Ultra low power Cochlea for biodiversity monitoring

Francois Danneville, Larach Hicham, Pierre Boulet, Philippe Devienne, Hervé Glotin, Christophe Loyez

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Ultra low power Cochlea for biodiversity monitoring

François Danneville[1]

Hicham Larrach[1], Pierre Boulet[2], Philippe Devienne[2], Hervé Glotin[3], Christophe Loyez[1]

Colloque Biocomp 2023, Banyuls sur Mer

1. *IRCICA, UAR CNRS 3380 et IEMN, UMR CNRS 8520, Villeneuve d'Ascq*
2. *CRISTAL, UMR CNRS 9189, Villeneuve d'Ascq*
3. *LIS, UMR CNRS 7020, Toulon*

CRIStAL Centre de Recherche en Informatique, Signal et Automatique de Lille

iemn Institut d'Electronique, de Microélectronique et de Nanotechnologie UMR CNRS 8520

Université de Lille

Biodiversity

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Biodiversity Loss

Major scientific and Societal challenge

Stimulate research in AI

Requirement of passive acoustic sensors:

- ❑ Detection, Classification, Localization
- ❑ Human / Nature acoustic Event
- ❑ 2 challenges:
  - Biodiversity Monitoring
  - Energetic frugality (carbon footpring as low as possible)

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Biodiversity / Data Deluge

- Biodiversity :
  - Between 1970 and 2018, 69% of wildlife* population declined :
    - Terrestrial environment and/or Marine ecosystems
    - **26%** Marine and/or Terrestrial mammals and **14%** birds are threatened (**)
- Data deluge :
  - Digital data (processing / communication) grows exponentially
  - ICT technologies represent 4% of carbon footprint worlwide (projection is **14%** *** en 2040)

* *Perrine Mouterde, Le Monde, 13 Octobre 2022*

** *https://www.ecologie.gouv.fr/biodiversite-presentation-et-informations-cles#scroll-nav__4*

*** *L. Belkhir et al, « Assessing global emission footprint : Trends to 2040 & recommendations", Journal of Cleaner Production, 2018*

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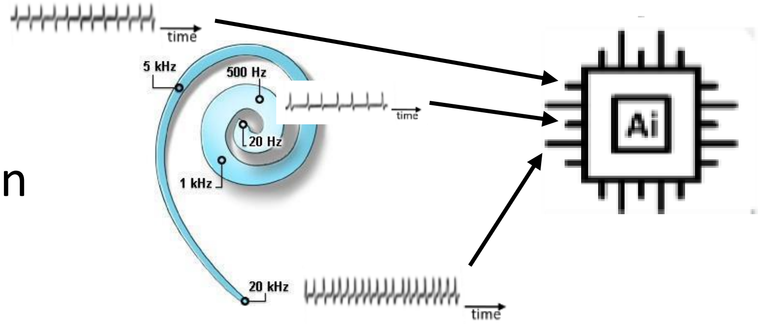
Objective (i)

Development of a quasi-autonomous « embedded » electronic system (maintenance every 3 years)

Artificial Cochlea :

- Analog information pre-processing
- Ultra frugal (power consumption)
- Mature CMOS Technology



« local » information processing:

- Information Processing of « natural data » provided by the cochlea, **locally carried out** (« off the cloud »)

Biodiversity Monitoring:

- Passive Bioacoustic Technology (**non-invasive**, respect wildlife)

Objectives (ii)

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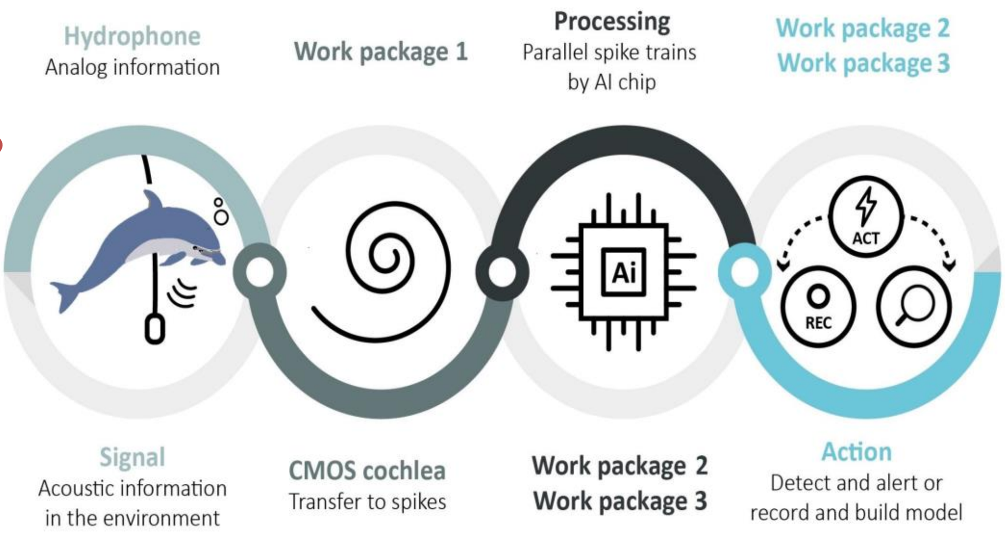

