \xi(t)$,
- denoising retrieves the pure signal $x(t)$,
- feature extraction e.g., estimates $f(t) = f_1 + (f_2 - f_1)\frac{t+\nu}{2\nu}$.

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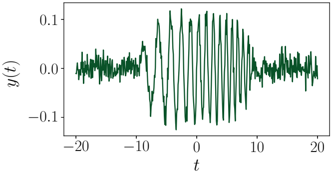
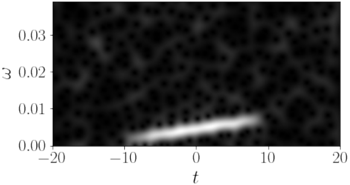
Time *and* frequency Short-Time Fourier Transform with window h:

$$V_h y(t,\omega) \triangleq \int_{-\infty}^{\infty} \overline{y(u)} h(u-t) \exp(-\mathrm{i}\omega u)\,\mathrm{d}u$$



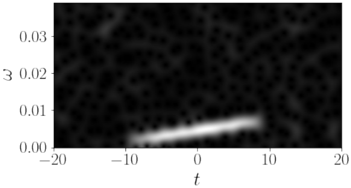


Energy density interpretation $S_h y(t,\omega) = |V_h y(t,\omega)|^2$ the *spectrogram*

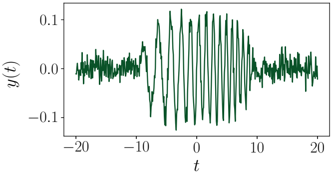
$$\int \int_{-\infty}^{+\infty} S_h y(t,\omega)\,\mathrm{d}t \frac{\mathrm{d}\omega}{2\pi} = \int_{-\infty}^{+\infty} |x(t)|^2\,\mathrm{d}t \quad \text{if} \quad \|h\|_2^2 = 1$$

Signal, i.e., information of interest: regions of **maximal** energy.

spectrogram

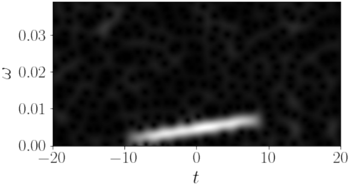


noisy observation

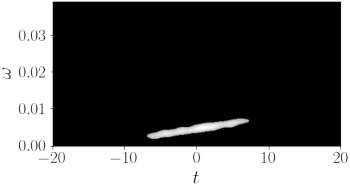


Denoising in the time-frequency plane: $y = \text{snr} \times x + \xi$, snr $= 2$

spectrogram



only maxima



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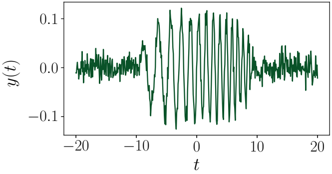
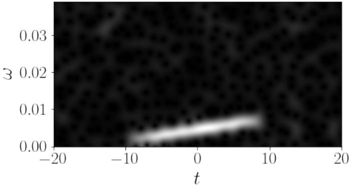


<u>Inversion formula</u> $$y(t) = \int \int_{-\infty}^{+\infty} \overline{V_h y(u, \omega)} h(t-u) \exp(\mathrm{i}\omega u) \, \mathrm{d}u \frac{\mathrm{d}\omega}{2\pi}$$

spectrogram



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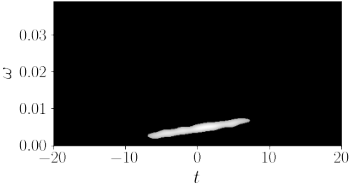

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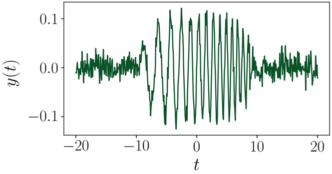
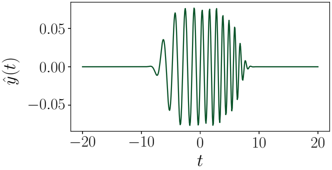


denoised estimate



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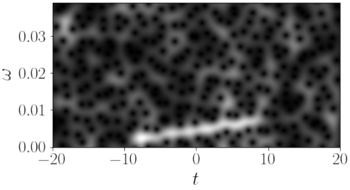
spectrogram



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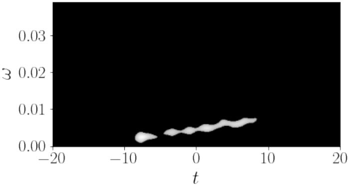
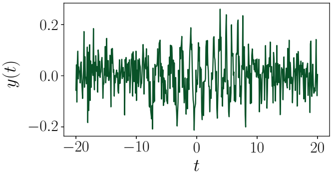
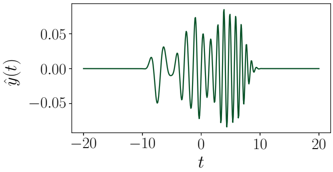


noisy observation



estimate



Denoising in the time-frequency plane: $y = \mathrm{snr} \times x + \xi$, $\quad$ $\mathrm{snr} = 0.5$

<u>Inversion formula</u> $$y(t) = \int \int_{-\infty}^{+\infty} \overline{V_h y(u,\omega)} h(t-u) \exp(\mathrm{i}\omega u) \, \mathrm{d}u \frac{\mathrm{d}\omega}{2\pi}$$

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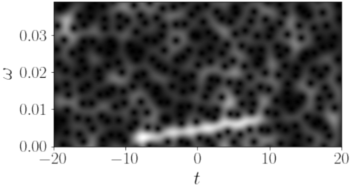

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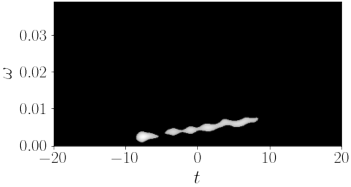
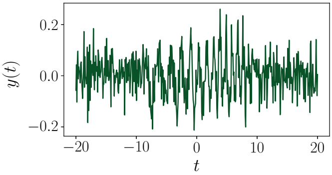


noisy observation



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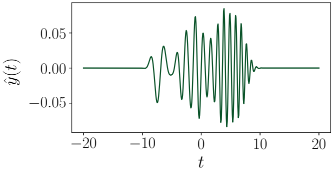

Maxima localization: *reassignment, synchrosqueezing, ridge extraction*

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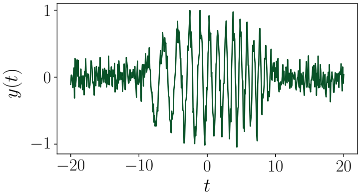
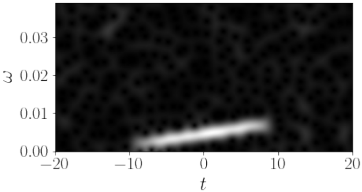
Restriction to the **circular Gaussian window**: $g(t) = \pi^{-1/4} \mathrm{e}^{-t^2/2}$





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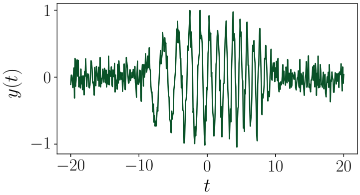

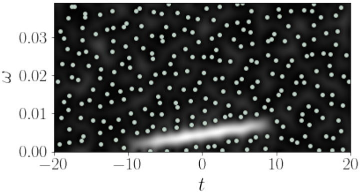

Instead of maxima, look for the **zeros**: (t_i, ω_i) such that $|V_g y(t_i, \omega_i)|^2 = 0$

(Gardner & Magnasco, 2006), (Flandrin, 2015)

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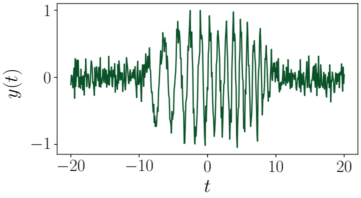

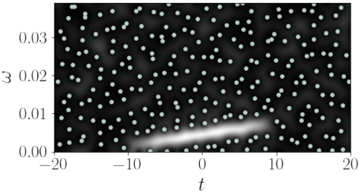

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Observations:

- In the noise region zeros are evenly spread.
- There exists a short-range repulsion between zeros.
- Zeros are repelled by the signal.

