Fundamentals in signal analysis of passive acoustic data

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gipsa-lab

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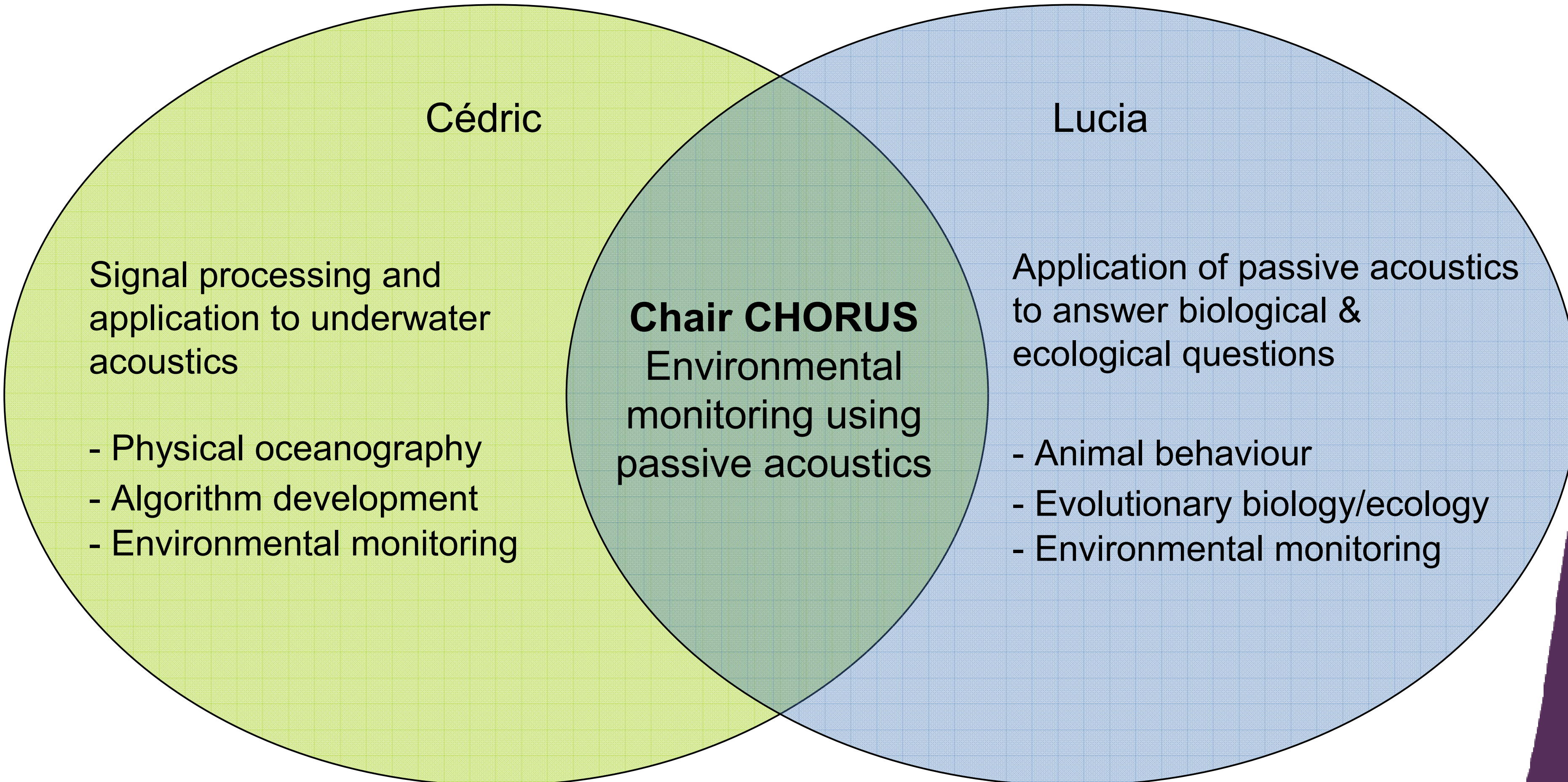
Chaire CHORUS
Remote sensing of Aquatic Environment
By
Passive Acoustics

Outline

- Introduction
- Introduction to sound
- Measurement chain
- Spectral analysis of acoustic measurements
- Time-frequency representation
- Applied examples from our own research

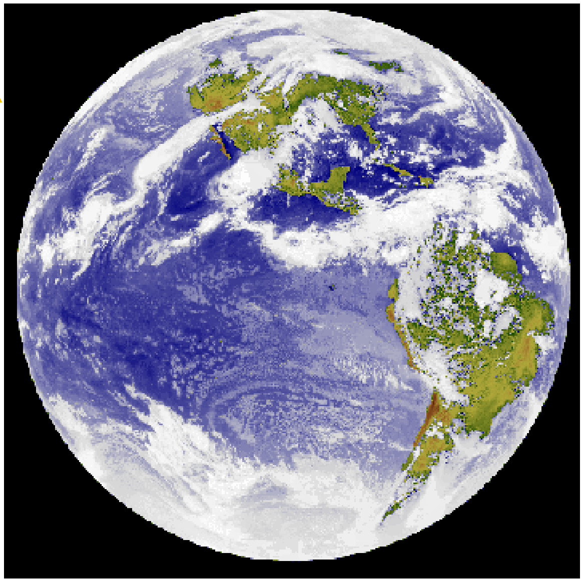
Who are we ?


Cédric
Lucia
Signal processing and application to underwater acoustics
- Physical oceanography
- Algorithm development
- Environmental monitoring
Chair CHORUS
Environmental monitoring using passive acoustics
Application of passive acoustics to answer biological & ecological questions
- Animal behaviour
- Evolutionary biology/ecology
- Environmental monitoring

Why sound in a time series conference?

hosts

medium

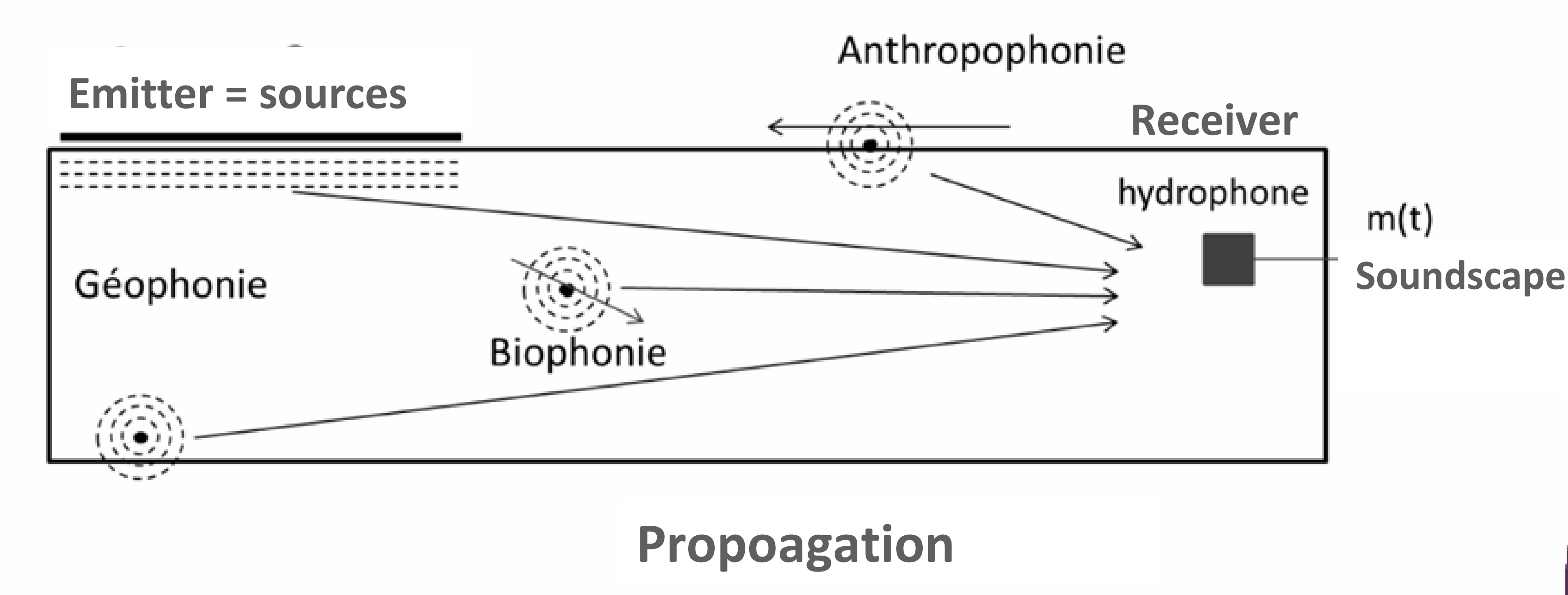


Services deriving from the hydrosphere : 20 900 billions $ / year

The ocean: a vast still largely unknown environment
Its observation : a priority of the 21st century

Costanza, R.; d'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.; Paruelo, J. & others (1997), 'The value of the world's ecosystem services and natural capital', *Nature* ***387(6630), 253--260.***

Why sound in a time series conference?



AQUATIC ENVIRONMENT = ACOUSTIC SOUNDSCAPE

- Pijanowski, B.; Villanueva-Rivera, L.; Dumyahn, S.; Farina, A.; Krause, B.; Napoletano, B.; Gage, S. & Pieretti, N. (2011), 'Soundscape ecology: the science of sound in the landscape', *BioScience* ***61(3), 203--216.***

- Radford, C.; Stanley, J.; Tindle, C.; Montgomery, J. & Jeffs, A. (2010), 'Localised coastal habitats have distinct underwater sound signatures', *Mar. Ecol. Prog. Ser.* ***401, 21-29***

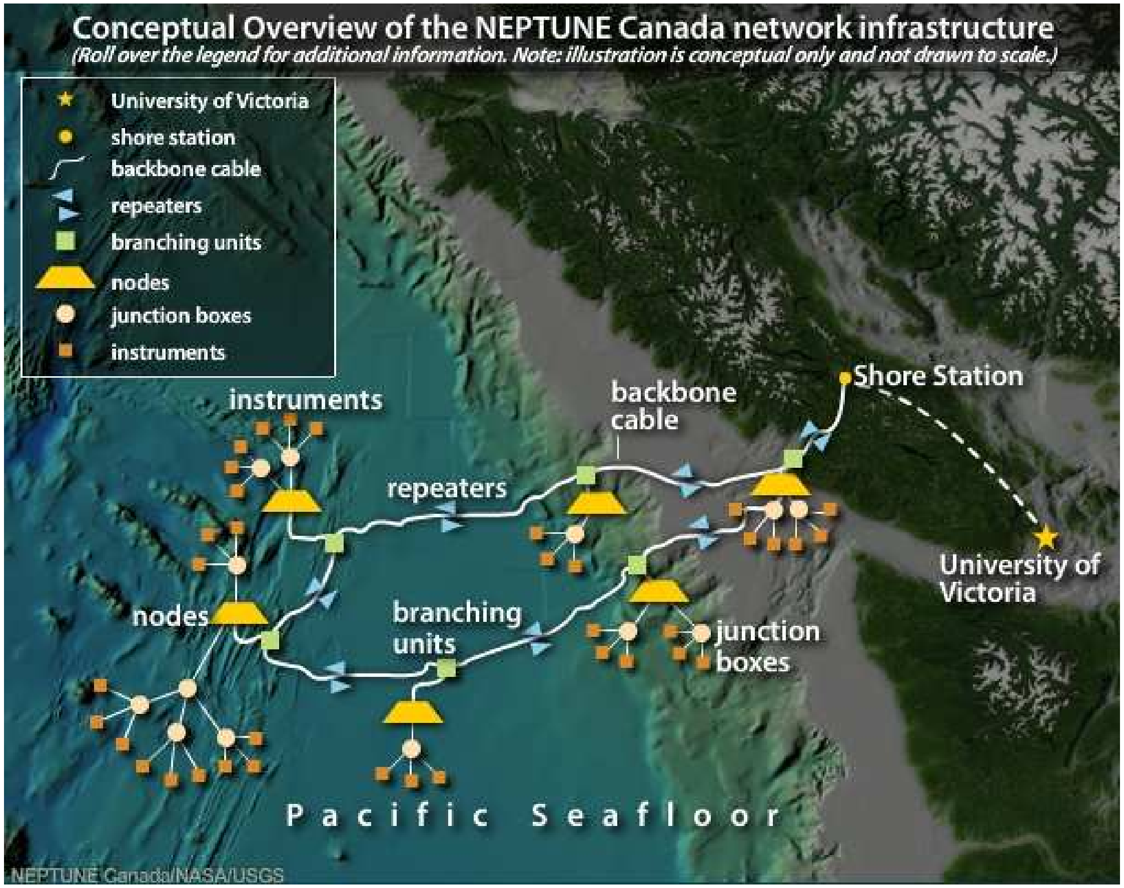
- Kennedy, E.; Holderied, M.; Mair, J.; Guzman, H. & Simpson, S. (2010), 'Spatial patterns in reef-generated noise relate to habitats and communities: Evidence from a Panamanian case study', *Journal of Experimental Marine Biology and Ecology* **395**(1-2), 85--92.

- Gervaise, C.; Di Iorio, L.; Grall, J.; Chauvaud, L. ; Jolivet, A. ; Clavier, J. (2012),'La polyphonie côtière : des sons au fonctionnement des écosystèmes', *Chapitre HDR*

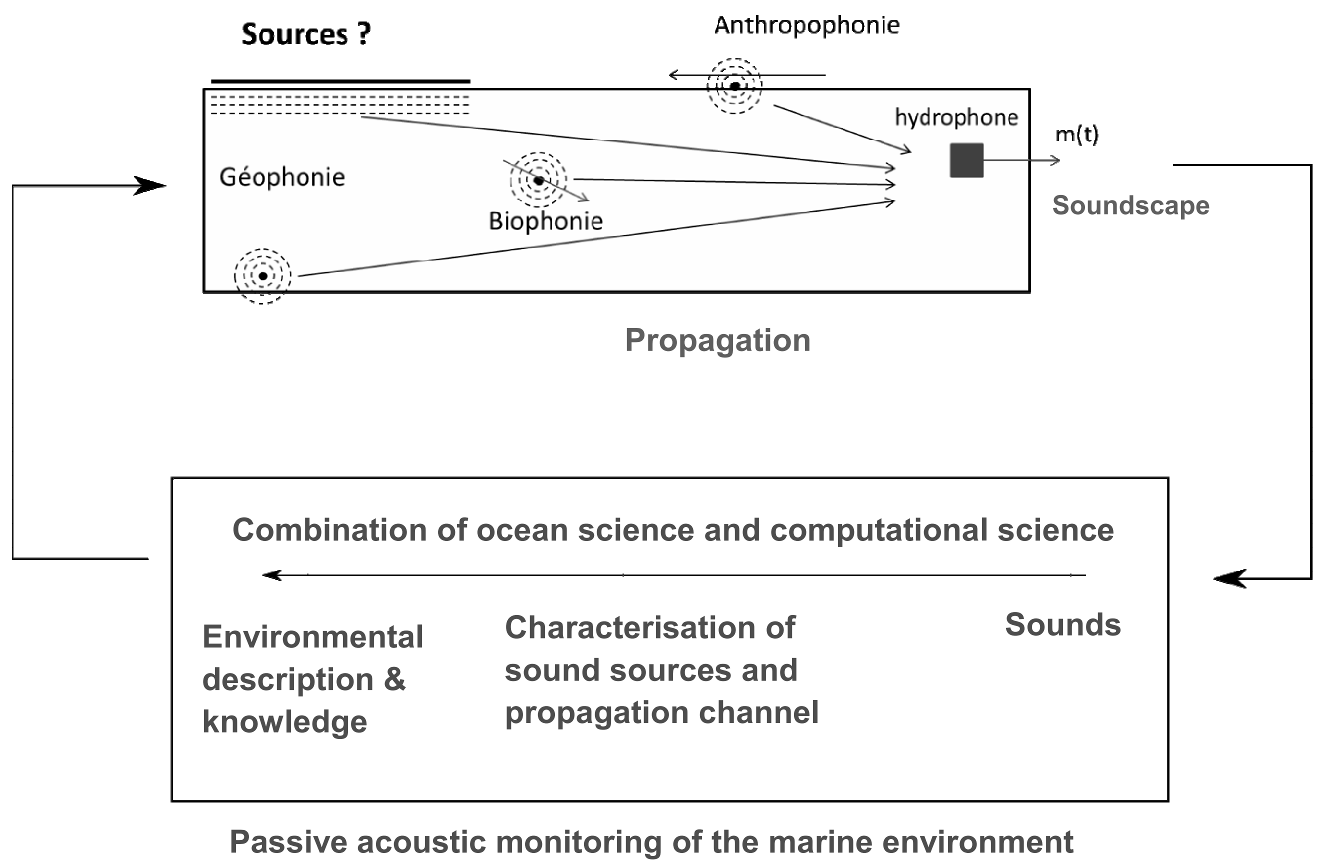
Why sound in a time series conference?

- Recent technological advances in sound acquisition
- Long-term monitoring,
- Continuous recordings,
- High resolution,
- Deployment in areas/substrates difficult to access,
- Relatively cost-effective,
- Real-time acquisition possible....

Why sound in a time series conference?



Why sound in a time series conference?



Passive acoustic monitoring = an indirect measurement that needs processing!

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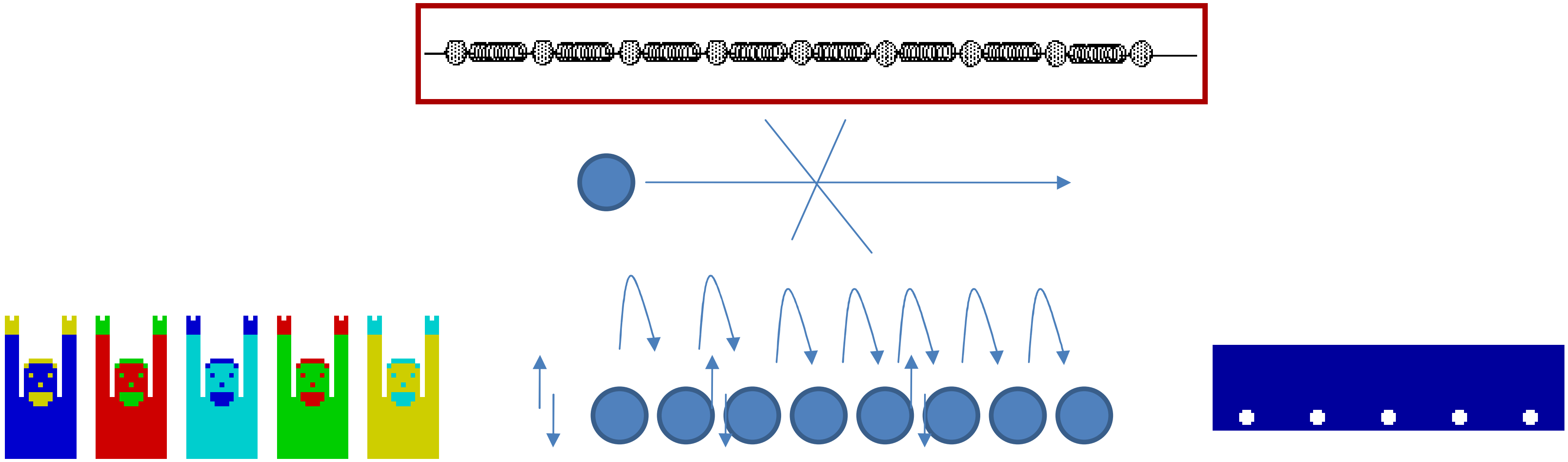
What is a wave ?

A mechanical WAVE



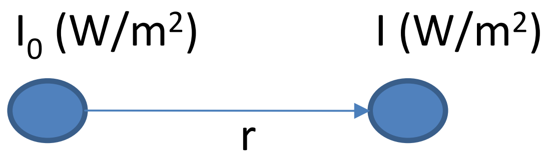
Initial information
Oscillation of a particle

Propagation of information
Transmission of oscillation

Different possible waves to explore the marine environment:

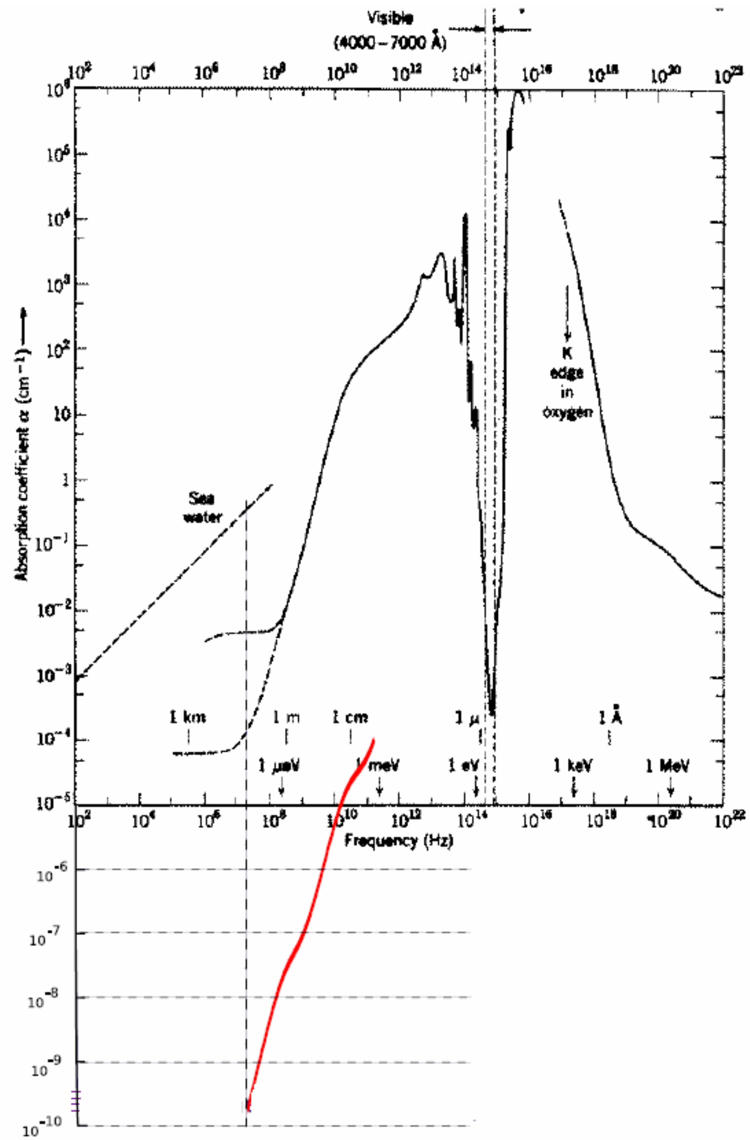
- electromagnetic
- optic
- acoustic

Why acoustic waves?

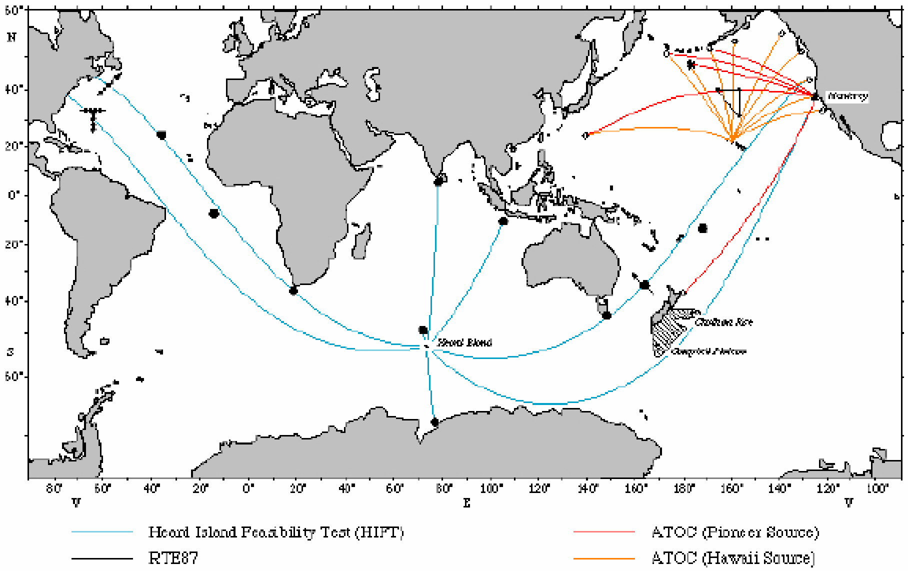


$$I(r) = I_0 e^{-\alpha r}$$

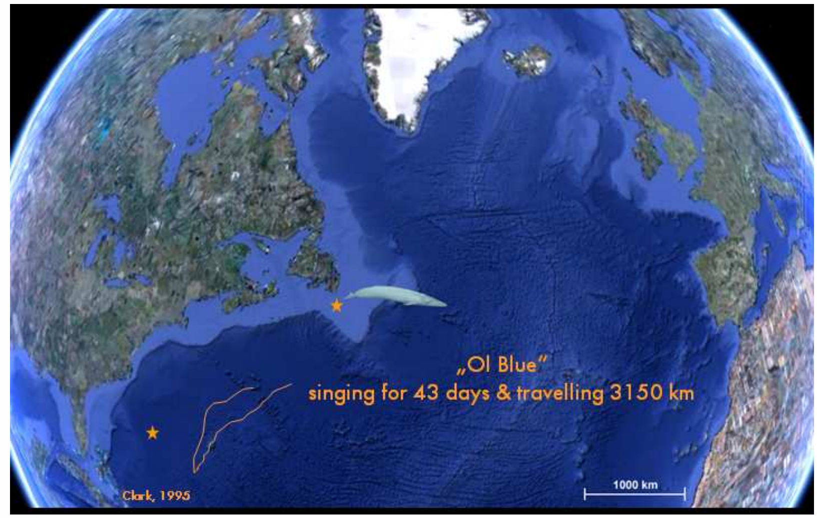
with α = coefficient of absorption (here in cm^{-1})



Why acoustic waves?



Frequency 50Hz, range 20000km!



Frequency 18Hz, range > 3000km

Frequency	10 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1MHz
Absorption (dB/km)	10^{-5}!!	10^{-3}	0.06	1	33	300 !!
Range	>1000km		100 km	10 km	300m	25 m
Wavelength	150 m	15 m	1.5 m	15 cm	1.5 cm	15 mm

Munk, W.; Spindel, R.; Baggeroer, A. & Birdsall, T. (1994), 'The Heard Island Feasibility Test', *The Journal of the Acoustical Society of America* ***96(4), 2330-2342.***

Clark, C. W. & Gagnon, G. J. 2004. Low-frequency vocal behaviors of baleen whales in the North Atlantic: Insights from integrated Undersea Surveillance System detections, locations, and tracking from 1992 to 1996. *Journal of Underwater Acoustics (USN),* **52**.

What is an acoustic wave ?

The equation of wave propagation is obtained from:

- the law of conservation of mass
- the law of conservation of momentum
- the law of fluid dynamics (linking P to ρ)

and from their 1st order linearization around the equilibrium pressure + $v = 0 ms^{-1}$

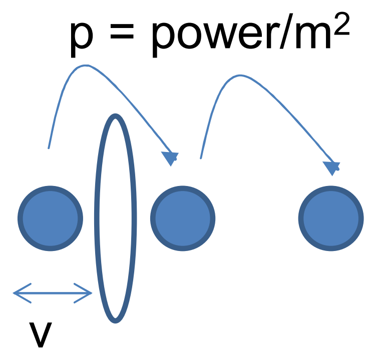
$$\Delta p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

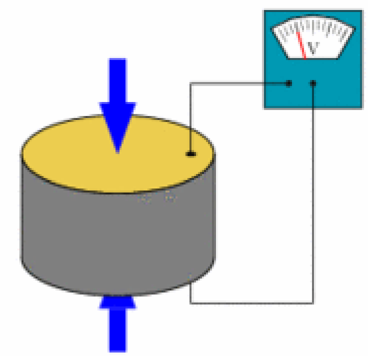
Wave equation

$$\rho c^2 = p$$

$$\rho_0 \frac{\partial \vec{v}}{\partial t} + \vec{\nabla} p = 0$$

source





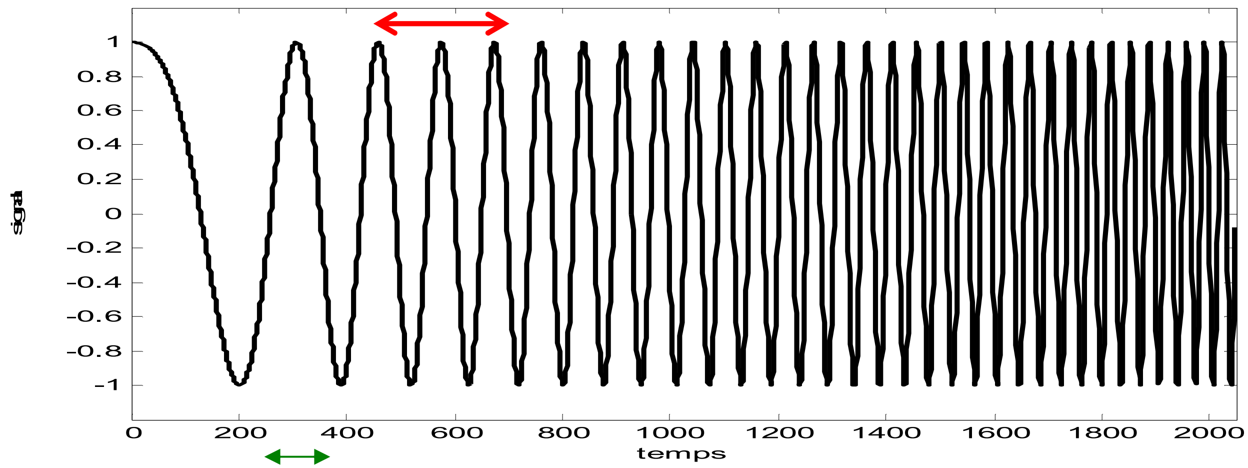
Piezo-electric receiver

Jensen, F. (1994), *Computational ocean acoustics, Amer Inst of Physics.*

What is a sound ?

Level (received µPa, emitted µPa@1m ?) in decibel as a function of:

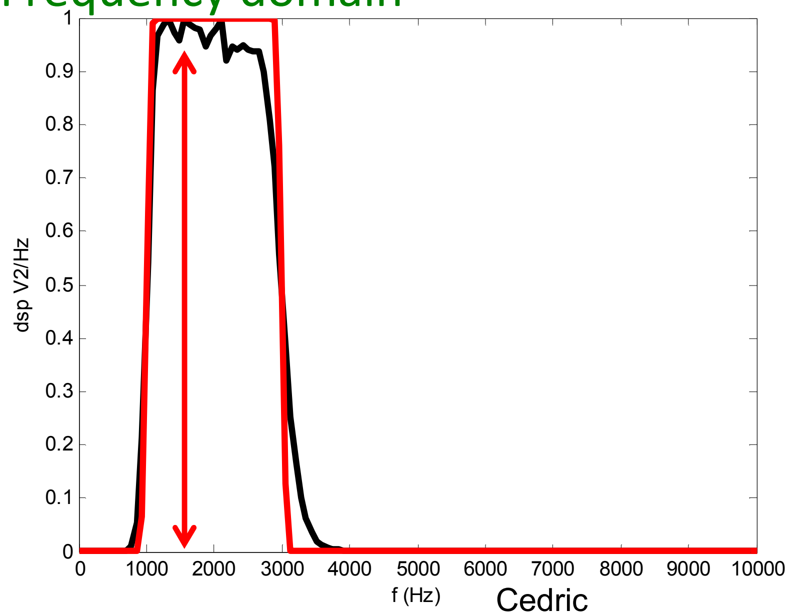
Time domain



Sound intensity level:

$$P_{|dB\,re\,P_0} = 10\log_{10}\left(\frac{P}{P_0}\right)$$

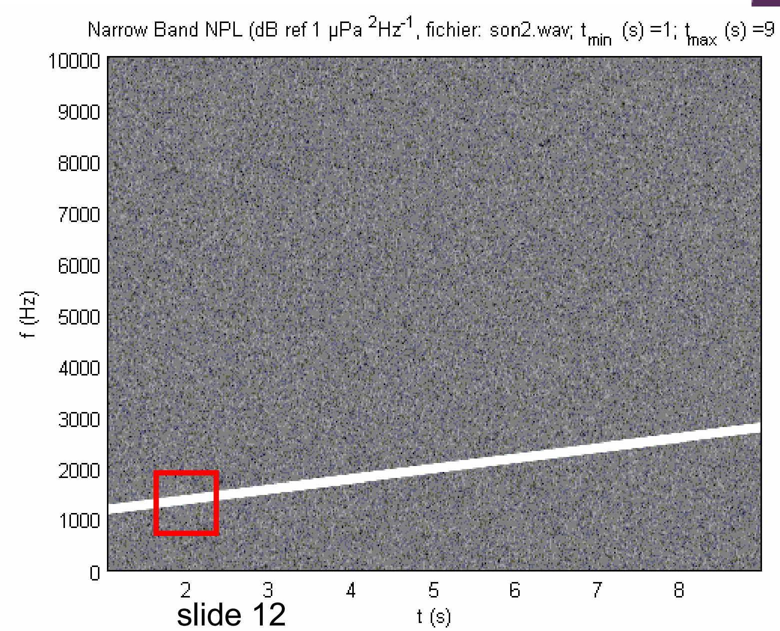
Frequency domain



Cedric

T = 1/f

Time-frequency



slide 12

Sound speed

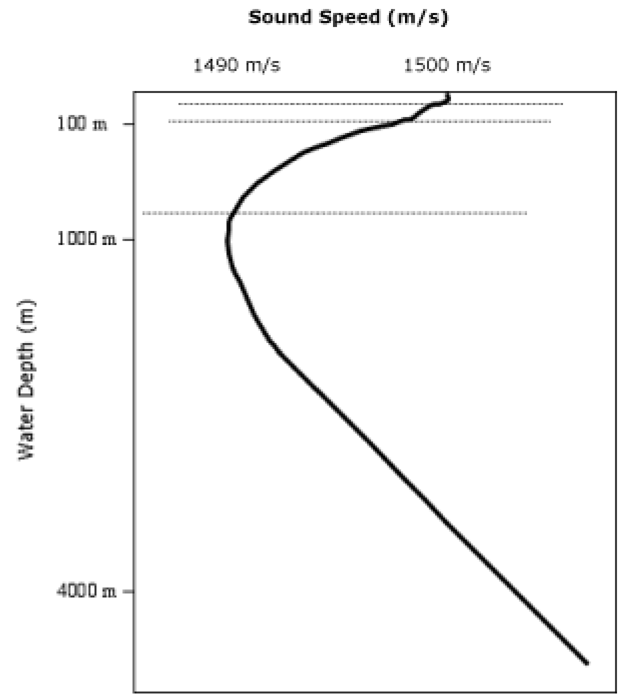
$$\Delta p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

$$\rho c^2 = p$$

air, c=330 ms^{-1}

water, c=1500 ms^{-1}

rock, c =4000 ms^{-1}



Sea water sound velocity
c= G(T,p,S)=H(T,z,S)

Take home message (for T= 0°C and S = 35° /°°)

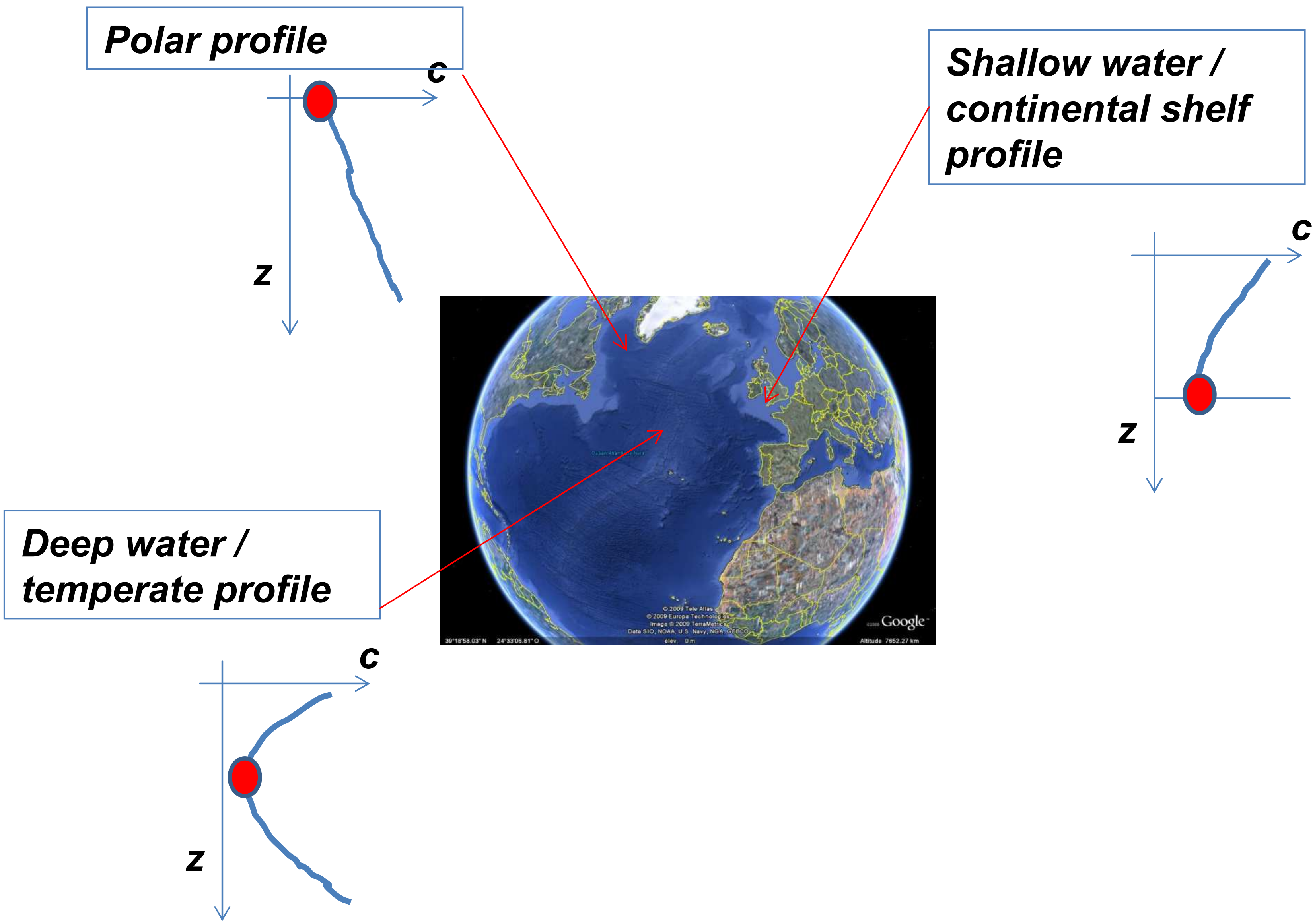
- c increases with T (4.6m/s for ΔT = 1°C)
- c increases with S (1.4m/s for ΔS = 1 ° /°°)
- c increases with p and z (1.7m/s for ΔS = 1000m)

Sound speed

If sound velocity c changes with depth z, sound waves do not propagate on a straight line, they are refracted.

Sound waves always tend to converge towards the sound speed minimum.

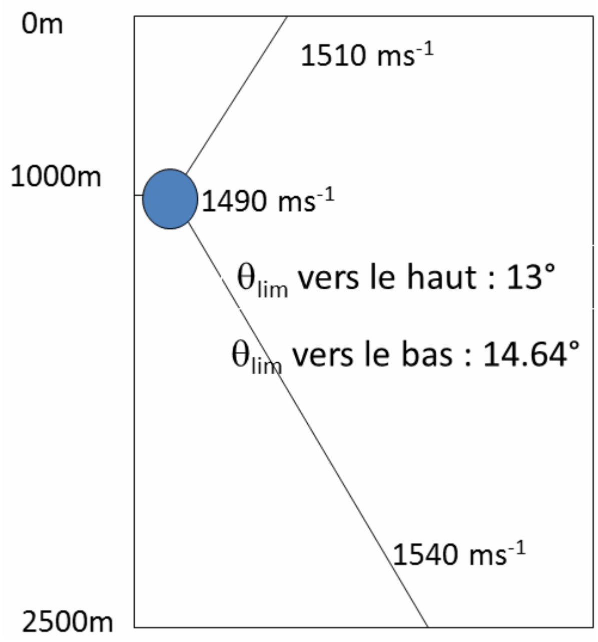
Sound speed

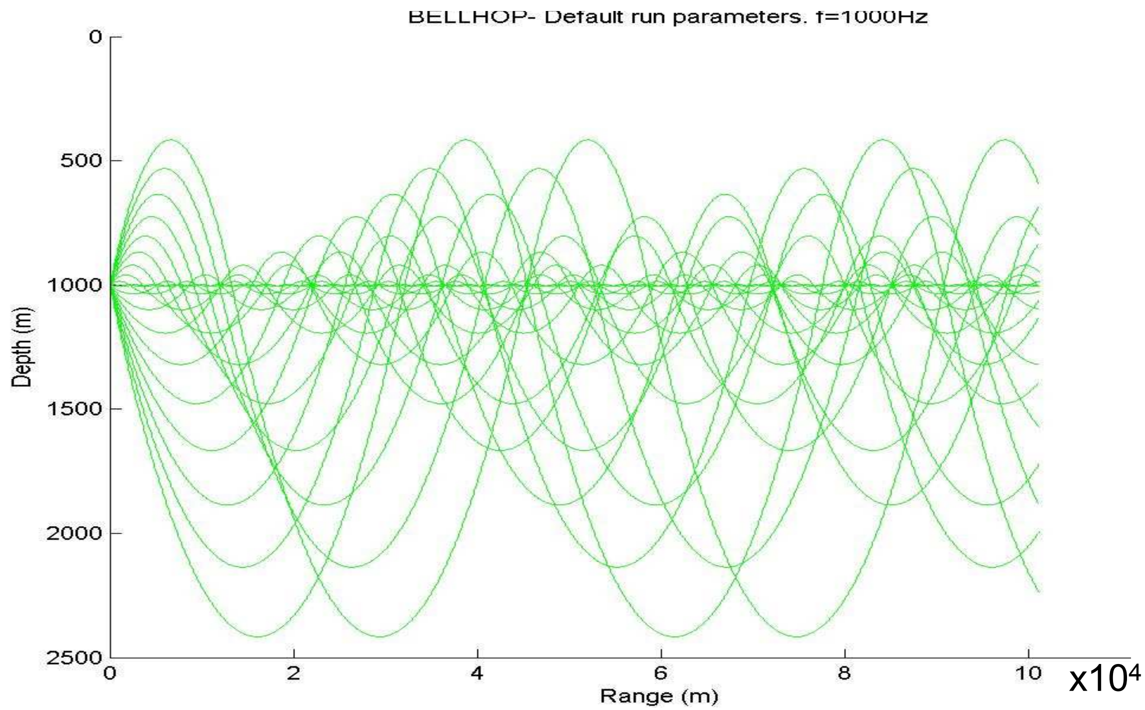

Polar profile
c
z
Shallow water / continental shelf profile
c
z
Deep water / temperate profile
c
z

Temperate deep water sound popagation

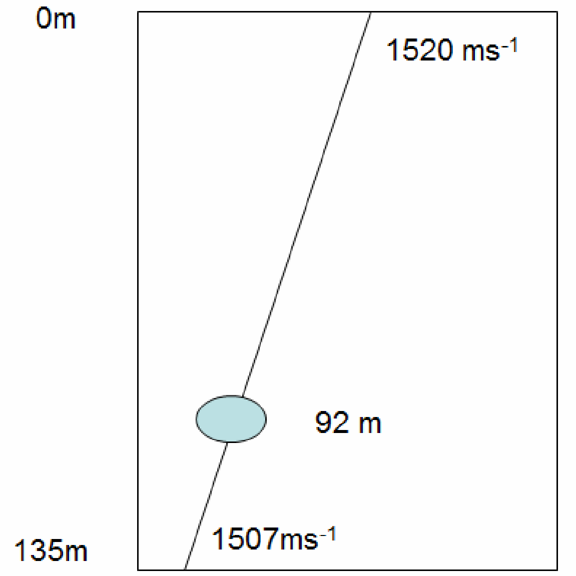
Canal SOFAR

« Sound Fixing & Ranging »

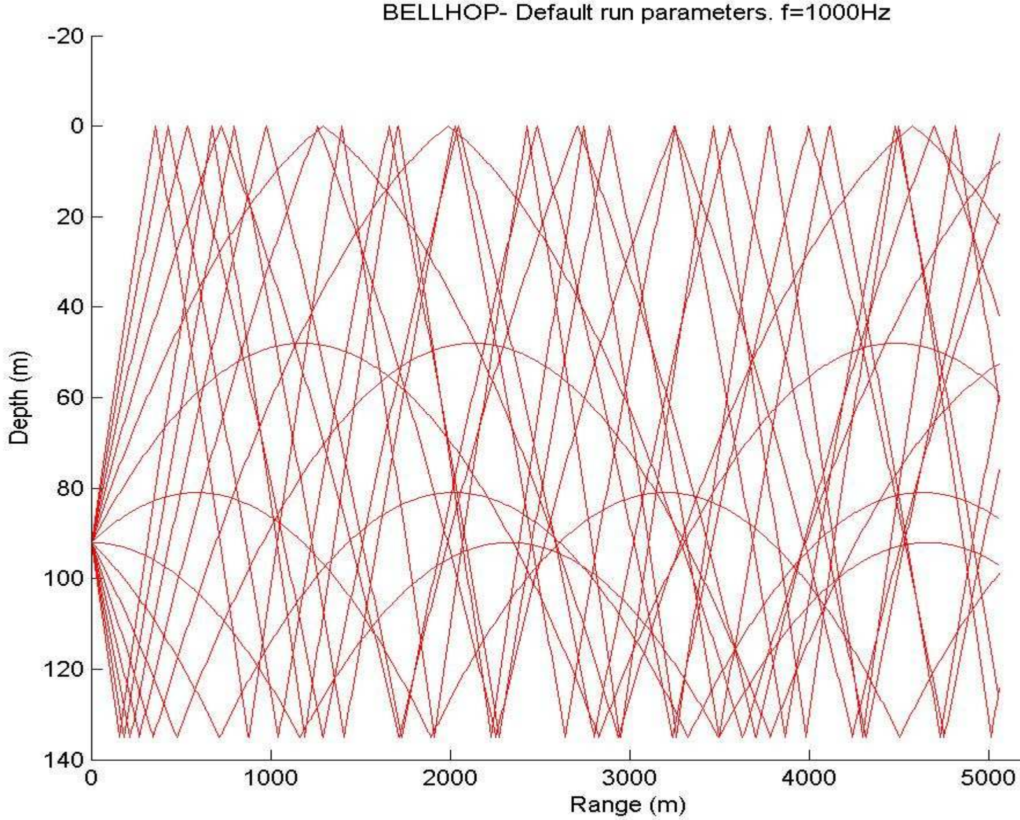




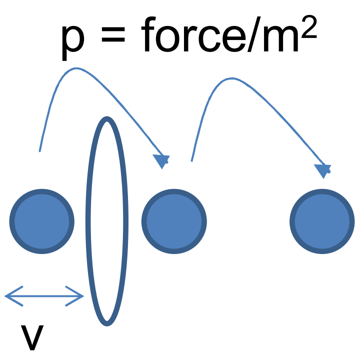
Temperate shallow water propagation



θ_{lim} vers le haut : 6.23°



The intensity of sound



Power = strength x velocity

Intensity = amount of power transmitted through a unit area (m^2) = pressure x speed
(W/m^2)

For planar waves :

$$I = \frac{p^2}{\rho c}$$

The intensity of sound

Example = sound wave with an amplitude of 1 Pa

In water: (ρ=1000kg/m^2; c=1500ms^{-1}) => I_{eau} =6.10^{-7}W/m^2

In air: (ρ=1.2kg/m^2; c=330ms^{-1}) => I_{air} =2,5.10^{-3}W/m^2

I_{air} / I_{eau} = 4166 !!!!!!!!!!!

$$I = \frac{p^2}{\rho c}$$

Air : compressible gaz
Water : incompressible fluide

Decibels – unit of Sound (pressure) Level

J represents a quantity and J_{ref} a reference quantity

$$J\ dB\ (ref\ \text{à}\ J_{ref}) = 20log_{10}\left(\frac{J}{J_{ref}}\right).$$ *if J is an amplitude*

$$J\ dB\ (ref\ \text{à}\ J_{ref}) = 10log_{10}\left(\frac{J}{J_{ref}}\right).$$ *if J is an intensity*

Decibels are used to represent and compare amplitude quantities. The sound level in dB is a scale based on multiples of 10 (logarithmic scale):

10dB = 1* 10 $^{-11}$ W/m^2 -> acoustic pressure increases 10 times

20dB = 1* 10 $^{-10}$ W/m^2 -> acoustic pressure increases 100 times

40dB = 1* 10 $^{-8}$ W/m^2 -> acoustic pressure increases 10000 times

Can Decibels be a source of confusion ? Yes or No !