- Sensor characteristics:
  - Classification/counting of ceteceans (unsupervised learning)
  - Compact design
  - Carbon footprint as low as possible
  - Low cost

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Objectives (iii)

- ❑ Design of a monaural / binaural analog artificial Cochlea
  - *Ultra low power (< 30 µWatt), 100 kHz Bandwidth*
  - *Coincidence Detector for sound localization*

- ❑ Design of AI chip to carry out biocomputing of « natural data » (generated by the Cochlea)
  - *Software Development based on Spiking Neural Networks trained for Ceteceans classification*

- ❑ Detection / Localization of specific acoustic events with main goal to preserve Ceteceans
  - *Add « alert » functionality to detect anthropogenic noise perturbing biodiversity*

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Objectives (iv)

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- Design of a monaural / binaural analog artificial Cochlea
  - *Ultra low power (< 30 µWatt), 100 kHz Bandwidth*
  - *Coincidence Detector for sound localization*

- Design of AI chip to carry out biocomputing of « natural data » (generated by the Cochlea)
  - *Software Development based on Spiking Neural Networks trained for Ceteceans classification*

- Detection / Localization of specific acoustic events with main goal to preserve Ceteceans
  - *Add « alert » functionality to detect anthropogenic noise perturbing biodiversity*

Biological Cochlea

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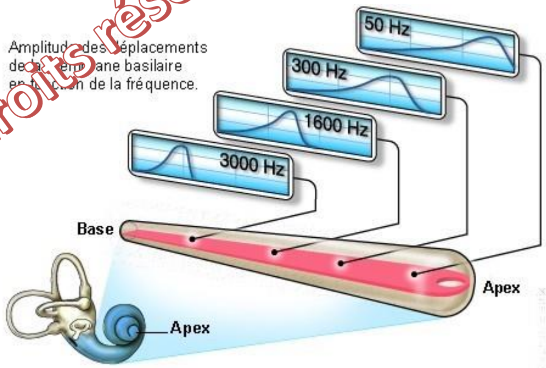
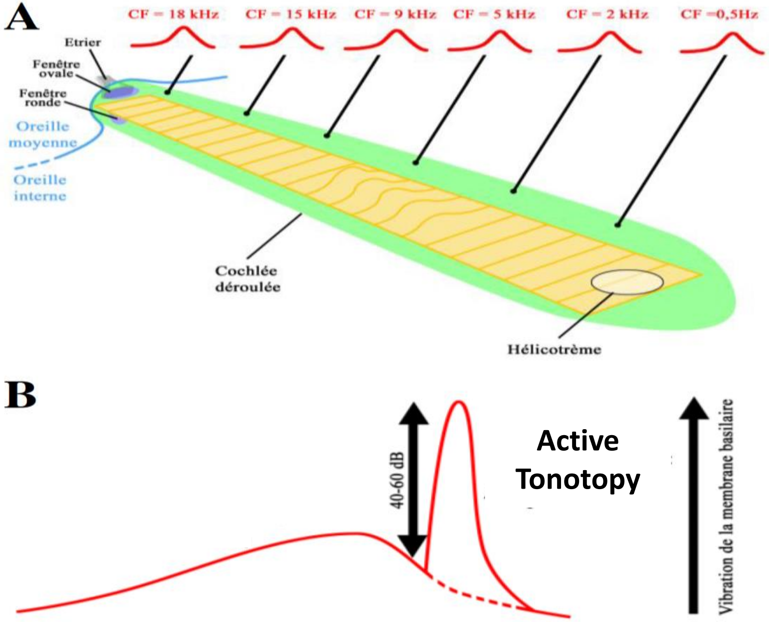
Johnstone et Boyle ~ 1970