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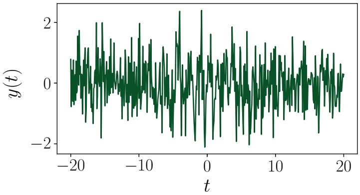

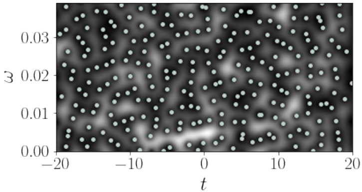

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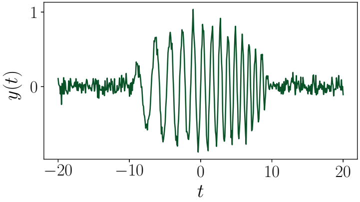

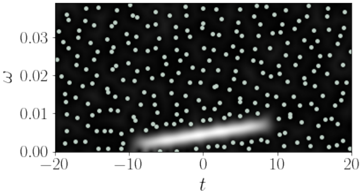

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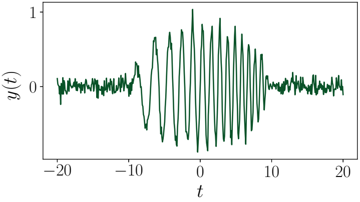

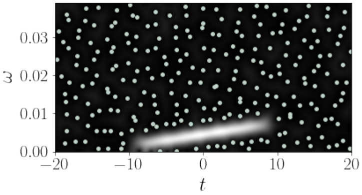

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<u>Observations:</u>

- In the noise region zeros are evenly spread.
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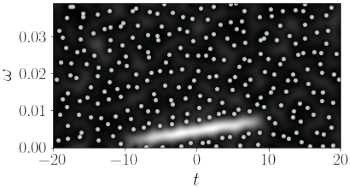
- Zeros are repelled by the signal.

What can be said theoretically about the zeros pattern?

Idea assimilate the time-frequency plane with $\mathbb{C}$ through $z = (\omega + \mathrm{i}t)/\sqrt{2}$



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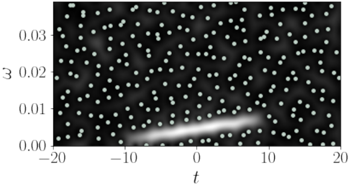

Bargmann factorization

$$V_g y(t,\omega) = \mathrm{e}^{-|z|^2/2}\mathrm{e}^{-\mathrm{i}\omega t/2} By(z)$$

g the circular Gaussian window

Bargmann transform of the signal y

$$By(z) \triangleq \pi^{-1/4}\mathrm{e}^{-z^2/2}\int_{\mathbb{R}} \overline{y(u)} \exp\left(\sqrt{2}uz - u^2/2\right) \mathrm{d}u,$$

By is an **entire** function, almost characterized by its infinitely many zeros:

$$By(z) = z^m \mathrm{e}^{C_0 + C_1 z + C_2 z^2} \prod_{n\in\mathbb{N}} \left(1 - \frac{z}{z_n}\right) \exp\left(\frac{z}{z_n} + \frac{1}{2}\left(\frac{z}{z_n}\right)^2\right)$$

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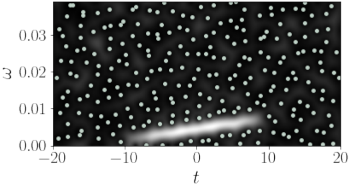


Bargmann factorization

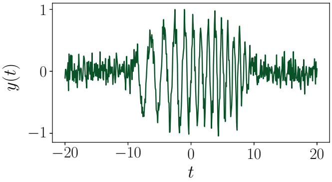
$$V_g y(t, \omega) = \mathrm{e}^{-|z|^2/2} \mathrm{e}^{-\mathrm{i}\omega t/2} By(z)$$

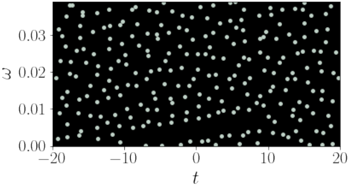
g the circular Gaussian window

Theorem The zeros of the Gaussian spectrogram $V_g y(t, \omega)$

- coincide with the zeros of the **entire** function By,
- hence are **isolated** and constitute a **Point Process**,
- which almost completely **characterizes** the spectrogram.

(Flandrin, 2015)





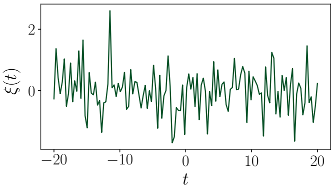
Advantages of working with the zeros

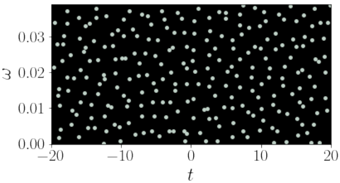
- Easy to find compared to relative maxima.
- Form a robust pattern in the time-frequency plane.
- Require little memory space for storage.
- Efficient tools were recently developed in **stochastic geometry**.

Need for a rigorous characterization of the distribution of the zeros.

Continuous complex white Gaussian noise

$$\xi(t) = \sum_{n=0}^{\infty} \xi[n] h_n(t),\ \xi[n] \sim \mathcal{N}_{\mathbb{C}}(0,1), \quad \{h_n, k = 0, 1, \ldots\} \text{ Hermite functions}$$





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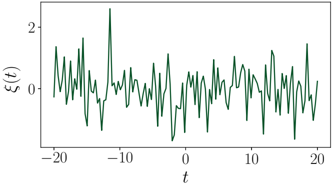
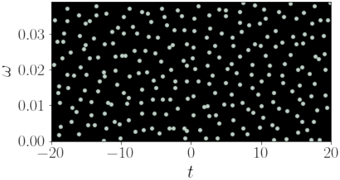
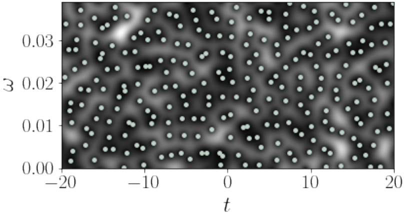




Theorem $\quad V_g\xi(t,\omega) = \mathrm{e}^{-|z|^2/4}\mathrm{e}^{-\mathrm{i}\omega t/2}\,\mathrm{GAF}_{\mathbb{C}}(z)$ (Bardenet & Hardy, 2021)

$$\mathrm{GAF}_{\mathbb{C}}(z) = \sum_{n=0}^{\infty} \xi[n] \frac{z^n}{\sqrt{n!}}$$ the *planar Gaussian Analytic Function* and $z = \frac{\omega + \mathrm{i}t}{\sqrt{2}}$.