Two sounds with the following levels:

Son 1 : 100 dB ref 1µPa
Son 2 : 100 dB ref 1µPa²

Are the sound of equal amplitudes ?

Son 1 => ref 1µPa, The quantity is an amplitude: $100 = 20log_{10}\left(\frac{p}{p_{ref}}\right)$ donc

$$\text{p} = p_{ref} \times 10^{100/20} = 10^5 p_{ref}$$

Son 2 => ref 1µPa² remember $Q = \frac{p^2}{\rho c}$ The quantity is an intensity:

$$100 = 10log_{10}\left(\frac{I}{I_{ref}}\right)$$

$$\text{I} = I_{ref} \times 10^{100/10}$$

$$\text{I} \sim p^2$$

Donc

$$p^2 = {p^2}_{ref} \times 10^{100/10}$$

$$\text{p} = p_{ref} \times 10^{100/20} = 10^5 p_{ref}$$

Can Decibels be a source of confusion ? Yes or No !

- The sound level in dB of a sum of acoustic signals is not equal to the sum of the sound levels of each signa   l!!!!!!!!!!!!!!

- Two independent sounds => intensity of the sum = sum of the intensities in a **linear** scale:

- Son 1 : Q1 dB , son 2: Q2 dB, et soit son3 = son1+son2   *(son = sound)*

$$I_{son3} = I_{son1} + I_{son2}$$
$$I_{son3} = 10^{Q1/10} + 10^{Q2/10}$$
$$I_{son3}dB = 10 \times log10(10^{Q1/10} + 10^{Q2/10})$$

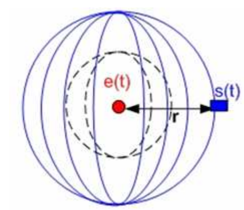
- Si Q1=Q2=100dB then $I_{son3}dB$=Q1 dB+3=103 dB
- Si Q1=100dB, Q2=90dB then $I_{son3}dB$=100.41dB

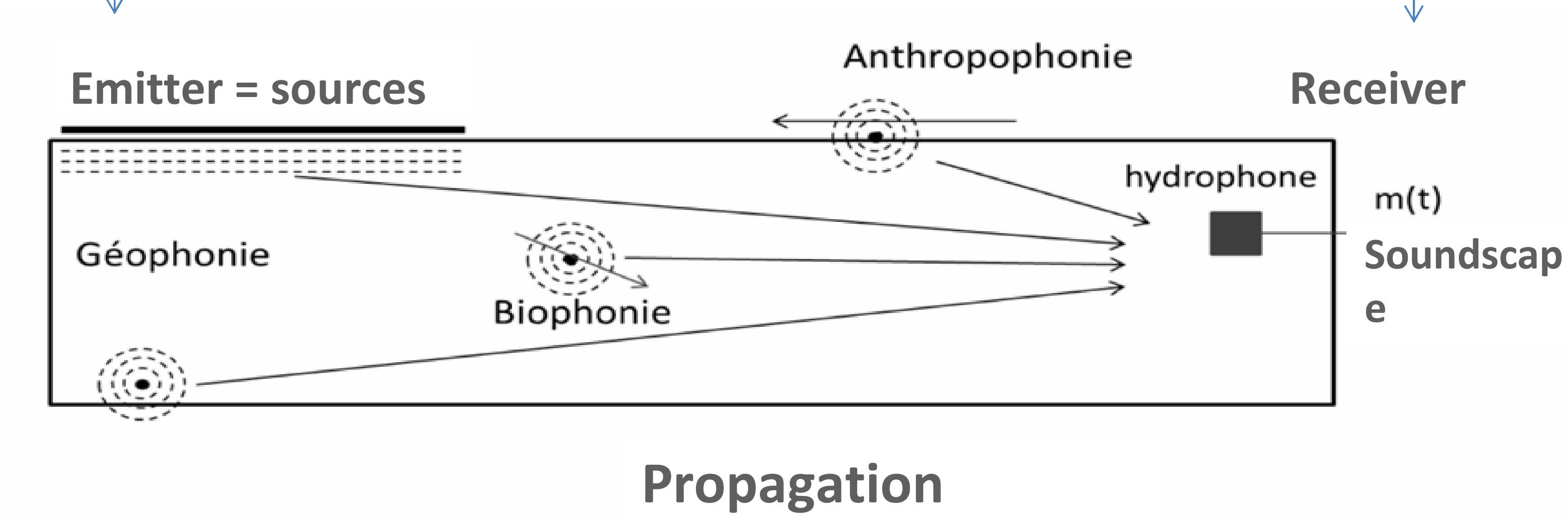
Source Level & Reveived Level

Source Level
SL dB re
1µPa²**@1m**…..

Level heared if @ 1m form an isotropic source

Received Level
RL dB ref
1µPa²…..





Acoustic intensity : The energetic budget of a singing blue whale

Mean source level of blue whale song note: 160 dB re 1μPa @ 1m (188 dB peak), signal duration = 18s with 960 signals/day, energetic value of krill = 96kcal/100g.

Biophony

From invertebrates…

Range

1m - > 200m

10m - > 1km

> 100m - > 1000km

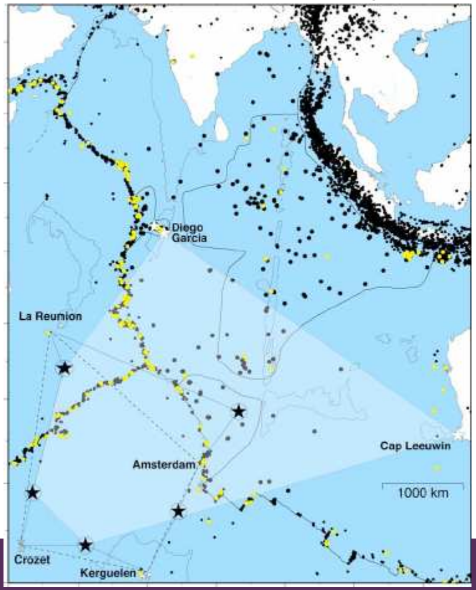
… to marine mammals

Geophony

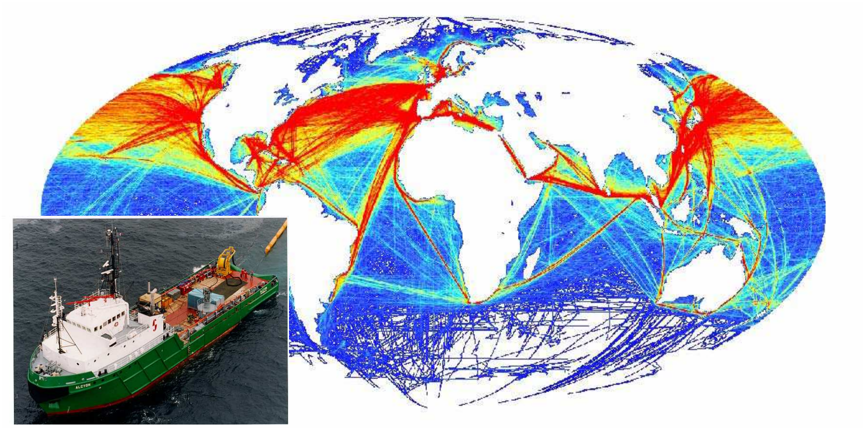
Wind & rain

Sounds of breaking ice

Underwater earthquake



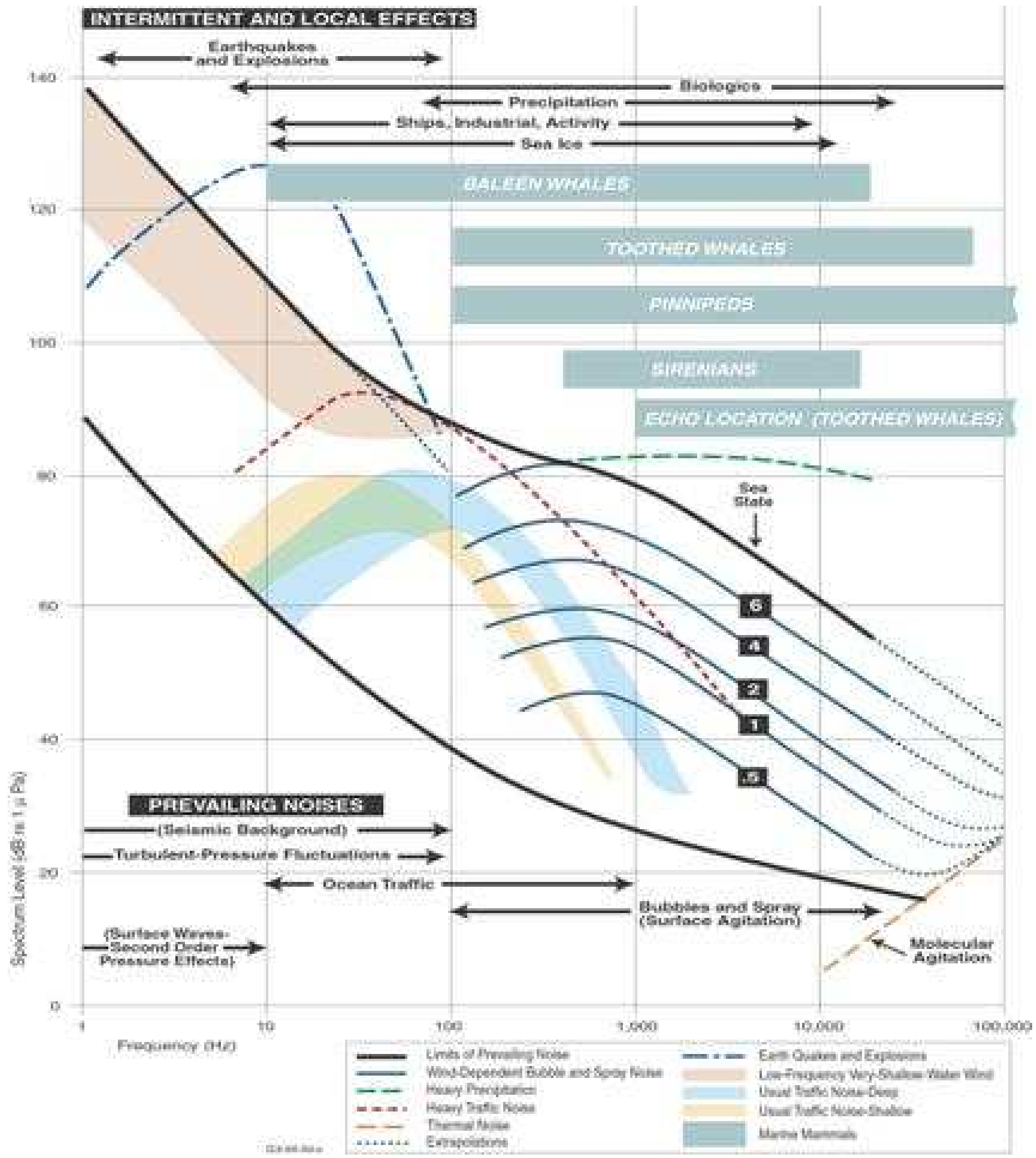
Anthropophony



Sound Levels

Source (SL)	Mesure (RL)
Wideband effective source level (SL), $SL = 10\log_{10}(rl);\ dB\,ref\,1\mu Pa^2\,@1m$ $sl = \frac{1}{T}\int_T m(t)^2\,dt$	Wideband effective received level (RL), $RL = 10\log_{10}(rl);\ dB\,ref\,1\mu Pa^2$ $rl = \frac{1}{T}\int_T m(t)^2\,dt$
Narrowband source level Power spectral density $\gamma_{SL}(f) = dB\,ref\,1\mu Pa^2\,/Hz\,@1m$	Narrowband received level Power spectral density $\gamma_{RL}(f) = dB\,ref\,1\mu Pa^2\,/Hz$
	Sound exposure level (SEL) $SEL = 10\log_{10}(sel);\ dB\,ref\,1\mu Pa^2 s$ $sel = \int_T m(t)^2\,dt$

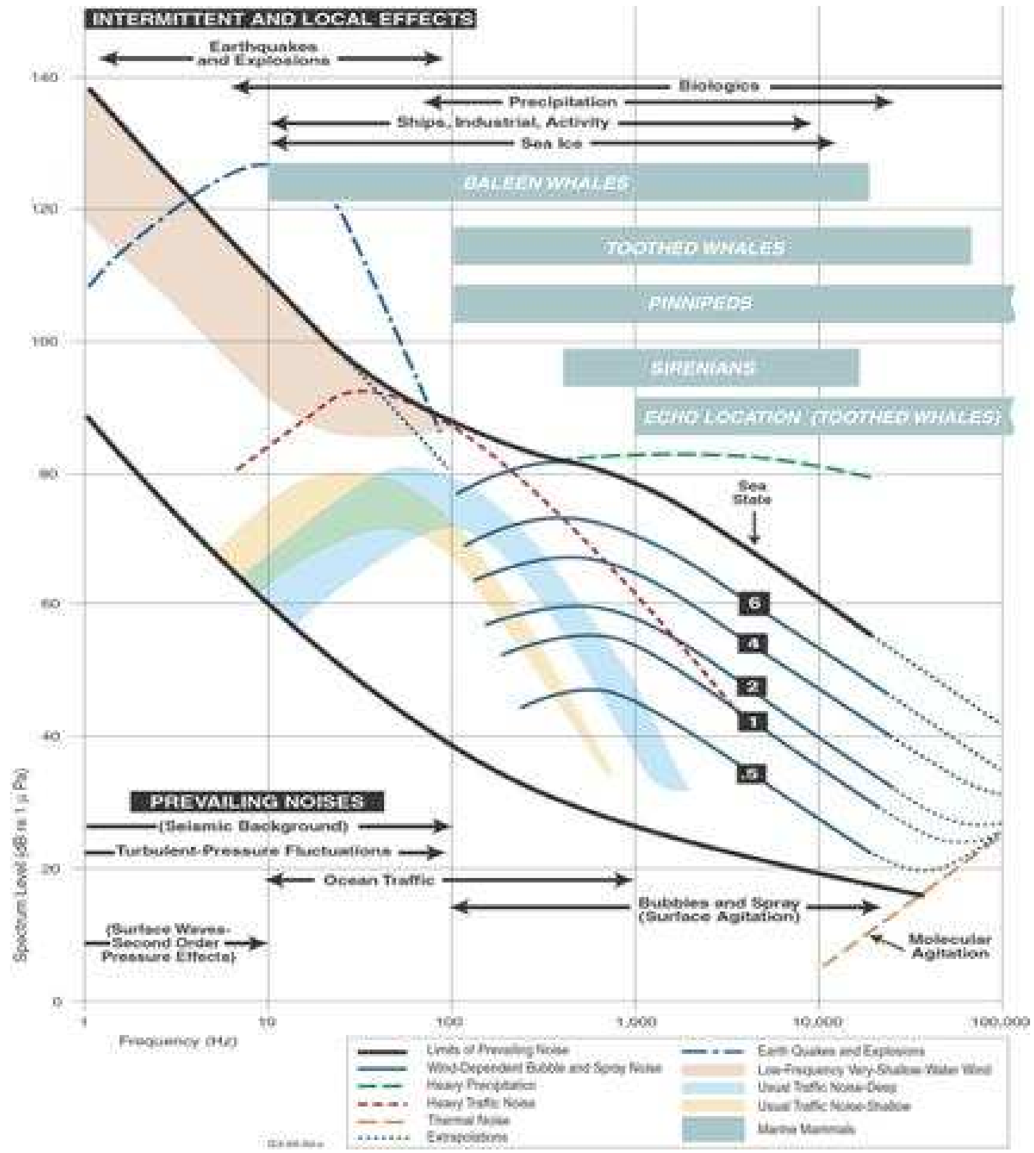
An inventory initatied by 2nd world war and cold war



Source whoi.edu, Wenz 1962, Wenz 1972, Urick 1984

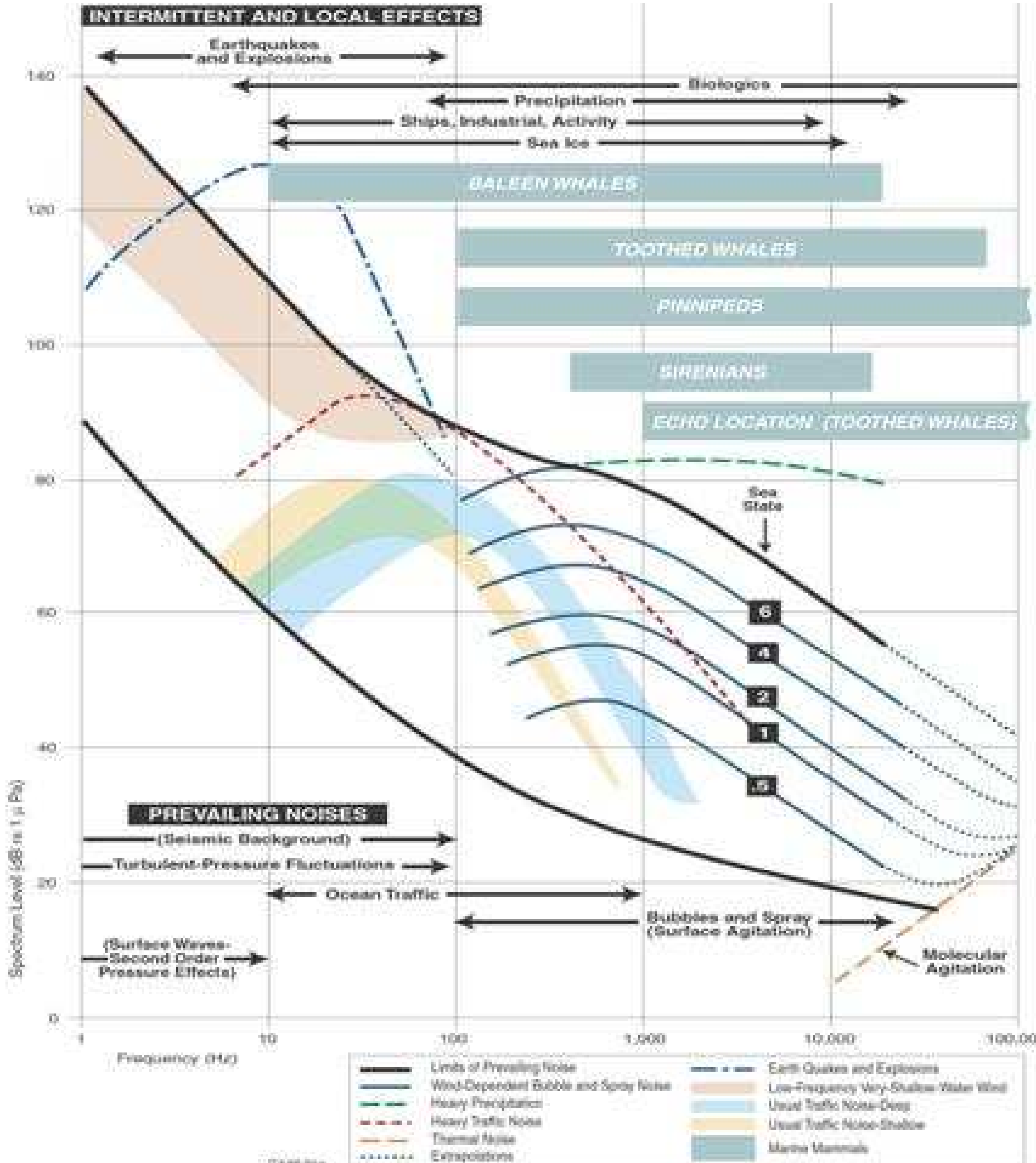
Natural sources
Abiotic
Biotic

Anthropogenic sources

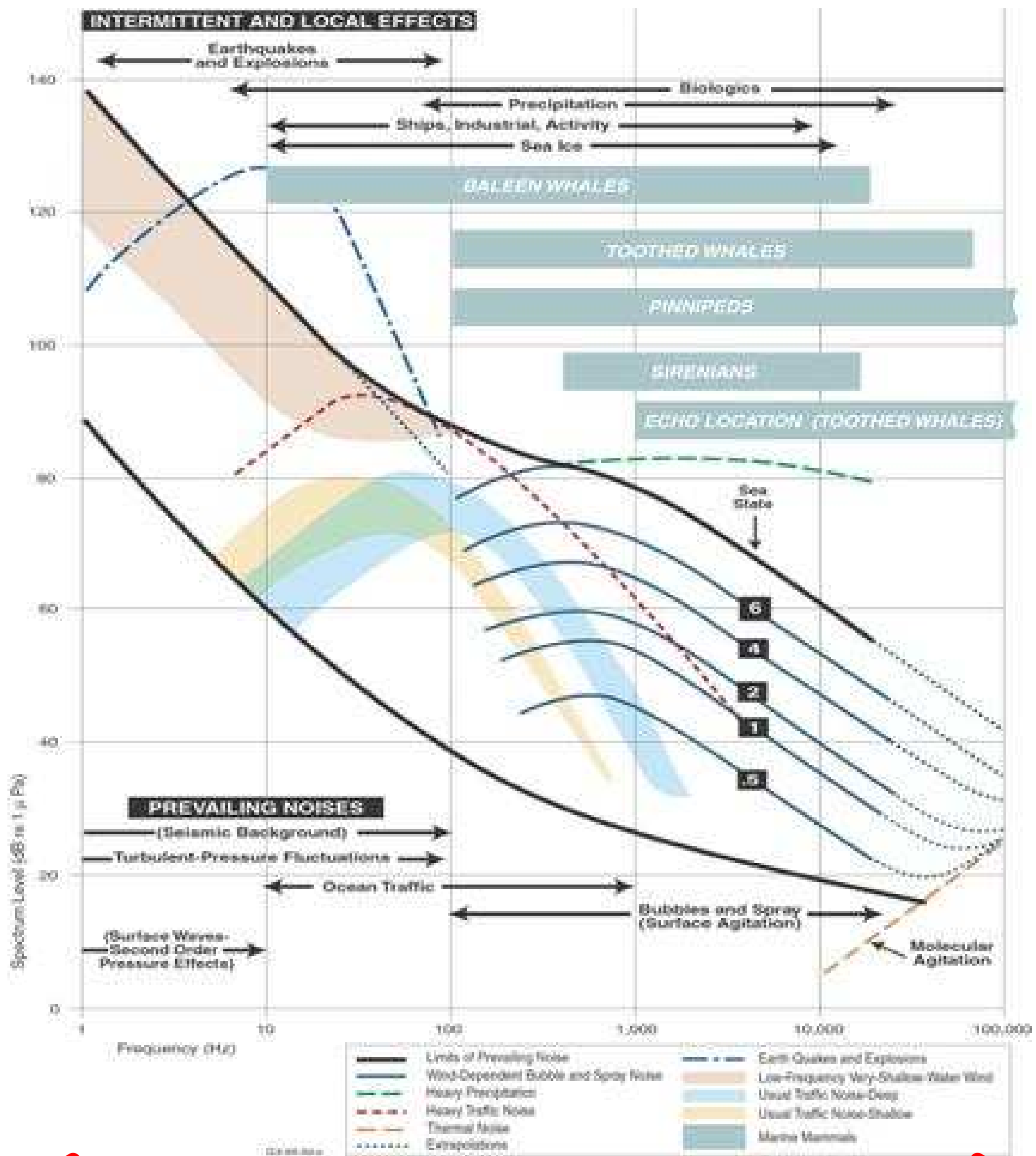


Ambient noise

Background noise from many different sources excluding individually identifiable sounds



Very large amplitude dynamic



Very large frequency dynamic

Hildebrand, J. (2009), 'Anthropogenic and natural sources of ambient noise in the ocean', Marine Ecology Progress Series 395, 5--20.

Wenz, G. (1972), 'Review of underwater acoustics research: Noise', The Journal of the Acoustical Society of America 51, 1010.

Wenz, G. M. (1962), 'Acoustic Ambient Noise in the Ocean: Spectra and Sources', The Journal of the Acoustical Society of America 34(12), 1936-1956.

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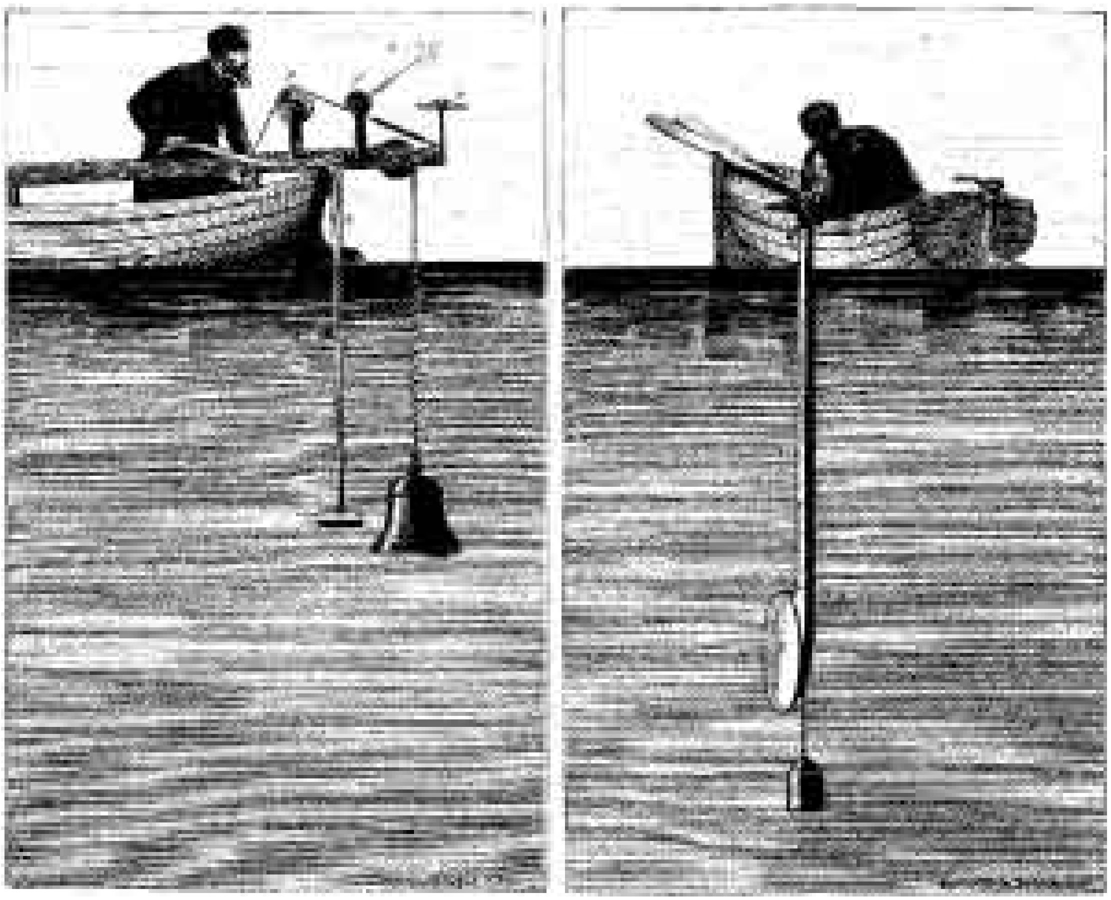
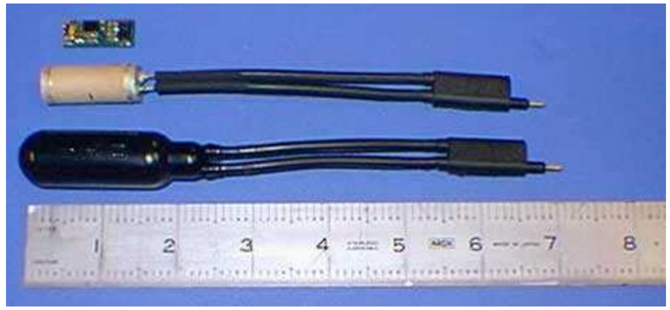
Some measurement devices

10 miles

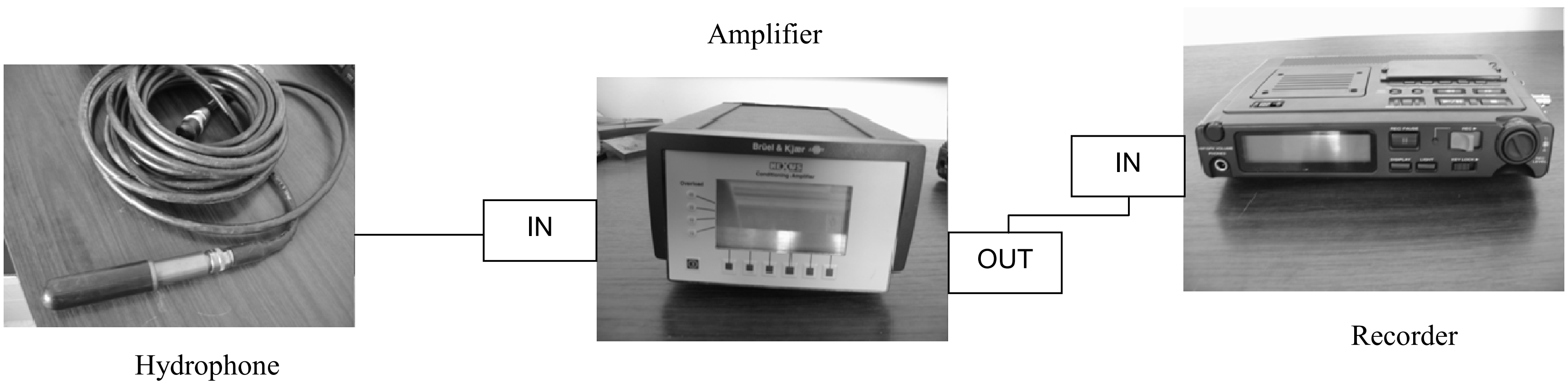


1826, lake of Geneva: Calladon & Strum

Some measurement devices

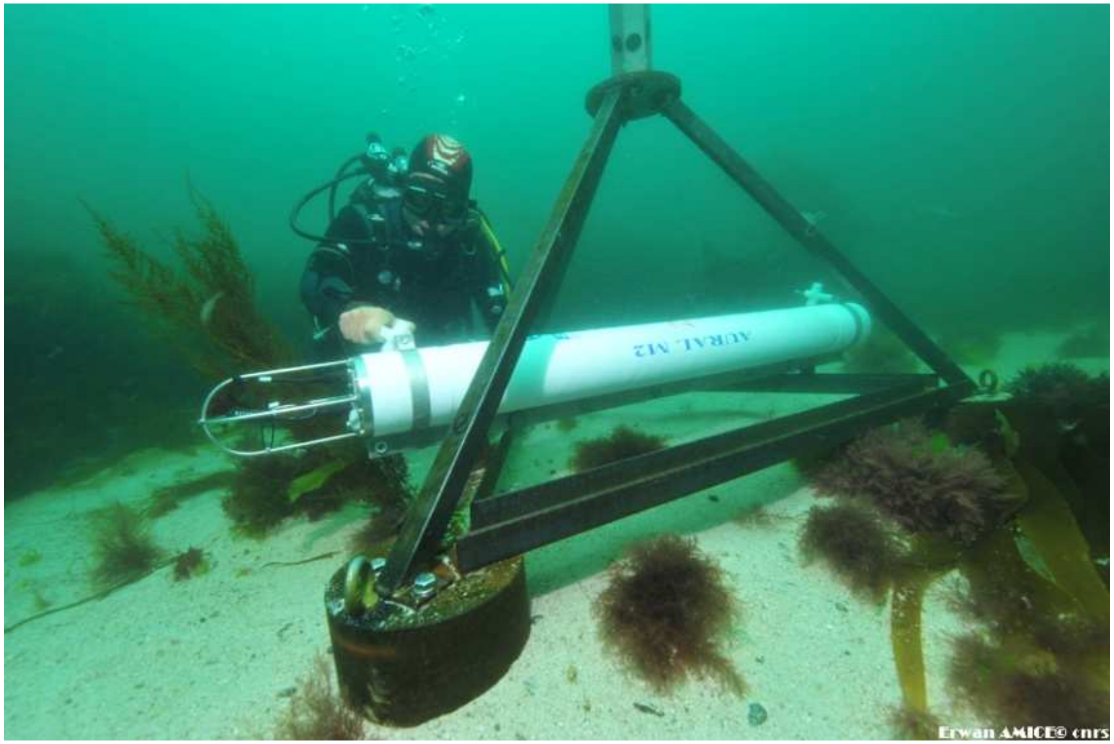


Portable device



Some measurement devices

Autonomous recorders



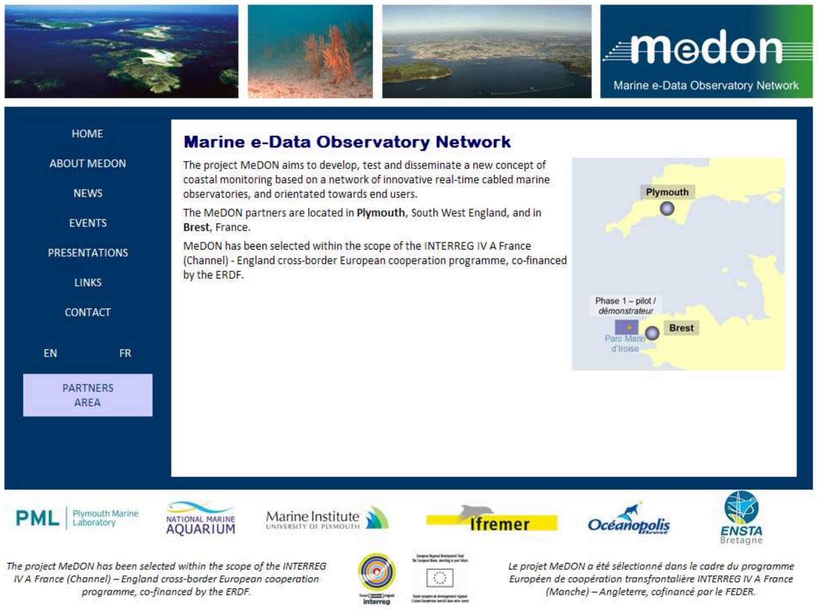
Aural, Multi-Electronique, Qc.

RT SYS, France

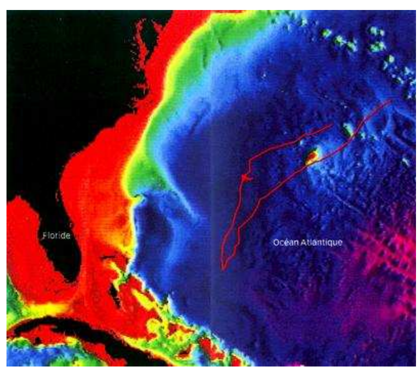
Some measurement devices

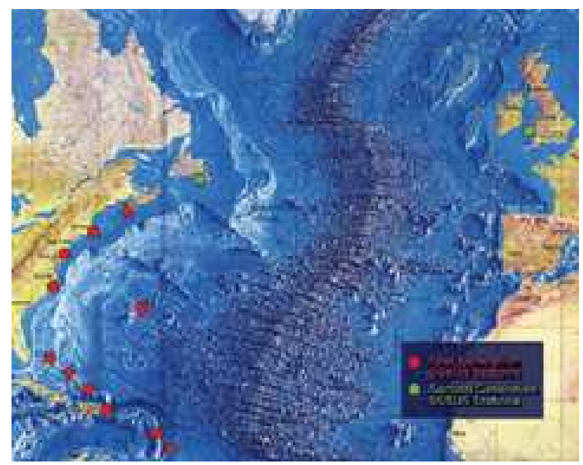
Cabled systems

http://www.medon.info/

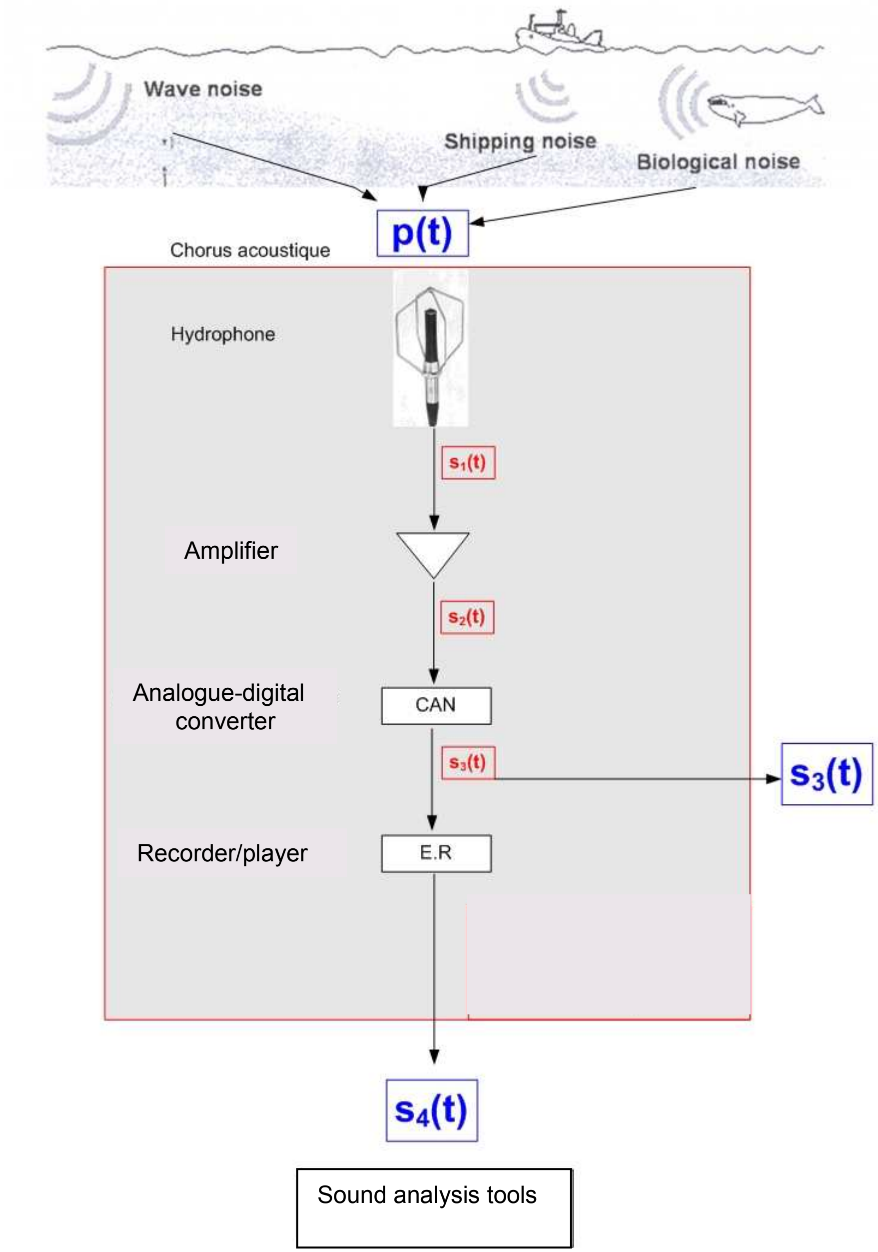


***SO**und **SU**rveillance **S**ystem*





The elements of the acquisition chain



$$|s_1| = 10^{\frac{RS}{20}}|p|$$

$$|s_1|_{dB} = |p|_{dB} + RS$$

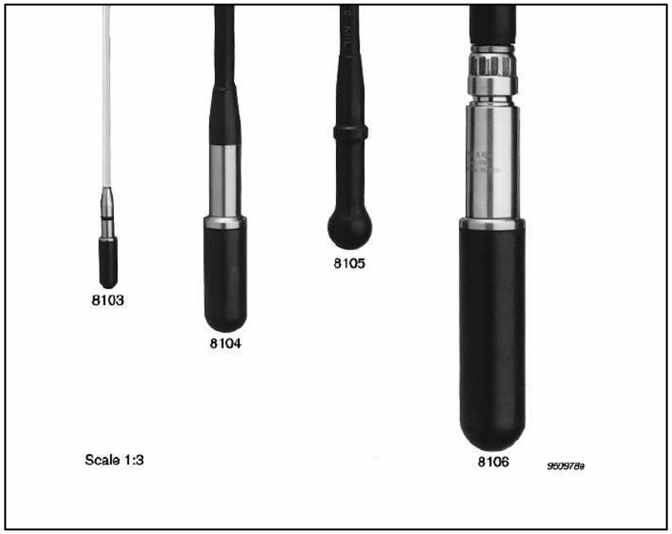
$$|s_2| = 10^{\frac{G}{20}}|s_1|$$

$$|s_2|_{dB} = |s_1|_{dB} + G$$

$$|s_3| = E\left(\frac{|s_2|}{D}2^{nb-1}\right)$$

$$|s_3|_{dB} = |s_2|_{dB} + 20\log 10\left(\frac{2^{nb-1}}{D}\right)$$

Receiver sensitivity



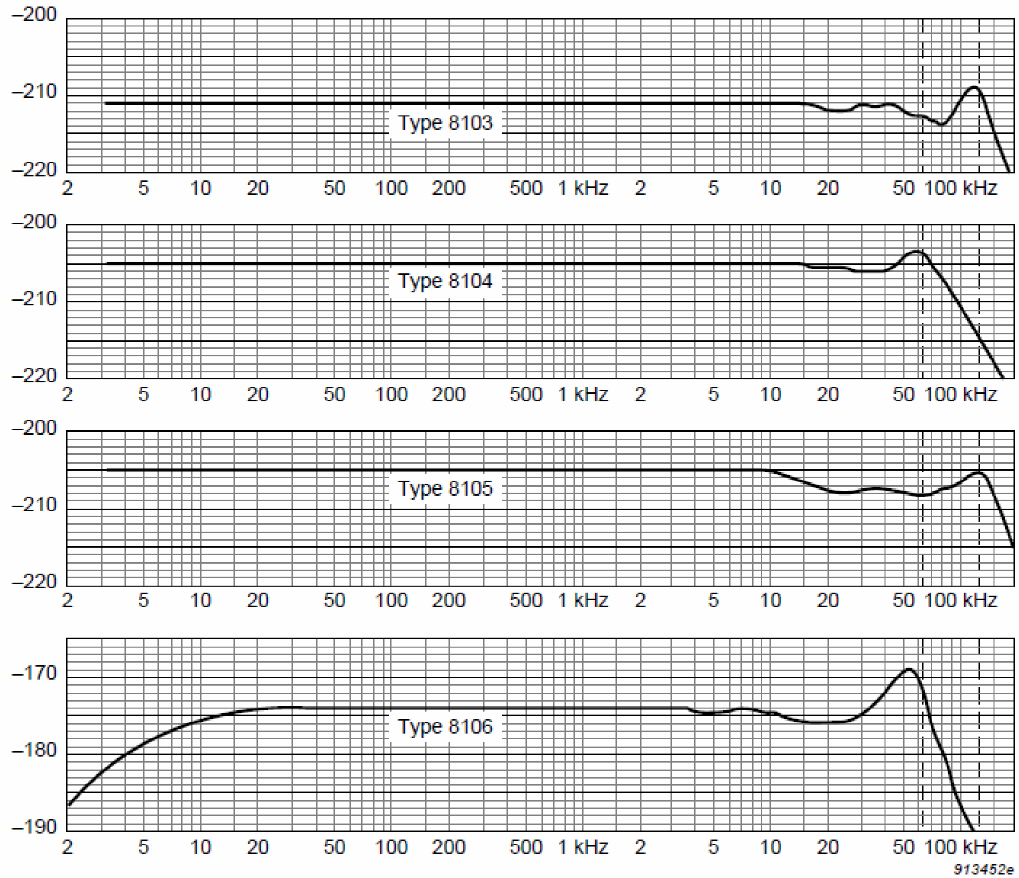


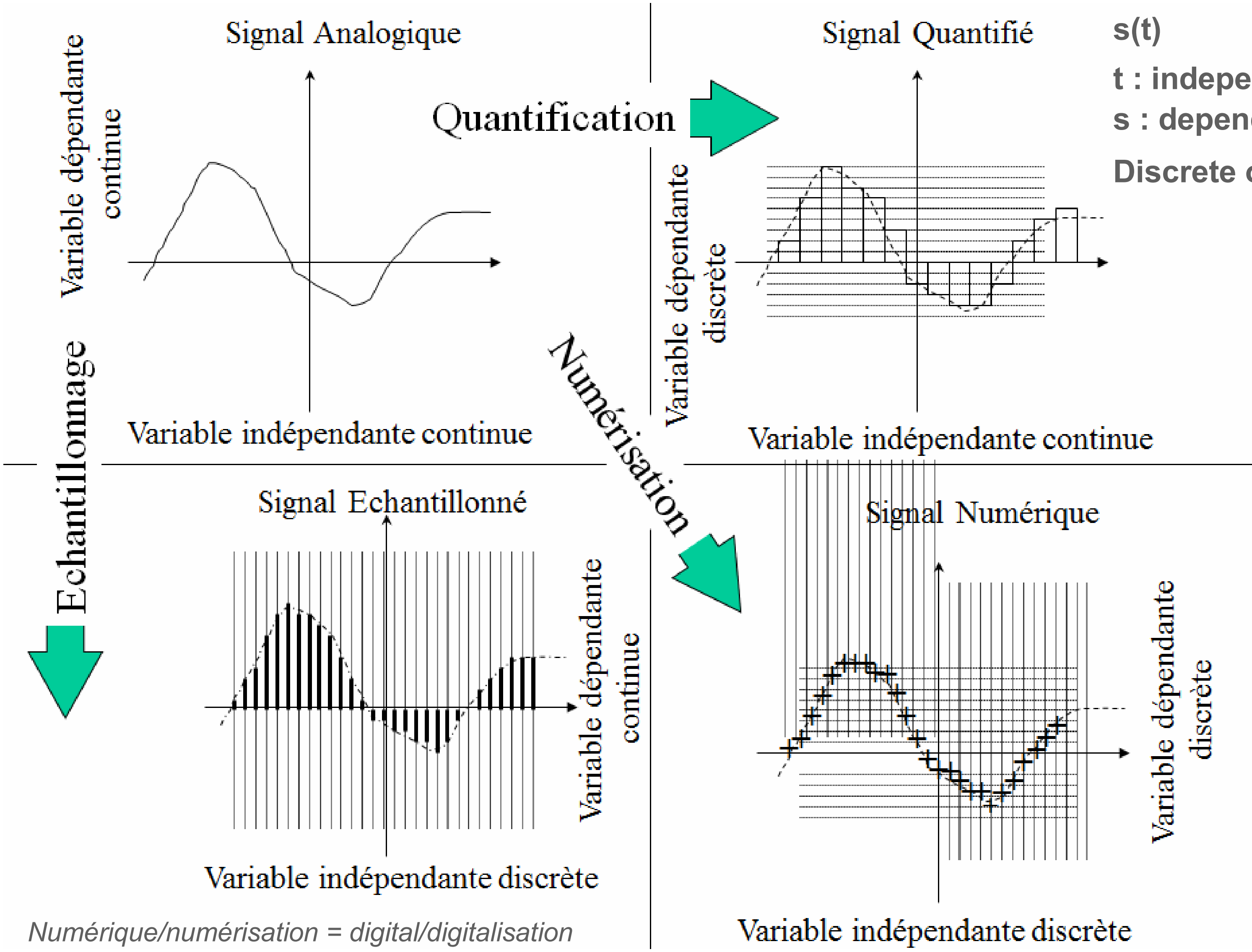
Fig. 5 Typical receiving frequency characteristics of Hydrophones Types 8103, 8104, 8105 and 8106 (dB re 1 V/µPa)

$RS\, dB\ ref\ 1V/1\mu Pa$

A key element : the analogue to digital conversion

It allows the use of digital technology to process the acquired data.