G. V. Békésy ~ 1960*



Passive Tonotopy



* https://www.cochlea.eu/cochlee/fonctionnement

Artificial Cochlea : the Pioneers (i)

IEEE TRANSACTIONS ON ACOUSTICS, SPEECH, AND SIGNAL PROCESSING, VOL. 36, NO. 7, JULY 1988

An Analog Electronic Cochlea

RICHARD F. LYON, MEMBER, IEEE, AND CARVER MEAD

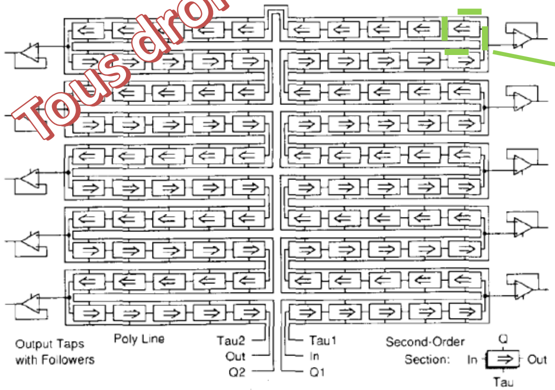


Fig. 8. Floorplan of 100-stage cochlea chip, in serpentine arrangement. The wires that are shown connecting the TAU and Q control terminals of the filter stages are built using a resistive polysilicon line, to act as a voltage divider that adjusts the bias currents in the cascade as an exponential function of distance from the input.

Basic Unit :

2^{nd} order Filter

$$H(s) = \frac{1}{\tau^2 s^2 + \frac{1}{Q}\tau s + 1}$$

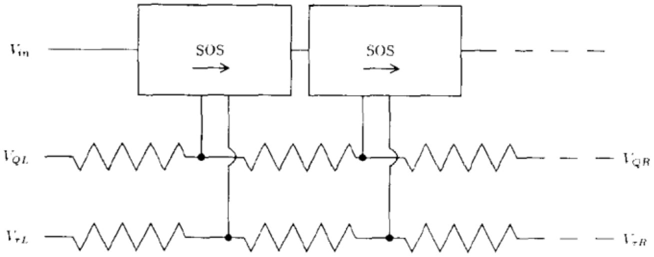


Fig. 3. Silicon cochlea, consisting of a serial cascade of second-order sections and tilted bias lines.

Artificial Cochlea : the Pioneers (ii)

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IEEE TRANSACTIONS ON ACOUSTICS, SPEECH, AND SIGNAL PROCESSING, VOL. 36, NO. 7, JULY 1988

An Analog Electronic Cochlea

RICHARD F. LYON, MEMBER, IEEE, AND CARVER MEAD

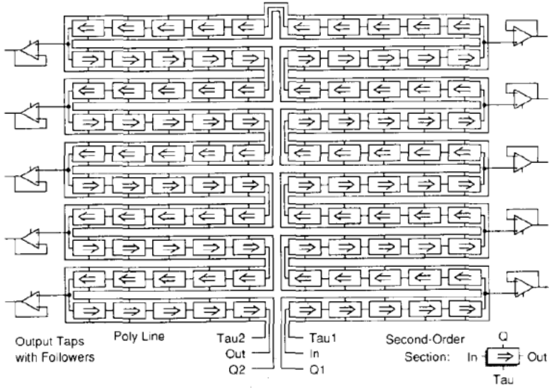
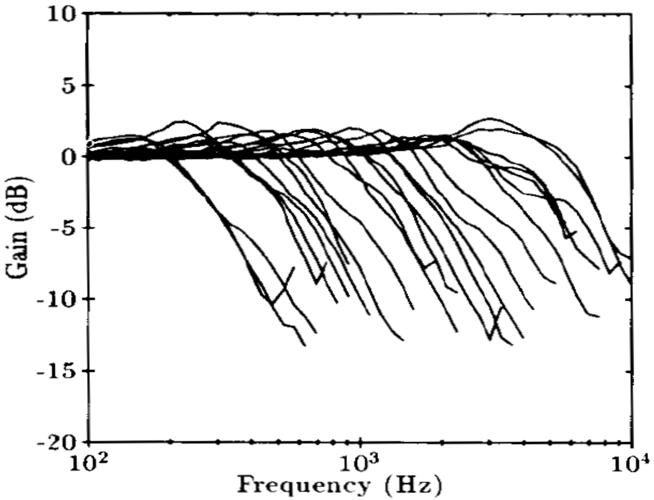


Fig. 8. Floorplan of 100-stage cochlea chip, in serpentine arrangement. The wires that are shown connecting the TAU and Q control terminals of the filter stages are built using a resistive polysilicon line, to act as a voltage divider that adjusts the bias currents in the cascade as an exponential function of distance from the input.