The zeros of the planar Gaussian Analytic Function



$$V_g\xi(t,\omega) \overset{\text{non-vanishing}}{\propto} \mathrm{GAF}_{\mathbb{C}}(z)$$

$$z = (\omega + \mathrm{i}t)/\sqrt{2}$$

$$|V_g y(t_i,\omega_i)|^2 = 0 \quad \Longleftrightarrow \mathrm{GAF}_{\mathbb{C}}(z_i) = 0$$

$\longrightarrow$ zeros of Gaussian Analytic Functions studied by probabilists

Zeros of the Planar Gaussian Analytic Function

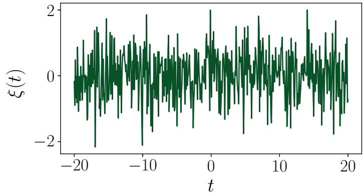
$$\{z_i \in \mathbb{C}, \quad \mathrm{GAF}_{\mathbb{C}}(z_i) = 0\}$$

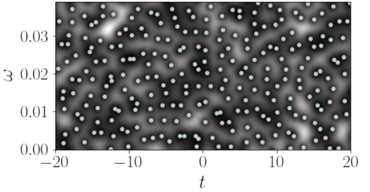
- form a *point process* : random configuration of points
- is stationary : invariant under translations
- has a uniform density $\rho^{(1)}(z) = \rho^{(1)} = 1/\pi$

(Bardenet, Flamant & Chainais, 2020)

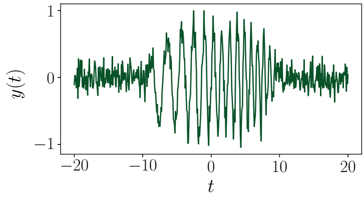
- $\mathbf{H}_0$ white noisy only, i.e., $y(t) = \xi(t)$
- $\mathbf{H}_1$ presence of a signal, i.e., $y(t) = \text{snr} \times x(t) + \xi(t)$, $\text{snr} > 0$

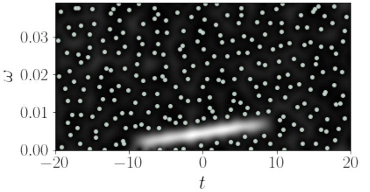
null hypothesis





alternative hypothesis

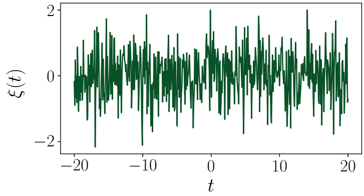


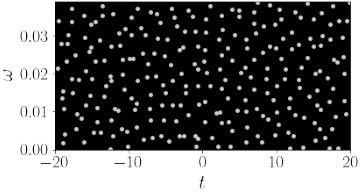


(Bardenet, Flamant & Chainais, 2020)

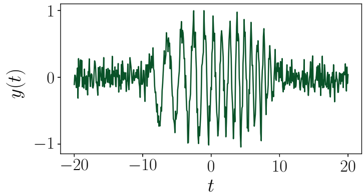
- $\mathbf{H}_0$ white noisy only, i.e., $y(t) = \xi(t)$
- $\mathbf{H}_1$ presence of a signal, i.e., $y(t) = \text{snr} \times x(t) + \xi(t)$, $\text{snr} > 0$

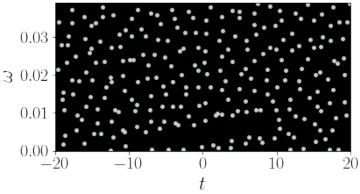
null hypothesis





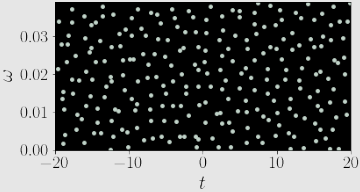
alternative hypothesis





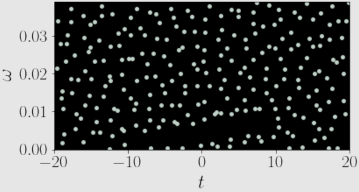
Purpose: summary statistic s, such that for $y = \text{snr} \times x + \xi$

$\mathbb{E}[s(y)|\mathbf{H}_0] = 0$



$\text{snr} = 0$

$\mathbb{E}[s(y)|\mathbf{H}_1] > 0$

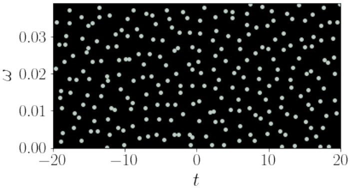


$\text{snr} > 0$

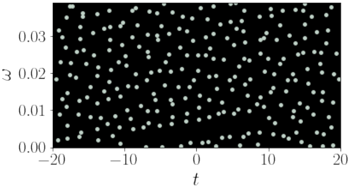
'**Large value of $s(y)$ is a strong indication that there is a signal.**'

Tools from **stochastic geometry** to capture spatial statistics of the zeros.

Unorthodox path: zeros of Gaussian Analytic Functions

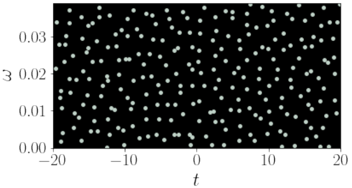


snr $= 0$

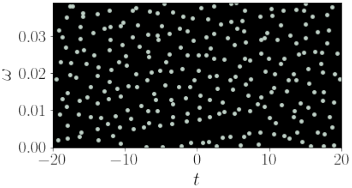


snr > 0

The signal creates **holes** in the zeros pattern: **second order** statistics.



snr $= 0$



snr > 0

The signal creates **holes** in the zeros pattern: **second order** statistics.

A functional statistic: the empty space function

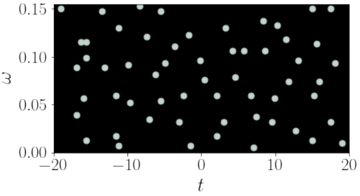
Z a stationary point process, z_0 any reference point

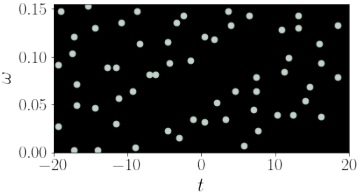
$$F(r) = \mathbb{P}\left(\inf_{z_i \in Z} \mathrm{d}(z_0, z_i) < r\right)$$

$\rightarrow$ probability to find a zero at distance less than r from z_0

Estimation of the F-function of a **stationary** Point Process (Møller, 2007)

$$F(r) = \mathbb{P}\left(\inf_{z_i \in Z} \mathrm{d}(z_0, z_i) < r\right) : \textbf{ empty space function}$$





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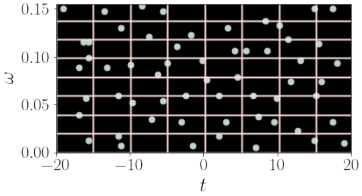
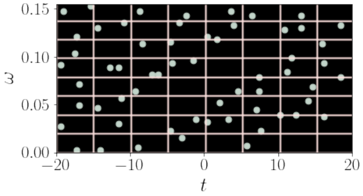
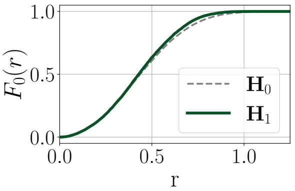




$$\widehat{F}(r) = \frac{1}{N_\#} \sum_{j=1}^{N_\#} \mathbf{1}\left(\inf_{z \in \textbf{Zeros}} \mathrm{d}\left(z_j, z\right) < r\right)$$



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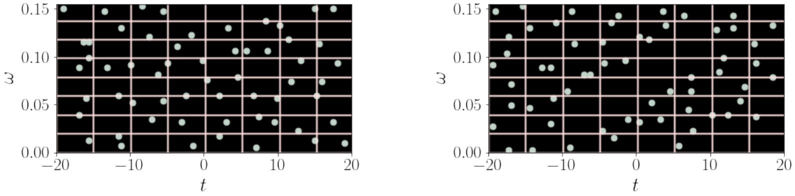

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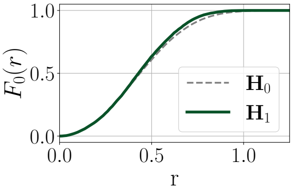

- Monte Carlo envelope test based on the discrepancy between $\widehat{F}$ and F_0