The analogue to digital conversion



s(t)

t : independent variable
s : dependent variable

Discrete or continuous variable

Numérique/numérisation = digital/digitalisation
Echantillonnage = sampling rate

Sampling rate

f_{max} is the maximal frequency of a signal s(t)

only if

$$\forall f > f_{max}, S(f) = 0$$

The sampling of a signal s(t) **is reversible**

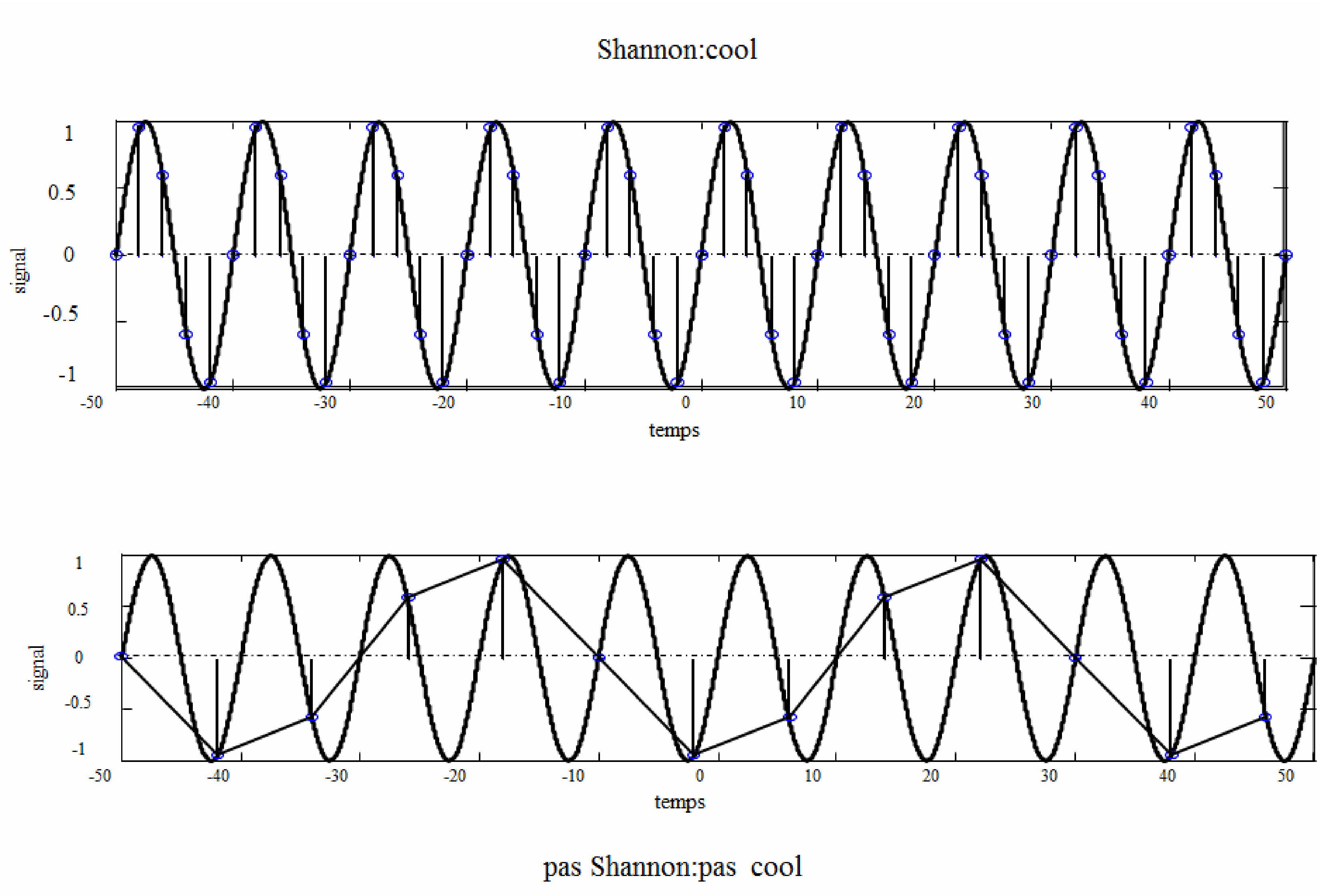
only if

s(t) is low-pass

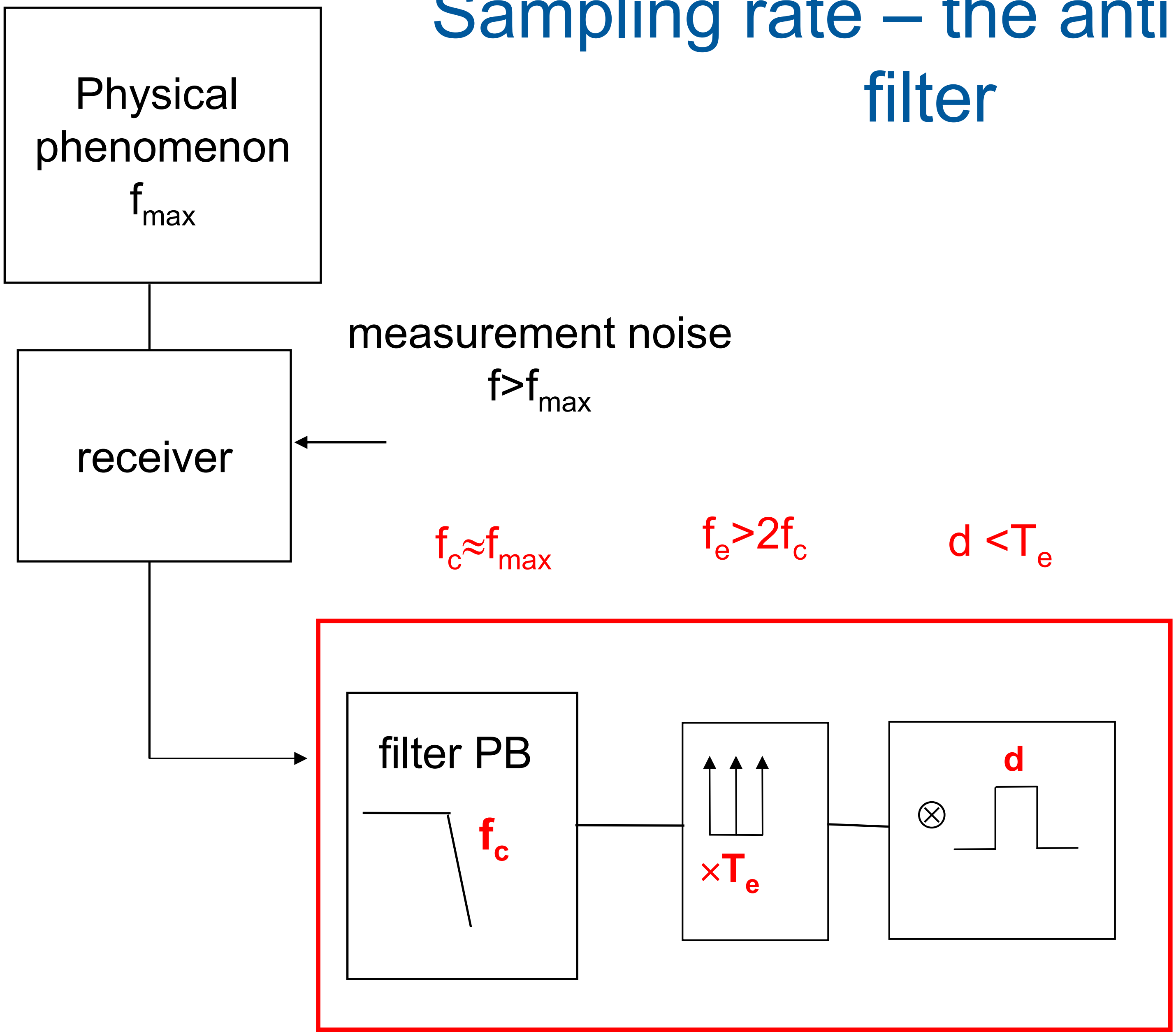
and

$\mathbf{f_e > 2f_{max}}$

Sampling rate



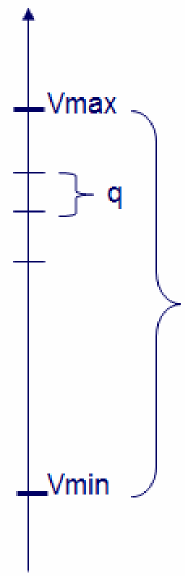
Sampling rate – the anti aliasing filter



Quantification

The 3 key parameters:
- V_{min}
- V_{max}
- **Number of quantification levels N**

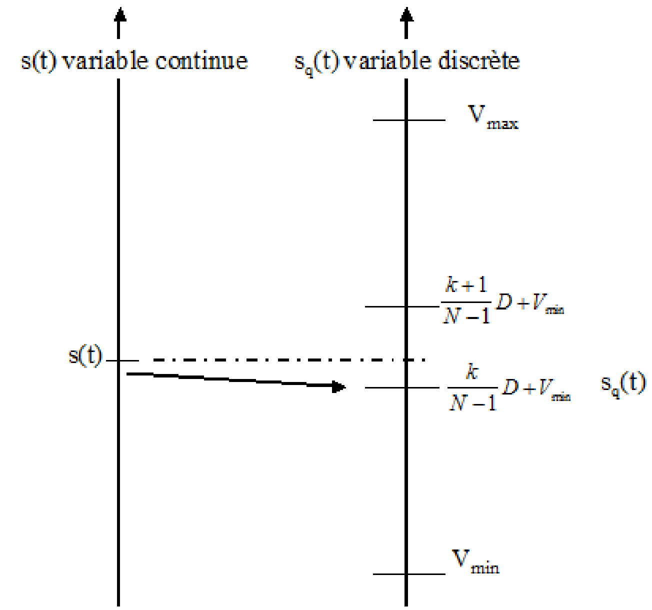
$$E_p = \{V/\exists k \in (0,1,...,N-1), V = \frac{k}{N-1}(Vmax - Vmin) + V_{min}\}$$



D : dynamic range $\quad D = V_{max} - V_{min}$

q : quantification step $\quad q = \frac{Vmax - Vmin}{N-1}$

b : number of bits $\quad N = 2^b$



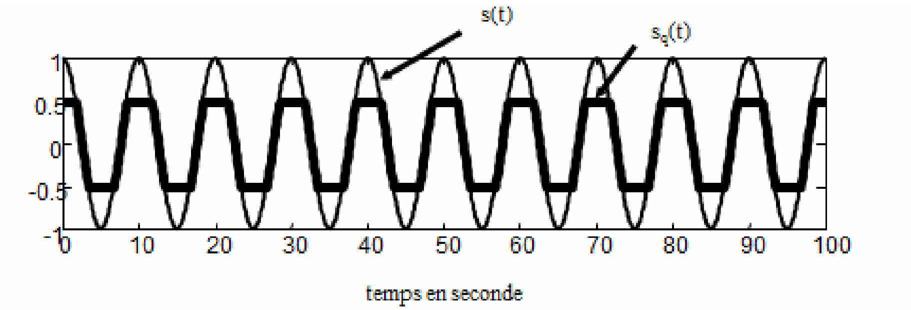
Quantification rule: :

$$s_q(t) = \underset{V \in E_p}{arg\ min} |s(t) - V|$$

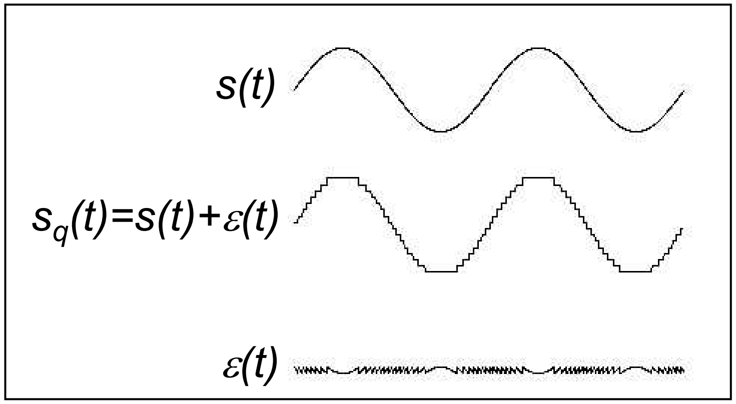
Quantification errors

$$s_q(t) = s(t) + \epsilon(t)$$

Saturation



Discretization



The quantification error **ε : s(t) ∈[Vmin,Vmax]**

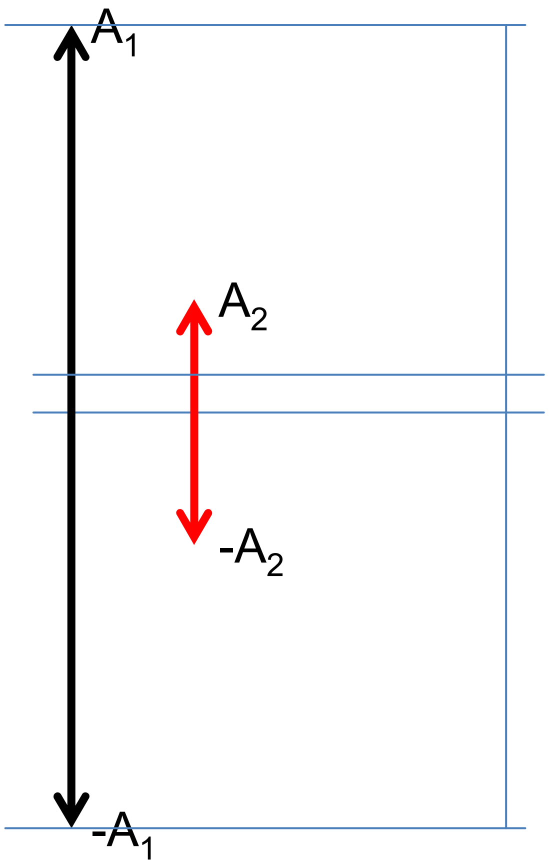
- **ε(t)** limited ∈ **[–q/2, q/2]**
- Evenly distributed over **[–q/2, q/2]**

$$E(\epsilon(t)) = 0 \qquad E(\epsilon^2(t)) = \frac{q^2}{12}$$

- **ε(t)** white noise -> constant spetral component **ıstante** high frequencies

How to set a quantification chain?

Case: need to measure two signals: an intense (amplitude A1) and a low one (amplitude A2)



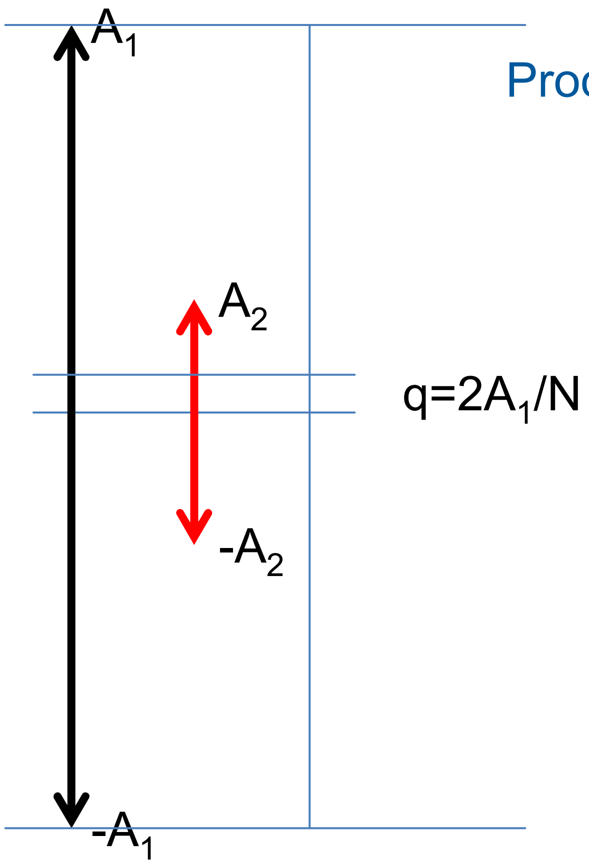
$q=2A_1/N$

Choose Vmin, Vmax, N in order to :

1) Avoid saturation of the intense signal
2) Record the faint signal with a minimal signal to noise ratio (so that it is audible)

Choose Vmin, Vmax, N in order to :

1) Avoid saturation of the intense signal
2) Record the faint signal with a minimal signal to noise ratio (SNR)



N = quantification

Procedure to estimate quantification N

- $V_{max} = -V_{min} = A_1$
- $q = \frac{2A_1}{N}$
- $RSB_2 = \frac{(A_2)^2}{q^2/12}$
- $RSB_2 = 3N^2\frac{(A_2)^2}{(A_1)^2}$
- $RSB_2dB + 10\log10\left(\frac{(A_2)^2}{(A_1)^2}\right) - 10log10(3) = 20\log10(N)$
- $RSB_2dB + 10\log10\left(\frac{(A_2)^2}{(A_1)^2}\right) - 4 = 7\log2(N)$

RSB = SNR

Example

Calculate the parameters of a measurement chain that allows to record dolphin whistles at 1000 meters of the hydrophone and simultaneously ship noise at 100 meters. SNR of dolphin signals = 20dB.

<u>Sampling rate</u>: Low-frequency ship noise, dolphin whistles (frequency range: few kHz to 30 kHz) => f_s > 60kHz; we choose f_s = 96kHz

<u>Quantification:</u>

-Intense signal: shipping noise => (180dB re 1μPa^2/Hz@1m around f_0=50Hz, spherical transmission loss -20log10(f) => 156dB re 1μPa^2

- Faint signal: dolphin whistle => (110 dB re 1μPa@1m, spherical transmission loss) => 50dB.

$20 + 106 - 4 = 7\log2(N) \Rightarrow \log2(N) = 17 \Rightarrow$ 24 bit needed

Outline

- Introduction
- Introduction to sound
- Measurement chain
- Spectral analysis of acoustic measurements
- Time-frequency representation
- Applied examples from our own research

Why ?

Phénomène physique
$\varphi(t)$

↔

Physicien
Expert
Expérimentateur

↔

Diagnostic
Décision
Action

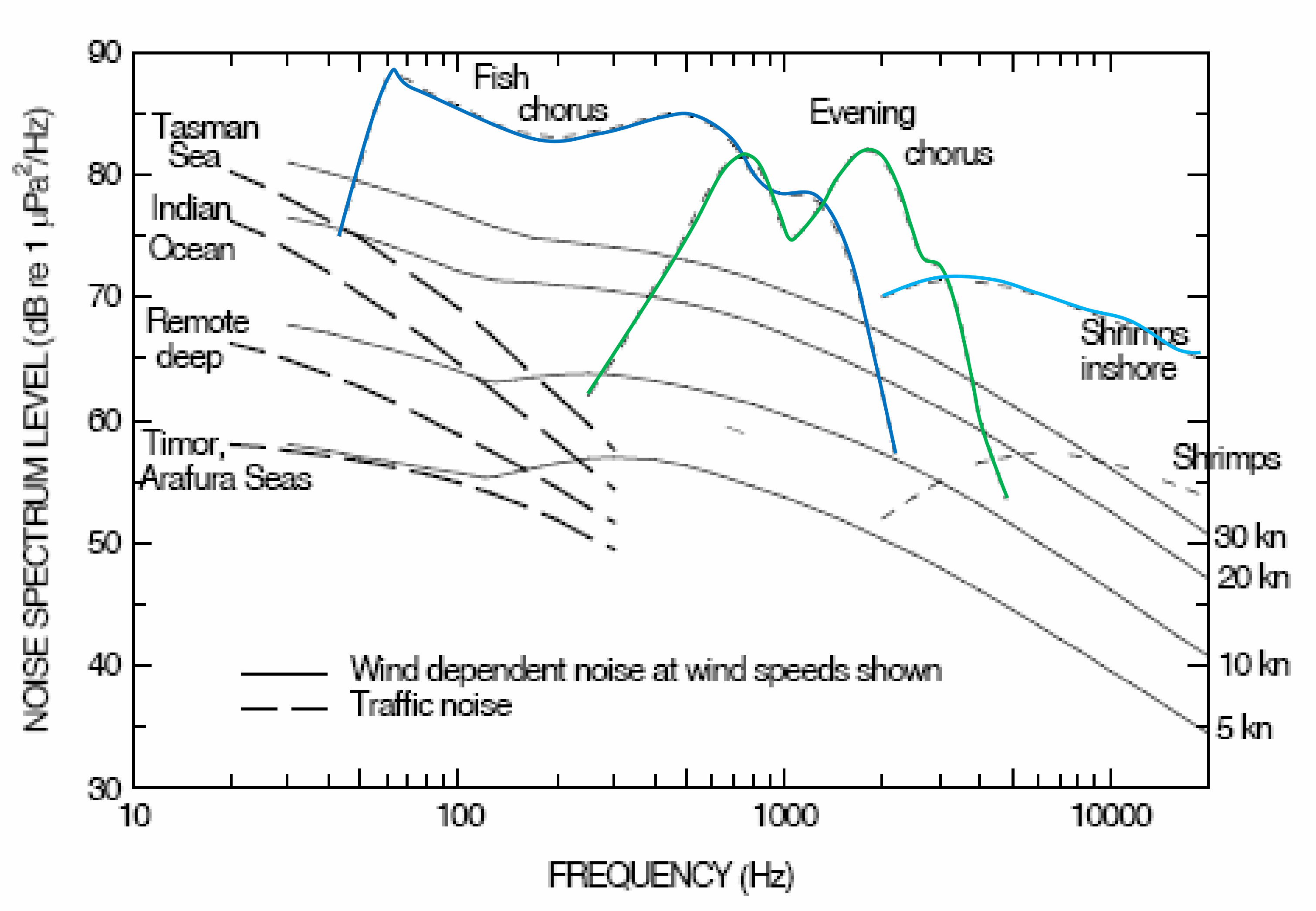
To represent the measurements to a scientist in the best way to understand its information content and to process them adequately.

Spectral analysis

- Frequency : number of repetitions of a phenomenon per second

- The frequency representation (rhythm of the repetitions naturally occurring in the measurement) allows sometimes to better understand the content of acoustic signals

Spectral analysis



Cato 2008, *Proc Inst Acoust*

Spectral analysis

Example: Description of the conent of a mailing box (L. Di Iorio)

Introduction to Fourier analysis

Temporal represenation

Mon	Tue	Wed	Thu	Fry	Sat	Sun	Mon	Tue	Wed
J	J	J	J	J+TV	J	J	J	J	J

Frequency represenation

amplitude

frequency

1 daily newspaper J (1/day) at 8 am

phase

\+

1 newspaper with a weekly TV magazine (1/7 days) at 8am every friday

How ? Easy

-cos(2πf_0t), sin(2πf_0t), exp(j2πf_0t) contain only the frequency f_0 !

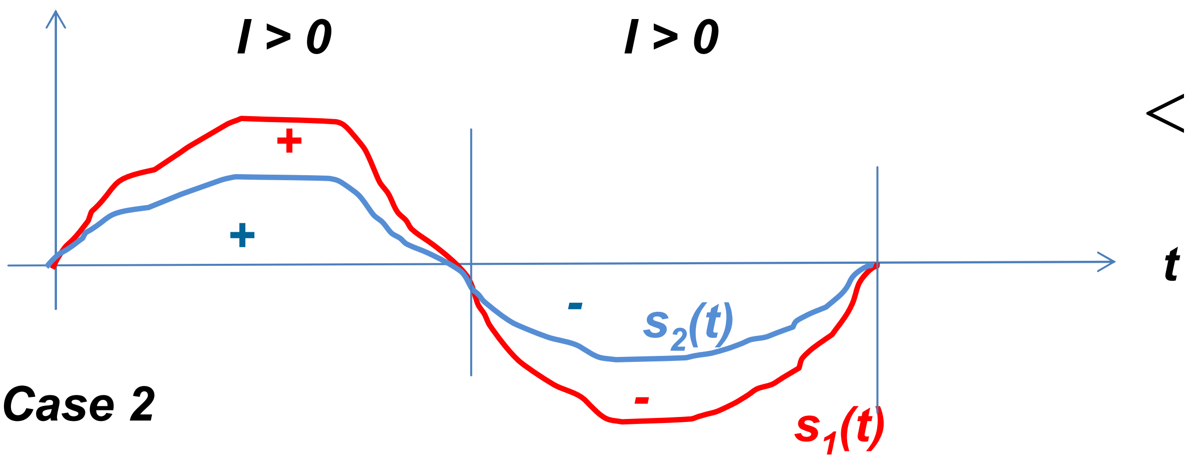
- ***s(t) contains the frequency f_0 if it looks like cos(2πf_0t), sin(2πf_0t), exp(j2πf_0t) !***

- ***s_1(t) looks like s_2(t) if their scalar products is high. (Linear Algebra)***

$$< s_1(t), s_2(t) > = \int s_1(t) s_2^*(t) dt$$

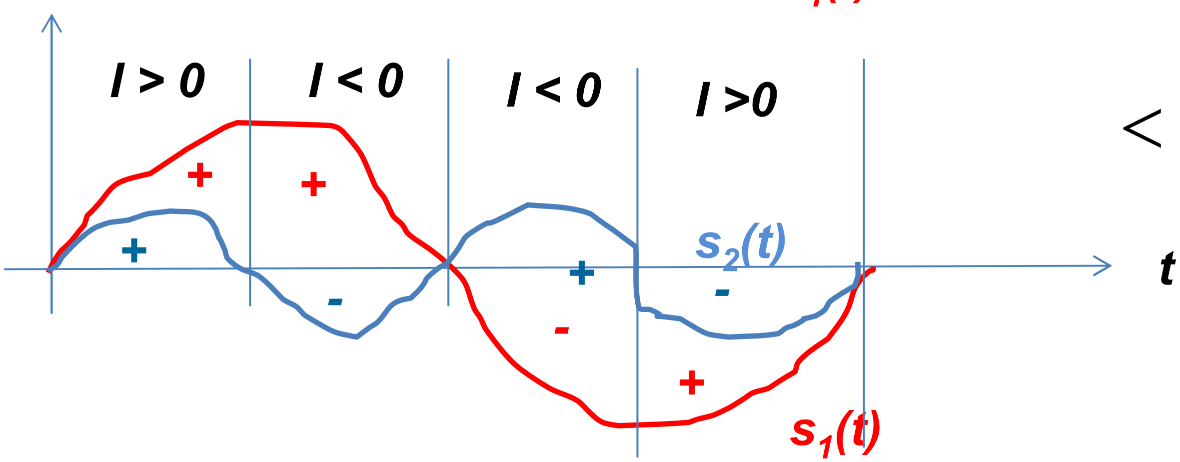
$$< s_1(t), s_2(t) >= \int s_1(t) s_2^*(t) dt$$

Case 1



$$< s_1(t), s_2(t) > \;\; > 0$$

Case 2



$$< s_1(t), s_2(t) > \;\; \approx 0$$

How ?

Analogue signal: Fourier transform (FT)

$s(t), t \in]-\infty, \infty[$ $$S(f) = \int_{-\infty}^{+\infty} s(t)\exp(-2\pi f t)dt$$

Digital signal: Fourier transform via Fast FT (FFT)

$s(n)\ n \in \{1,..,N\}$

$$DFTS(m) = \sum_{n=0}^{N-1} s(n)\exp(-2\pi j\frac{n \times m}{N})$$

$$= \sum_{n=0}^{N-1} s(n) \times W_N^{n \times m}$$

avec $W_N = \exp(-\frac{2\pi j}{N})$

How ?

For digital signals: the discrete Fourier transform (DFT) can be implemented real-time! through the FFT algorithm (of N^2 operations at Nlog2(N)

$s(nT_e), n \in [0, N-1]$

$N = 2^M$

DFTS

FFT

$DFTS(m), m \in [0, N-1]$

$N = 2^M$

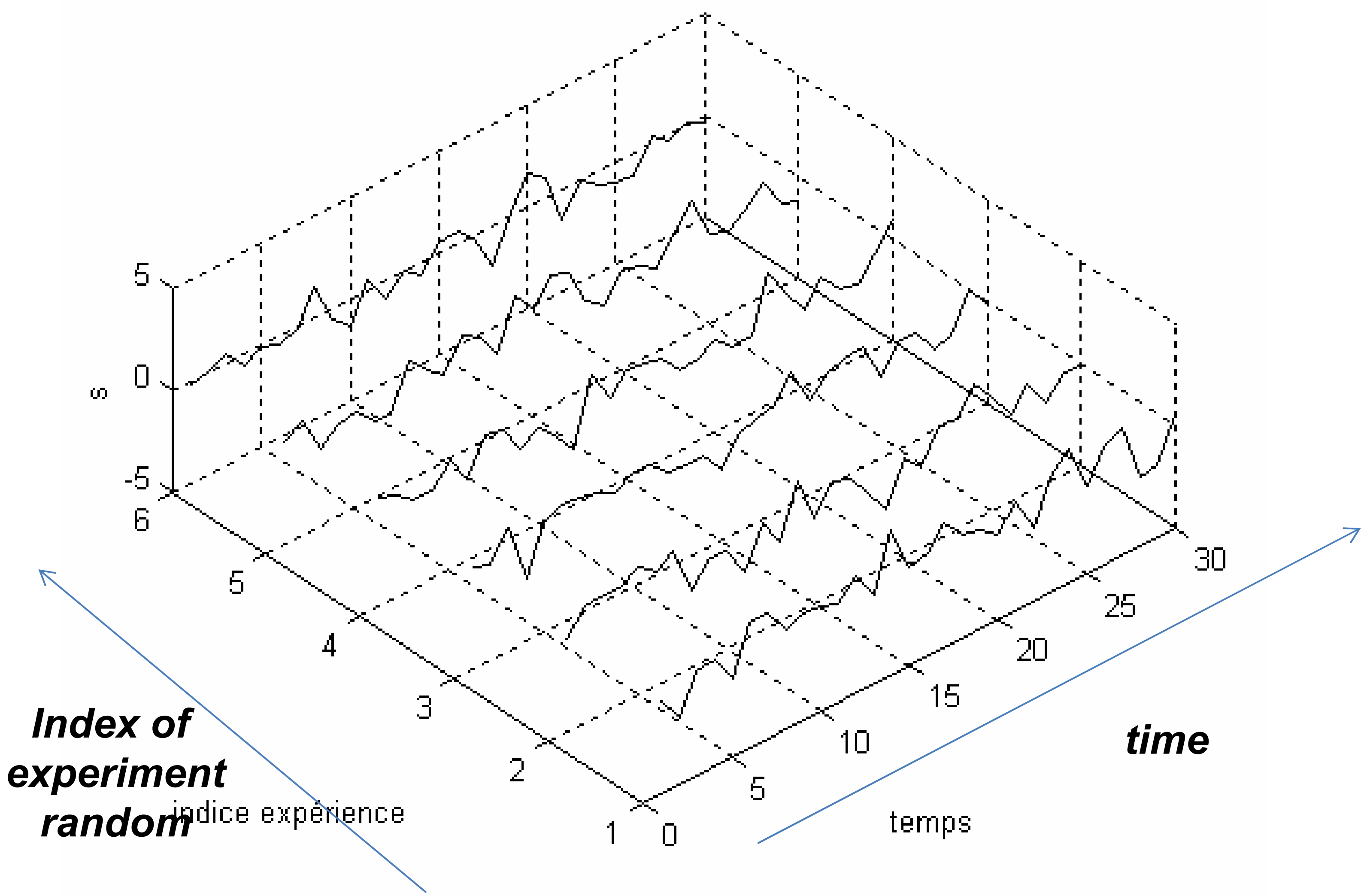
$$\left\{ f_m = \frac{mf_e}{N}, m \in [0,..,N-1] \right\}$$

$$\hat{S}(f = m\frac{f_e}{N}) = DFTS(m) = S_e^N(f_m) \approx ou \neq S(f = m\frac{f_e}{N})$$

The case of random signals

- A random signal depends on time and hazard ε.
- Two recordings carried out within exactly the same conditions produce different measurements.
- $m(t,\varepsilon)$

s(t,ξ) !!!!!!!



5
0
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s
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5
4
3
2
1
0
5
10
15
20
25
30
indice expérience
temps
Index of experiment random
time

The case of random signals

- For random signals, the Fourier transform cannot be applied directly!