Monte Carlo envelope test from an observation y

Settings: α level of significance, m number of samples under $\mathbf{H}_0$

Index k, chosen so that $\alpha = k/(m+1)$

Monte Carlo envelope test from an observation y

Settings: α level of significance, m number of samples under $\mathbf{H}_0$

$$\text{Index } k, \text{ chosen so that } \alpha = k/(m+1)$$

(i) generate m independent samples of complex white Gaussian noise

$$\xi_1, \xi_2, \ldots, \xi_m$$

compute their spectrograms and find their zeros;

Monte Carlo envelope test from an observation y

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Index k, chosen so that $\alpha = k/(m+1)$

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$$\xi_1, \xi_2, \ldots, \xi_m$$

compute their spectrograms and find their zeros;

(ii) compute the summary statistics from the zeros

$$\forall \mu = 1, 2, \ldots, m, \quad s(\mu) = \sqrt{\int_{r_1}^{r_2} \left| \widehat{F}_\mu(r) - F_0(r) \right|^2}$$

and sort them in decreasing order $s_1 \geq s_2 \geq \ldots \geq s_m$;

Monte Carlo envelope test from an observation y

Settings: α level of significance, m number of samples under $\mathbf{H}_0$

Index k, chosen so that $\alpha = k/(m+1)$

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(iii) compute the summary statistics of the observations y under concern;

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Index k, chosen so that $\alpha = k/(m+1)$

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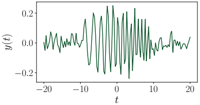
and sort them in decreasing order $s_1 \geq s_2 \geq \dots \geq s_m$;

(iii) compute the summary statistics of the observations y under concern;

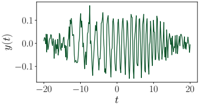
(iv) if $s(y) \geq s_k$, then reject the null hypothesis with confidence $1 - \alpha$.

Signal detection based on spectrogram zeros - I snr $= 1.5$

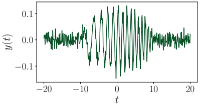
Detection of a noisy chirp of duration $2\nu = 30$ s



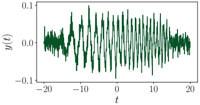
$N = 128$



$N = 256$

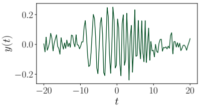


$N = 512$



$N = 1024$

Detection of a noisy chirp of duration $2\nu = 30$ s



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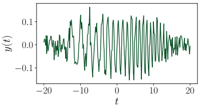
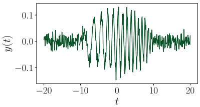
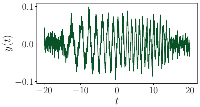


$N = 256$

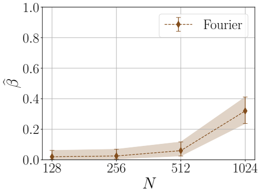


$N = 512$



$N = 1024$

Performance: power of the test computed over 200 samples



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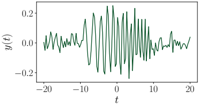

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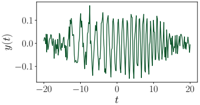

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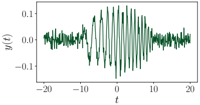

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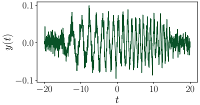

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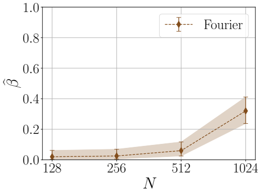
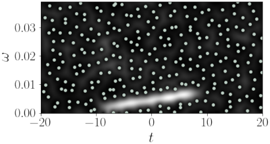
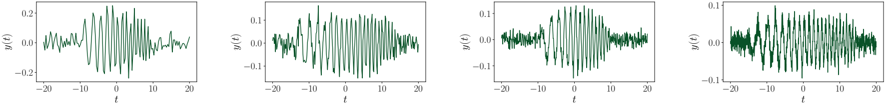


- ✓ Fast Fourier Transform
- ✗ low detection power
- ✗ requires large number of samples

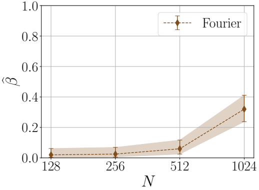


Detection of a noisy chirp of duration $2\nu = 30$ s



$N = 128$ $N = 256$ $N = 512$ $N = 1024$

Performance: power of the test computed over 200 samples



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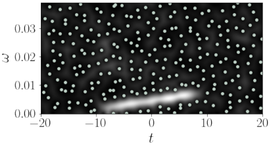
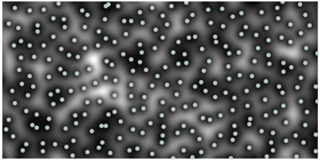


Limitations:

- necessary discretization of the STFT: arbitrary resolution
- observe only a bounded window: edge correction to compute $\widehat{F}(r)$

Unbounded phase space $\mathbb{C}$



→ edge corrections

Short-Time Fourier Transform

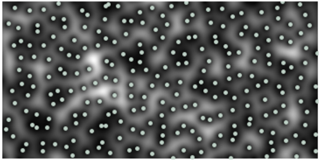
$$V_g\xi(t,\omega) \propto \mathrm{GAF}_{\mathbb{C}}(z) = \sum_{n=0}^{\infty} \xi[n] \frac{z^n}{\sqrt{n!}}$$

Other Gaussian Analytic Functions, other transforms?

Short-Time Fourier Transform

$$V_g\xi(t,\omega) \propto \mathrm{GAF}_{\mathbb{C}}(z) = \sum_{n=0}^{\infty} \xi[n] \frac{z^n}{\sqrt{n!}}$$

Unbounded phase space $\mathbb{C}$



$\rightarrow$ edge corrections

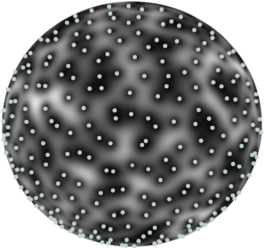
New transform?

$$? \quad \propto \mathrm{GAF}_{\mathbb{S}}(z) = \sum_{n=0}^{N} \boldsymbol{\xi}[n] \sqrt{\binom{N}{n}} z^n$$

stereographic projection $z = \cot(\vartheta/2)\mathrm{e}^{\mathrm{i}\varphi}$

$\rightarrow$ spherical coordinates $(\vartheta, \varphi) \in S^2$

Compact phase space S^2?



$\rightarrow$ no border!

Outline of the presentation

- Context and notations
- Time-frequency analysis: the Short-Time Fourier Transform

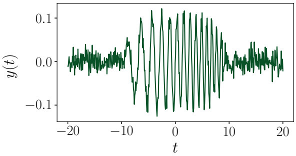
. . . .

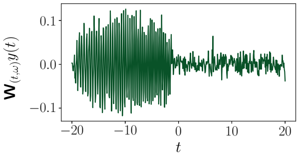
- Signal detection based on spectrogram zeros - I
- Covariance principle and stationary point processes

. . . .