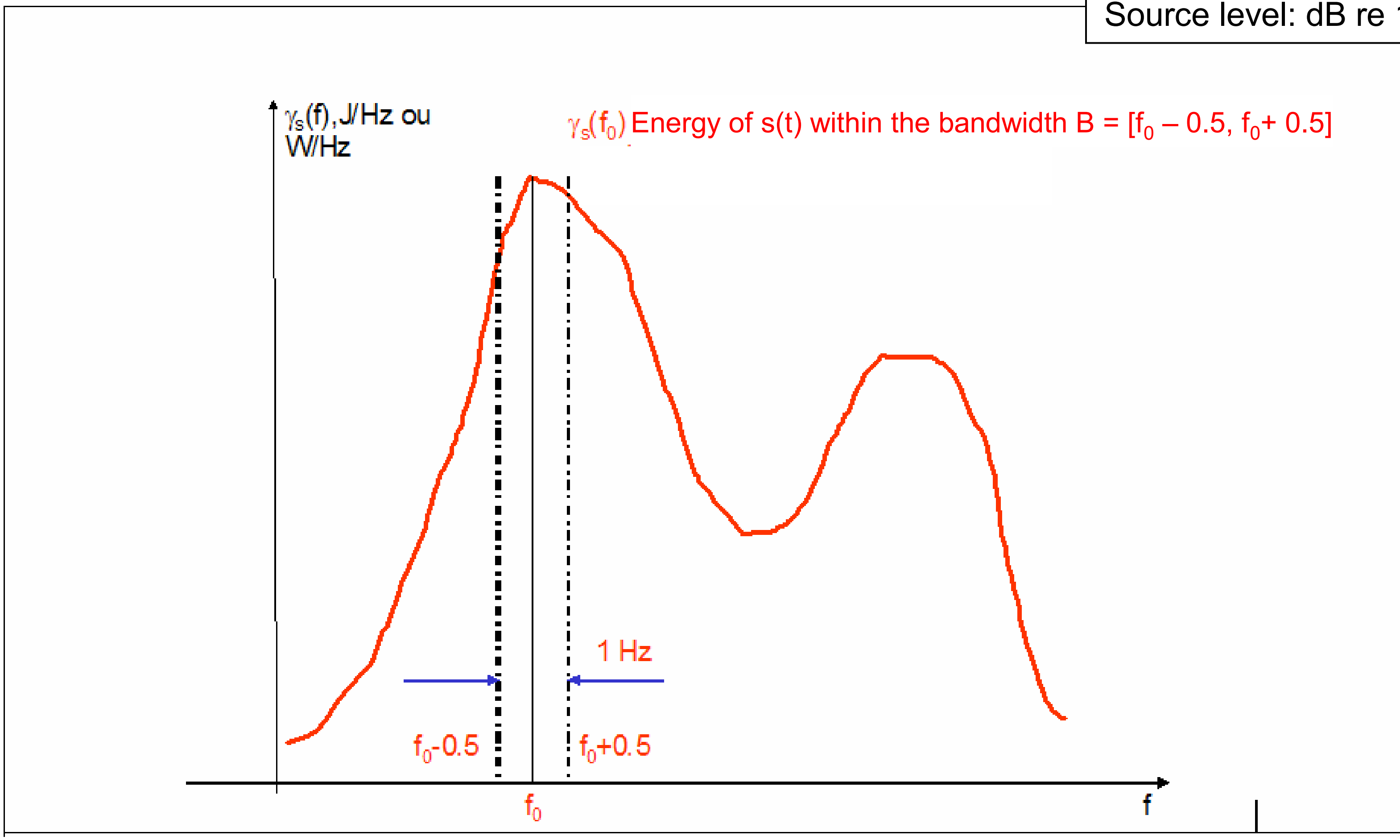
Analogue signals : Fourier Transform

$$s(t), t \in]-\infty, \infty[\qquad S(f) = \int_{-\infty}^{+\infty} s(t)\exp(-2\pi f t)dt$$

For random signals we estimate the power spectral density

= frequency distribution of the power of a random signal

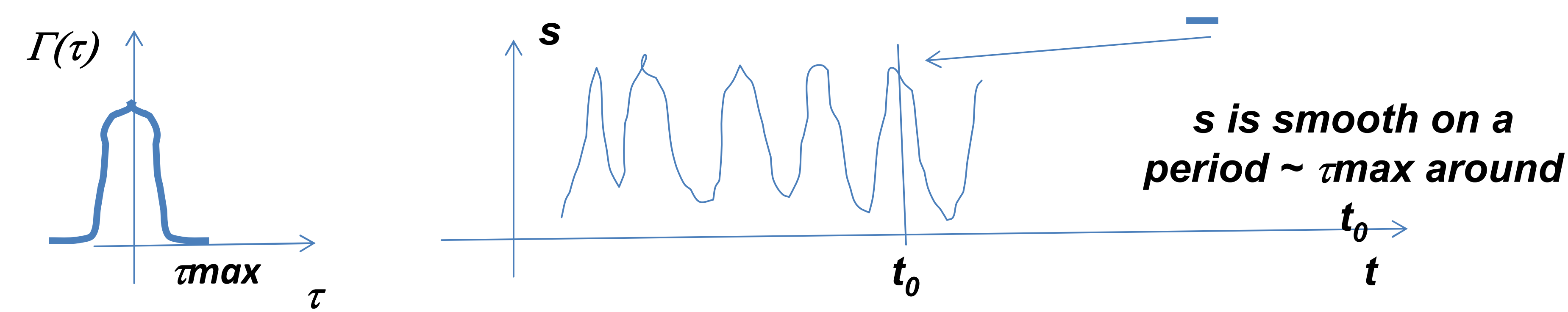
Received level : dB re 1μPa²/Hz
Source level: dB re 1μPa²/Hz@1m



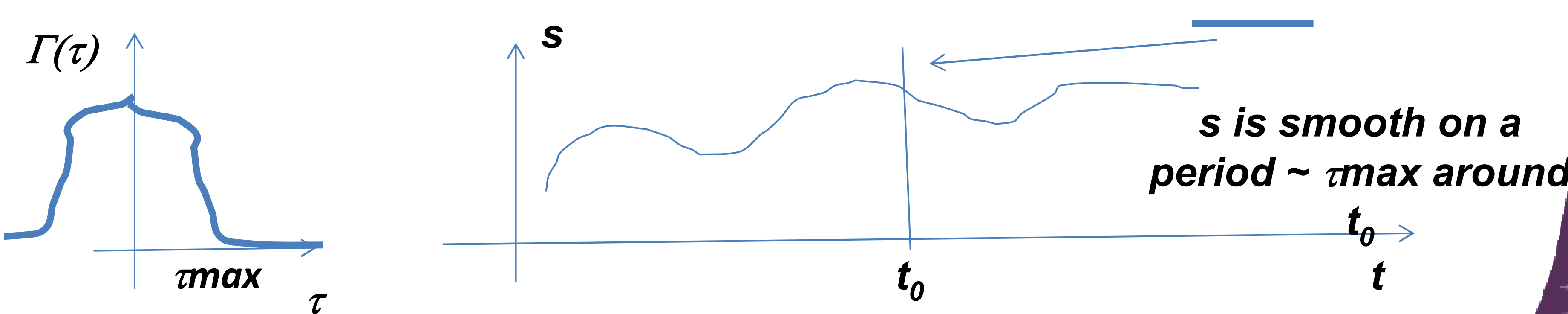
A tool for power spectral density estimation: the autocorrelation function

$$\Gamma_s(\tau) = < s(t), s(t-\tau) >$$

Case 1



Case 2



Γs(τ) commands the dynamic of variation of s(t)
Fast variation : high frequency
Slow variation : low frequency

Autocorrelation function

$$\Gamma_s(\tau) = < s(t), s(t-\tau) >$$ Autocorrelation function

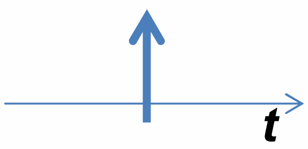
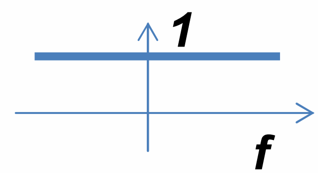
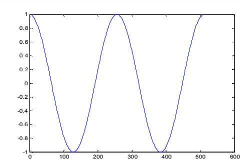
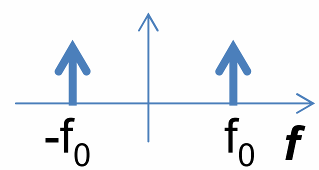
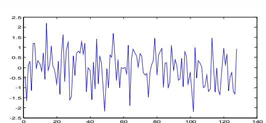
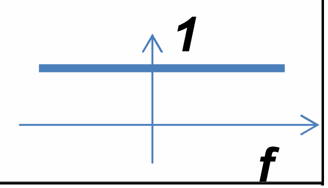
$$= \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} s(t)s(t-\tau)dt$$ For Deterministic signals

$$= E(s(t_0,\xi)s(t_0-\tau,\xi))$$ For random signals S.O2

$$\gamma_s(f) = F(\Gamma_s(\tau)); (V^2/Hz)$$ Power spectral density

$$= \lim_{T\to\infty} \frac{1}{T} |S_T(f)|^2$$ For Deterministic signals

Fourier transform of ‘classical’ signals

	s(t)	S(f)	
	$\delta(t)$	$\Delta(f) = 1 \forall f$	
	$cos(2\pi f_0 t)$	$C(f) =$ $0{,}5\delta(f - f_0)$ $+0{,}5\delta(f + f_0)$	
	$bb(t, \epsilon)$ $\gamma(\tau) = \delta(\tau)$	$\gamma(f) = 1 \forall f$	

The use of a PC to apply the theory to real measures

Analogue signal with infinite temporal domain
and infinite number of experiences

$$s(t,\varepsilon),\ t \in \left]-\infty,+\infty\right[$$

$$(f) = \int_{-\infty}^{+\infty} s(t)\exp(-2\pi j f t)dt$$

Signal
carrying the entire information
not usable

Spectrum carrying information

$$S(f)$$

Physical
phenomenon
inducing a
magnitude to
change s(t)

$$\hat{S}(f) \overset{?}{=} S(f)$$

Digital signal with finite temporal domain and
one experience

$$s(nT_e,\varepsilon_1),\ n \in [0, N-1]$$

$$\hat{S}(f)$$

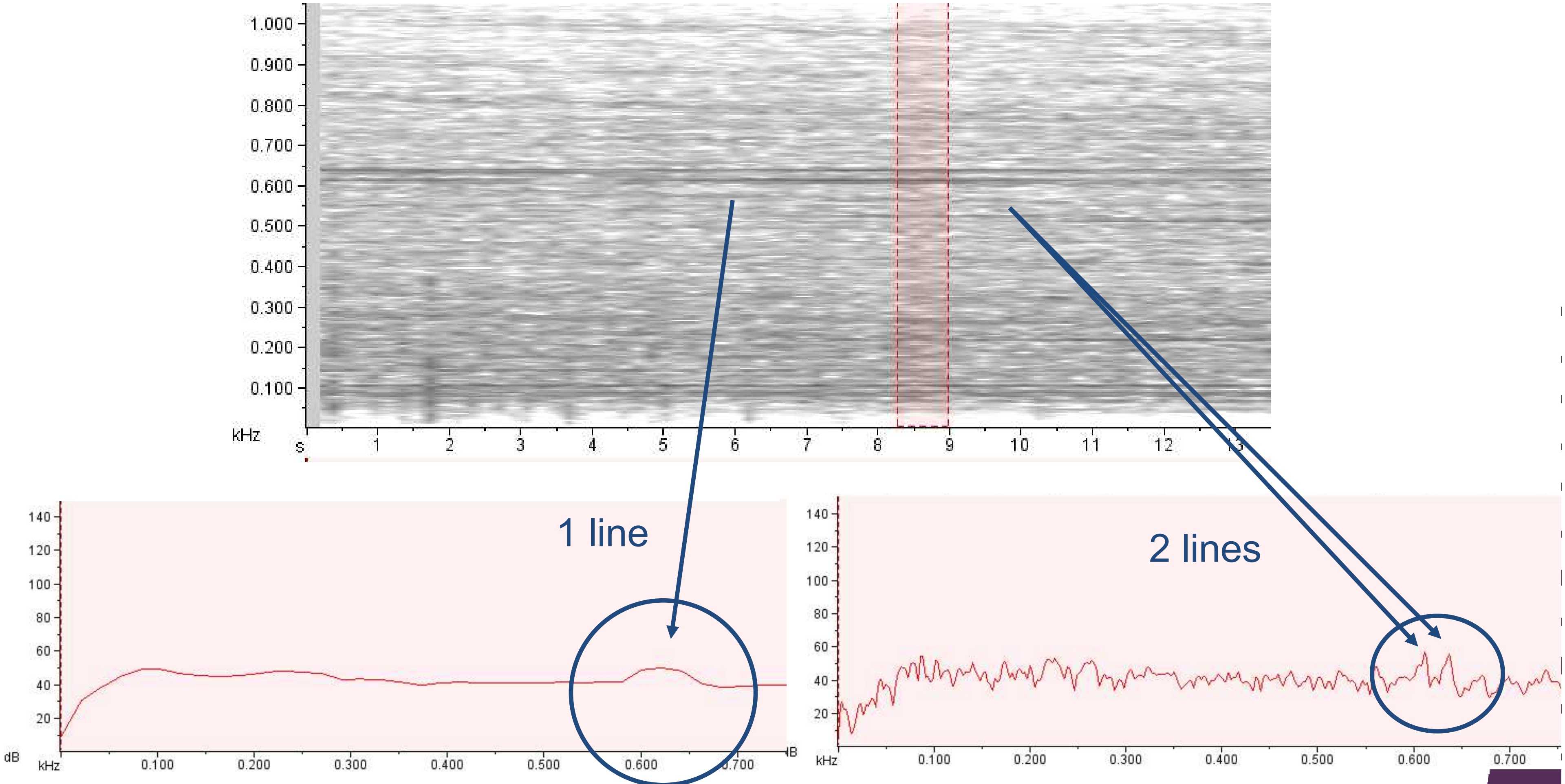
Signal
not carrying the entire information
usable

$$\hat{S}(f) = \sum_{n=0}^{N-1} s(nT_e)\exp(-2\pi j f n T_e)$$

Frequency resolution

How many propellers, blades ?
Which states ?

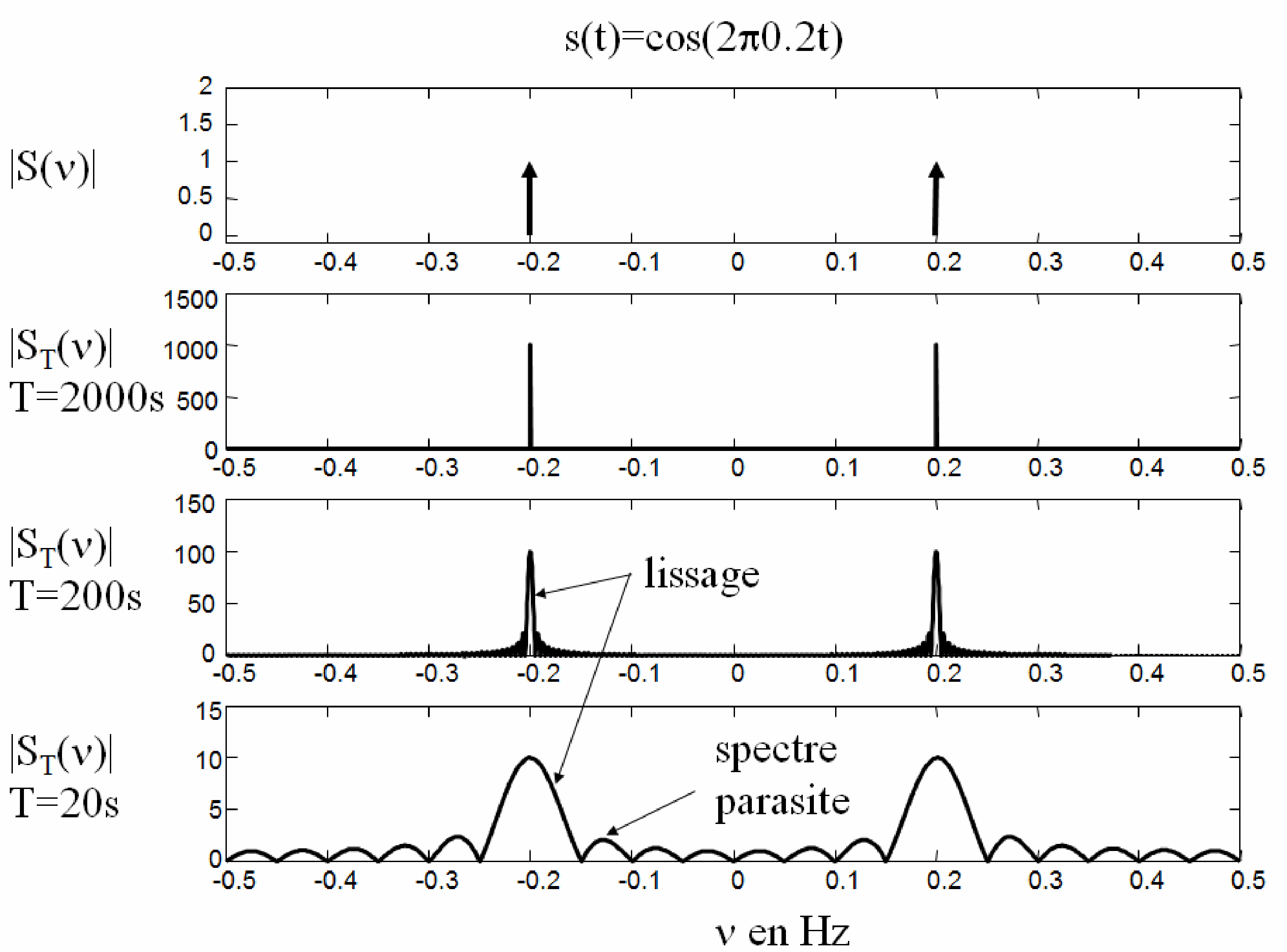
Frequency resolution



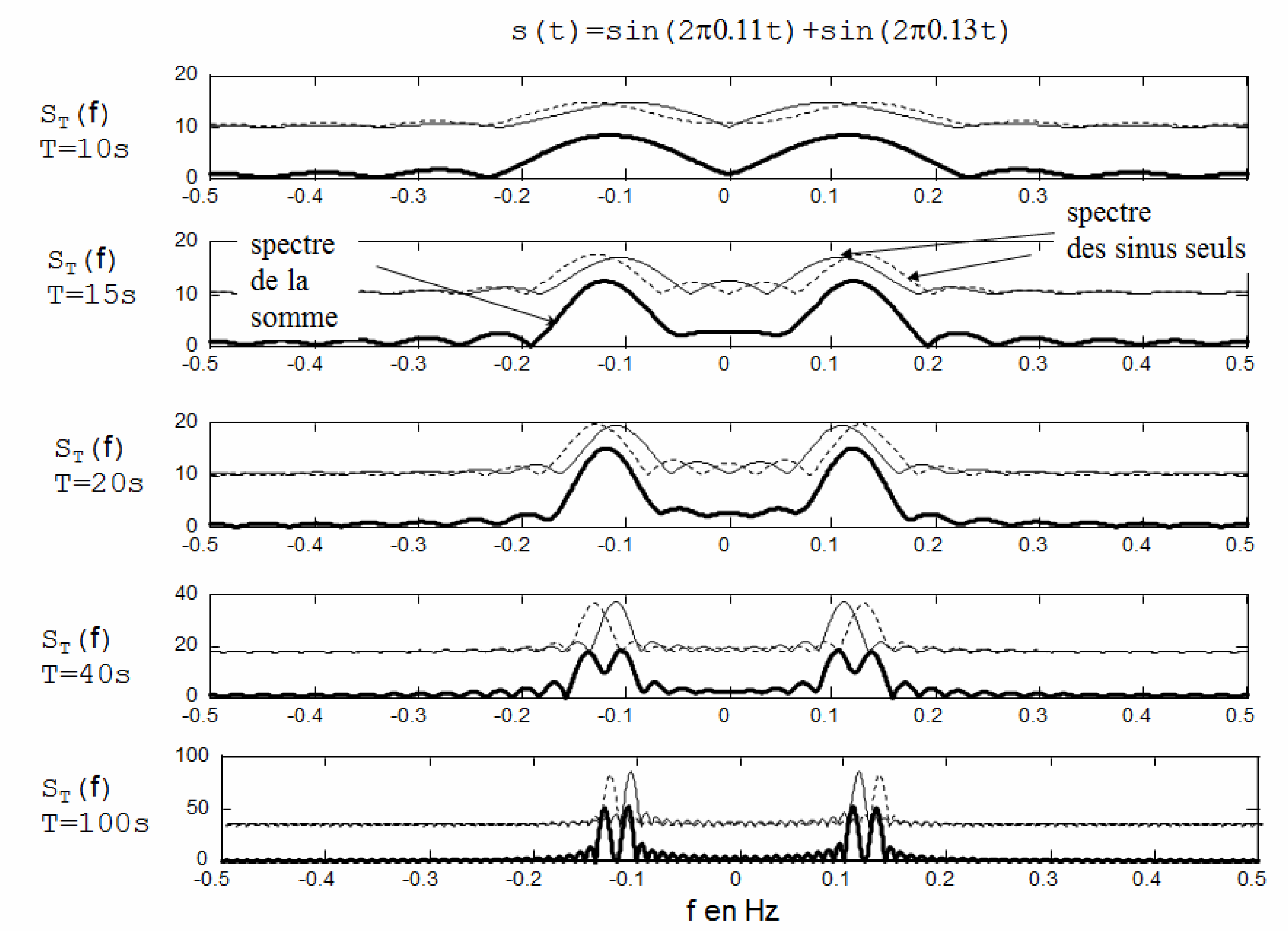
‚bad‘ frequency resolution: „ lines „blured“

‚good‘ frequency resolution: 2 lines

FFT errors: The frequency resolution – separation of two close frequencies



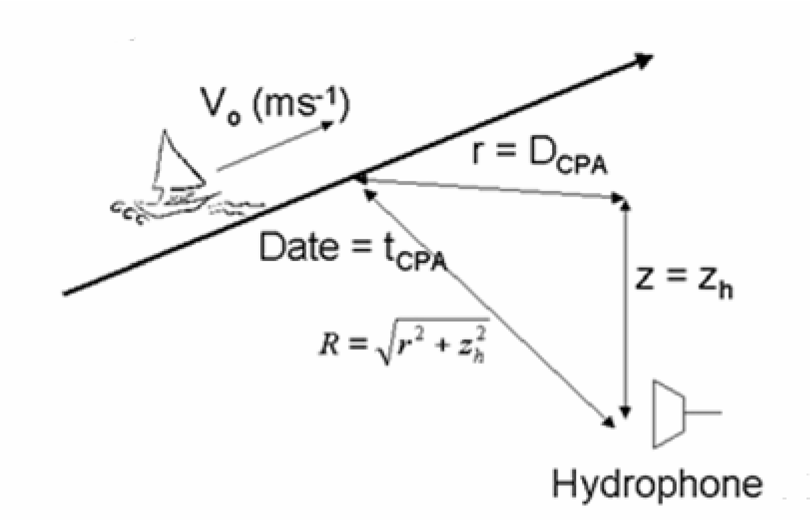
FFT errors: The frequency resolution – separation of two close frequencies



FFT errors: The frequency resolution – separation of two close frequencies

Frequency resolution is the ability to distinguish the presence of two components of similar frequencies

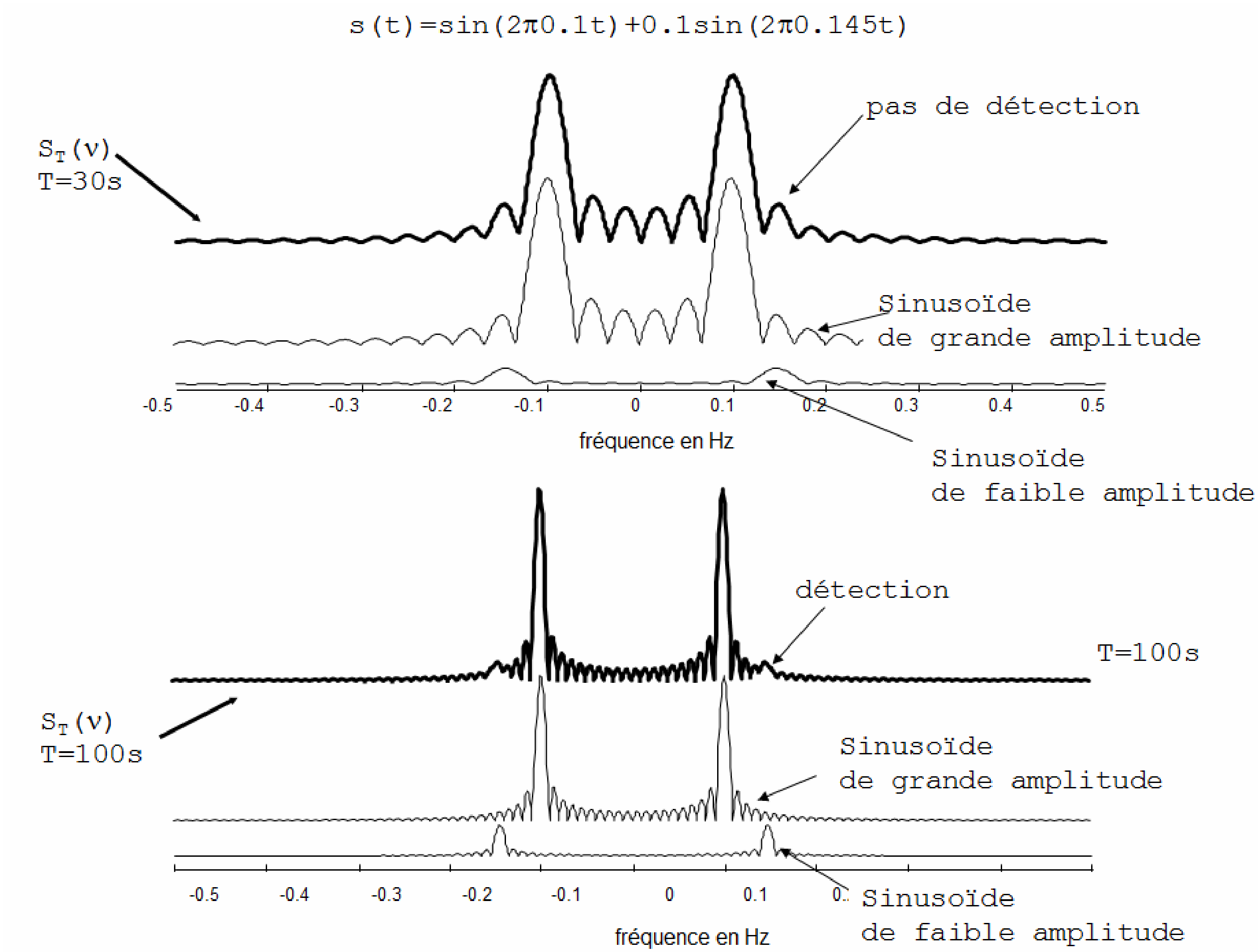
$$frequency\ resolution \propto \frac{1}{T}$$



trawler Domingo, Off Barcelona, Spain September 2006

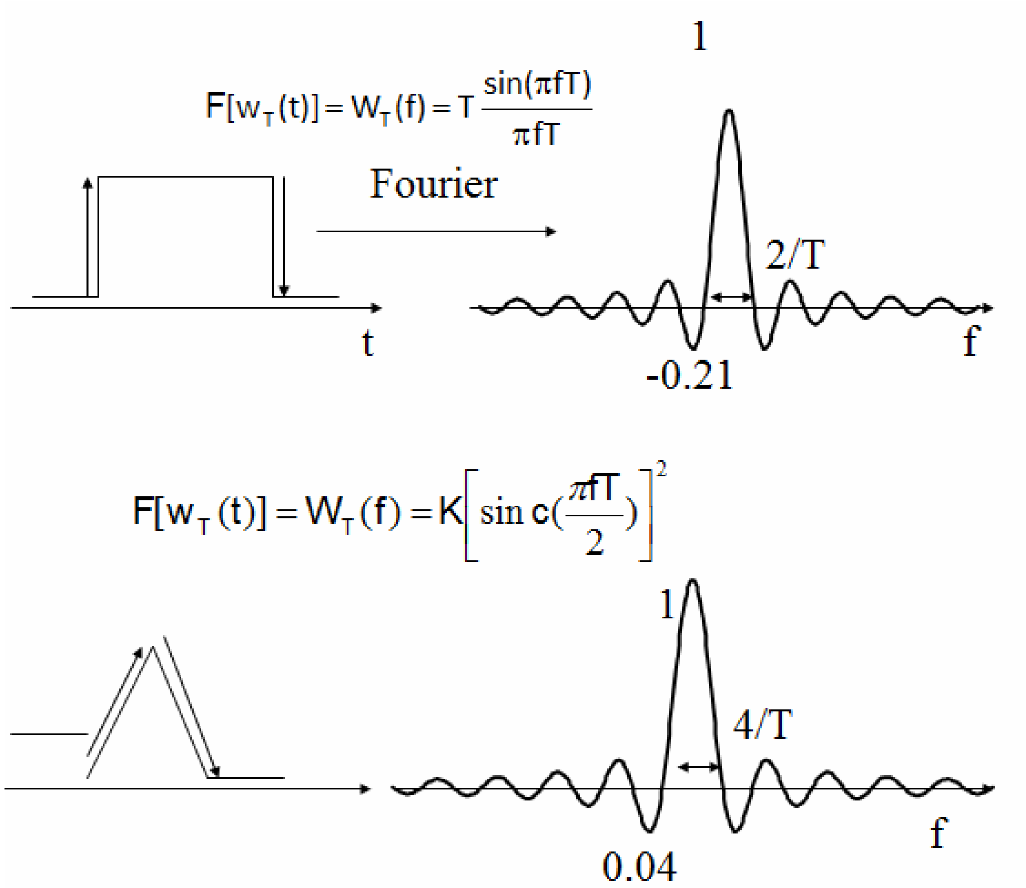
- Radiale domingo + adobe

FFT errors: The amplitude resolution – simultaneous distinction of a faint and intense signal



FFT errors: The amplitude resolution – simultaneous distinction of a faint and intense signal

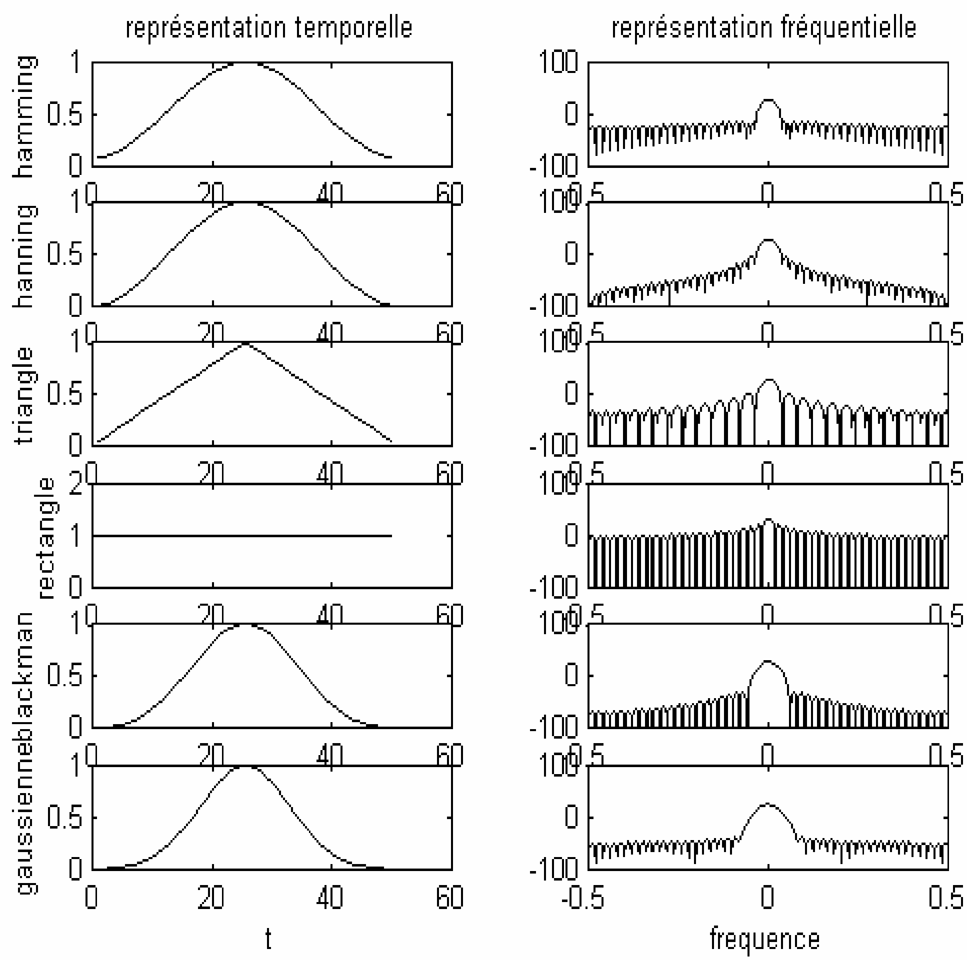
$s(t,\xi),\ t \in \left]-\infty, +\infty\right[$ $\qquad s(nT_e, \xi_0),\ n \in [0, N-1]$



$s_i(t) = w(t) \times s(t)$
w(t)
Windows with smoothed or sharp shape (upward and downward front)

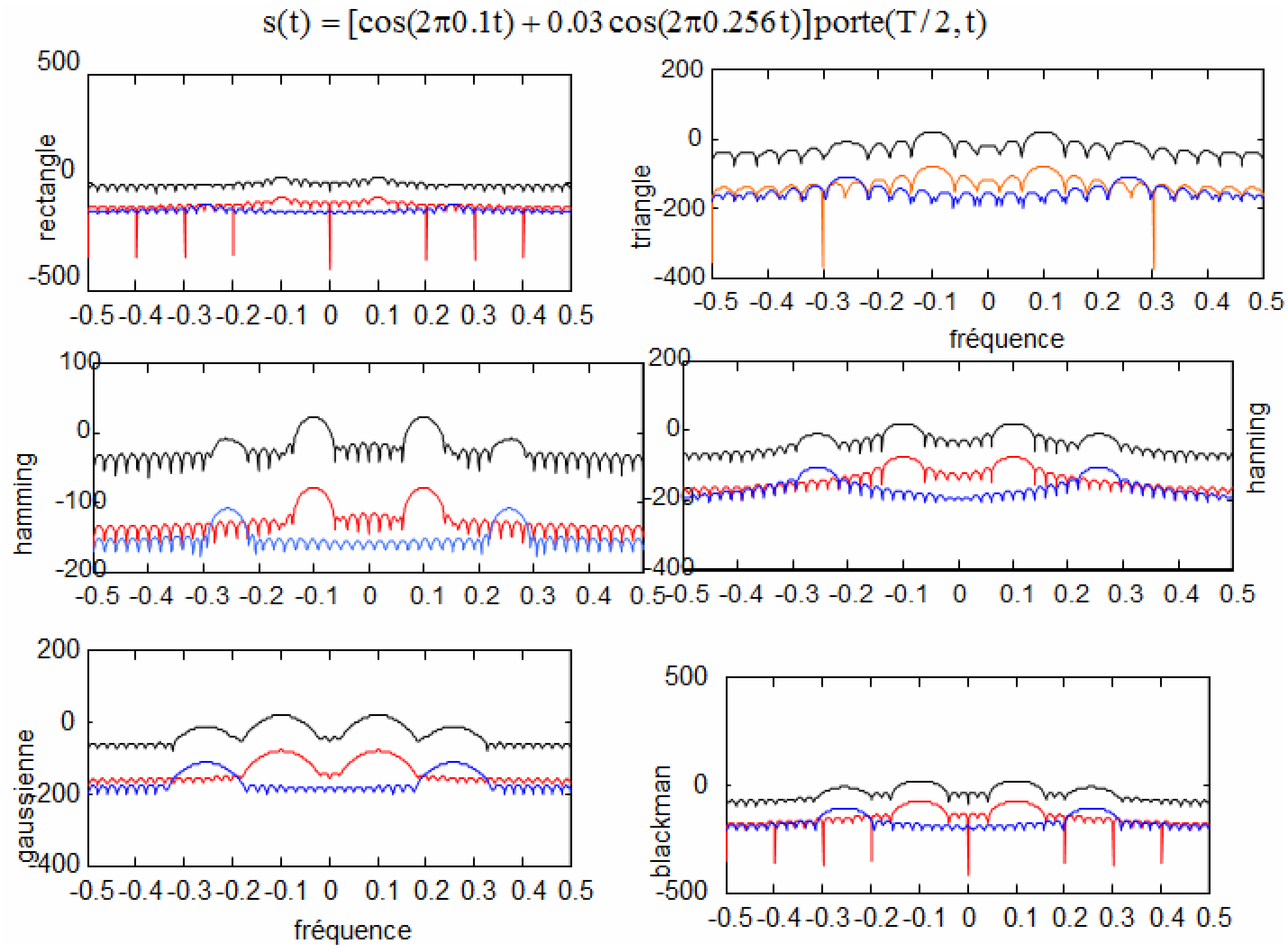
FFT errors: The amplitude resolution – simultaneous distinction of a faint and intense signal

$$s(t,\xi),\ t \in \left]-\infty, +\infty\right[\qquad s(nT_e,\xi_0),\ n \in [0, N-1]$$



$s_i(t) = w(t) \times s(t)$
w(t) Windows with smoothed or sharp shape (upward and downward front)

Types of analysis windows



Take home message FFT errors

1] **Frequency resolution:** determines the ability to separate components of similar frequencies. The limiting value δf is inversely proportional to the duration of observation (window) and dependent on the type of the analysis window.

2] **Amplitude resolution:** determines the ability to detect a faint component in the presence of an intense one. It is dependent on the analysis window. In the case of a rectangular window, a component with a 5 times smaller amplitude compared to another component might not be detected.

3] **To increase the amplitude resolution**,
We must chose a weighting Windows with a smooth shape. As a consequence, the size (duration) of the analysis window is reduced, implying a degradation of the frequency resolution.

Power spectral density of Random signal

Periodogram

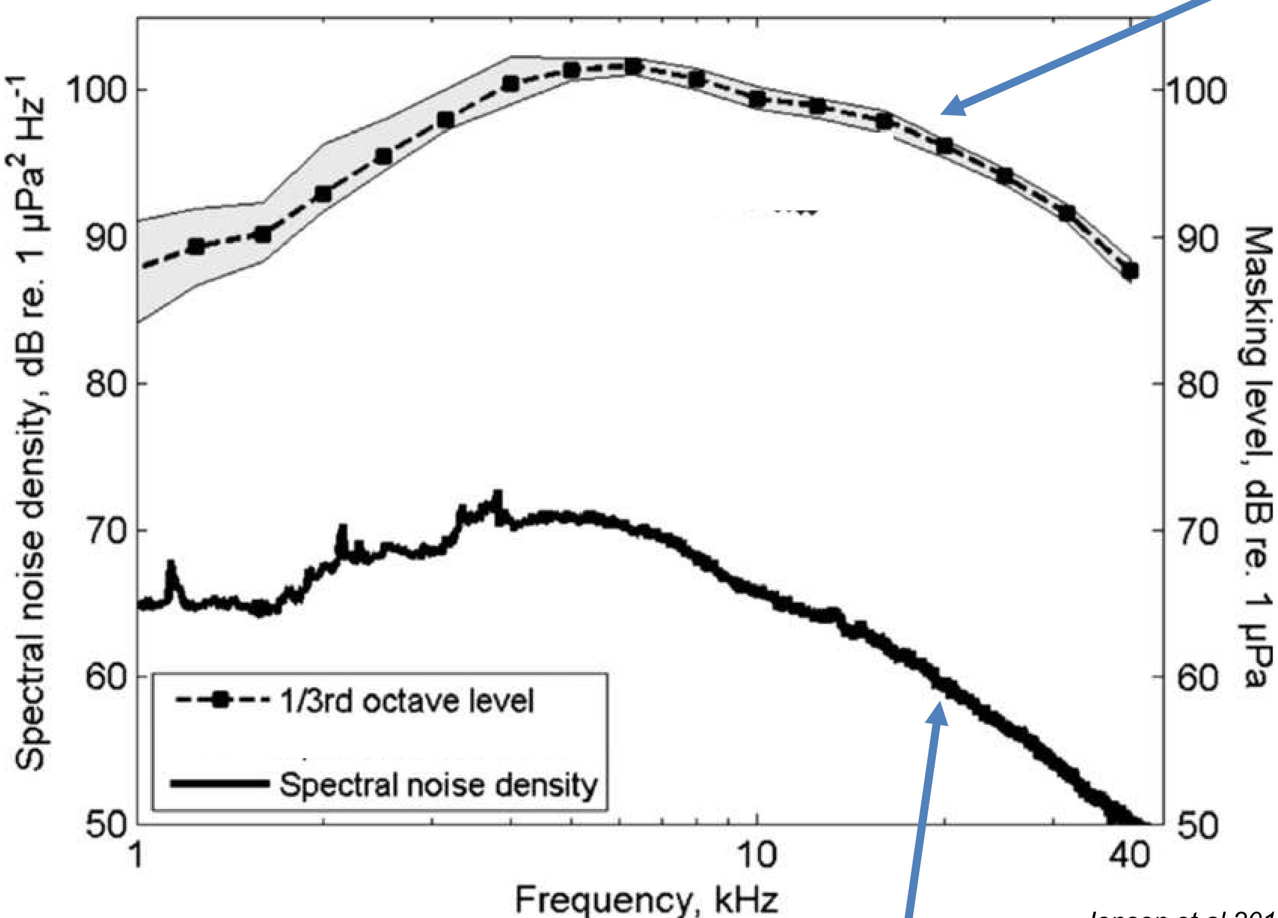
$$s = [s(1,\xi_1); s(2,\xi_1); s(3,\xi_1) \ldots; s(N,\xi_1)]$$

$$\tilde{\gamma}_s(f) = \frac{1}{Nf_s} \left| FFT(s) \right|^2$$

Estimated with FFT => corrupted with error
(frequency resolution, amplitude resolution, dispersion)

Types of spectra – choice depends on use

Octave or 1/3 octave levels: Noise impact studies on mammalian ears (masking)



Jensen et al.2012, JASA

Narrowband (1Hz bands) levels: Ambient noise descriptions

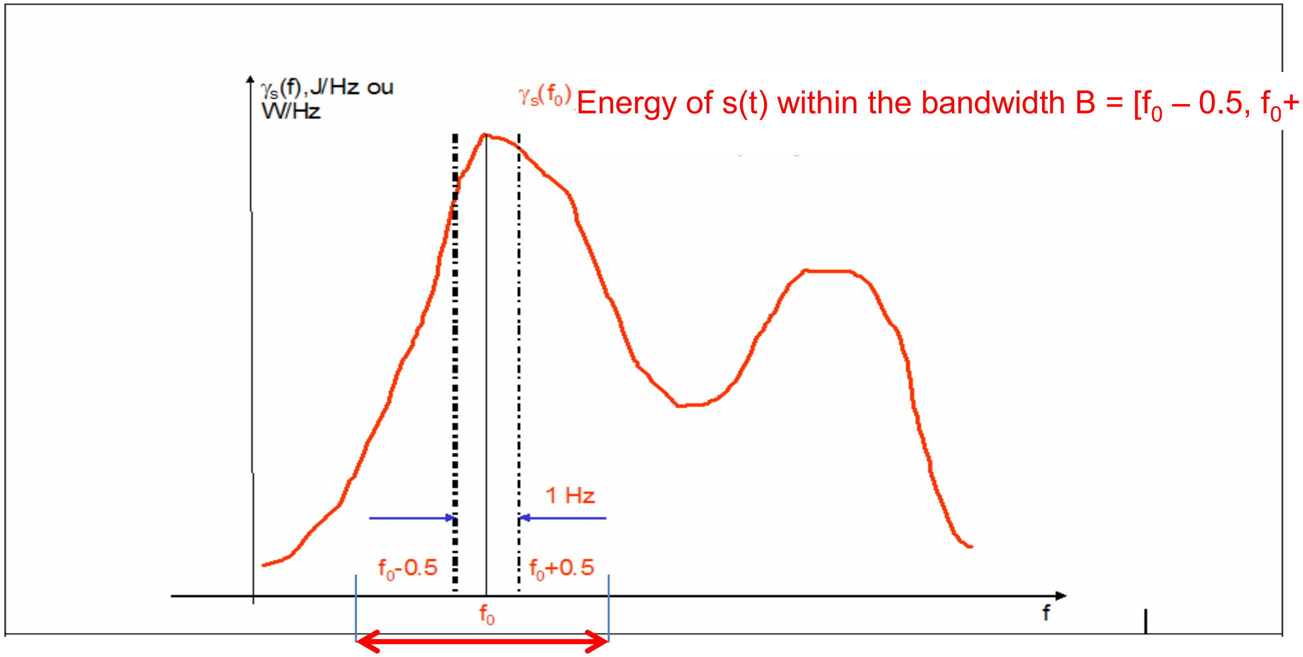
From the narrowband to the wideband, octave and 1/3 octava-band spectra

1/3 d'Octave band around f_0

$$B = [f_1 = \frac{f_0}{2^{1/6}}, f_2 = 2^{1/6} f_0]$$

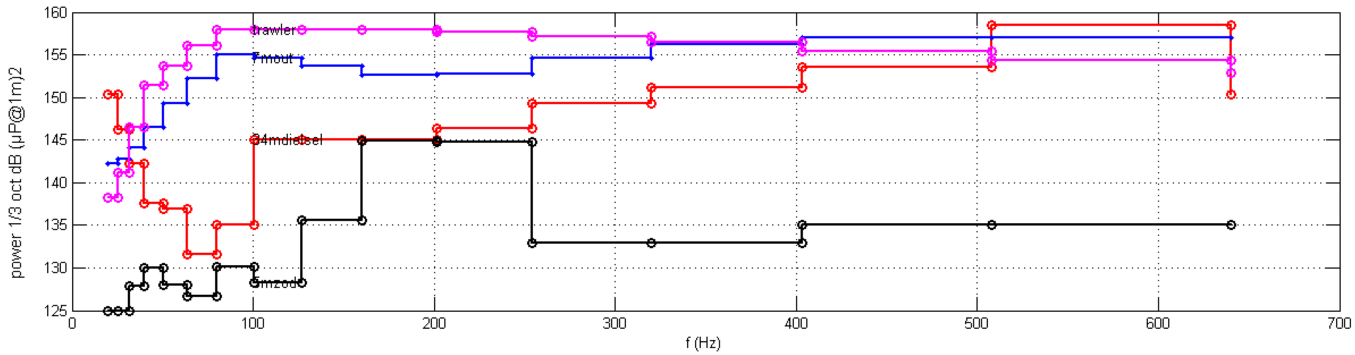
Octave band around f_0

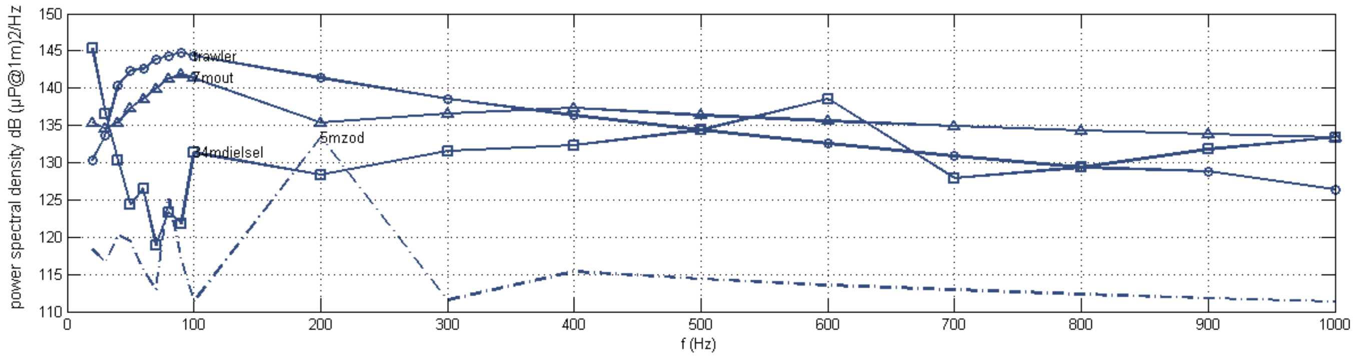
$$B = [f_1 = \frac{f_0}{\sqrt{2}}, f_2 = \sqrt{2} f_0]$$



$$sl(B) = \int_{f_1}^{f_2} \gamma(f) df$$

From the narrowband to the wideband, octave and 1/3 octava-band spectra

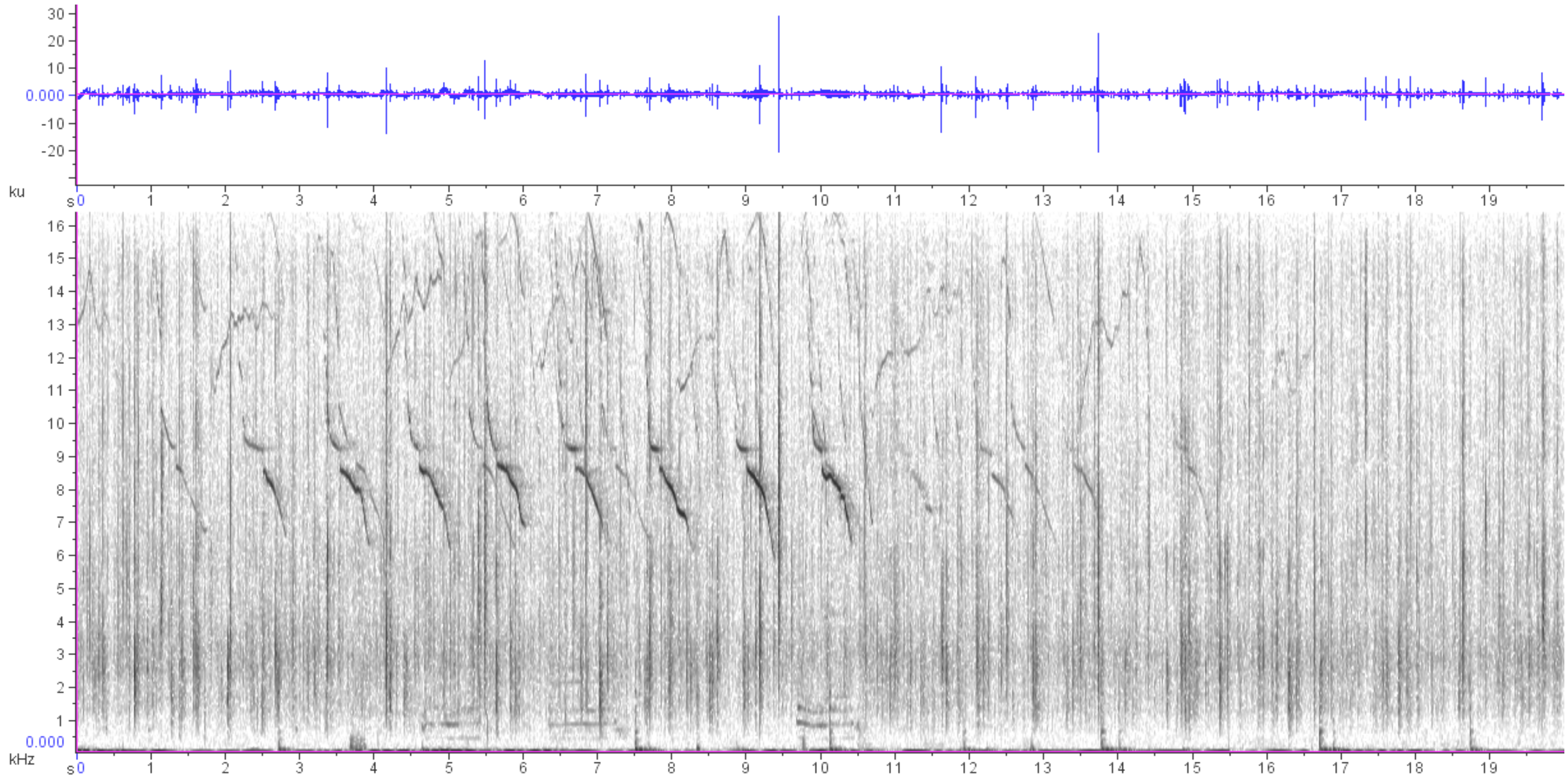




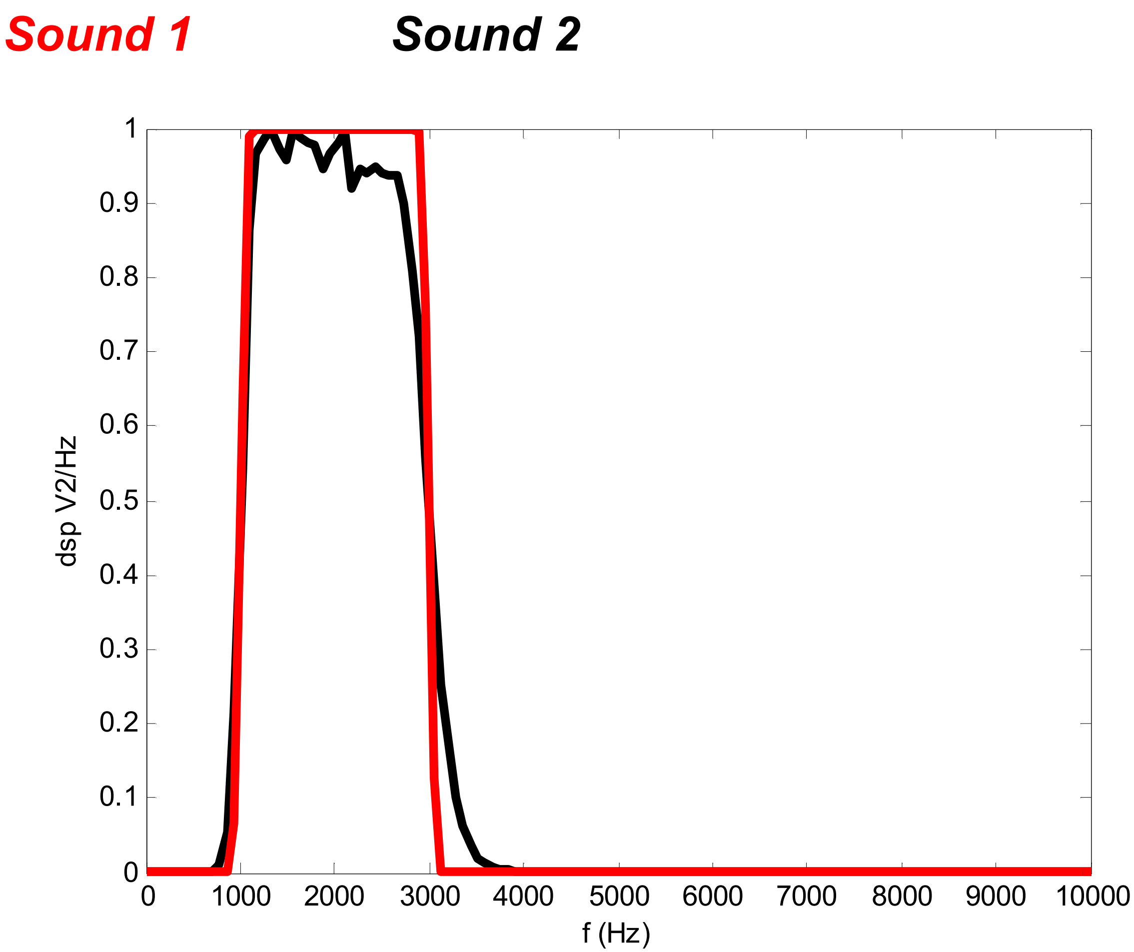
Outline

- Introduction
- Introduction to sound
- Measurement chain
- Spectral analysis of acoustic measurements
- Time-frequency representation
- Applied examples from our own research

Time-frequency representation
Spectrogram



Introducing the spectrogram – why?