- The Kravchuk transform and its zeros
- Signal detection based on spectrogram zeros - II

Time and frequency shifts $\boldsymbol{W}_{(t,\omega)} y(u) = e^{-\mathrm{i}\omega u} y(u-t)$





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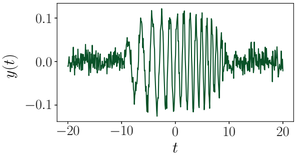
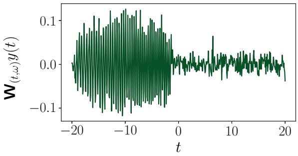
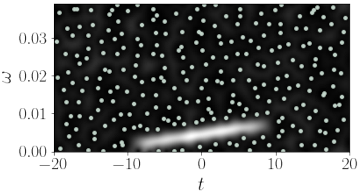
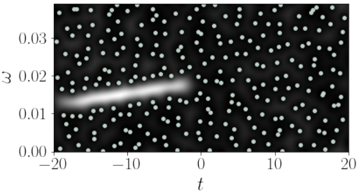




$$V_h[\boldsymbol{W}_{(t,\omega)}y](t',\omega') \overset{\text{(covariance)}}{=} \mathrm{e}^{-\mathrm{i}(\omega'-\omega)t}V_h y(t'-t,\omega'-\omega),$$





Time and frequency shifts $\boldsymbol{W}_{(t,\omega)} y(u) = e^{-\mathrm{i}\omega u} y(u-t)$

$$\left| V_h[\boldsymbol{W}_{(t,\omega)} y](t',\omega') \right|^2 \overset{\text{(covariance)}}{=} \left| V_h y(t'-t,\omega'-\omega) \right|^2,$$

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Complex white Gaussian noise $\widetilde{\xi} = \boldsymbol{W}_{(t,\omega)}\xi$

- $\mathbb{E}[\widetilde{\xi}(u)] \quad = e^{-\mathrm{i}\omega u}\mathbb{E}[\xi(u-t)] \quad = 0$

Time and frequency shifts $\boldsymbol{W}_{(t,\omega)} y(u) = e^{-\mathrm{i}\omega u} y(u-t)$

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- $\mathbb{E}[\widetilde{\xi}(u)] \quad = e^{-\mathrm{i}\omega u} \mathbb{E}[\xi(u-t)] \quad = 0$
- $\mathbb{E}[\overline{\widetilde{\xi}(u)} \widetilde{\xi}(u')] = e^{\mathrm{i}\omega(u-u')} \mathbb{E}[\overline{\xi(u)} \xi(u')] = \delta(u-u')$

Algebraic interpretation: covariance under a symmetry group

Time and frequency shifts $\boldsymbol{W}_{(t,\omega)} y(u) = e^{-\mathrm{i}\omega u} y(u-t)$

$$\left|V_h[\boldsymbol{W}_{(t,\omega)} y](t',\omega')\right|^2 \overset{\text{(covariance)}}{=} \left|V_h y(t'-t,\omega'-\omega)\right|^2,$$

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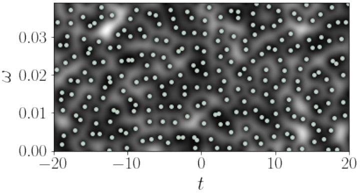
- $\mathbb{E}[\overline{\widetilde{\xi}(u)}\widetilde{\xi}(u')] = e^{\mathrm{i}\omega(u-u')}\mathbb{E}[\overline{\xi(u)}\xi(u')] = \delta(u-u')$

Invariance under time-frequency shifts:

$$\widetilde{\xi} = \boldsymbol{W}_{(t,\omega)}\xi \overset{\text{(law)}}{=} \xi$$



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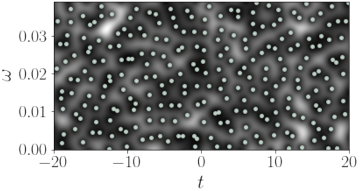
Complex white Gaussian noise $\widetilde{\xi} = \boldsymbol{W}_{(t,\omega)} \xi$

- $\mathbb{E}[\widetilde{\xi}(u)] = e^{-\mathrm{i}\omega u} \mathbb{E}[\xi(u-t)] = 0$
- $\mathbb{E}[\overline{\widetilde{\xi}(u)} \widetilde{\xi}(u')] = e^{\mathrm{i}\omega(u-u')} \mathbb{E}[\overline{\xi(u)} \xi(u')] = \delta(u-u')$

Invariance under time-frequency shifts:

$$\widetilde{\xi} = \boldsymbol{W}_{(t,\omega)} \xi \overset{\text{(law)}}{=} \xi$$



Covariance is the key to get **stationarity**: how to get covariant transforms?

Time and frequency shifts $\boldsymbol{W}_{(t,\omega)}y(u) = e^{-\mathrm{i}\omega u}y(u-t)$

$$\left|V_h[\boldsymbol{W}_{(t,\omega)}y](t',\omega')\right|^2 \overset{\text{(covariance)}}{=} \left|V_h y(t'-t,\omega'-\omega)\right|^2,$$

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Weyl-Heisenberg group $\{\mathrm{e}^{\mathrm{i}\gamma}\boldsymbol{W}_{(t,\omega)},\, (\gamma,t,\omega)\in[0,2\pi]\times\mathbb{R}^2\}$

$$\boldsymbol{W}_{(t',\omega')}\boldsymbol{W}_{(t,\omega)} = \mathrm{e}^{\mathrm{i}\omega t'}\boldsymbol{W}_{(t+t',\omega+\omega')}.$$

Algebraic interpretation: covariance under a symmetry group

Time and frequency shifts $\qquad \boldsymbol{W}_{(t,\omega)} y(u) = e^{-\mathrm{i}\omega u} y(u-t)$

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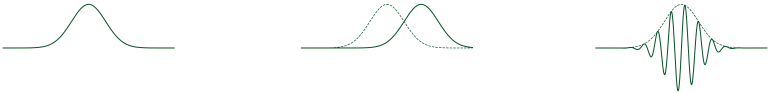
$$\boldsymbol{W}_{(t',\omega')} \boldsymbol{W}_{(t,\omega)} = \mathrm{e}^{\mathrm{i}\omega t'} \boldsymbol{W}_{(t+t',\omega+\omega')}.$$



$g(t) = \pi^{-1/4} \exp\left(-t^2/2\right)$ $\qquad \mathbf{T}_u g(t) = g(t-u)$ $\qquad \mathbf{M}_\omega g(t) = g(t) \exp\left(-\mathrm{i}\omega t\right)$

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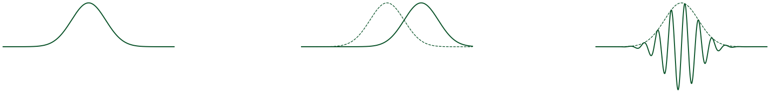
Coherent state interpretation $\{ \boldsymbol{W}_{(t,\omega)} h,\ t, \omega \in \mathbb{R} \}$ covariant family

$$V_h y(t,\omega) = \int_{-\infty}^{\infty} \overline{y(u)} h(u-t) \exp(-\mathrm{i}\omega u)\, \mathrm{d}u = \langle y, \boldsymbol{W}_{(t,\omega)} h \rangle$$



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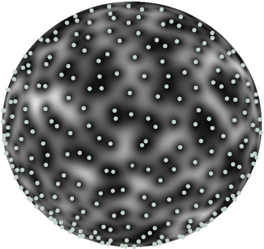
- Context and notations
- Time-frequency analysis: the Short-Time Fourier Transform

. . . .

- Signal detection based on spectrogram zeros - I
- Covariance principle and stationary point processes

. . . .