- live

The limitations of the Fourier Transform for non-stationary signals

The Fourier transform transforms a temporal signal into a frequency signal

It indicates the frequency content of a signal…

…but does not date the frequency content!

=> Reasons why it is appropriate for stationary signals, with a stationary signal = a signal who's frequency or spectral content do not change with respect to time!

Non stationary signals – frequency-modulated signals

Single frequency

$$s(t) = \cos(2\pi f_0 t)$$

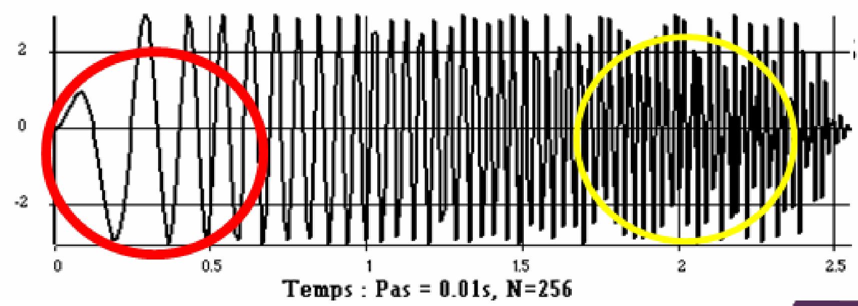
$$s(t) = \cos(\varphi(t)), \varphi(t) = 2\pi\int_0^t f_0 dt$$

$$f_0 = \frac{1}{2\pi}\frac{d\varphi(t)}{dt}$$

Varying frequency

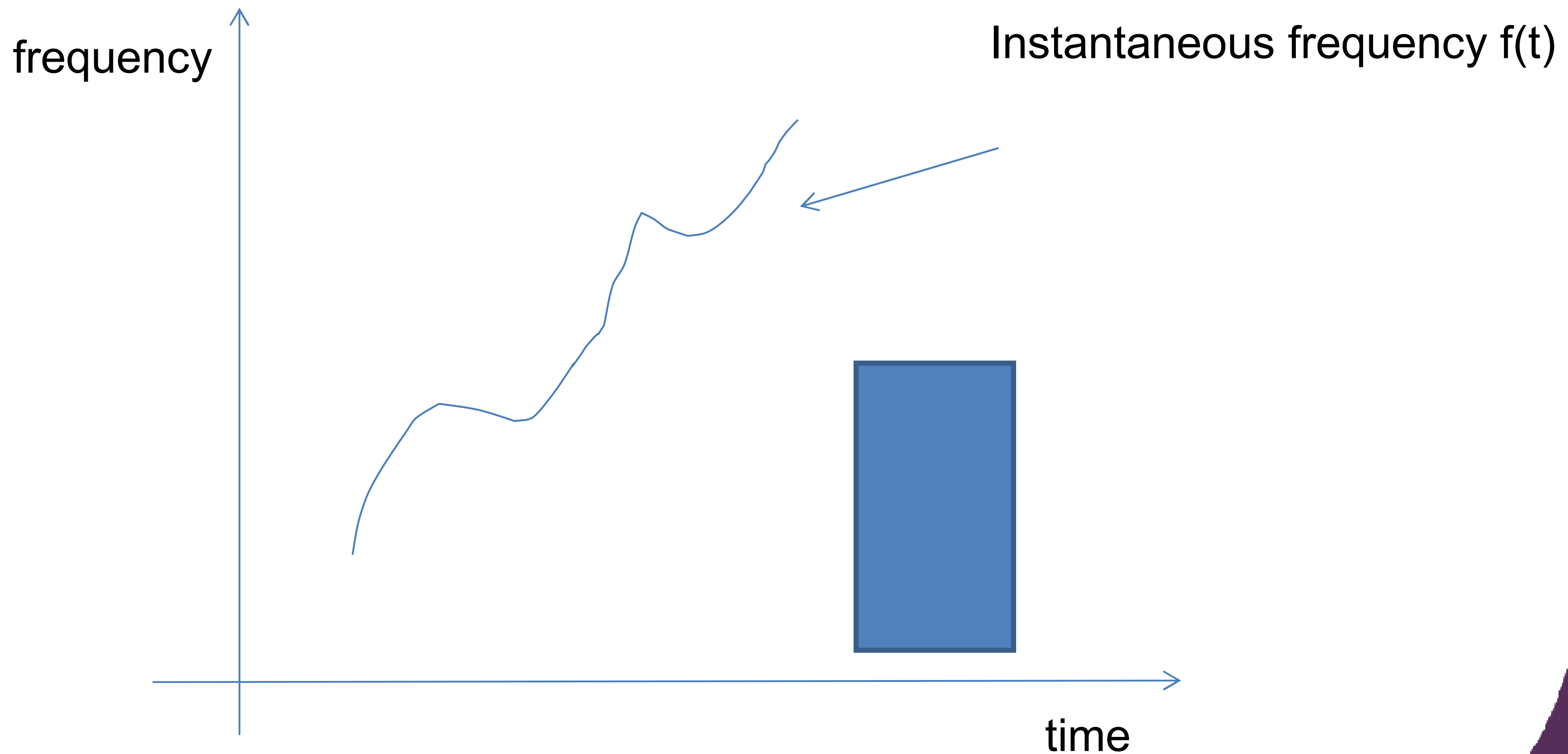
$$s(t) = \cos(\varphi(t))$$

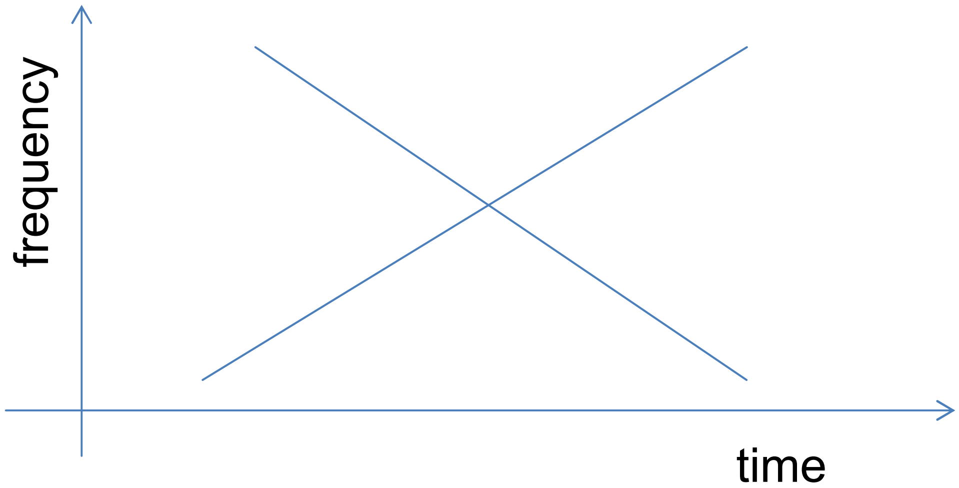
$$f_i(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt}$$

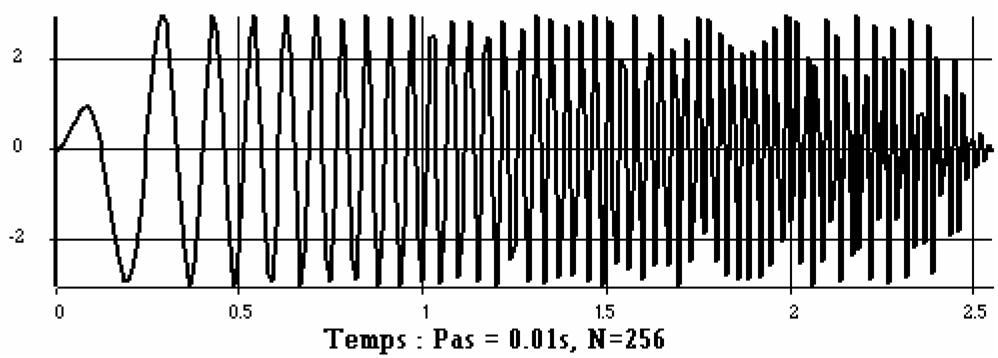


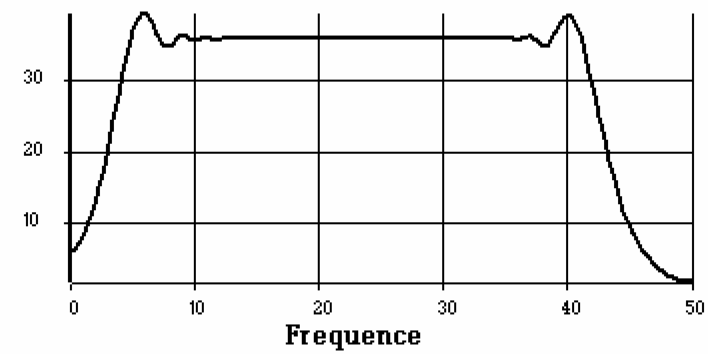
Need of a time-frequency representation: which frequency f(t) at time t ?

We want to map the power of a signal in a time-frequency plane




frequency
time


2
0
-2
0
0.5
1
1.5
2
2.5
Temps : Pas = 0.01s, N=256


30
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10
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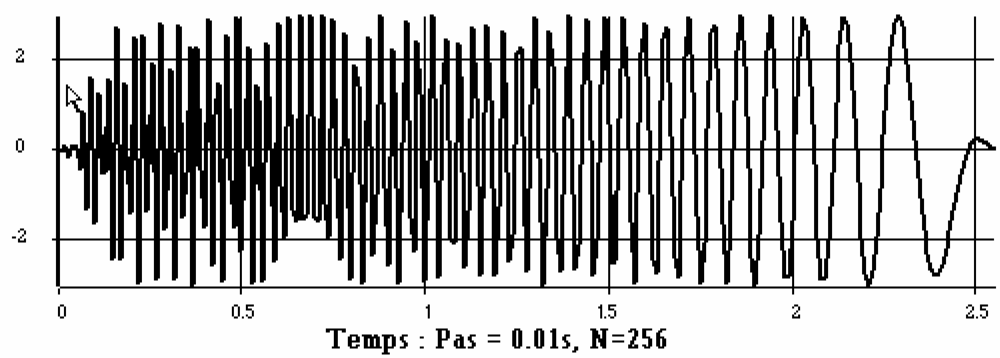
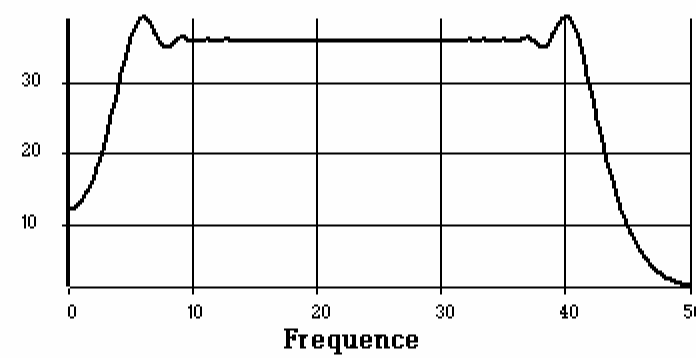
10
20
30
40
50
Frequence


2
0
-2
0
0.5
1
1.5
2
2.5
Temps : Pas = 0.01s, N=256


30
20
10
0
10
20
30
40
50
Frequence

For non-stationary signals

- Goal: for deterministic non-stationary signals, how to get from a frequency to a time-frequency representation
- The frequency : number of cycles per second
- Intrinsic problem : frequency is already time-dependant in a time-frequency representation we look for the instantaneous frequency (number of cycles during dt around t)….

The short-term Forurier Transform (STFT)
The Spectrogram

STFT corresponds to an adaptation of the Fourier transform – a spectral representation of consequent time segments

$$S(t_0, f_0) = \int s(t) \times w_T(t - t_0) \exp(-2\pi j f_0 t) dt$$

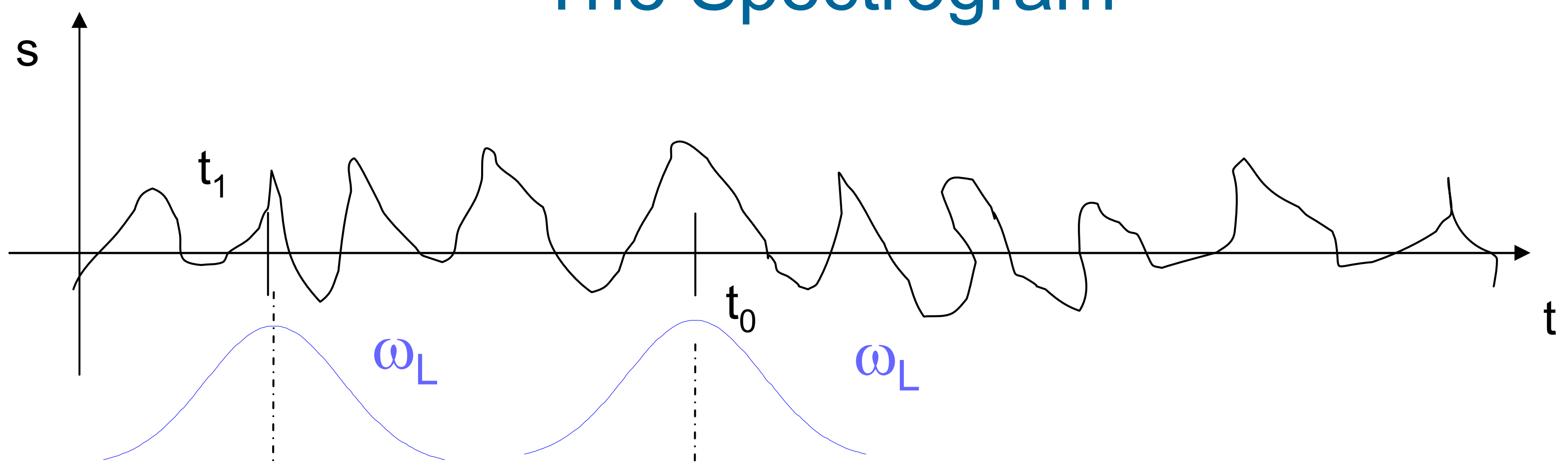
$$S(t_0, f_0) = F(s(t) \times w_T(t - t_0))$$

The spectrogram = the squared magnitude of the STFT of a signal s(t)

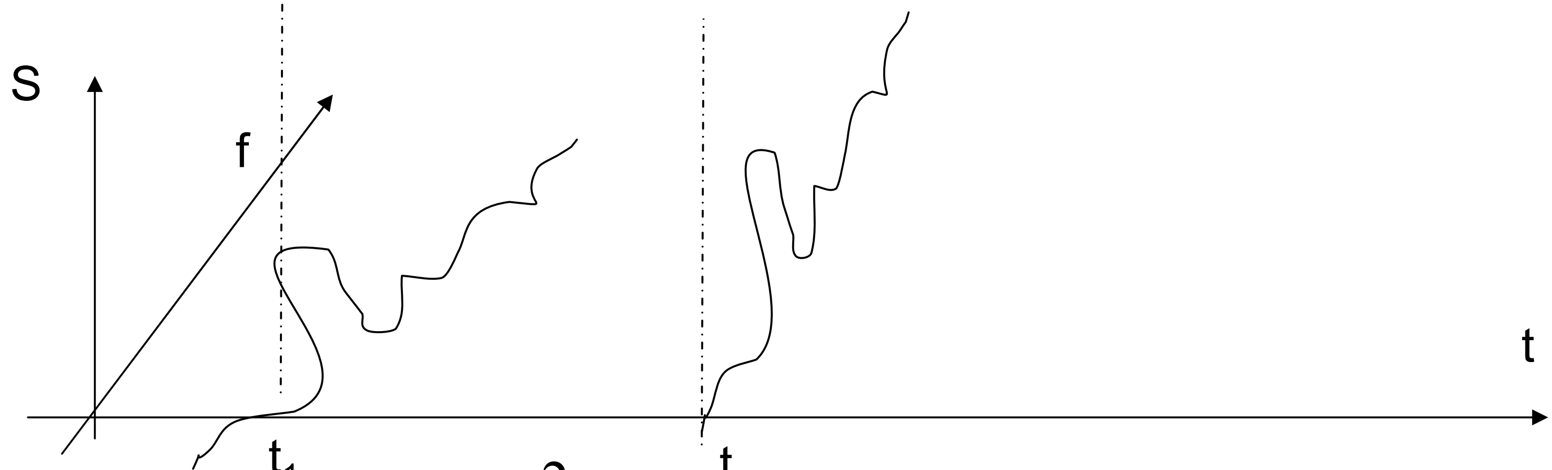
$$S_{pect}(t_0, f_0) = \left| S(t_0, f_0) \right|^2$$

The spectrogram = a map of signal energy in time-frequency plane

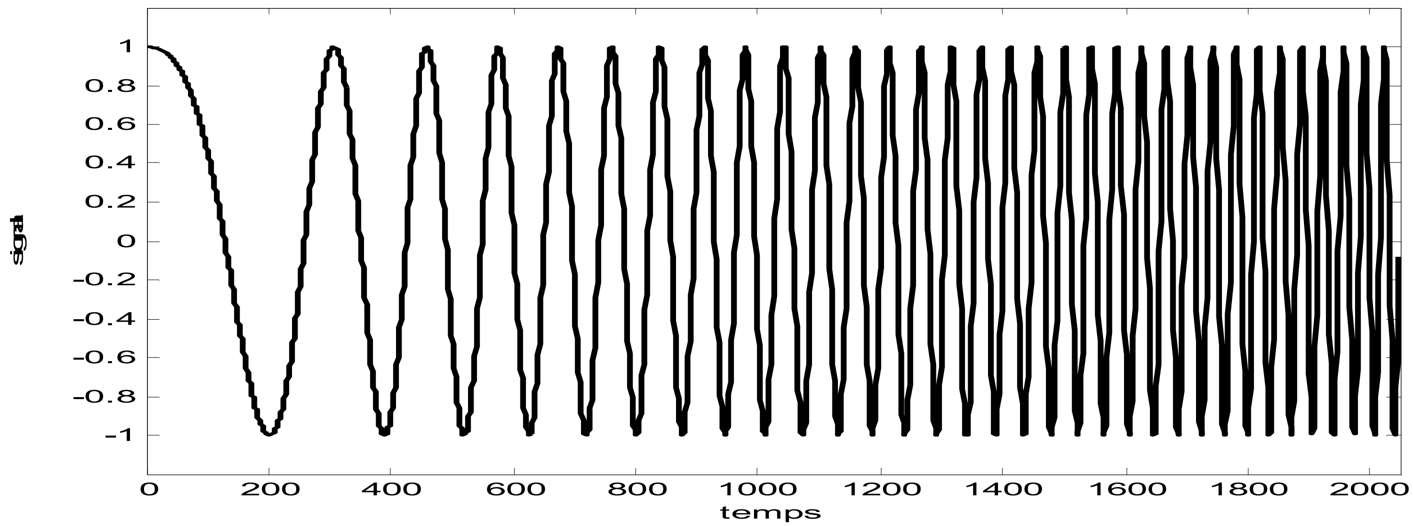
The short-term Forurier Transform (STFT)
The Spectrogram

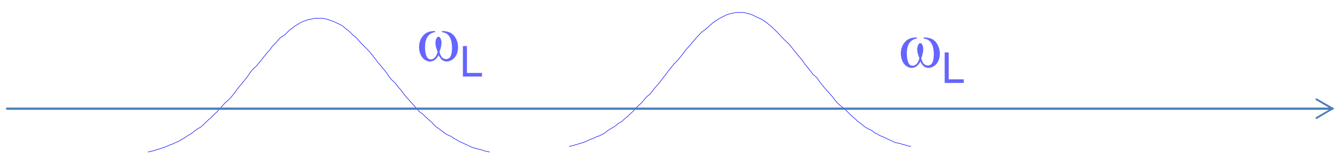


$$S(t_0, f) = F(s(t) \times \omega_L(t - t_0))$$

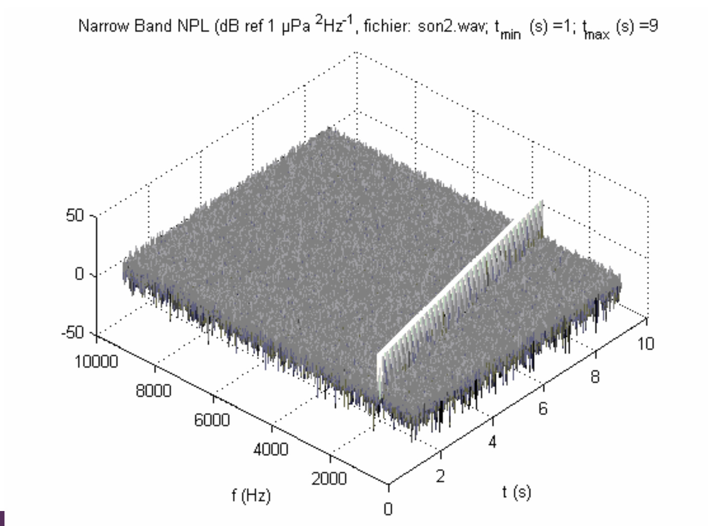


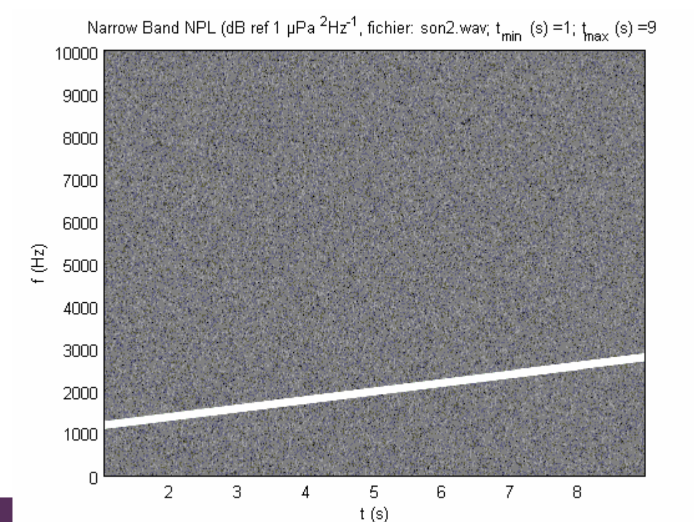
$$\left|S(t_0, f)\right|^2 = spectrogram$$





$$S(t_0, f) = F(s(t) \times \omega_L(t - t_0))$$





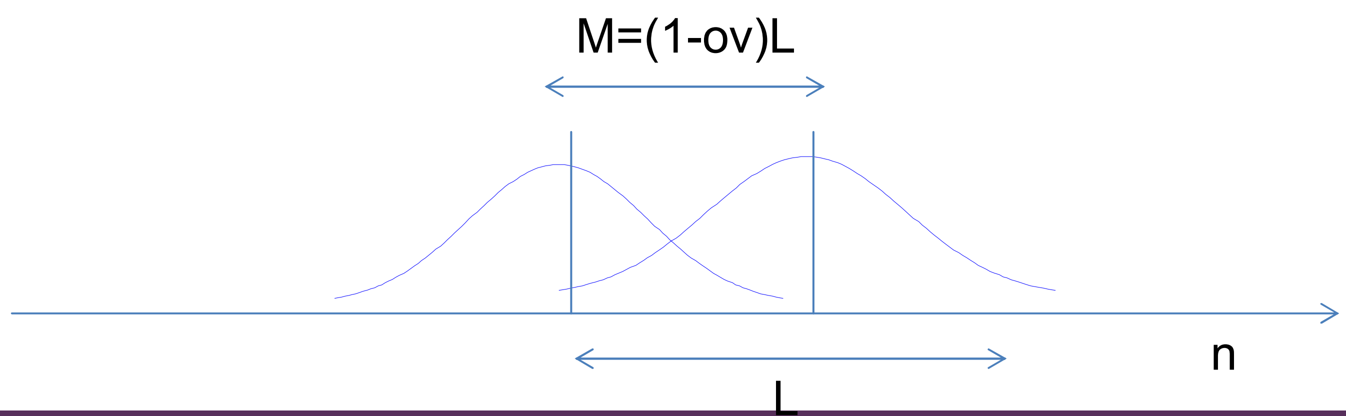
The short-term Forurier Transform (STFT)
The Spectrogram

Numerical implementation:

$$S(iM, j) = FFT_L(s(n) \times w_L(n - iM)), j \in \{0,.., L-1\}$$

$$t(s) = iM$$

$$f(Hz) = \frac{j}{L} f_e$$



- live,
  - Linear Frequency modulation
  - Dolphin’s whistles

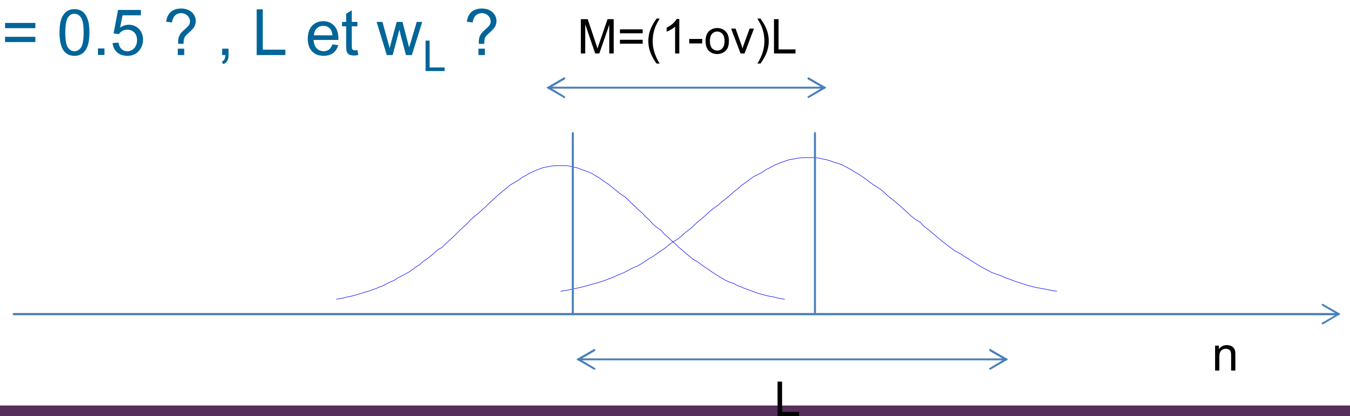
The short-term Forurier Transform (STFT)
The Spectrogram

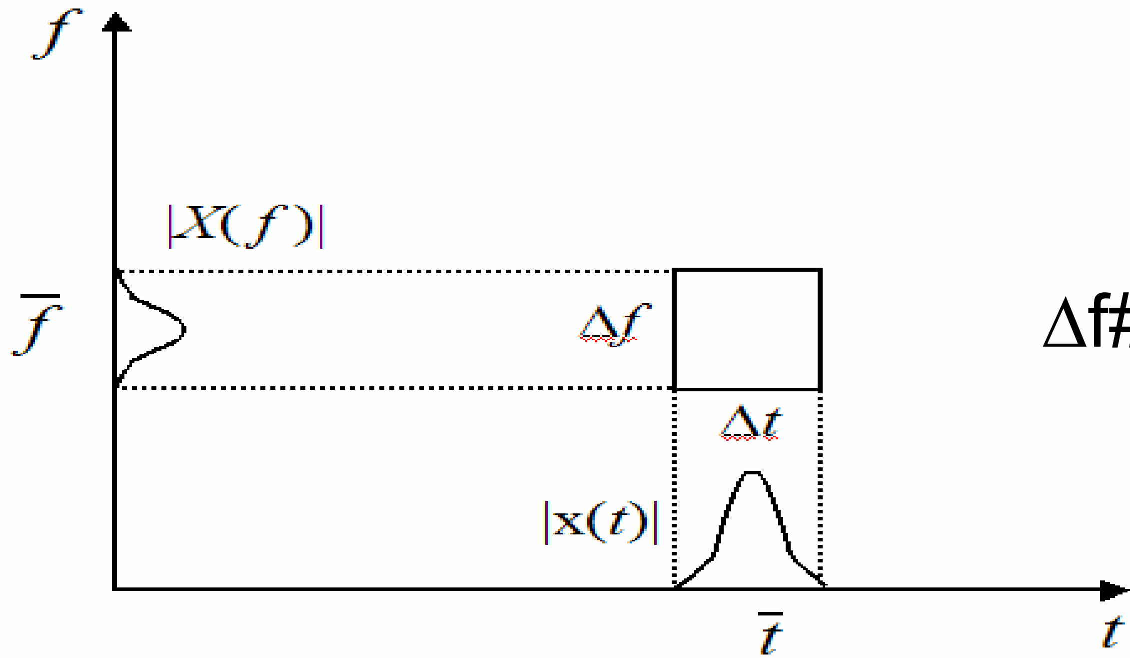
The degrees of freedom of the STFT

- window length : L
- window type : w_L
- window overlap : ov

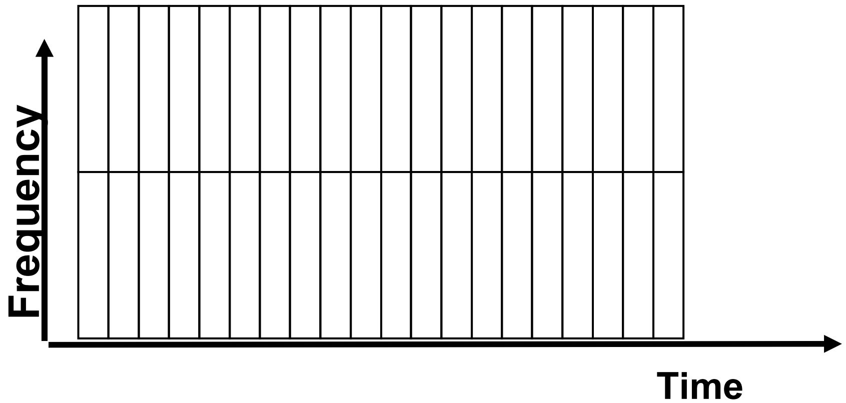
The choice of the degrees of freedom determines the properties of the time-frequency representation

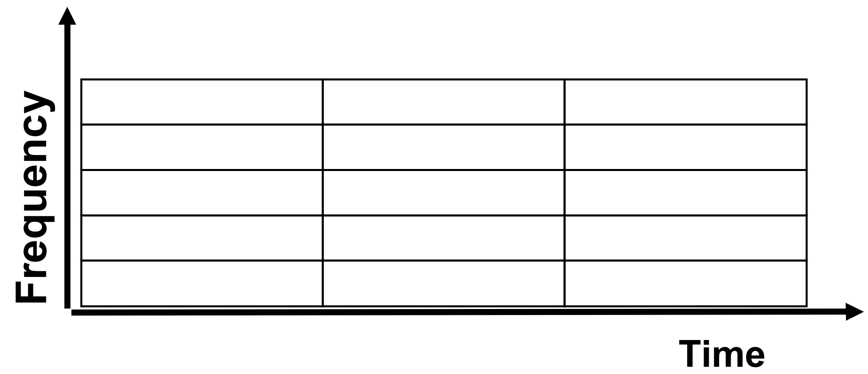
ov = 0.5 ? , L et w_L ?





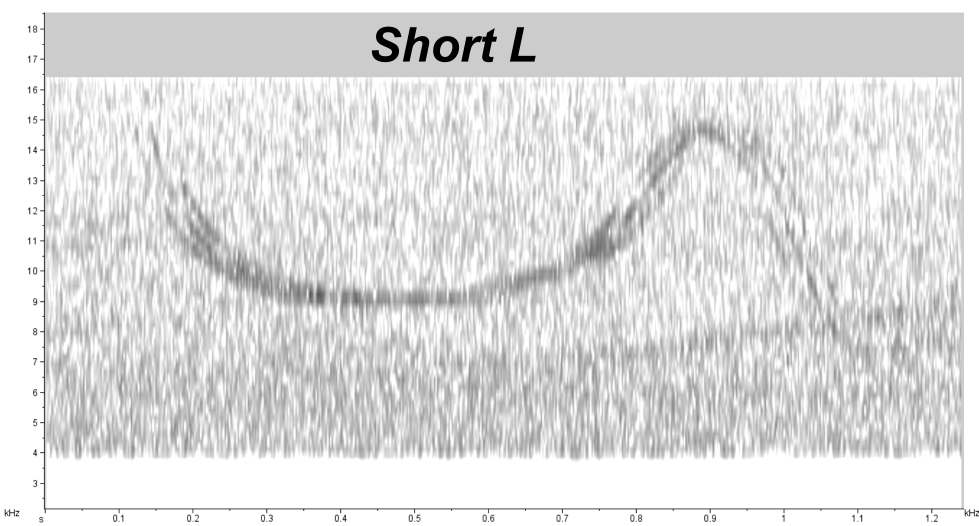
Δf#1/Δt

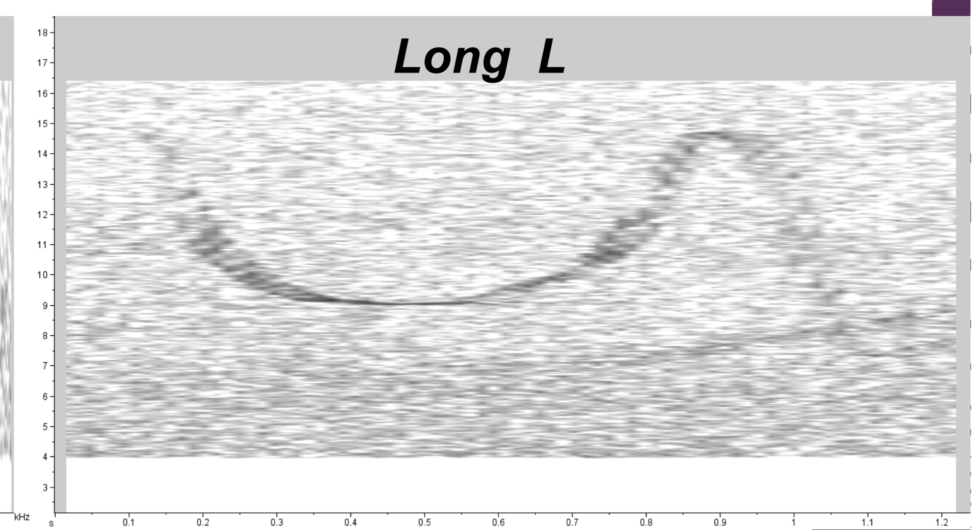




L= small:
Good time resolution
Bad frequency resolution

L= high :
Bad time resolution
Good frequency resolution





The short-term Forurier Transform (STFT)
The Spectrogram

The degrees of freedom of the STFT:

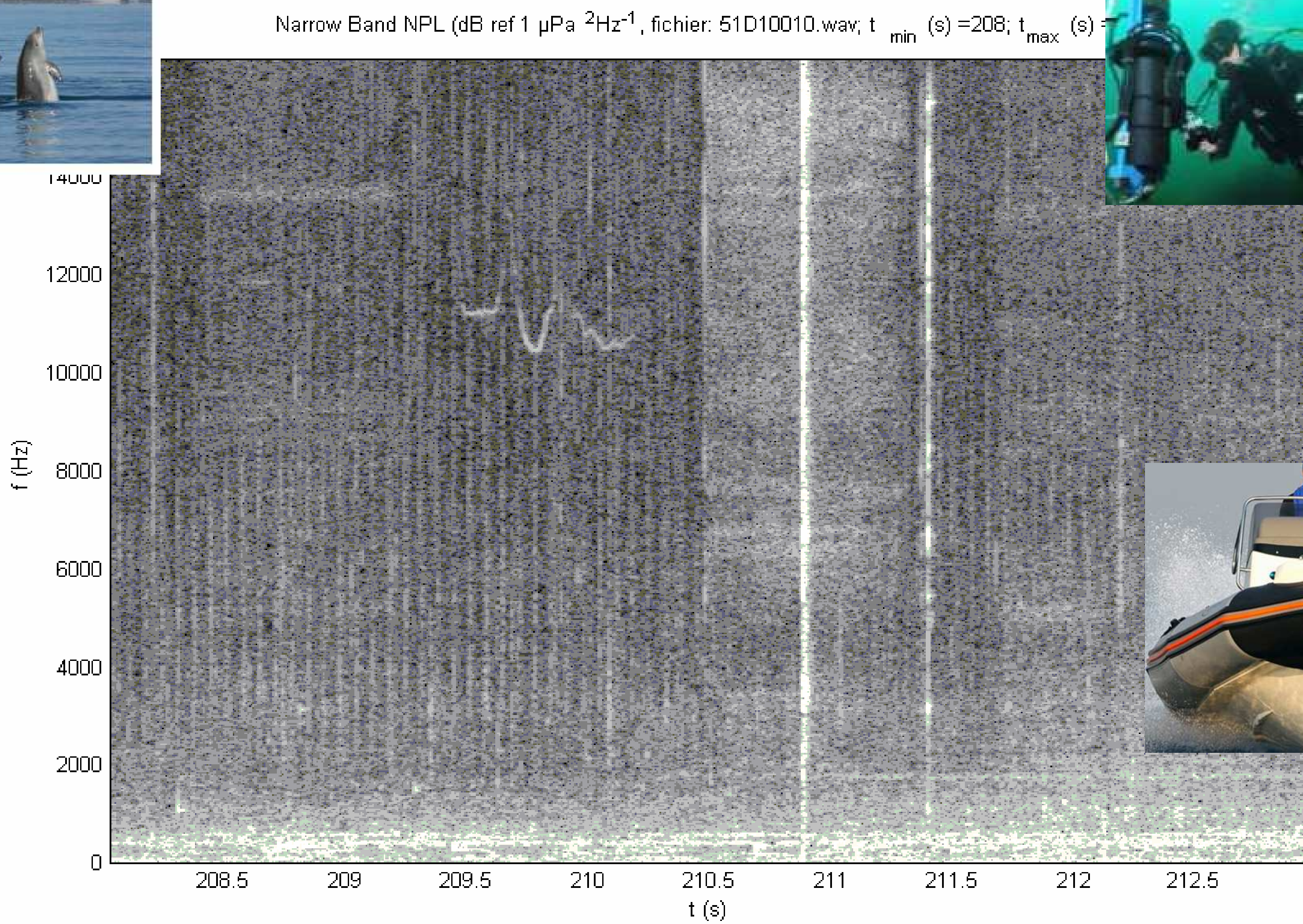
- the window length : L
  compromise between time and frequency resolution

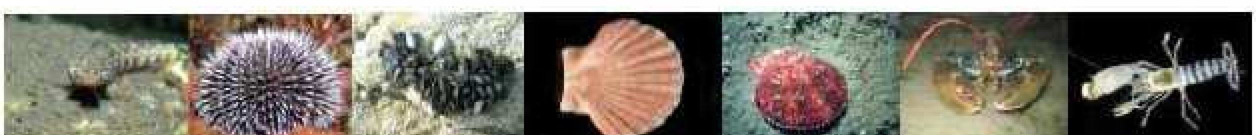
- the type of window : w_L
  compromise between frequency and amplitude resolution

- the window overlap : ov >0.5

- live on real data : sifflement.wav

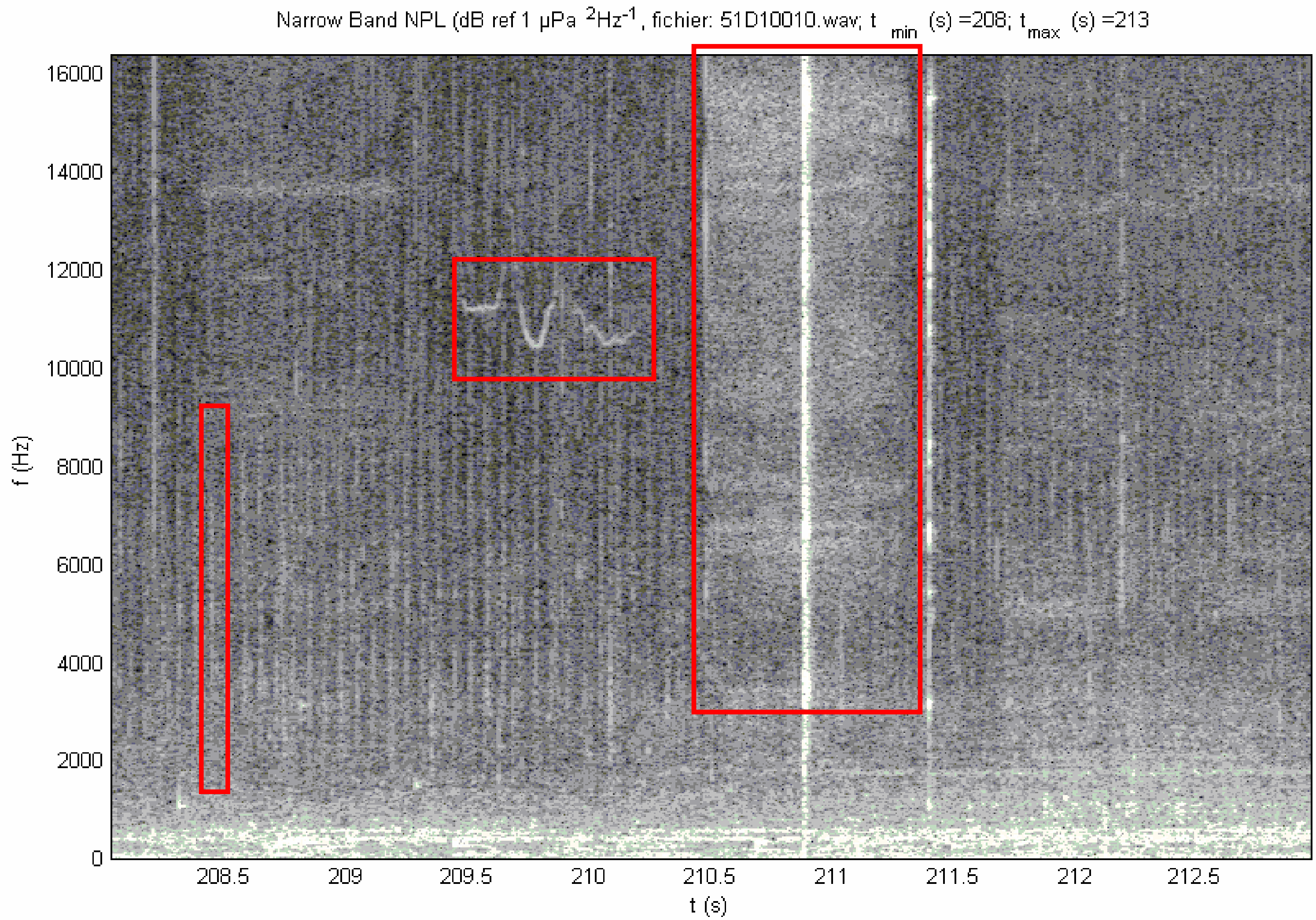
Extraction of key parts of a spectrogram





Lucia

Extraction of key parts of a spectrogram

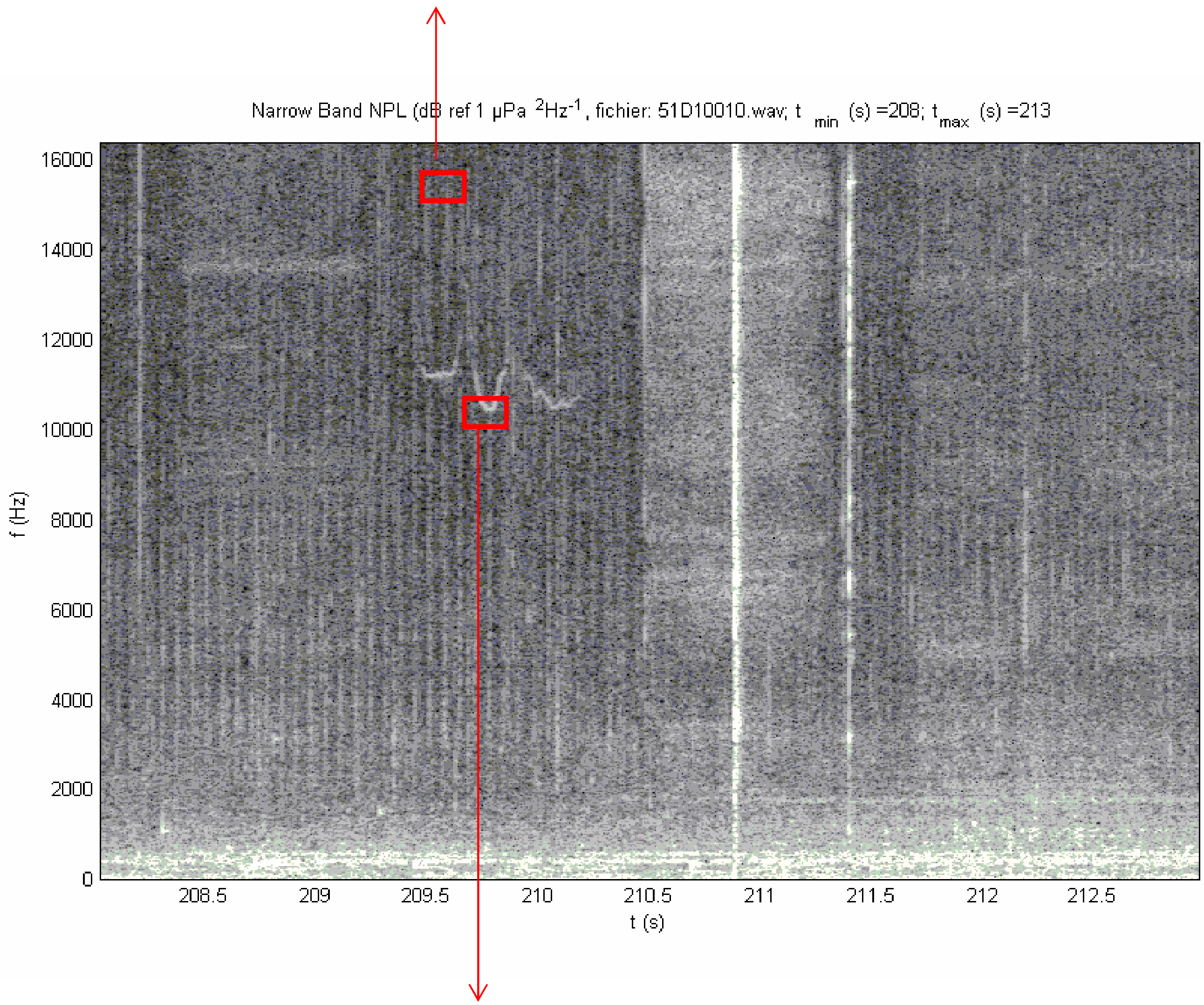


Extraction of key parts of a spectrogram

Method

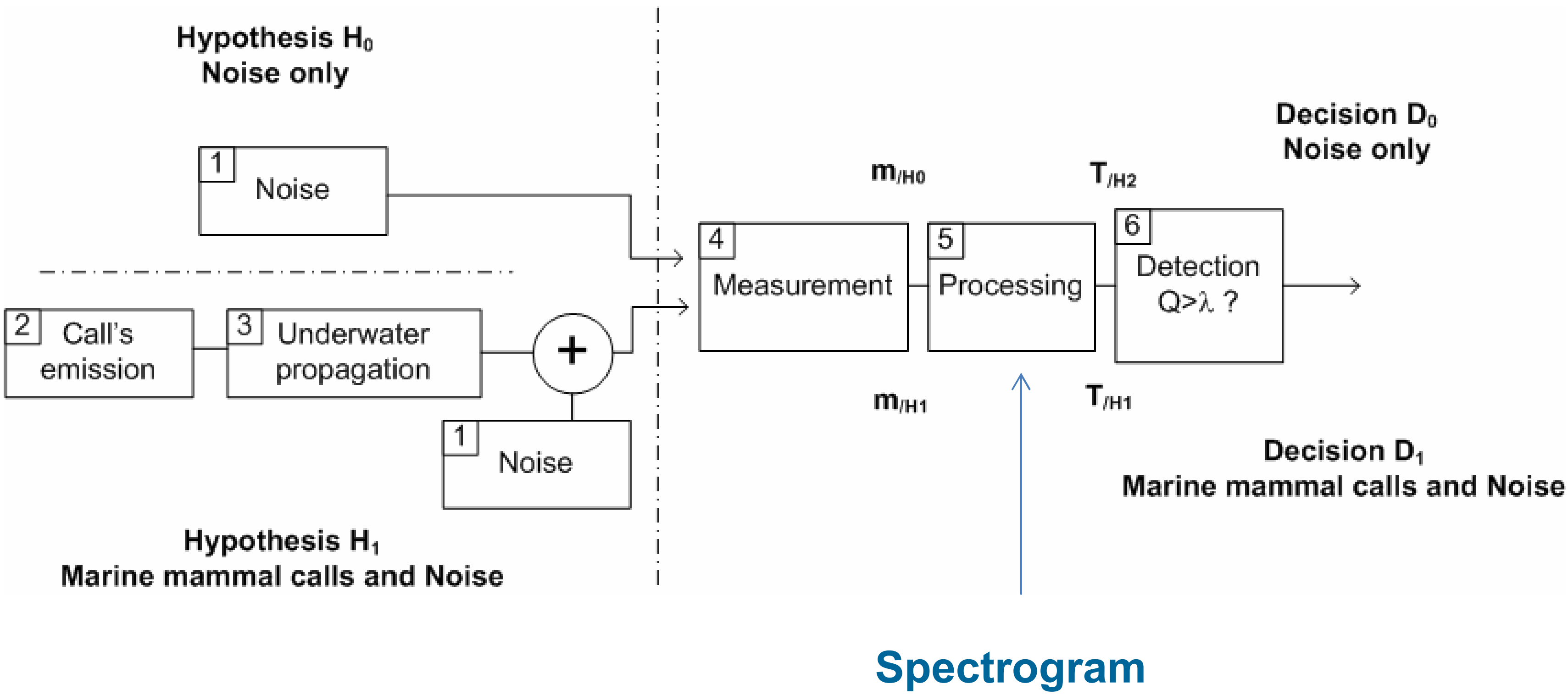
- Compute a spectrogram
- Segment the spectrogram into binary areas
  - 0=> H0 absence of target signal
  - 1=> H1 presence of target signal

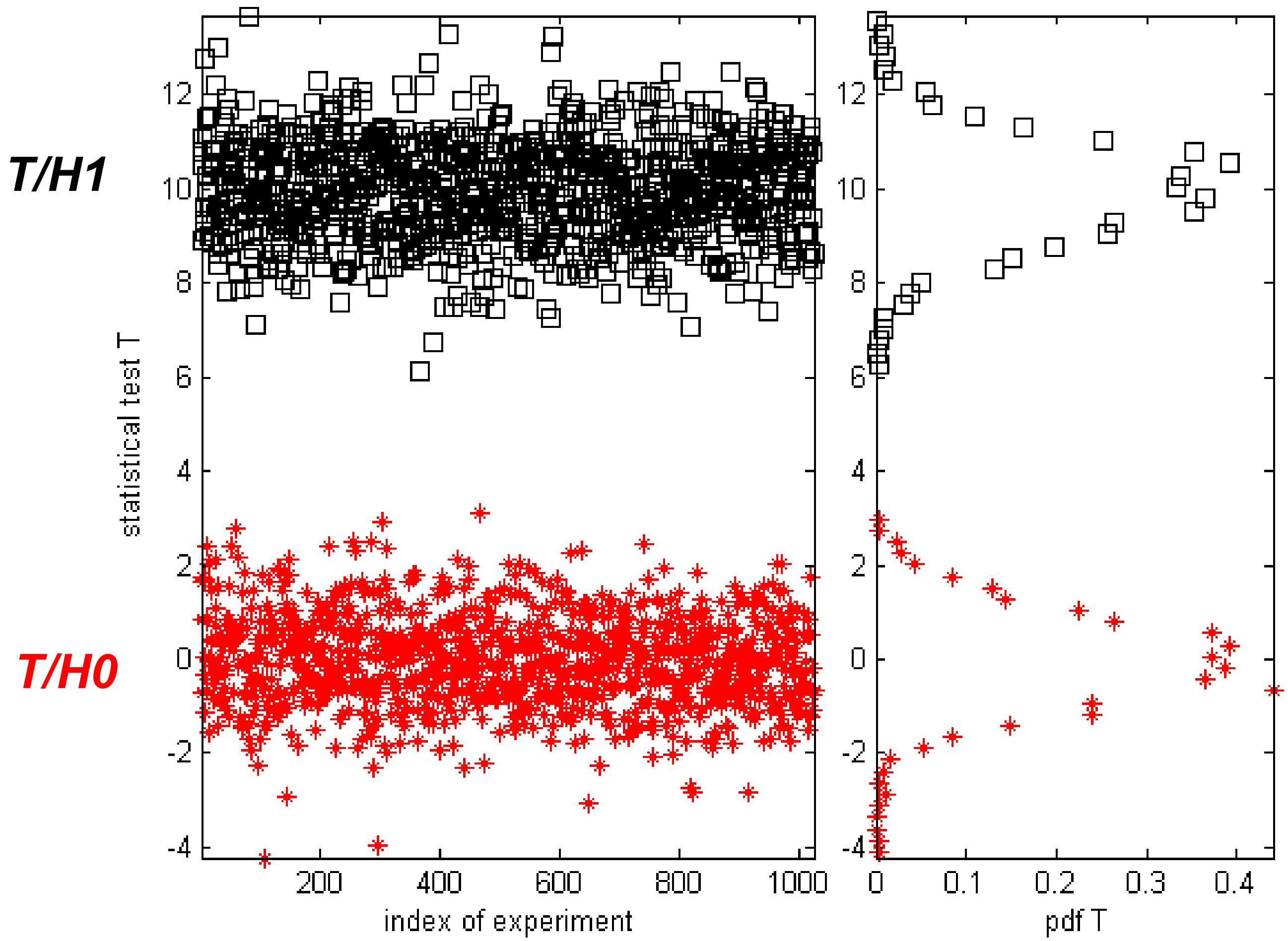
H0: signal absent, if D0 : good decision, if D1 : bad decision – false alarm (Pfa)

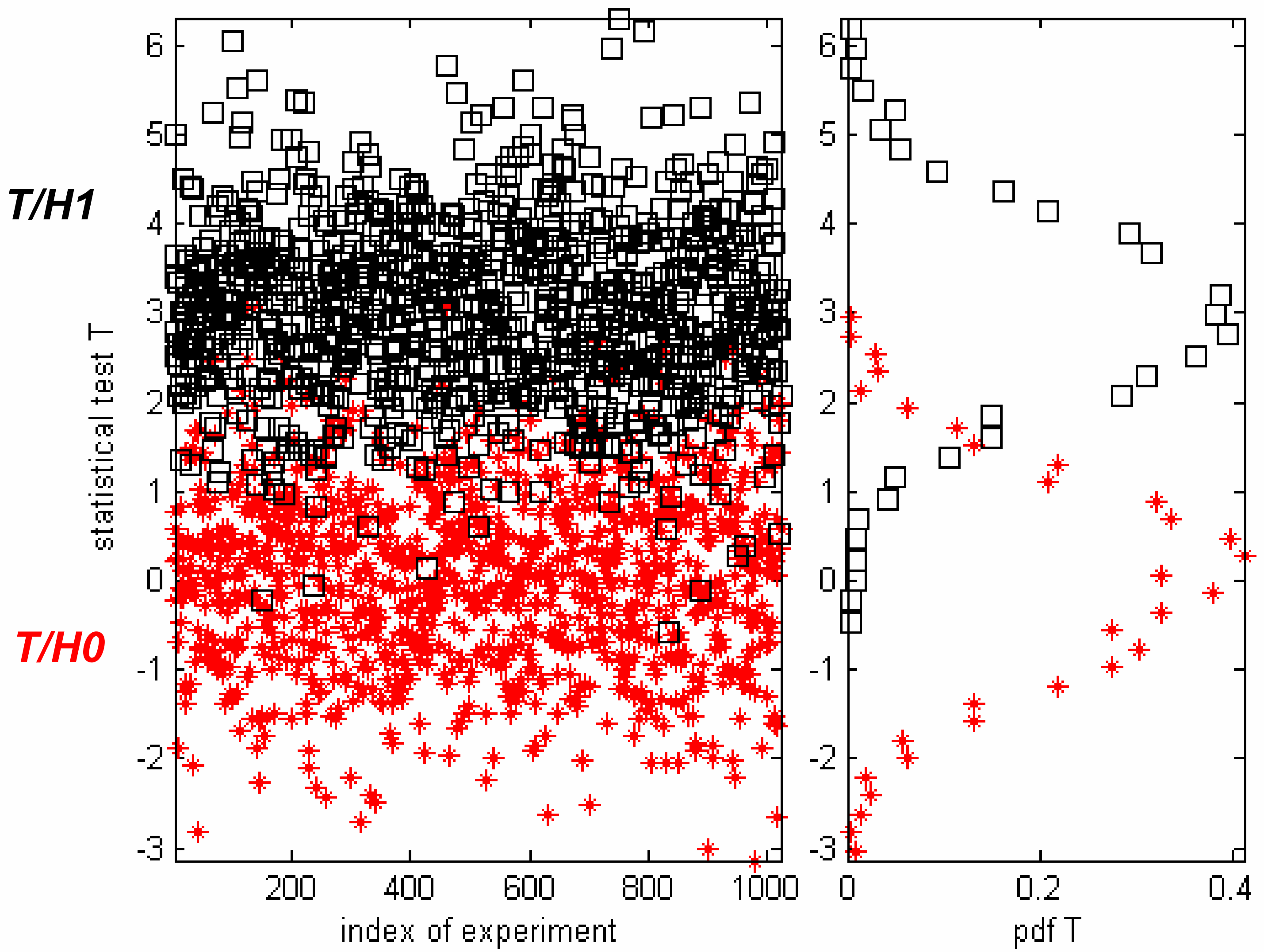


H1: signal present, if D1 : good decision (Pd), if D0 : no bad decision

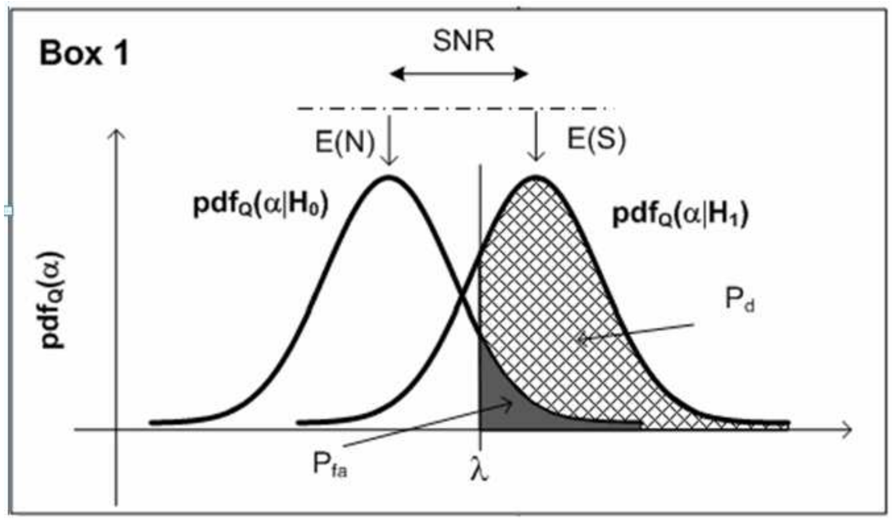
General architecture of a signal detector

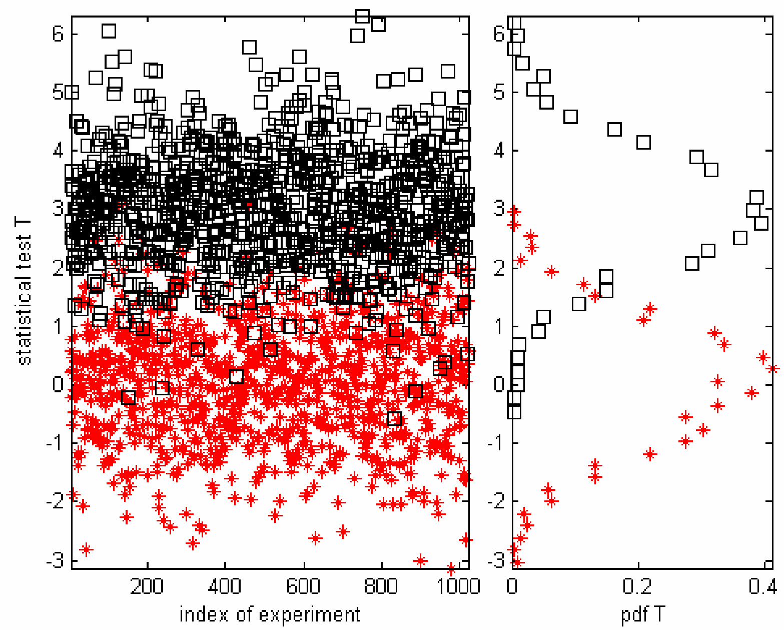



T/H1
T/H0
statistical test T
index of experiment
pdf T
12
10
8
6
4
2
0
-2
-4
200
400
600
800
1000
0
0.1
0.2
0.3
0.4


T/H1
T/H0
statistical test T
index of experiment
pdf T
6
5
4
3
2
1
0
-1
-2
-3
200
400
600
800
1000
0
0.2
0.4

Pfa et Pd





$$P_{fa} = \int_{\lambda}^{+\infty} \mathrm{pdf}_Q(\alpha | H0) d\alpha = 1 - \mathrm{cdf}_Q(\lambda | H_0) \qquad P_d = \int_{\lambda}^{+\infty} \mathrm{pdf}_Q(\alpha | H_1) d\alpha = 1 - \mathrm{cdf}_Q(\lambda | H_1)$$

Detector with a constant false alarm rate

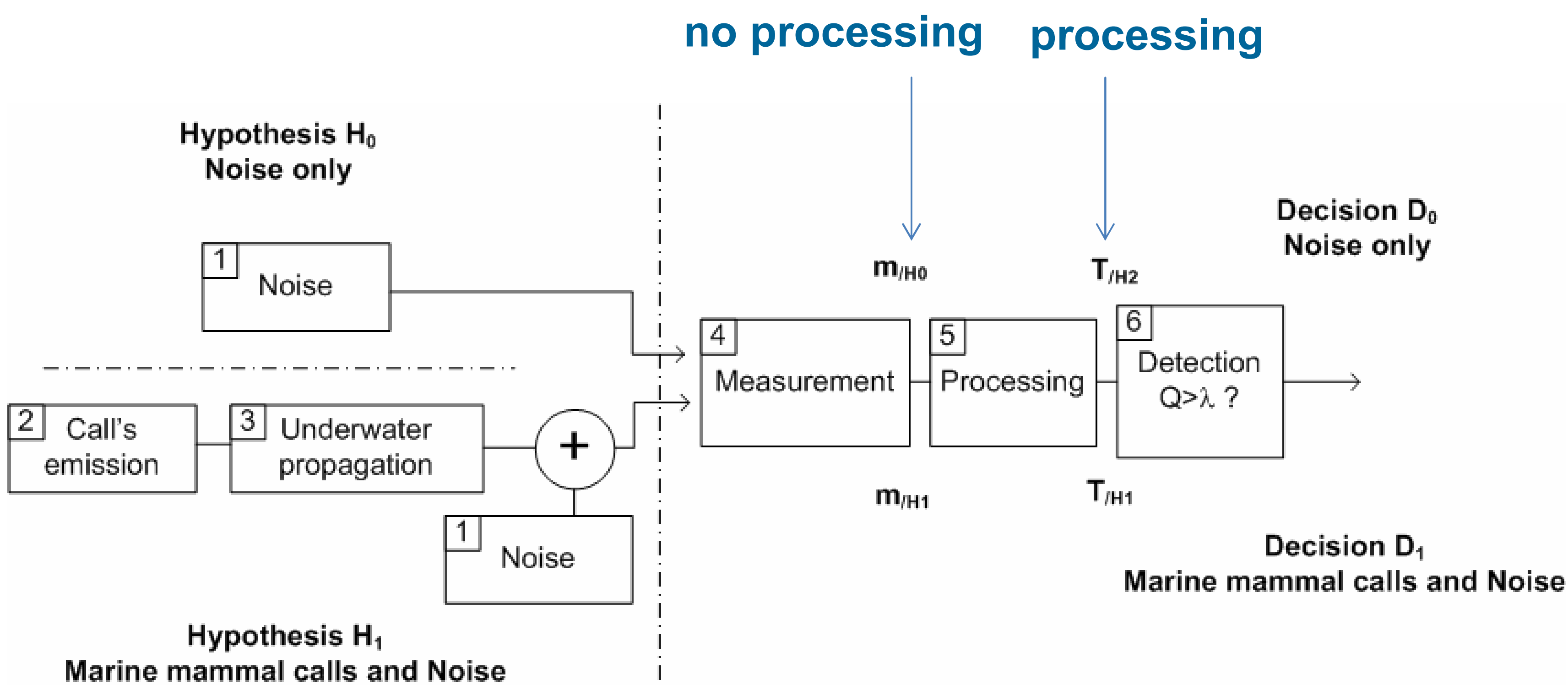
- In many application of signal detection, $f_Q(q)|H1$ is not well known.
- We define a detector with constant false alarm rate

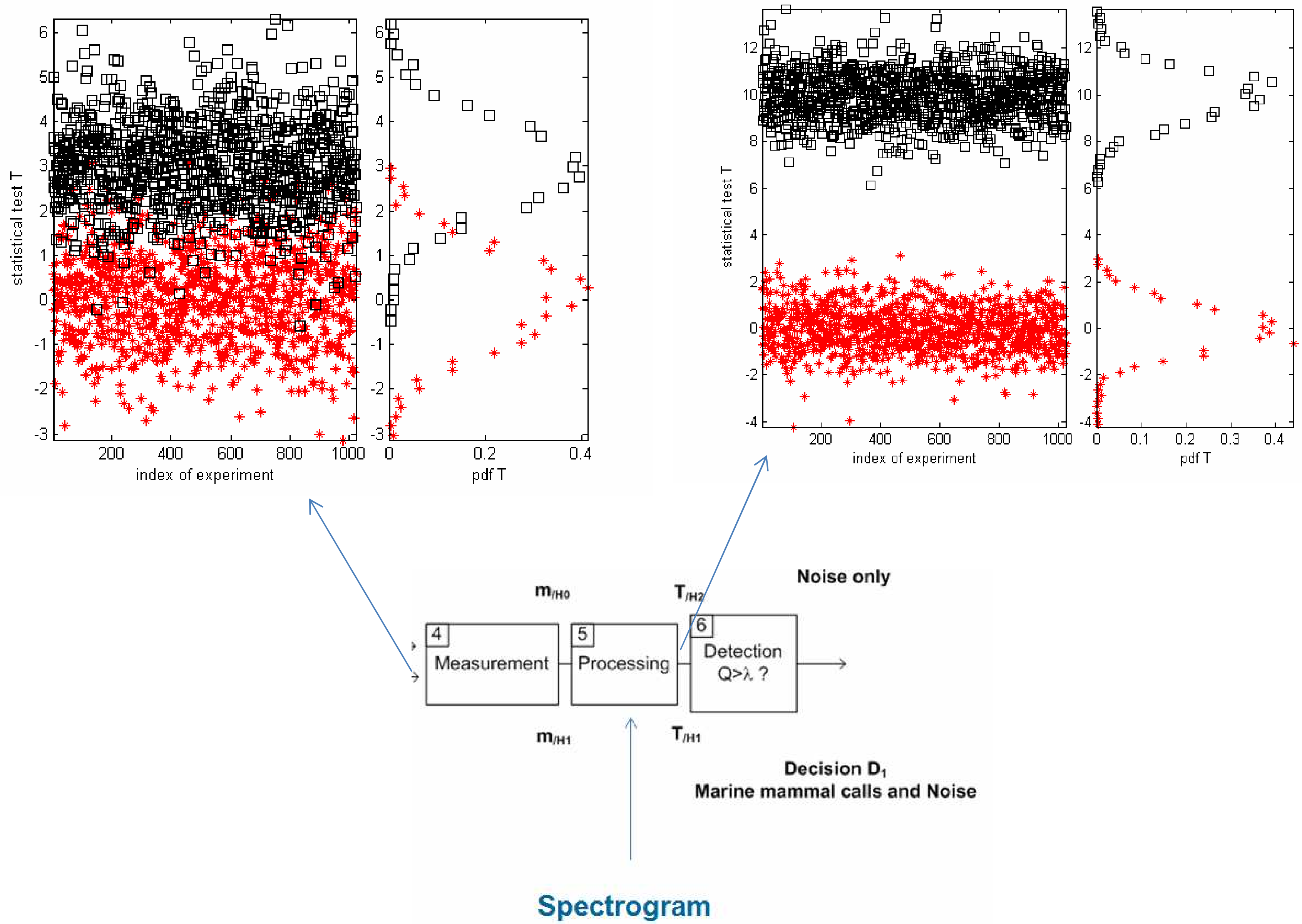
$$P_{fa} = 1 - cdf_Q(\lambda | H_0)$$

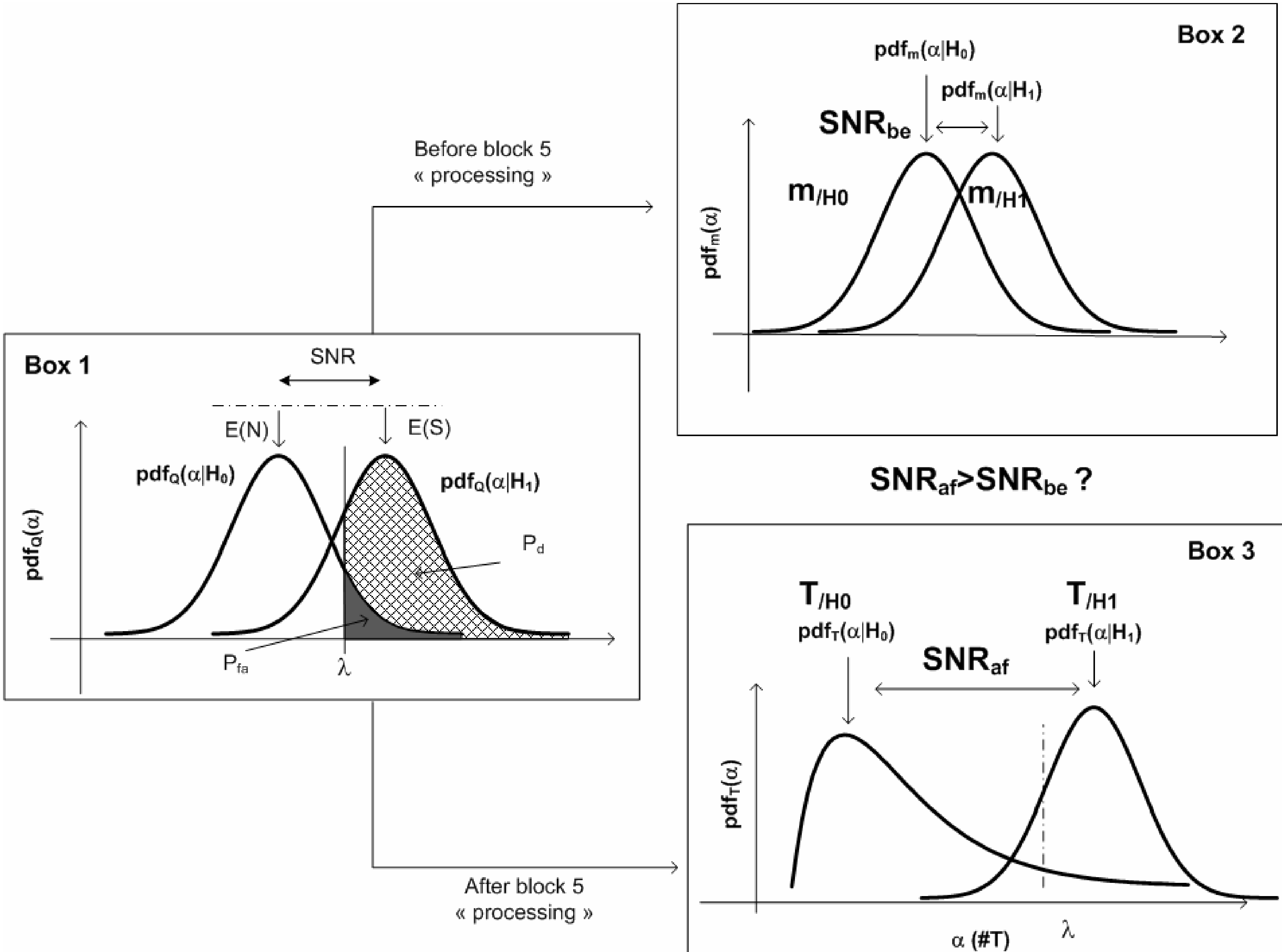
$$\lambda = cdf_Q^{-1}(1 - P_{fa} | H_0)$$

$$Pd = 1 - cdf_Q(cdf_Q^{-1}(1 - P_{fa} | H_0) | H_1)$$

Interest of data processing for signal detection




statistical test T
index of experiment
pdf T
statistical test T
index of experiment
pdf T
Noise only
m/H0
T/H2
4 Measurement
5 Processing
6 Detection Q>λ ?
m/H1
T/H1
Decision D1
Marine mammal calls and Noise
Spectrogram


Box 1
SNR
E(N)
E(S)
pdfQ(α|H0)
pdfQ(α|H1)
Pd
Pfa
λ
pdfQ(α)
Before block 5
« processing »
Box 2
pdfm(α|H0)
pdfm(α|H1)
SNRbe
m/H0
m/H1
pdfm(α)
SNRaf>SNRbe ?
Box 3
T/H0
T/H1
pdfT(α|H0)
pdfT(α|H1)
SNRaf
pdfT(α)
α (#T)
λ
After block 5
« processing »

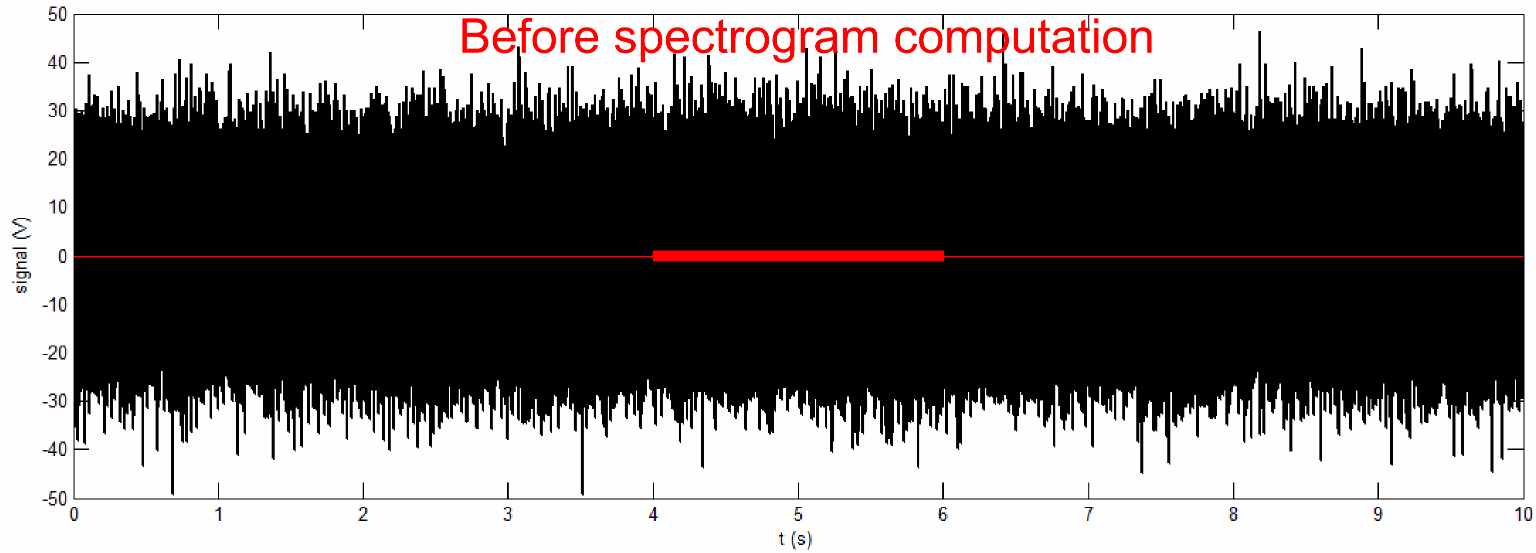
The processing: computation of the spectrogram

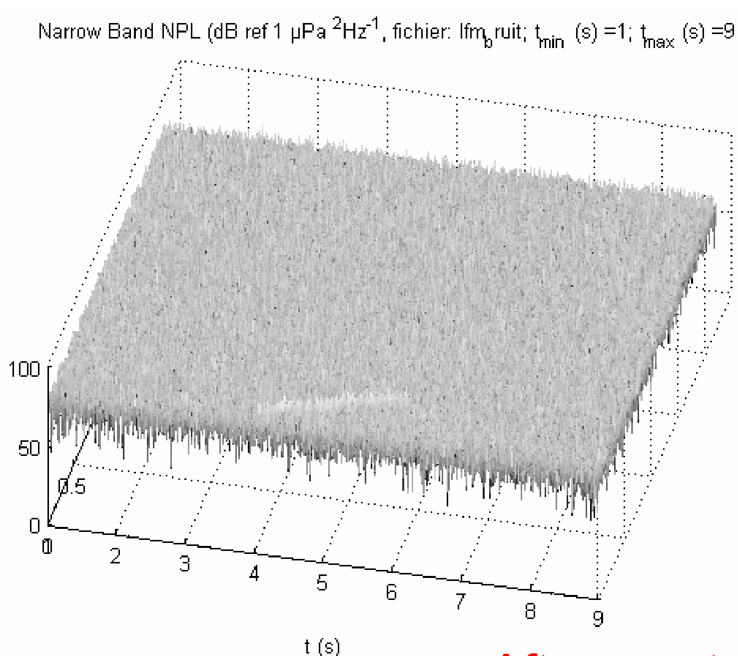
$$f_Q^{H_0}(q) = \frac{1}{L\sigma^2}\exp(-\frac{q}{L\sigma^2}), q \geq 0$$

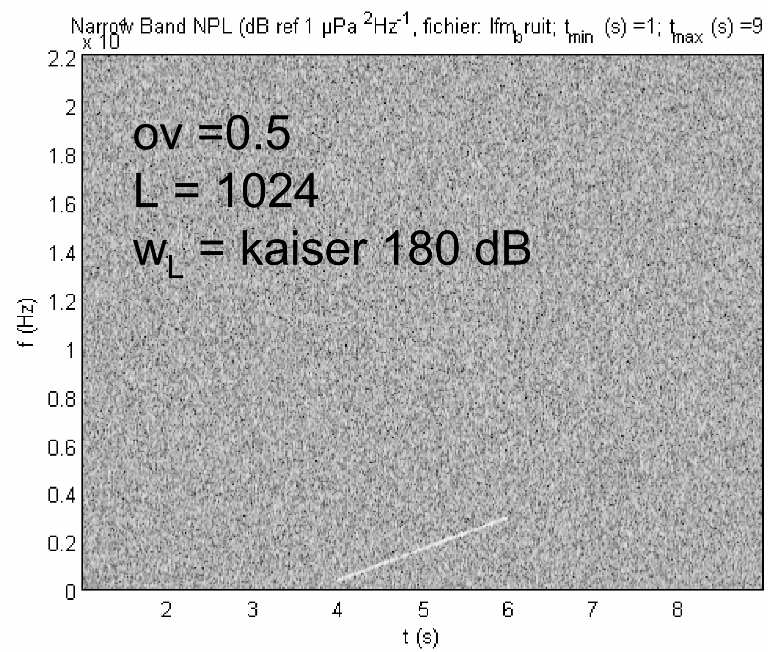
$$F_Q^{H_0}(q) = 1 - \exp(-\frac{q}{L\sigma^2})$$

$$\lambda = L\sigma^2 \log(P_{fa})$$

For a stationary Gaussian noise

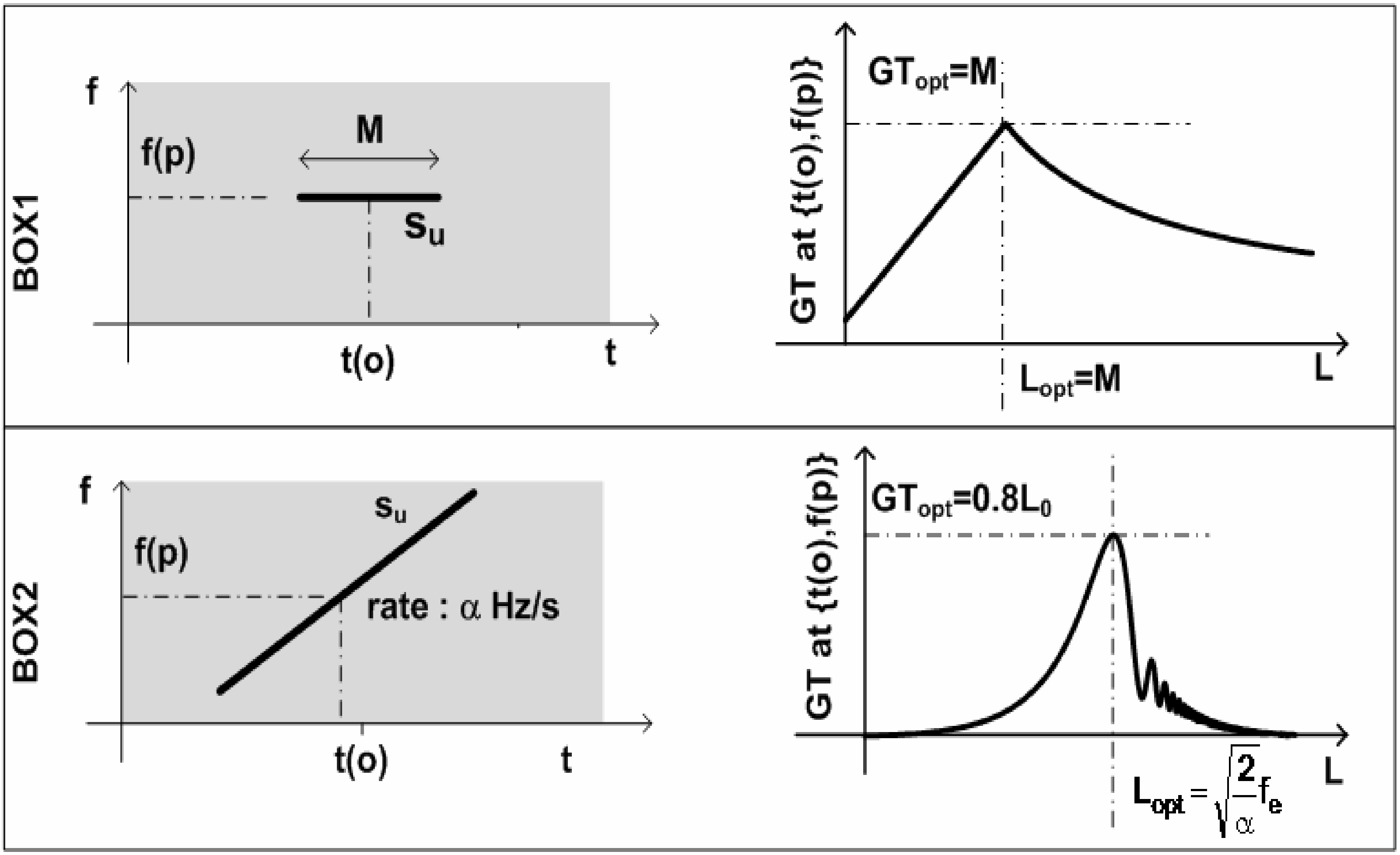




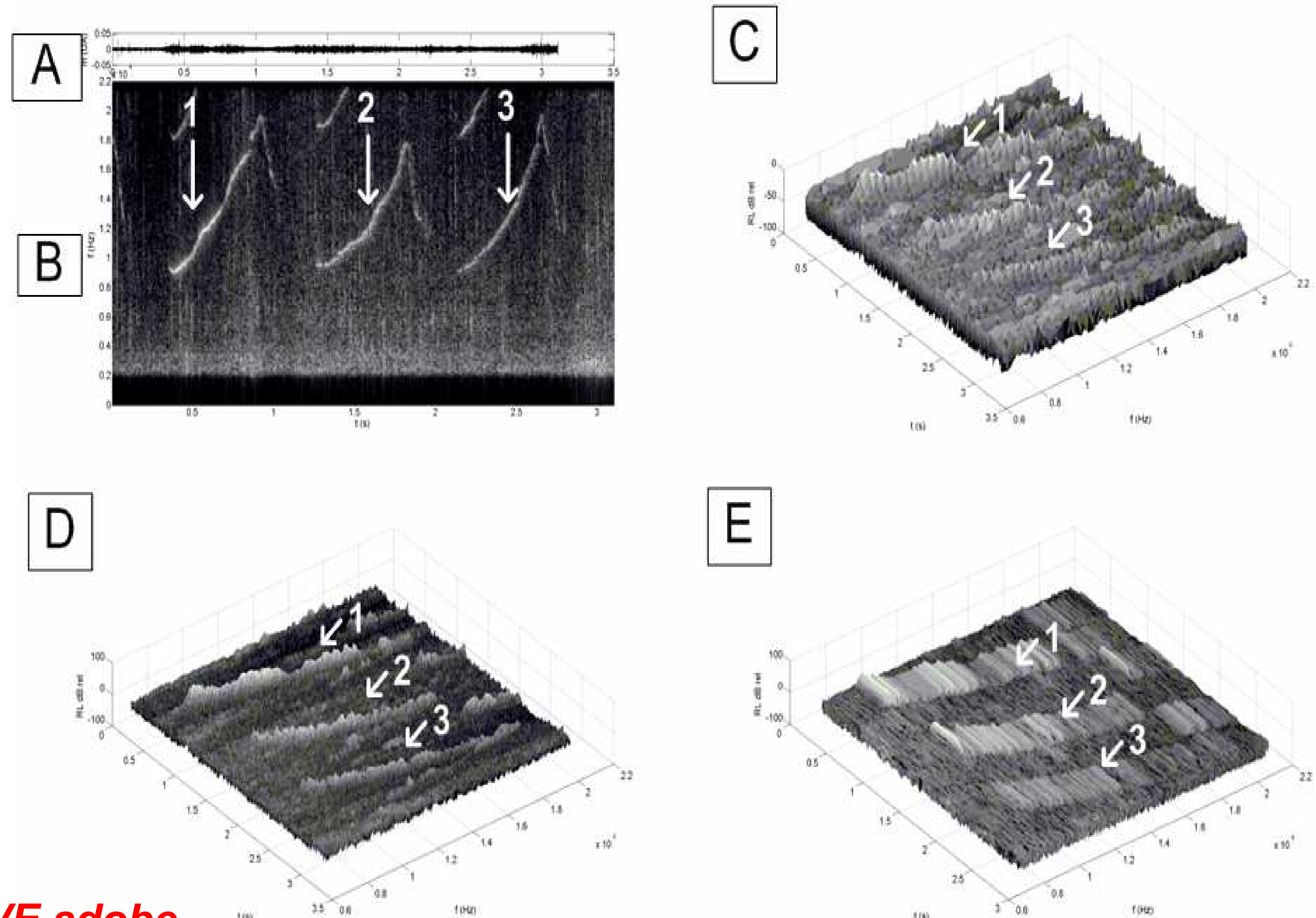


After spectrogram computation

Processing gain = function (L, signal)