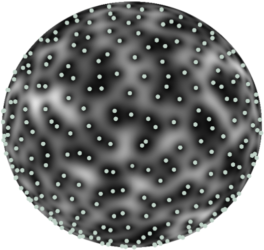
- The Kravchuk transform and its zeros
- Signal detection based on spectrogram zeros - II



Coherent state interpretation $\quad \boldsymbol{y} \in \mathbb{C}^{N+1}$

$$T\boldsymbol{y}(\vartheta, \varphi) = \langle \boldsymbol{y}, \boldsymbol{\Psi}_{(\vartheta,\varphi)} \rangle$$

$\vartheta \in [0, \pi], \varphi \in [0, 2\pi]$



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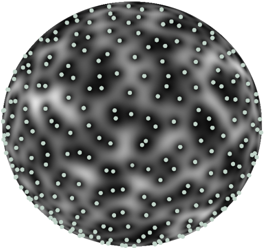
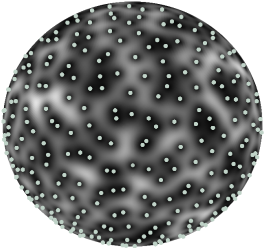


$\mathrm{SO}(3)$ **coherent states** (Gazeau, 2009)

$$\boldsymbol{\Psi}_{\vartheta,\varphi} = \sum_{n=0}^{N} \sqrt{\binom{N}{n}} \left(\cos\frac{\vartheta}{2}\right)^{n} \left(\sin\frac{\vartheta}{2}\right)^{N-n} \mathrm{e}^{\mathrm{i}n\varphi} \boldsymbol{q}_n = \boldsymbol{R}_{\boldsymbol{u}(\vartheta,\varphi)} \boldsymbol{\Psi}_{(0,0)},$$



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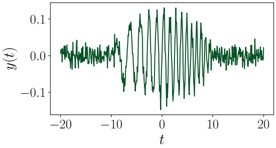
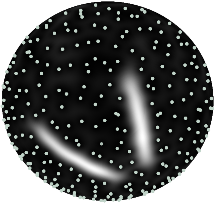
Kravchuk transform $\quad \{\boldsymbol{q}_n, n = 0, 1, ..., N\}$ the *Kravchuk functions*

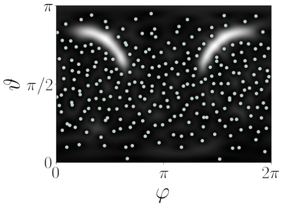
$$T\boldsymbol{y}(z) = \frac{1}{\sqrt{(1+|z|^2)^N}} \sum_{n=0}^{N} \langle \boldsymbol{y}, \boldsymbol{q}_n \rangle \sqrt{\binom{N}{n}} z^n, \quad z = \cot(\vartheta/2)\mathrm{e}^{\mathrm{i}\varphi}$$

Kravchuk transform

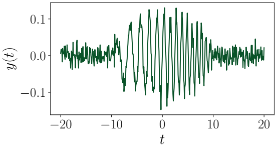
$$T\boldsymbol{y}(z) = \sqrt{(1+|z|^2)^{-N}} \sum_{n=0}^{N} \langle \boldsymbol{y}, \boldsymbol{q}_n \rangle \sqrt{\binom{N}{n}} z^n$$

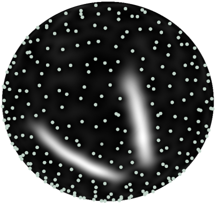


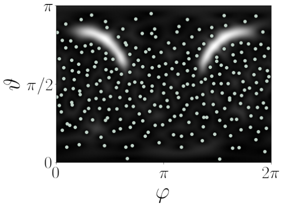




Kravchuk transform $$T\boldsymbol{y}(z) = \sqrt{(1+|z|^2)^{-N}}\sum_{n=0}^{N}\langle \boldsymbol{y}, \boldsymbol{q}_n\rangle\sqrt{\binom{N}{n}}z^n$$







Theorem $$T\boldsymbol{\xi}(\vartheta,\varphi) = \sqrt{(1+|z|^2)}^{-N}\,\mathrm{GAF}_{\mathbb{S}}(z), \qquad z = \cot(\vartheta/2)e^{i\varphi}$$

$\mathrm{GAF}_{\mathbb{S}}(z) = \sum_{n=0}^{N}\boldsymbol{\xi}[n]\sqrt{\binom{N}{n}}z^n$ the *spherical Gaussian Analytic Function*

(Pascal & Bardenet, 2022)

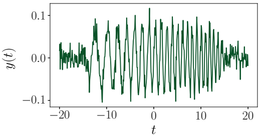
- Time-frequency analysis: the Short-Time Fourier Transform

- Signal detection based on spectrogram zeros - I
- Covariance principle and stationary point processes

- The Kravchuk transform and its zeros
- Numerical implementation of the Kravchuk transform
- **Signal detection based on spectrogram zeros - II**

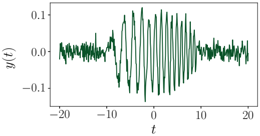
Fixed observation window of 40 **s**

long time event



duration $2\nu = 30$ s

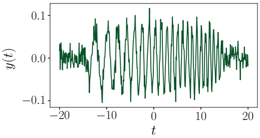
short time event



duration $2\nu = 20$ s

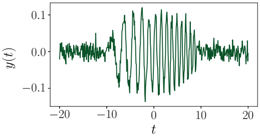
Fixed observation window of 40 s

long time event



duration $2\nu = 30$ s

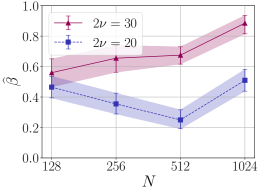
short time event



duration $2\nu = 20$ s

Robustness to small number of samples and short duration.

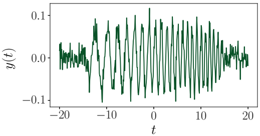
medium noise level



snr $= 2$

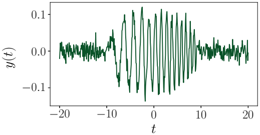
Fixed observation window of 40 s

long time event



duration $2\nu = 30$ s

short time event



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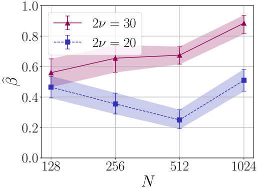
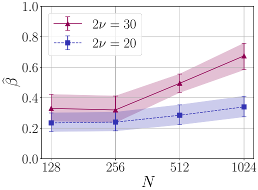
Robustness to small number of samples and short duration.

medium noise level



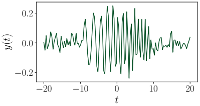
snr $= 2$

high noise level

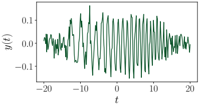


snr $= 1.5$

Detection of a noisy chirp of duration $2\nu = 30$ s



$N = 128$



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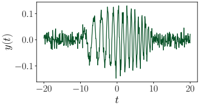
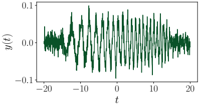


$N = 512$



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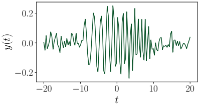
Detection of a noisy chirp of duration $2\nu = 30$ s



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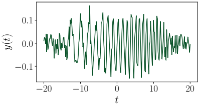

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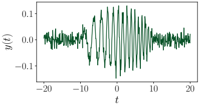

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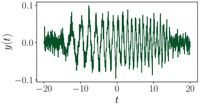
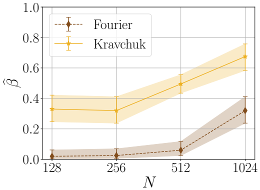
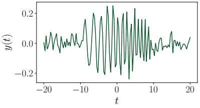


$N = 1024$

Performance: power of the test computed over 200 samples



Detection of a noisy chirp of duration $2\nu = 30$ s



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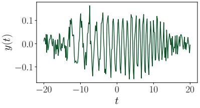

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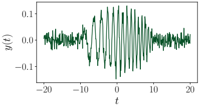

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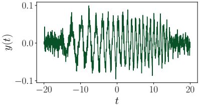

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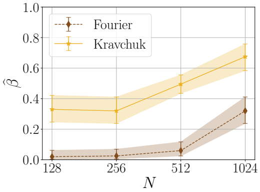
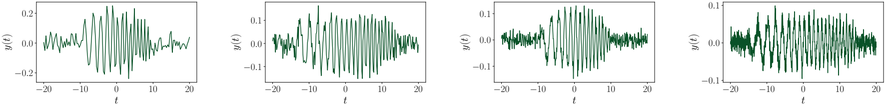


✓ higher detection power

✓ more robust to small N

✗ no fast algorithm yet

Detection of a noisy chirp of duration $2\nu = 30$ s



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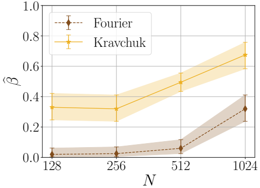