Bottlenose dolphins, Molène

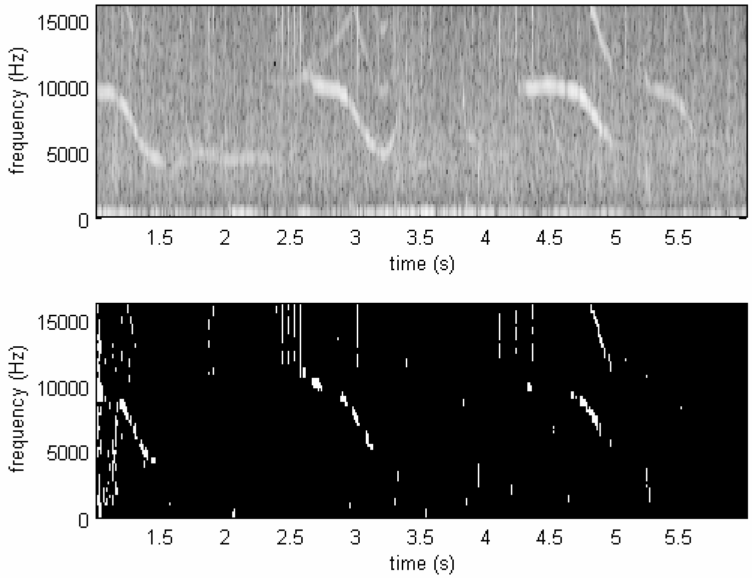


LIVE adobe

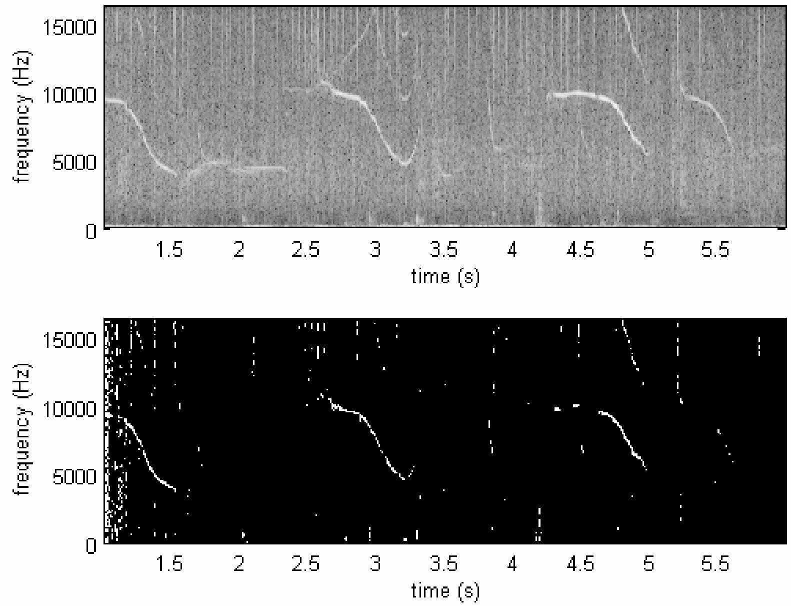
Pfa=10^{-6}

Example 2 : influence of L

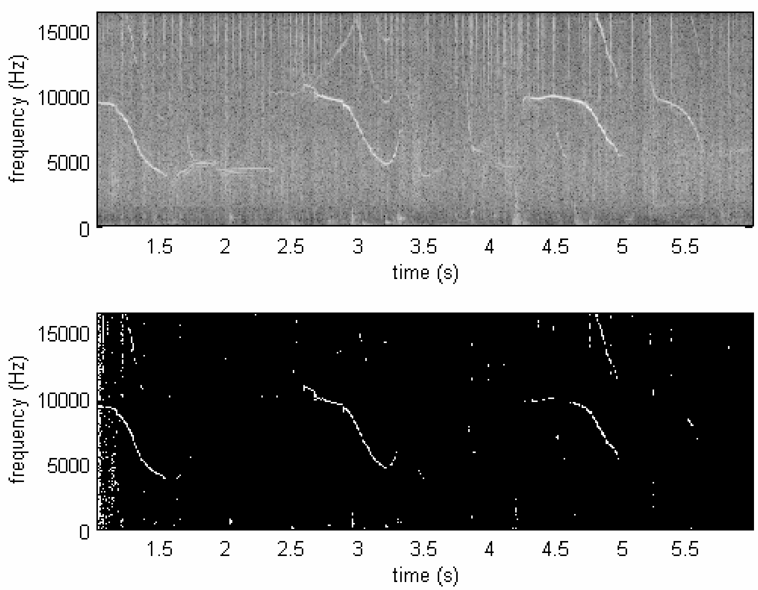
L=128



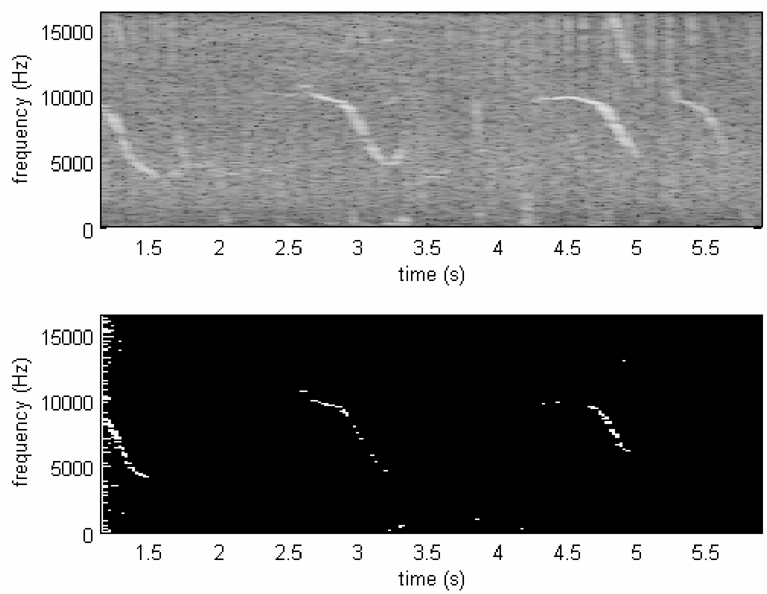
L=512



L=1024

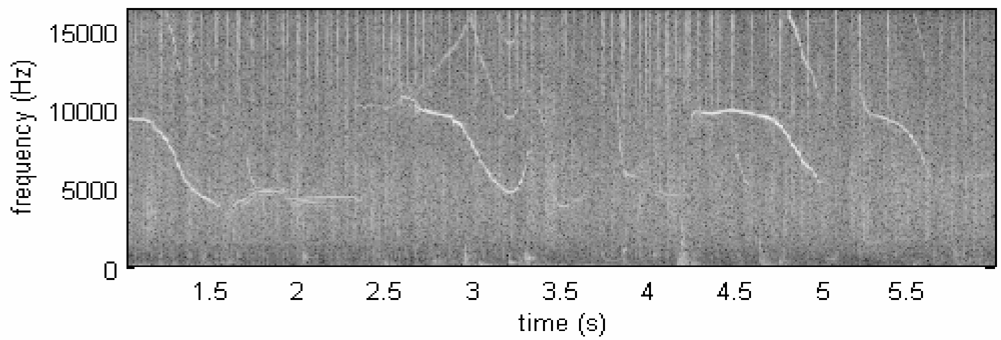


L=8192

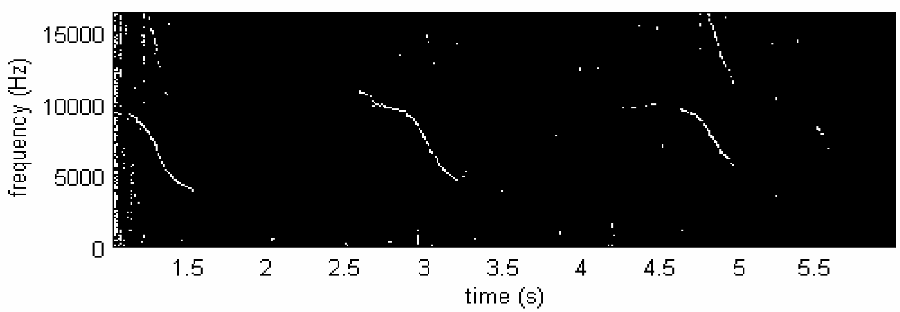


Example 1 : influence of the Pfa

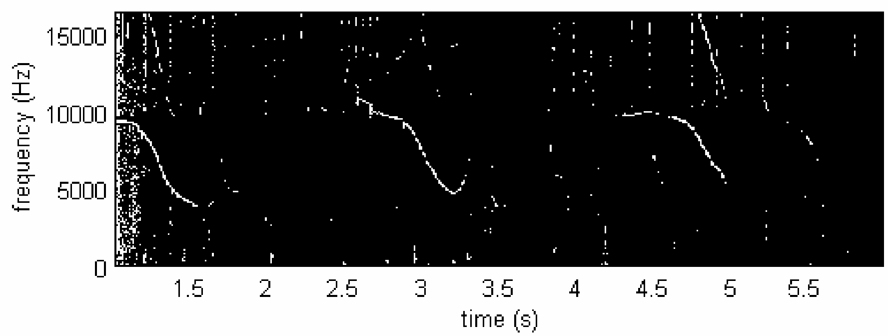
L=1024



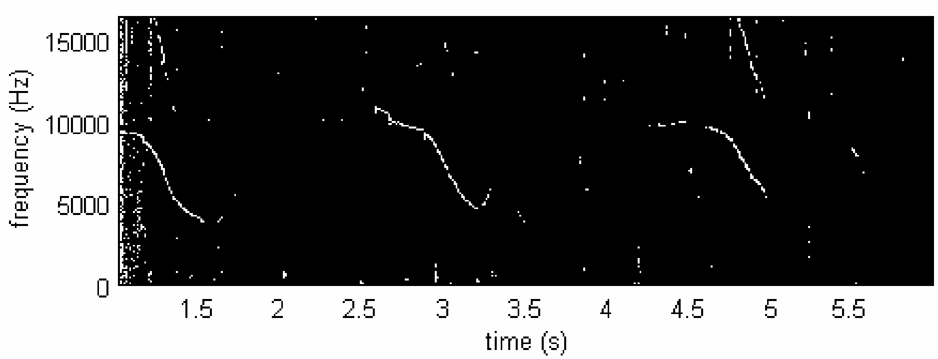
Pfa=10^{-8}



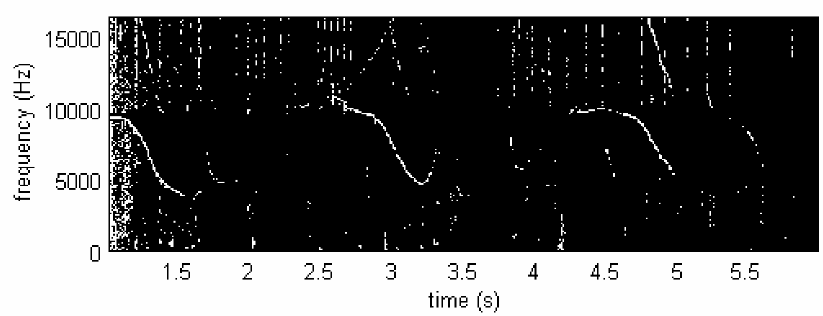
Pfa=10^{-4}



Pfa=10^{-6}



Pfa=10^{-3}



Specific literature

General

- R. Urick - Principles of Underwater Sound
- W.W.L. Au & M.C. Hastings - Principles of Marine Bioacoustics

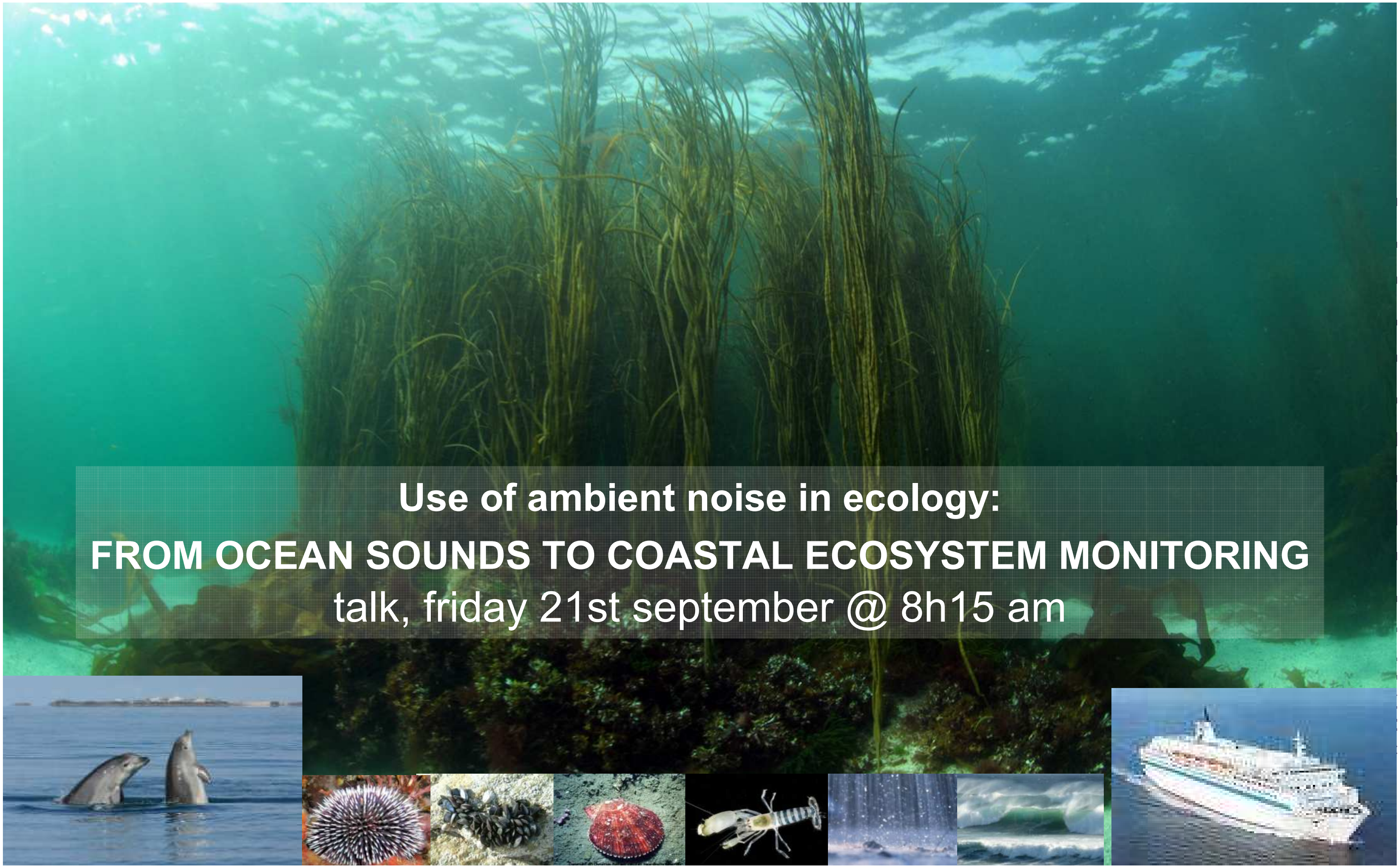
Signal processing (detection, time-frequency)

- Hlawatsch, F. & Boudreaux-Bartels, G. F. (1992), 'Linear and quadratic time-frequency signal representations', Signal processing magazine, IEEE 9(2), 21-67.
- Kay, S. (1998), Fundamentals of statistical signal processing, detection theory, Prentice Hall, New jersey.

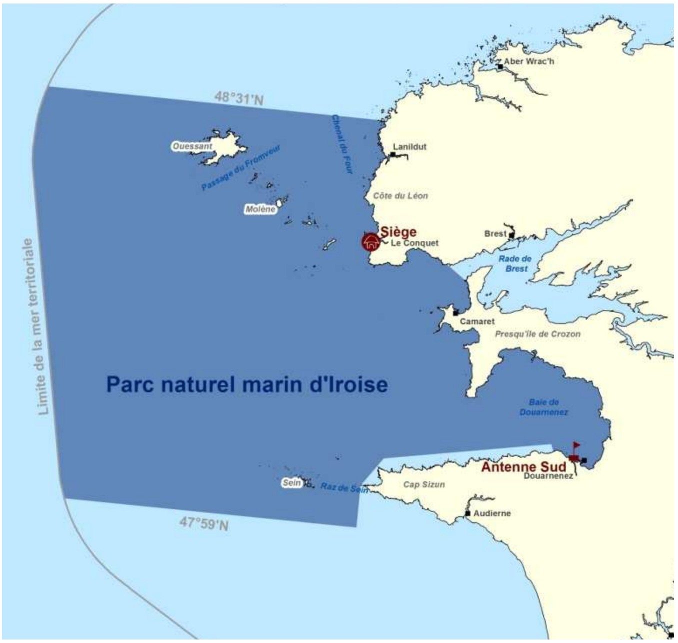
Outline

- Introduction
- Introduction to sound
- Measurement chain
- Spectral analysis of acoustic measurements
- Time-frequency representation
- Applied examples from our own research

Environmental applications - Molène 2011: dolphins & ships



Study site



- weather station
- models (weather, tides, currents…)

Study site

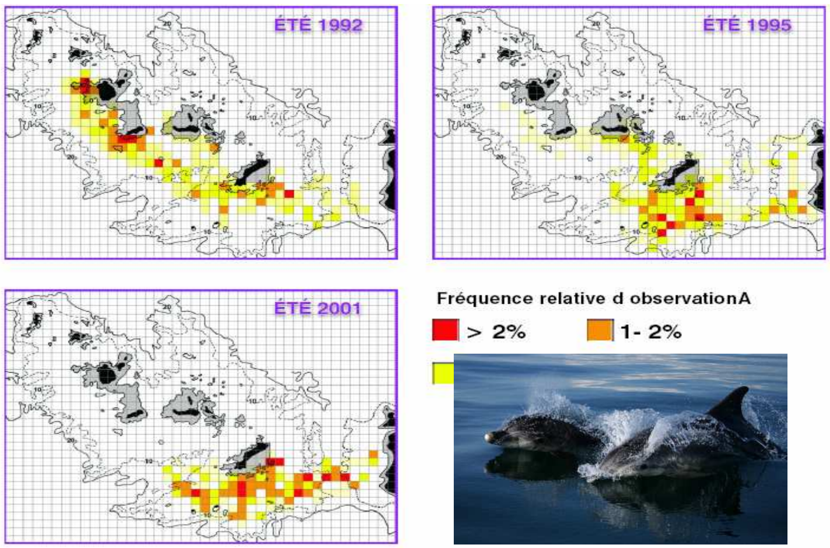
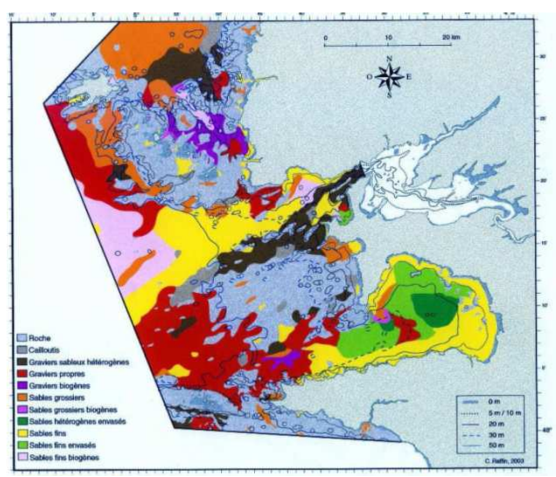


Figure 7
Répartition spatiale des grands dauphins au sein de l'archipel de Molène au cours des étés 1992, 1995 et 2001.

Resident population of ~40 bottlenose dolphins (*Tursiops truncatus*)

800 – 1000 animal species
300 - 400 species of algae & plants, (J. Grall, OSU RdB)



Alpheus macrocheles
1000 / ha
(Grall, J. OSU Brest, 2011)

Echinus esculentus
2000 / ha (100mx100m)
(Grall, J. OSU Brest, 2011)

Objectives

• How to describe the soundscape of Molène: which acoustic descriptors? Which algorithms ?

• Reconstruct an acoustic landscape through time series (3x6 months) of the descriptors

• Analyse the time series: their contribution to the description and understanding of the environment

-Biophony (bottlenose dolphin, benthic activity,)

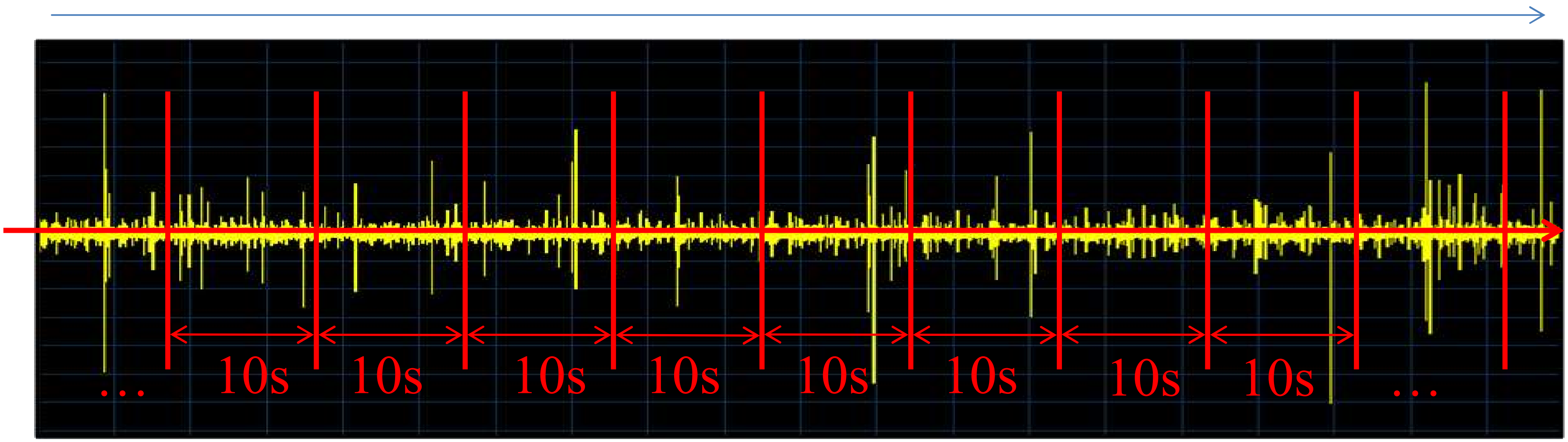
- Géophony (wind, rain)

- Anthropophony (mainly boats)

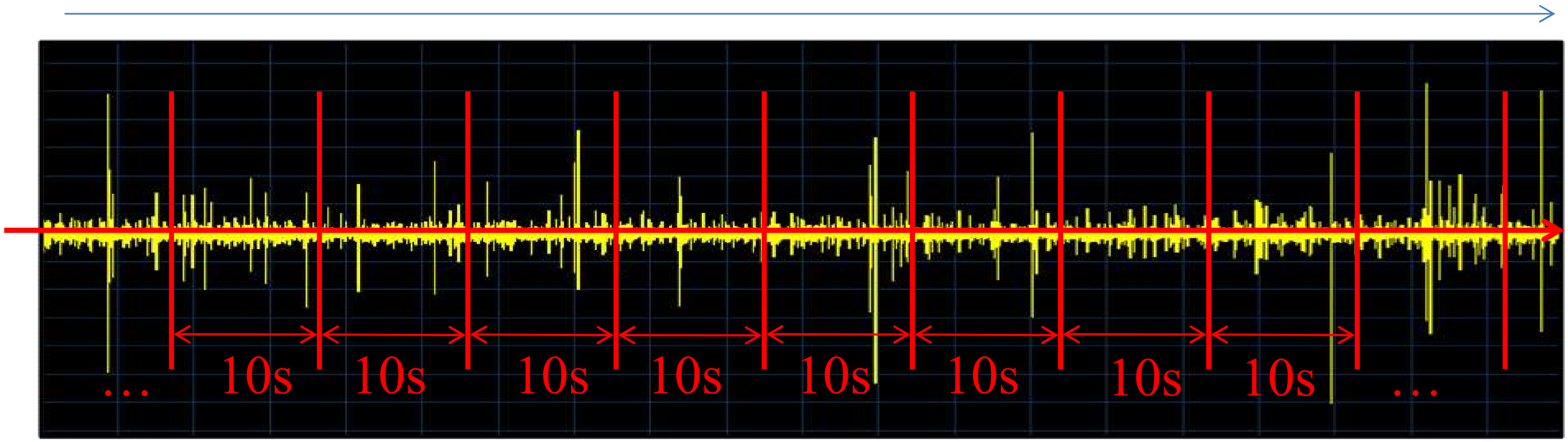
Some numbers

- 1 year = signal processing development & pilot experiments

- 6 months observations (3 terabytes raw data, 3 recorders 3x15 k€ , boat trips ~ 6 k€)



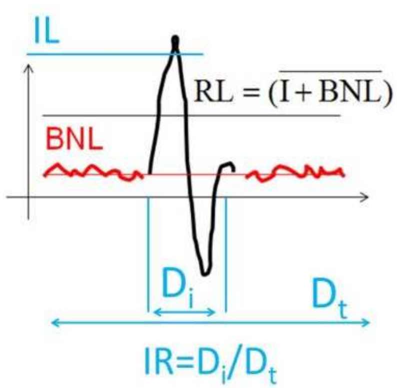
- two months of data processing & analysis
  => 35 days PC calculations
  => 1.5 Mio segments



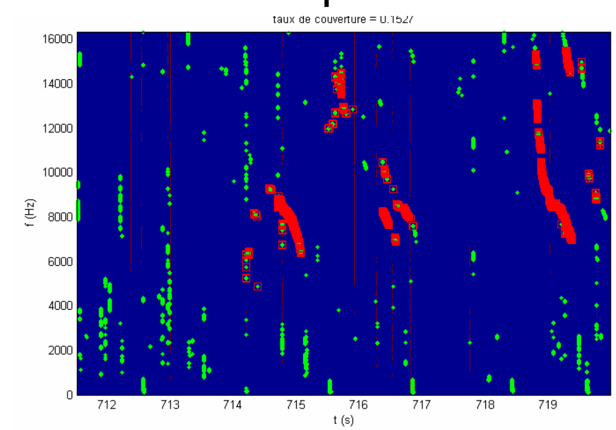
Processing algorithms

Acoustic descriptors

Ambient noise

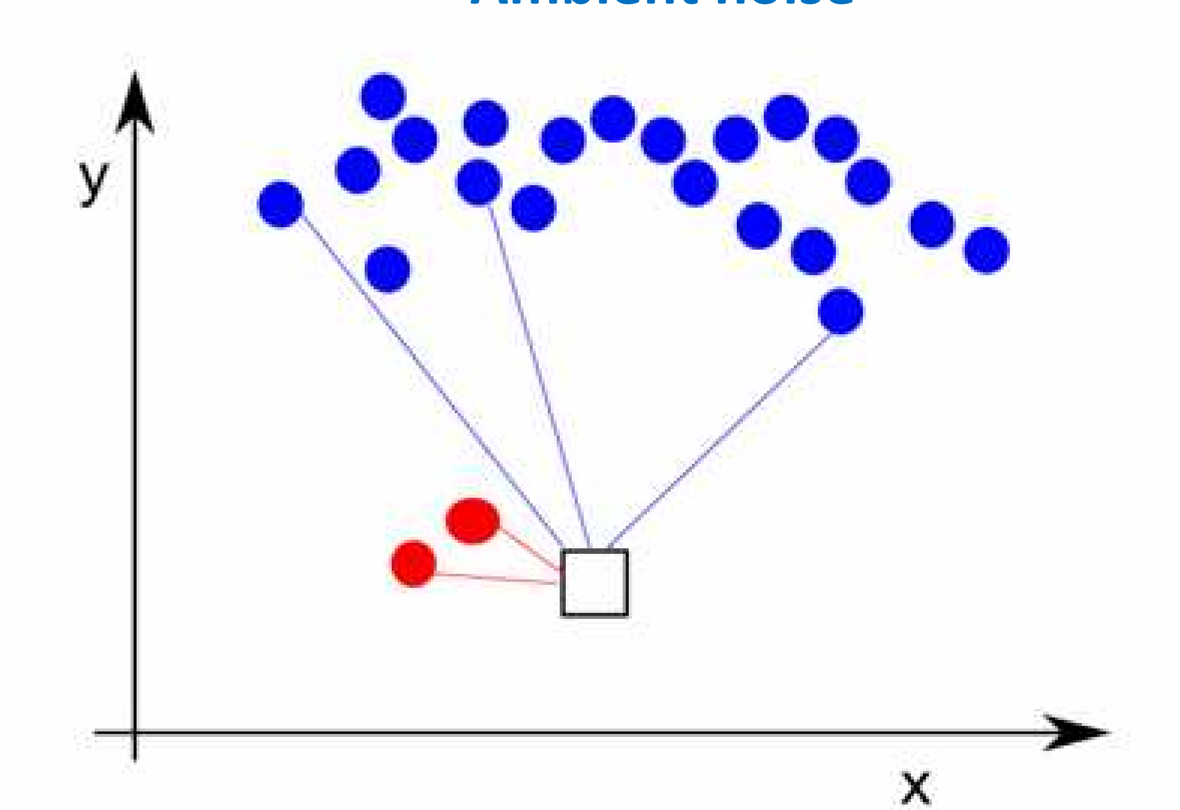


Dolphin detection



Ambient noise vs. close sources

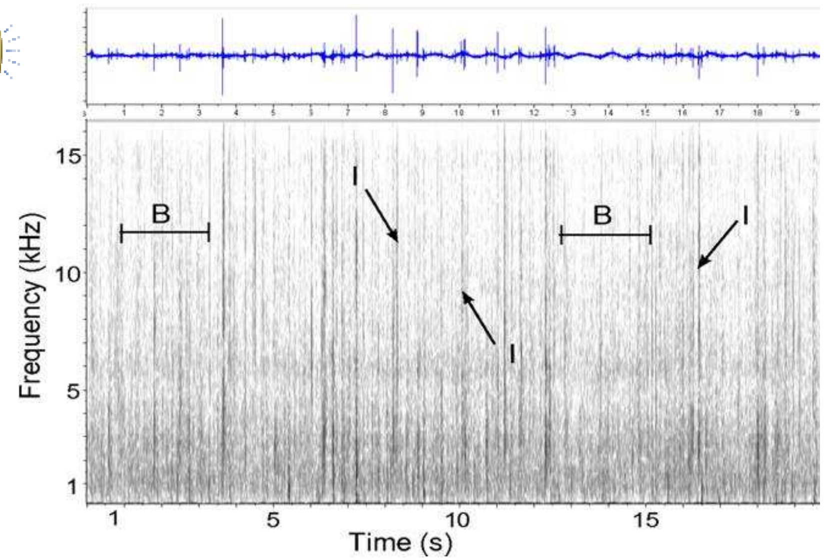
Ambient noise

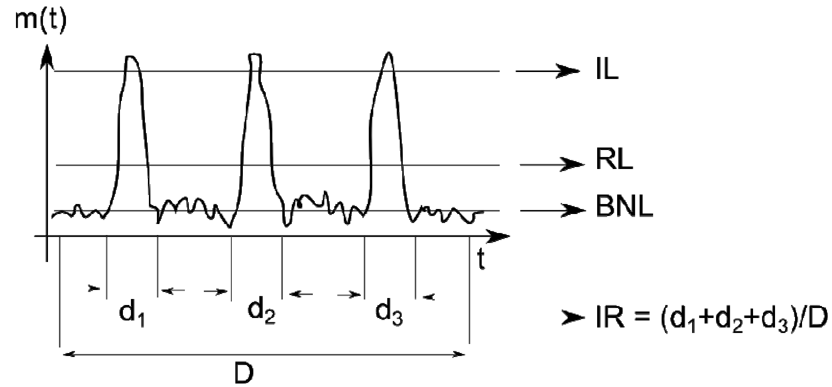


Individually distinctive sources

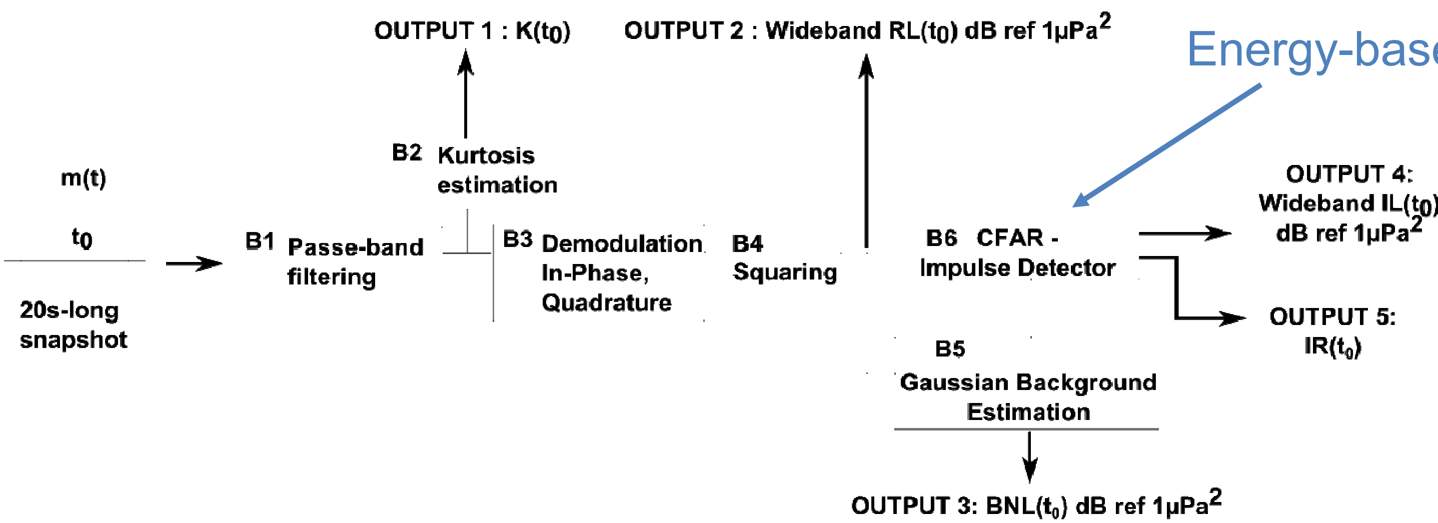
Algorithms – Ambient noise

wideband analysis (RL, BNL, IR, IL)



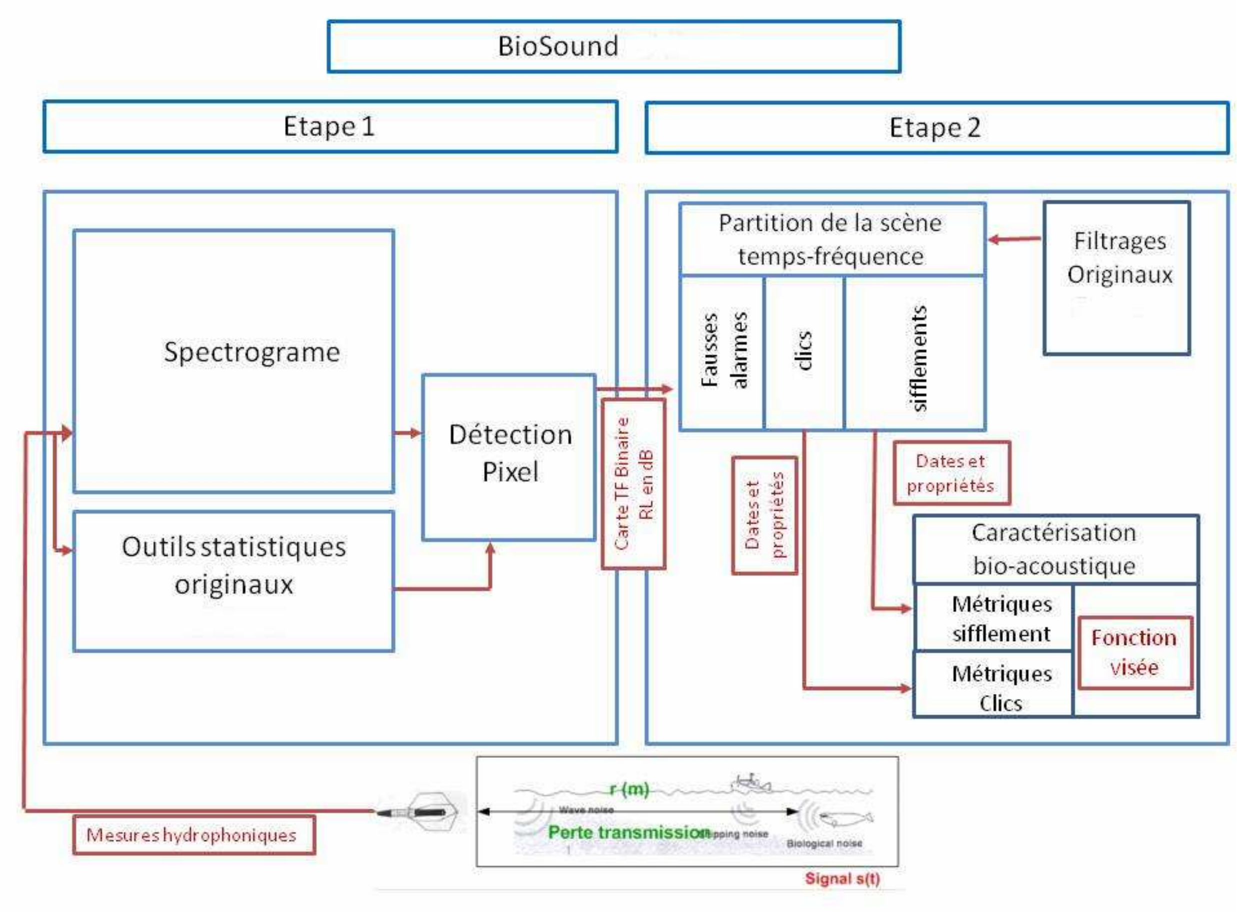


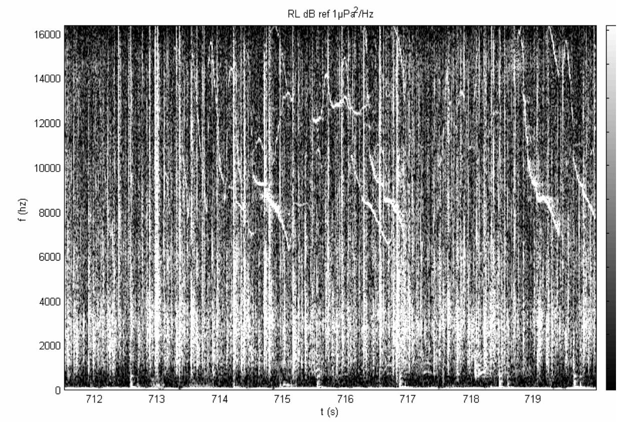
Energy-based detector

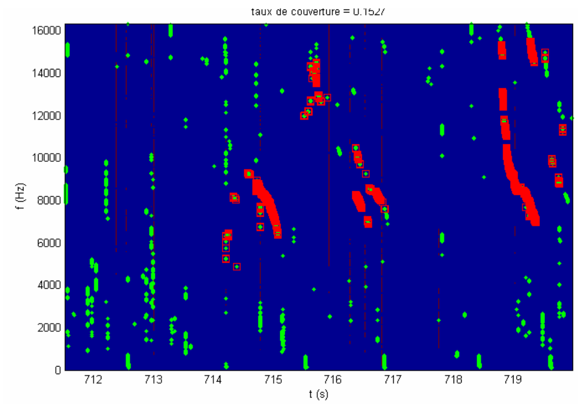


Algorithms – Frequency modulations

whistle detections (WR)







Spectrogram-based detector

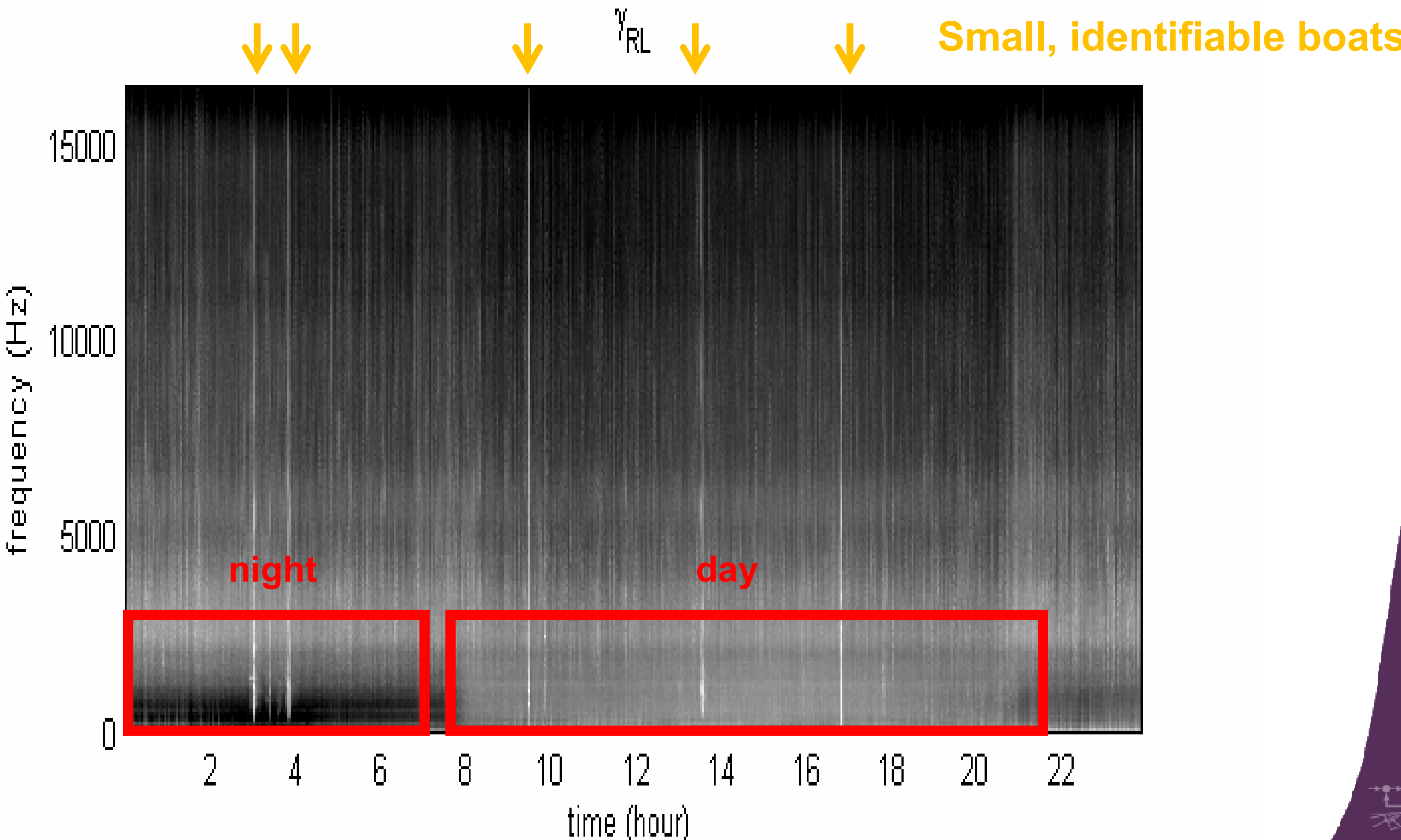
Anthropogenic activity in the Parc Naturel Marin d'Iroise

parc naturel marin Iroise

Agence des aires marines protégées

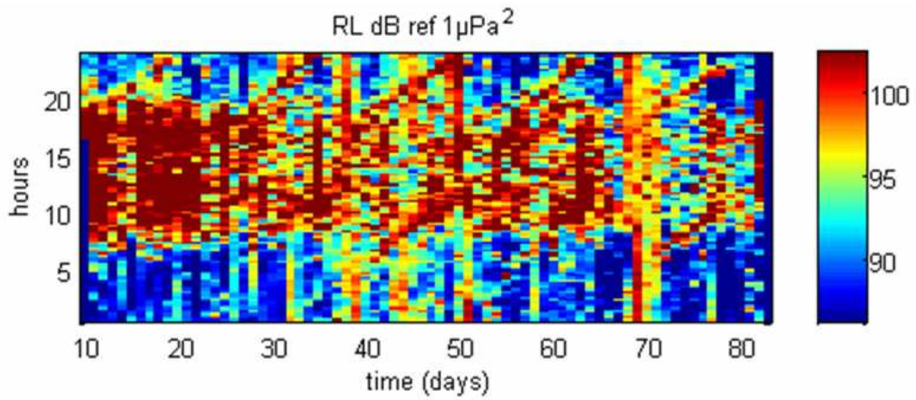
24h spectrogram

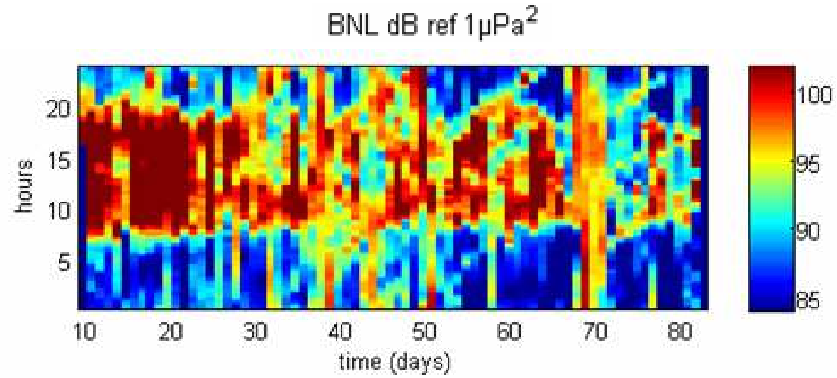
data inspection, choice of analysis band