✓ higher detection power

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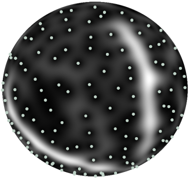
Advantages of using Kravchuk vs. Fourier spectrogram

- intrinsically encoded resolution: no need for prior knowledge
- compact phase space: no edge correction

- Novel covariant discrete Kravchuk transform

$$T\boldsymbol{y}(\vartheta,\varphi) = \frac{1}{\sqrt{(1+|z|^2)^N}} \sum_{n=0}^{N} \langle \boldsymbol{y}, \boldsymbol{q}_n \rangle \sqrt{\binom{N}{n}} z^n, \quad z = \cot(\vartheta/2)\mathrm{e}^{\mathrm{i}\varphi}$$

  - Interpreted as a coherent state decomposition $\langle \boldsymbol{y}, \boldsymbol{\Psi}_{(\vartheta,\varphi)} \rangle$
  - Representation on a compact phase space S^2
  - Zeros of the Kravchuk spectrogram of white noise characterized *via* $\mathrm{GAF}_{\mathbb{S}}$



- Signal detection based on spectrogram zeros
  - Robust to low snr and small N
  - Significant improvement using Kravchuk spectrogram

Pascal & Bardenet, 2022: `arxiv:2202.03835`
`GitHub: bpascal-fr/kravchuk-transform-and-its-zeros`

- Interpretation of the action of $\mathrm{SO}(3)$ on $\mathbb{C}^{N+1}$

$$\boldsymbol{\Psi}_{\vartheta,\varphi} = \sum_{n=0}^{N} \sqrt{\binom{N}{n}} \left(\cos\frac{\vartheta}{2}\right)^{n} \left(\sin\frac{\vartheta}{2}\right)^{N-n} \mathrm{e}^{\mathrm{i}n\varphi} \boldsymbol{q}_n = \boldsymbol{R}_{\boldsymbol{u}(\vartheta,\varphi)} \boldsymbol{\Psi}_{(0,0)},$$

- Implementation of the inversion formula: denoising based on zeros

$$\boldsymbol{y} = (4\pi)^{-1} \int_{S^2} \overline{T\boldsymbol{y}(\vartheta,\varphi)} \boldsymbol{\Psi}_{\vartheta,\varphi} \, \mathrm{d}\mu(\vartheta,\varphi)$$

- Design of a Kravchuk FFT counterpart

$$T\boldsymbol{y}(z) = \frac{1}{\sqrt{(1+|z^2|)^N}} \sum_{\ell=0}^{N} \sqrt{\binom{N}{\ell}} \overline{\boldsymbol{y}[\ell]} \frac{(1-z)^{\ell}(1+z)^{N-\ell}}{\sqrt{2^N}}$$

- Convergence of Kravchuk toward the Fourier spectrogram as $N \to \infty$

$$\boldsymbol{y}[\ell] = y(t_\ell), \quad t_\ell = T_0 + \frac{T_\mathrm{f} - T_0}{N}\ell, \quad \ell = 0, 1, \ldots, N$$

Kravchuk transform $\{\boldsymbol{q}_n, n = 0, 1, ..., N\}$ the Kravchuk basis

$$T\boldsymbol{y}(z) = \frac{1}{\sqrt{(1+|z|^2)^N}} \sum_{n=0}^{N} \langle \boldsymbol{y}, \boldsymbol{q}_n \rangle \sqrt{\binom{N}{n}} z^n, \quad z = \cot(\vartheta/2) \mathrm{e}^{\mathrm{i}\varphi}$$

$\rightarrow$ first: basis change, i.e., computation of $\langle \boldsymbol{y}, \boldsymbol{q}_n \rangle = \sum_{\ell=0}^{N} \overline{\boldsymbol{y}[\ell]} q_n(\ell; N)$

Practical computation of the Kravchuk transform

Kravchuk transform $\{\boldsymbol{q}_n, n = 0, 1, ..., N\}$ the Kravchuk basis

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Evaluation of Kravchuk functions $q_n(\ell; N) = \frac{1}{\sqrt{2^N}} \sqrt{\binom{N}{n}} Q_n(\ell; N) \sqrt{\binom{N}{\ell}}$

$$(N-n)Q_{n+1}(t; N) = (N-2t)Q_n(t; N) - nQ_{n-1}(t; N),$$

$\{Q_n(t; N), n = 0, 1, \ldots, N\}$ orthogonal family of Kravchuk polynomials

$$\sum_{\ell=0}^{N} \binom{N}{\ell} Q_n(\ell; N) Q_{n'}(\ell; N) = 2^N \binom{N}{n}^{-1} \delta_{n,n'}$$

Instability of the computation of Kravchuk polynomials

Evaluation of Kravchuk functions

(i) recursion to compute the Kravchuk polynomials

$$(N-n)Q_{n+1}(t;N) = (N-2t)Q_n(t;N) - nQ_{n-1}(t;N),$$

(ii) multiplication by the binomial coefficients

$$q_n(\ell;N) = \frac{1}{\sqrt{2^N}}\sqrt{\binom{N}{n}}Q_n(\ell;N)\sqrt{\binom{N}{\ell}}$$

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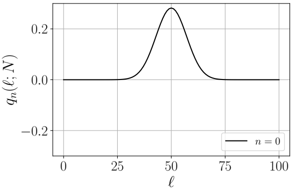

Evaluation of Kravchuk functions

(i) recursion to compute the Kravchuk polynomials

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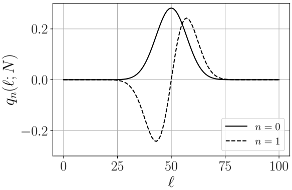

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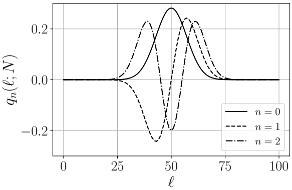

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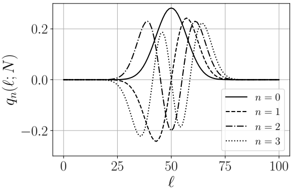

Instability of the computation of Kravchuk polynomials

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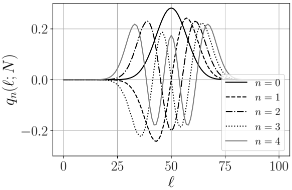

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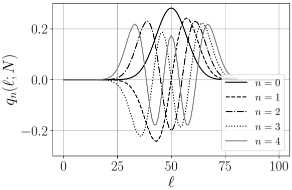

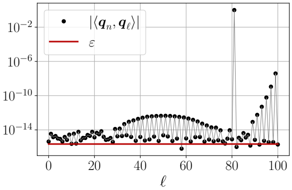

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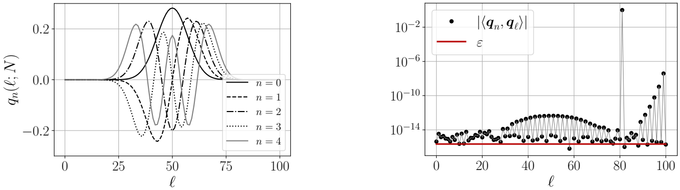


→ estimated basis is **not orthogonal**! Not possible to compute $\langle \boldsymbol{y}, \boldsymbol{q}_n \rangle$.

Kravchuk transform $\{\boldsymbol{q}_n, n = 0, 1, \dots, N\}$ the Kravchuk basis

$$T\boldsymbol{y}(z) = \frac{1}{\sqrt{(1+|z|^2)^N}} \sum_{n=0}^{N} \left(\sum_{\ell=0}^{N} \overline{\boldsymbol{y}[\ell]} q_n(\ell; N) \right) \sqrt{\binom{N}{n}} z^n \rightarrow \text{intractable}$$

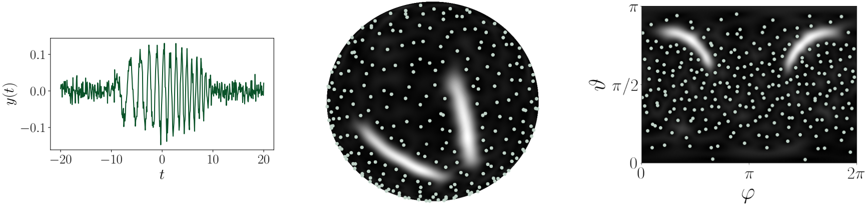
A generative function for Kravchuk polynomials

$$\sum_{n=0}^{N} \binom{N}{n} Q_n(\ell; N) z^n = (1-z)^{\ell} (1+z)^{N-\ell}$$

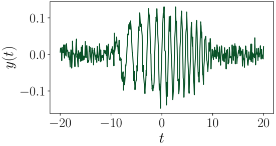
$$\Longrightarrow \quad \sum_{n=0}^{N} \sqrt{\binom{N}{n}} q_n(\ell; N) z^n = \sqrt{\binom{N}{\ell}} \frac{(1-z)^{\ell} (1+z)^{N-\ell}}{\sqrt{2^N}}$$

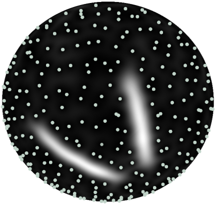
$$T\boldsymbol{y}(z) = \frac{1}{\sqrt{(1+|z^2|)^N}} \sum_{\ell=0}^{N} \sqrt{\binom{N}{\ell}} \overline{\boldsymbol{y}[\ell]} \frac{(1-z)^{\ell} (1+z)^{N-\ell}}{\sqrt{2^N}}$$

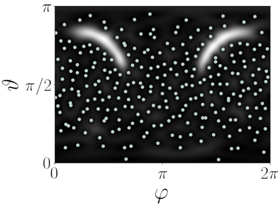
✗ no more Fast Fourier Transform algorithm using $z^n = \cot(\vartheta/2)^n \mathrm{e}^{\mathrm{i}n\varphi}$



Advantage compared to Fourier: can tune the resolution of phase space.







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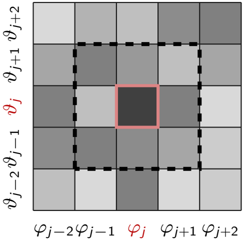
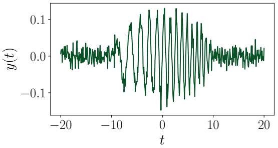
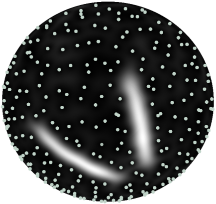
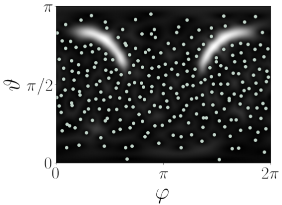


Minimal Grid Neighbors







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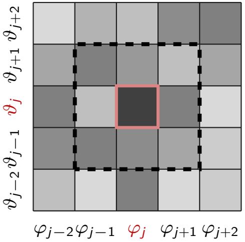

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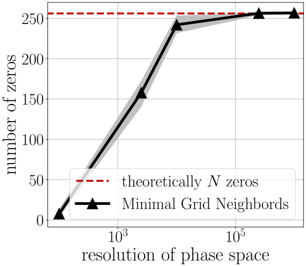
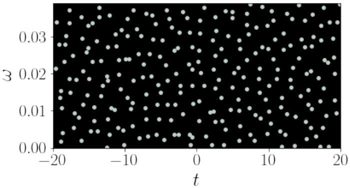
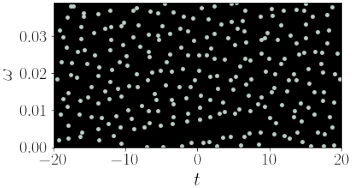


In progress: demonstrate that all local minima of $|Ty(z)|^2$ are zeros.



snr $= 0$

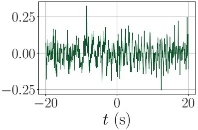


snr > 0

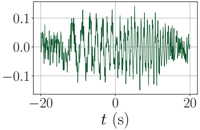
The signal creates **holes** in the zeros pattern: **second order** statistics.

Functional statistics:

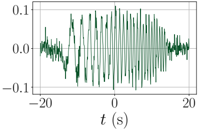
- the empty space function
  $F(r) = \mathbb{P}\left(\inf_{z_i \in Z} \mathrm{d}(z_0, z_i) < r\right)$: **probability to find a zero at less than** r
- Ripley's K-function
  $K(r) = 2\pi \int_0^r s g_0(s)\,\mathrm{d}s$: **expected # of pairs at distance less than** r



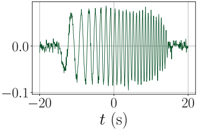
snr $= 0.5$



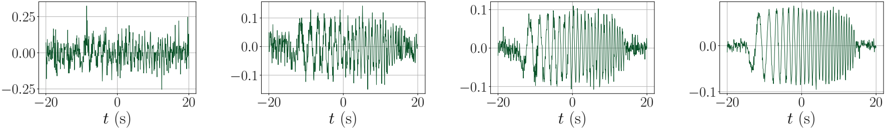
snr $= 1$



snr $= 2$

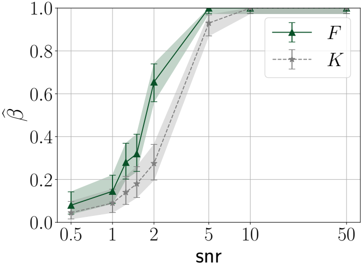


snr $= 5$

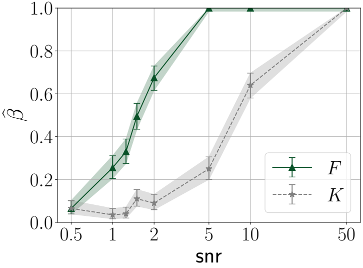


snr = 0.5 snr = 1 snr = 2 snr = 5

Ripley's K functional vs. empty space functional F

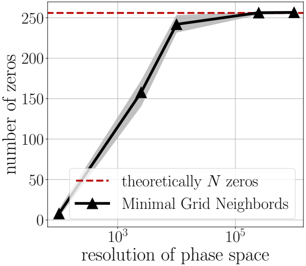


$N + 1 = 257$ points



$N + 1 = 513$ points

Opening: can the Kravchuk spectrogram have multiple zeros?



Spherical Gaussian Analytic Function

$$\mathrm{GAF}_{\mathbb{S}}(z) = \sum_{n=0}^{N} \boldsymbol{\xi}[n] \sqrt{\binom{N}{n}} z^n$$

with $\boldsymbol{\xi}[n] \sim \mathcal{N}_{\mathbb{C}}(0,1)$ i.i.d.

$\rightarrow$ only **simple** zeros

General case $\quad T\boldsymbol{y}(z) = \sqrt{(1+|z|^2)}^{-N} \sum_{n=0}^{N} \sqrt{\binom{N}{n}} (\mathbf{Q}\boldsymbol{y})[n] z^n$

If $\boldsymbol{y}$ deterministic, such that $(\mathbf{Q}\boldsymbol{y})[n] = \sqrt{\binom{N}{n}} a^{N-n} b^n, a \in \mathbb{C}, b \in \mathbb{C}^*$,

$$\sqrt{(1+|z|^2)}^{-N} \sum_{n=0}^{N} \sqrt{\binom{N}{n}} (\mathbf{Q}\boldsymbol{y})[n] z^n = (a+bz)^N$$

$\rightarrow -a/b$ multiple root of order of degeneracy N