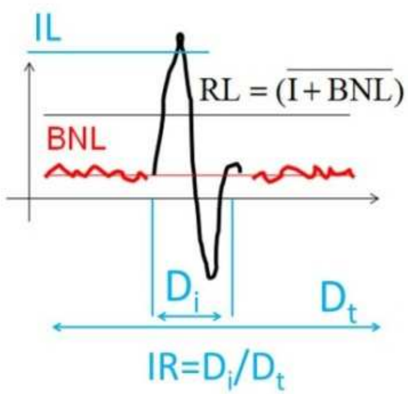


Anthropogenic ambient noise – low frequencies

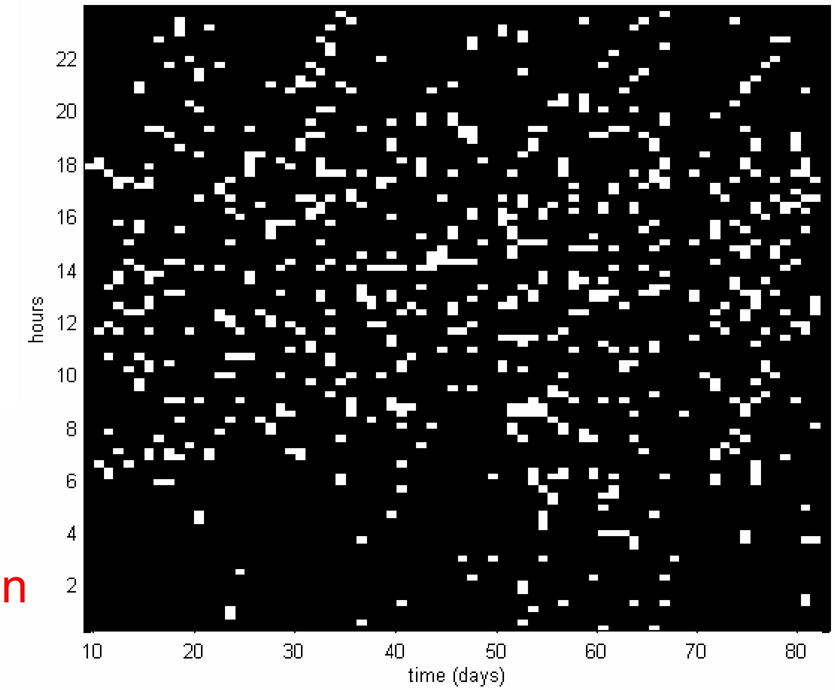
Small, identifiable boats





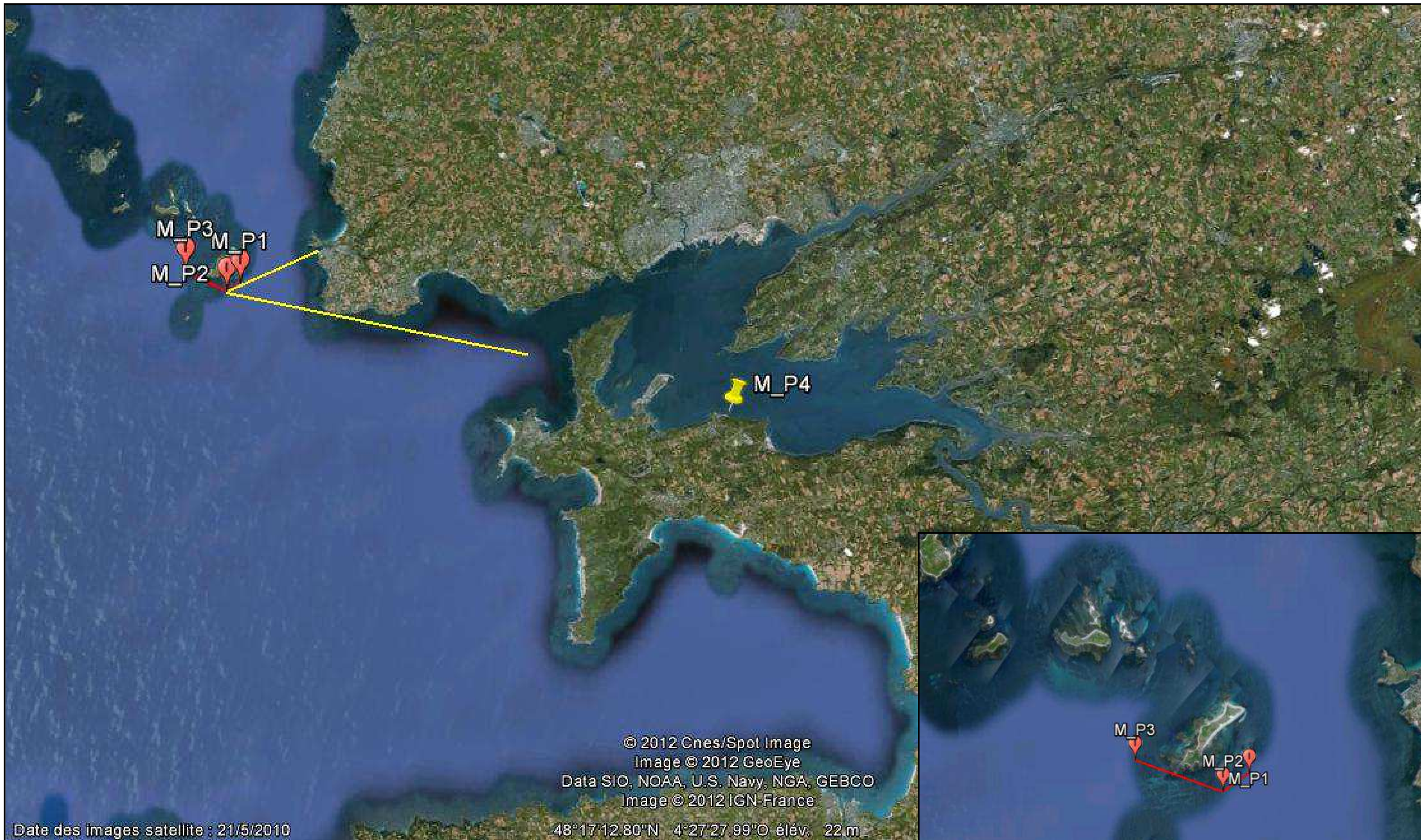


RL-BNL> Seuil => binarization

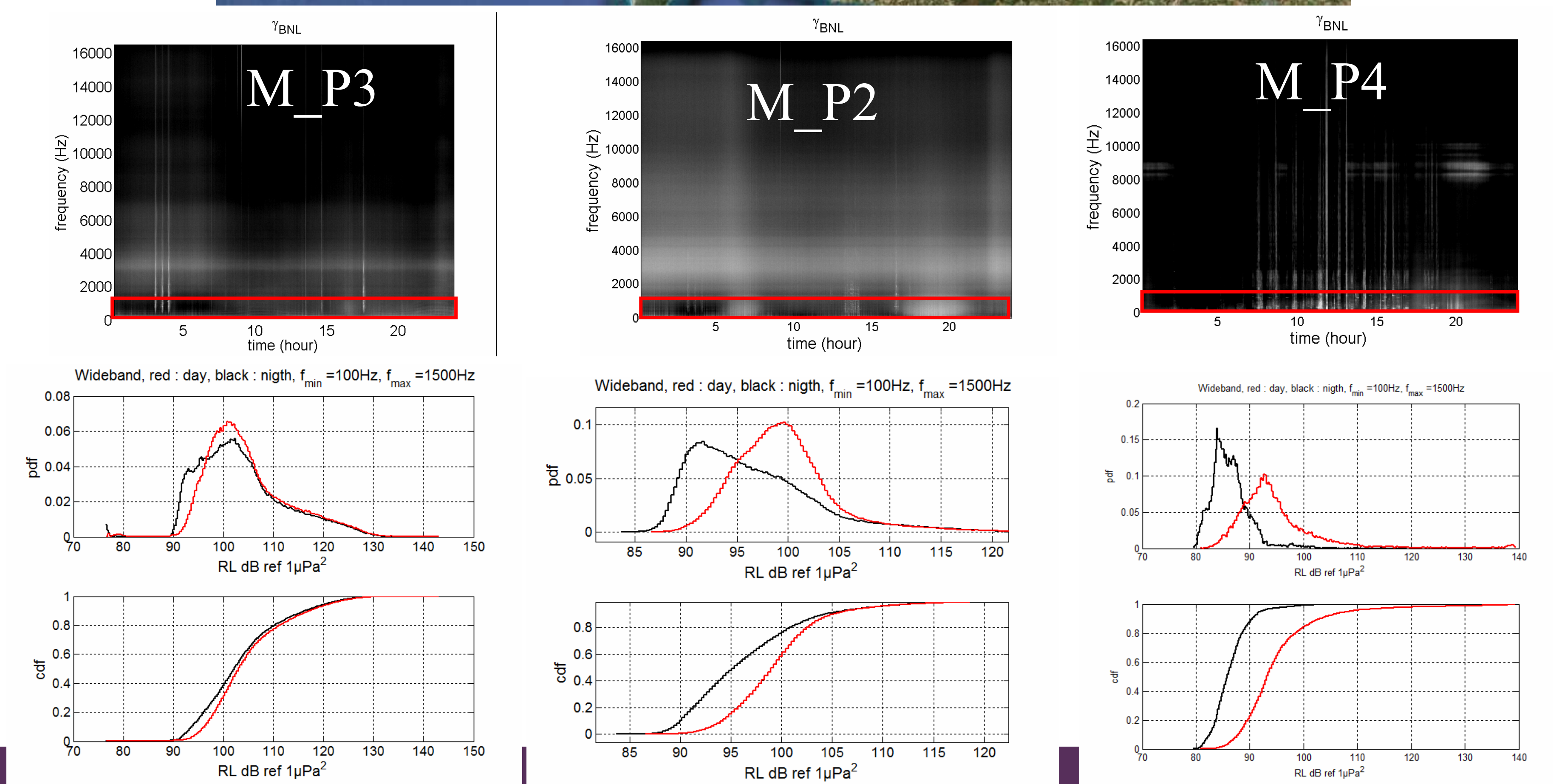


Energy-based detector
Analysis window size = 10min

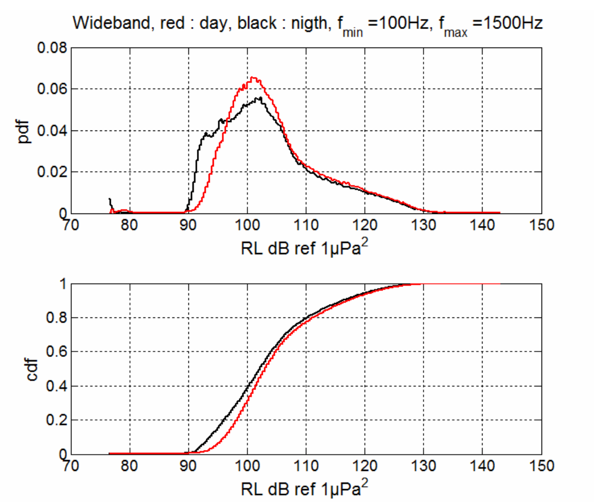
Anthropogenic background noise

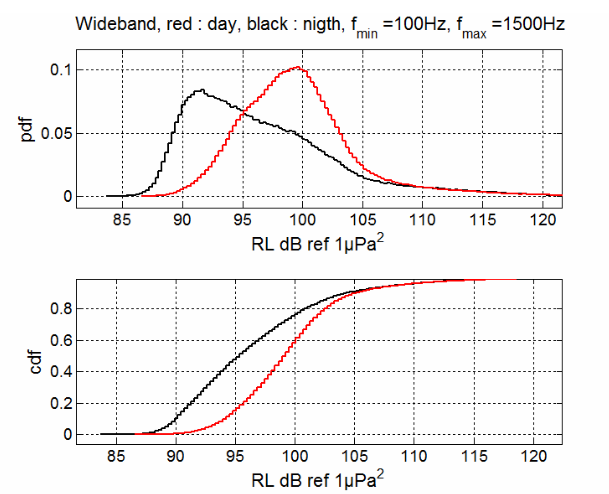


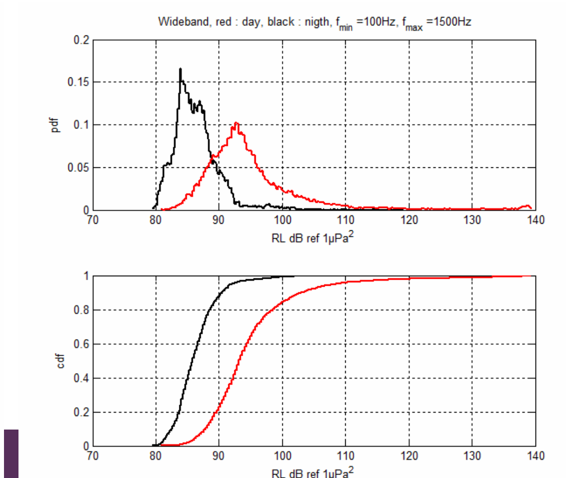

M_P3
M_P1
M_P2
M_P4


γBNL
M_P3
M_P2
M_P4
frequency (Hz)
time (hour)
Wideband, red : day, black : nigth, fmin =100Hz, fmax =1500Hz
pdf
cdf
RL dB ref 1μPa2

M_P3	M_P2	M_P4
Non-affected site: No, night-day difference	Affected site: 8dB between day & night propagation?!	Noise source: Rade de Brest – 8dB between night & day

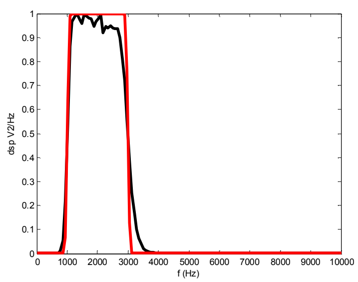


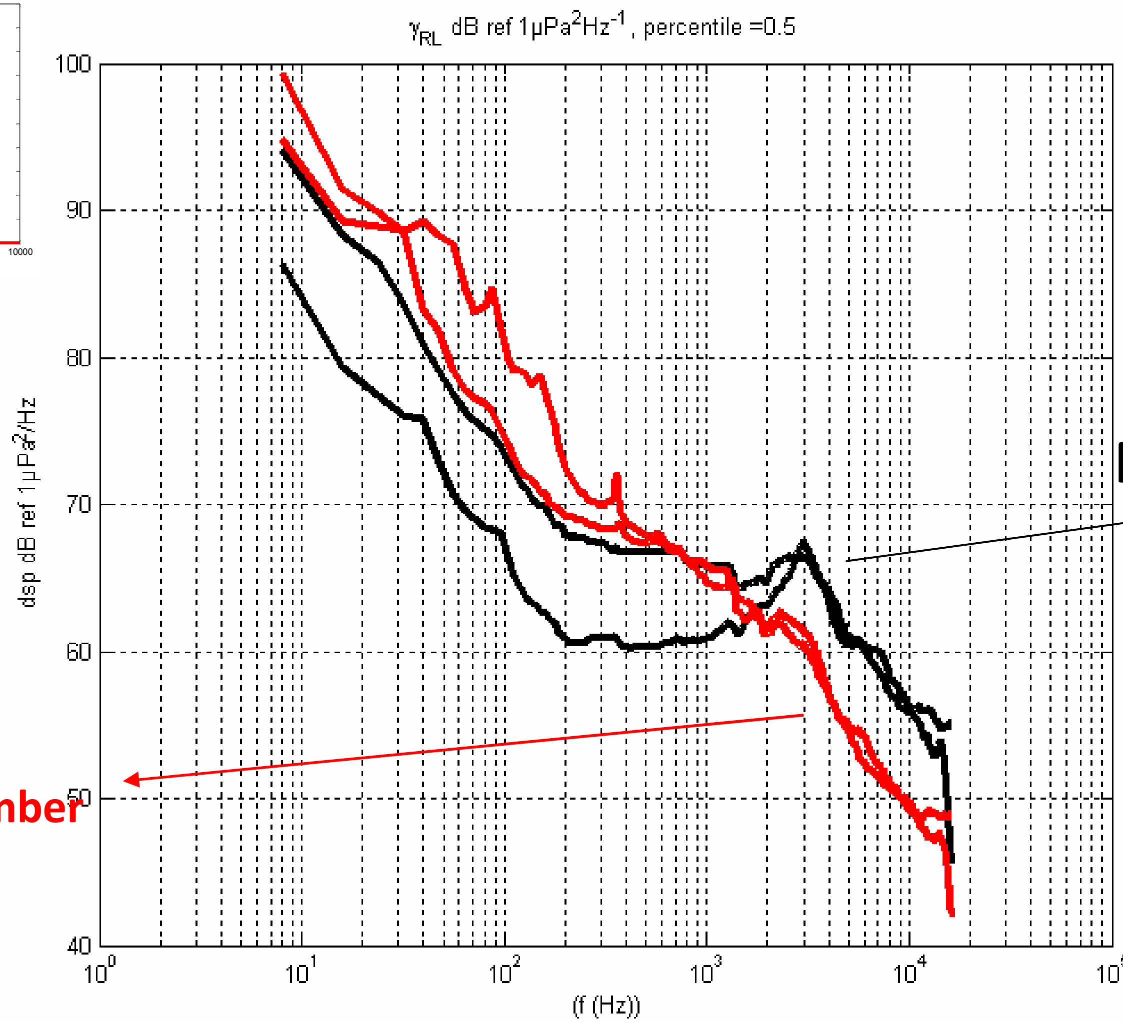




Intermezzo…

power apectral density of Molène ambient noise



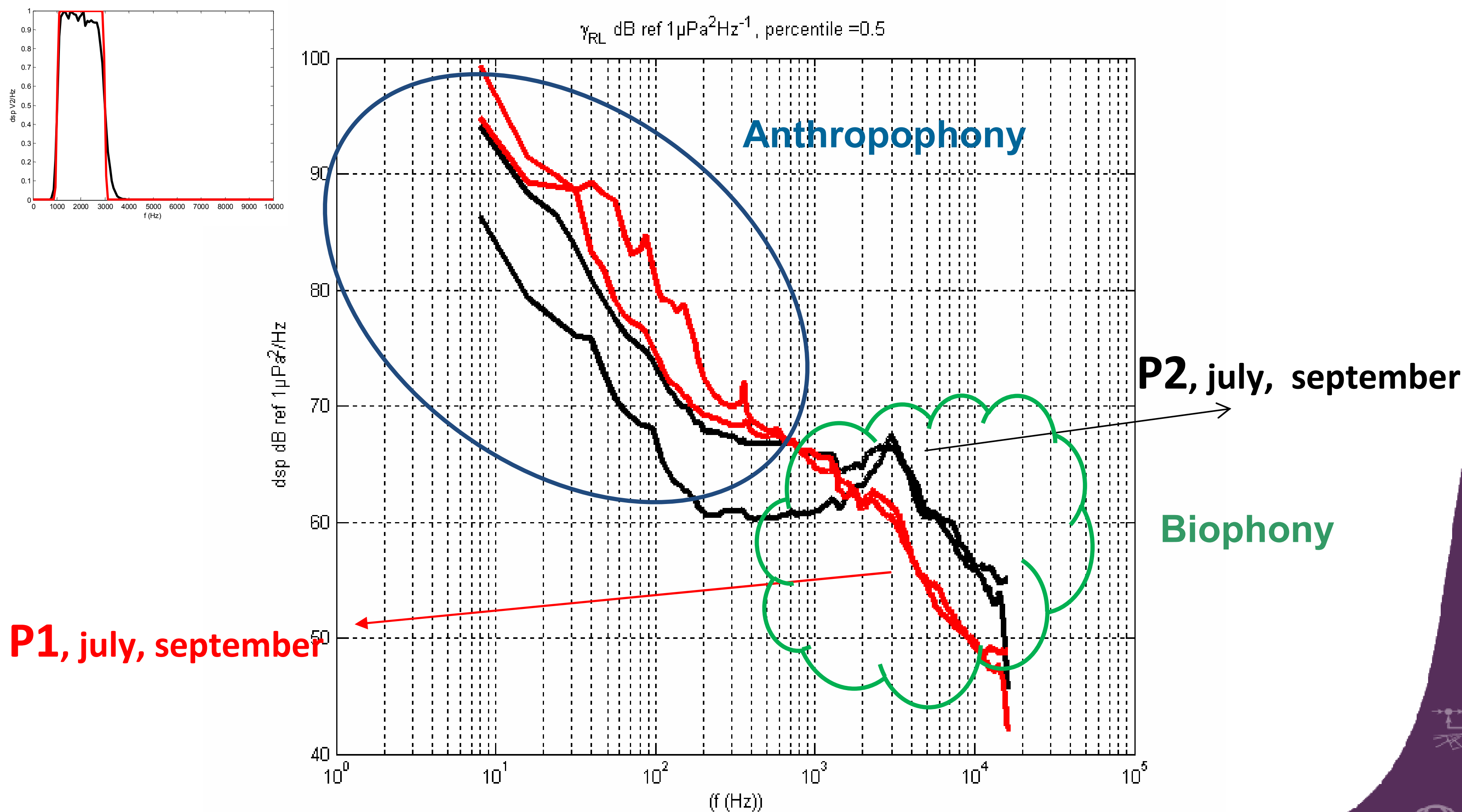


P2, july, september

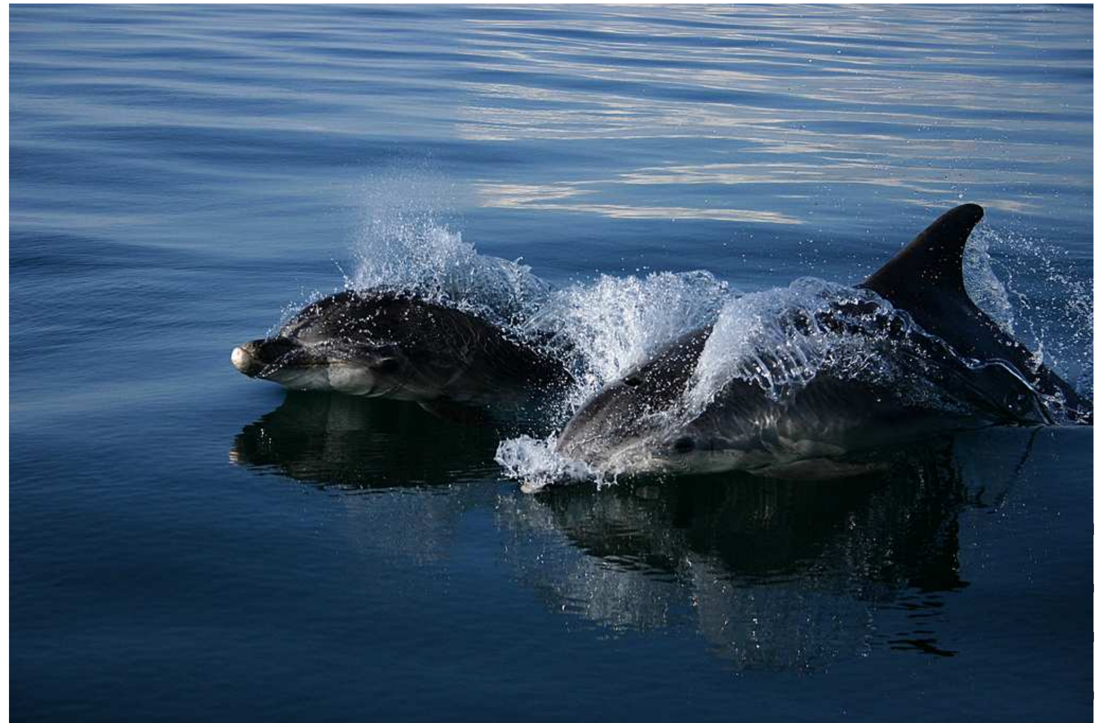
P1, july, september

Intermezzo…

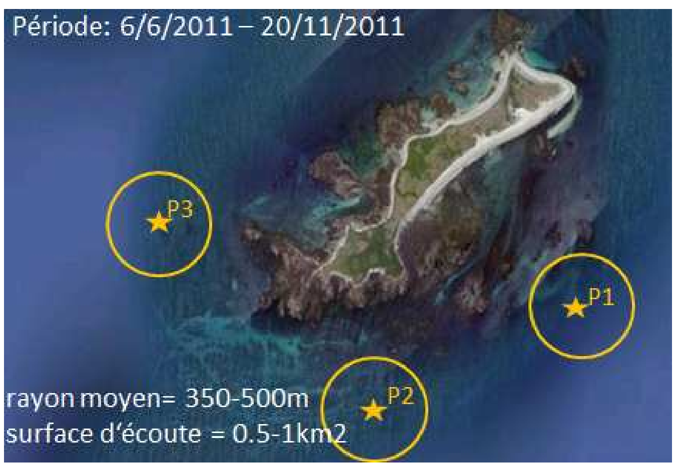
power apectral density of Molène ambient noise

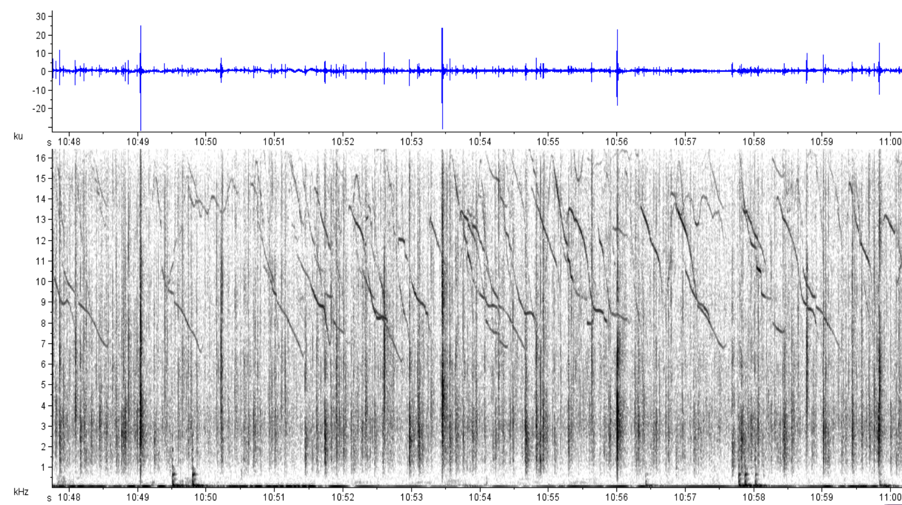


Habitat use by the bottlenose dolphins (*Tursiops truncatus*) of the PNMI



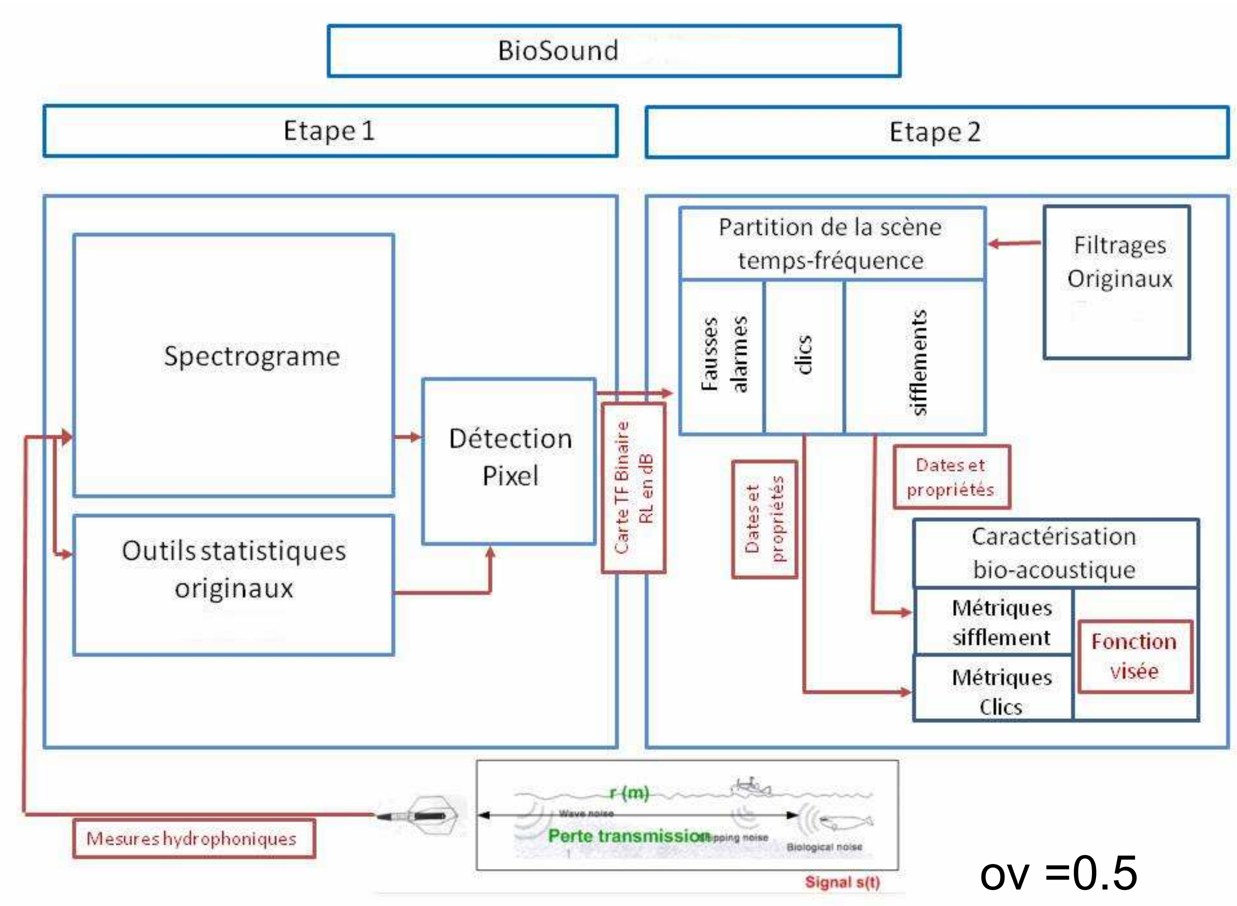

M_P3
M_P2
M_P1
Image © 2012 IGN-France
Image © 2012 GeoEye
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Date des images satellite : 4/6/2009
48°19'54.00"N 4°50'07.80"O élév. -3 m
Altitude 16.79 km


Période: 6/6/2011 – 20/11/2011
P3
P1
P2
rayon moyen= 350-500m
surface d'écoute = 0.5-1km2

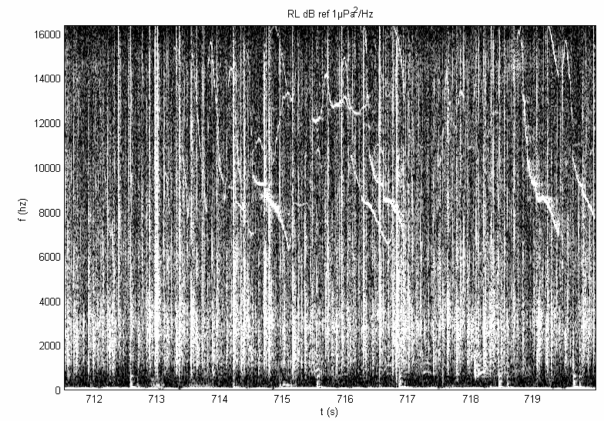

ku
kHz
10:48
10:49
10:50
10:51
10:52
10:53
10:54
10:55
10:56
10:57
10:58
10:59
11:00

Algorithms – Frequency modulations

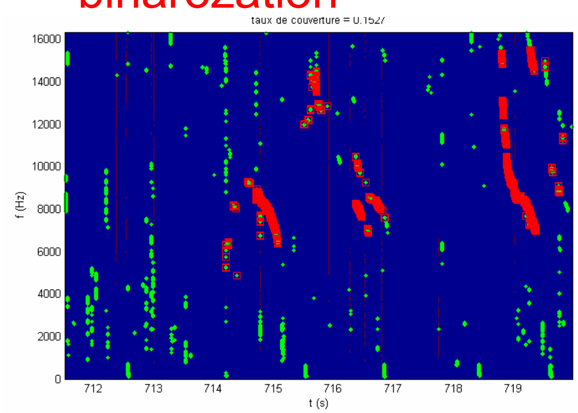
whistle detections (WR)



Spectrogram-based detector



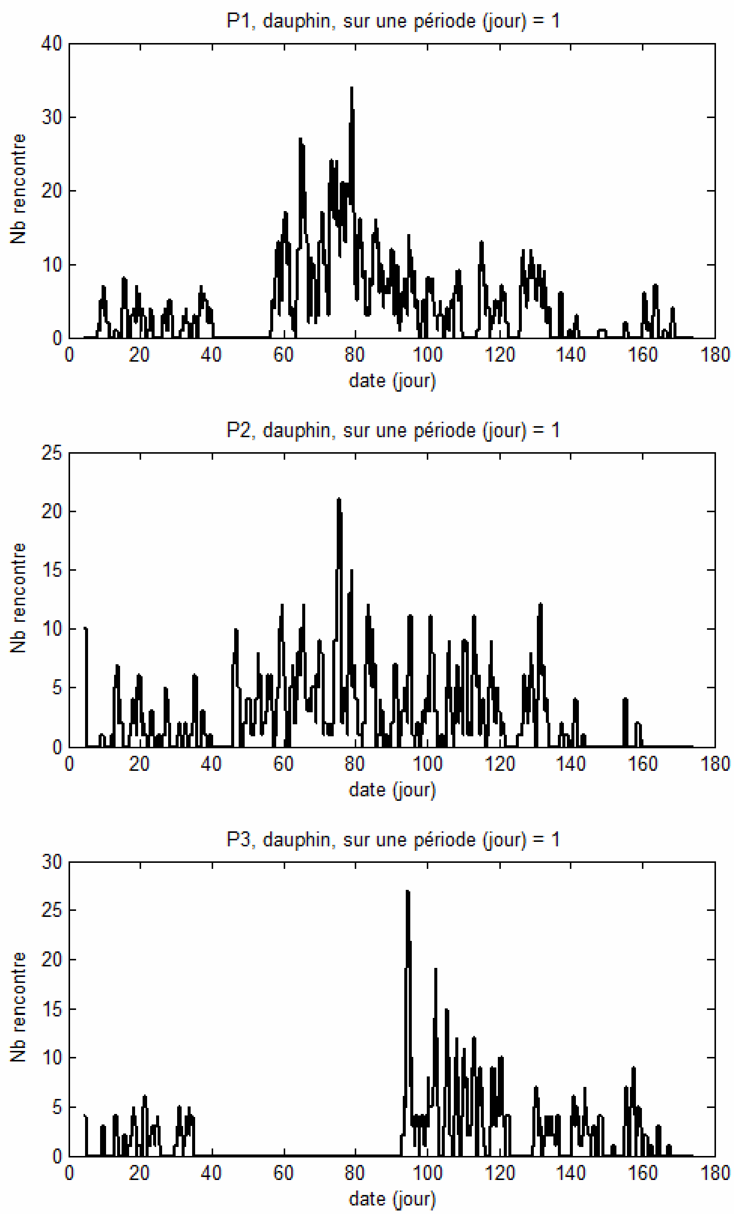
binarozation



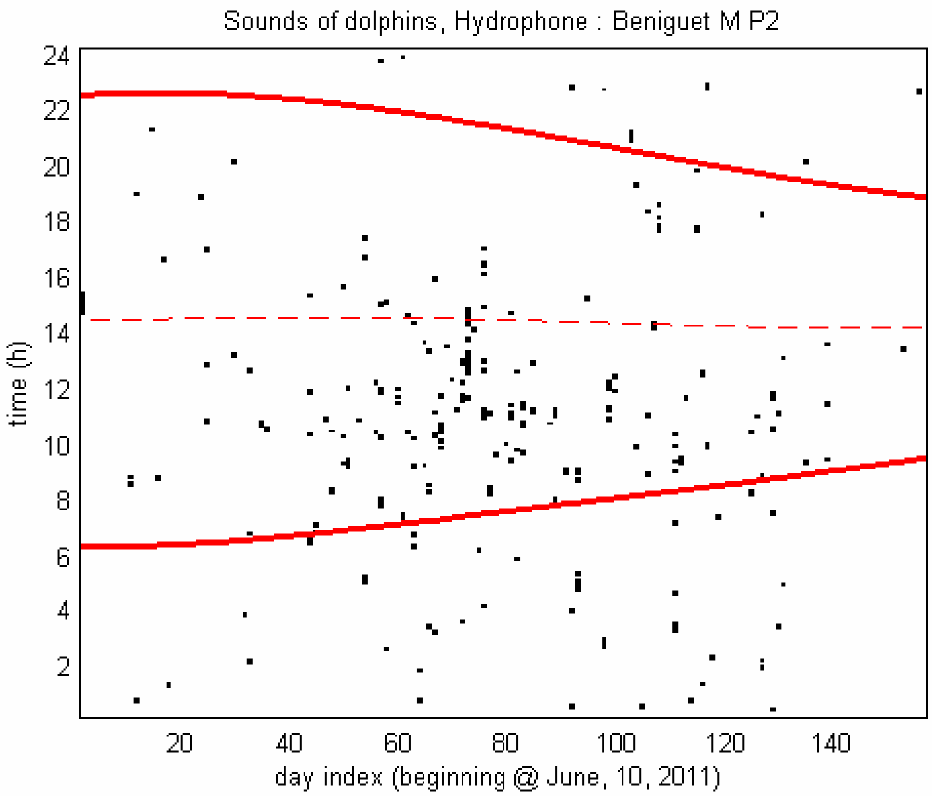
ov =0.5

L = 1024

w_L = kaiser 180 dB



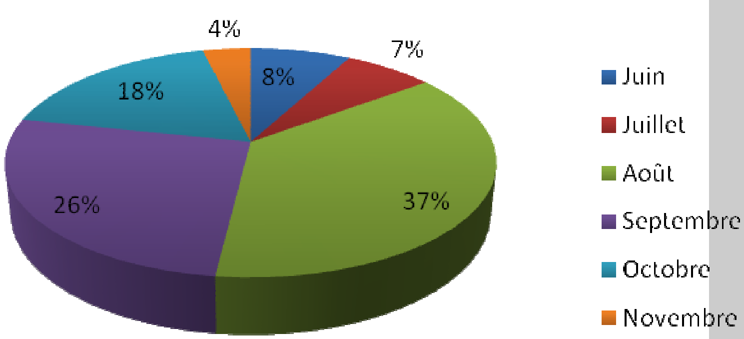
P1, dauphin, sur une période (jour) = 1
Nb rencontre
date (jour)
P2, dauphin, sur une période (jour) = 1
Nb rencontre
date (jour)
P3, dauphin, sur une période (jour) = 1
Nb rencontre
date (jour)

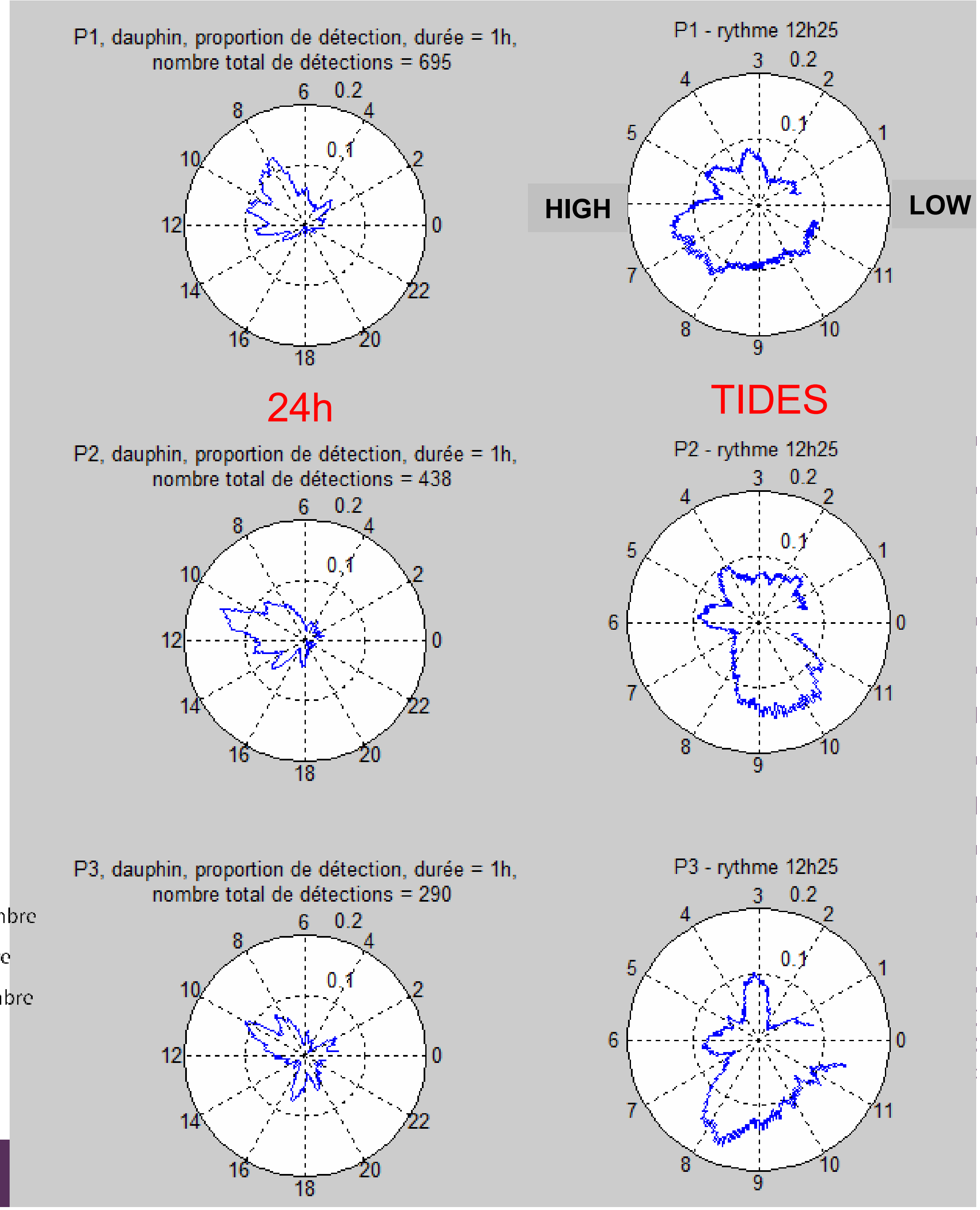


Sounds of dolphins, Hydrophone : Beniguet M P2
time (h)
day index (beginning @ June, 10, 2011)

Acoustic presence – time series of whistle detections

6 months





Comparison/combination of dolphin vs. boat detections (close)