Artificial Cochlea

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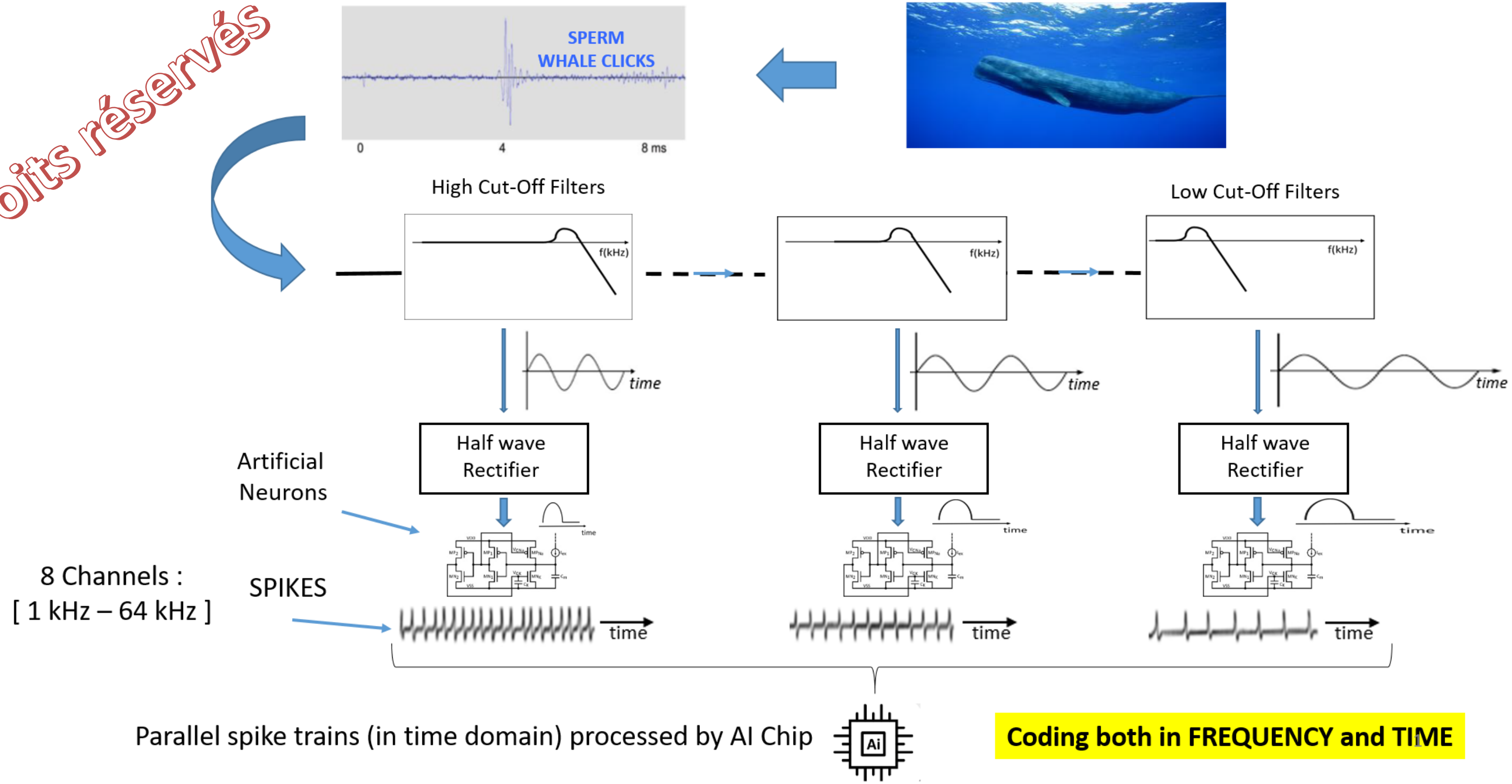
From acoustic signal sensing to spike encoding



Artificial Cochlea

Cascade of Filters

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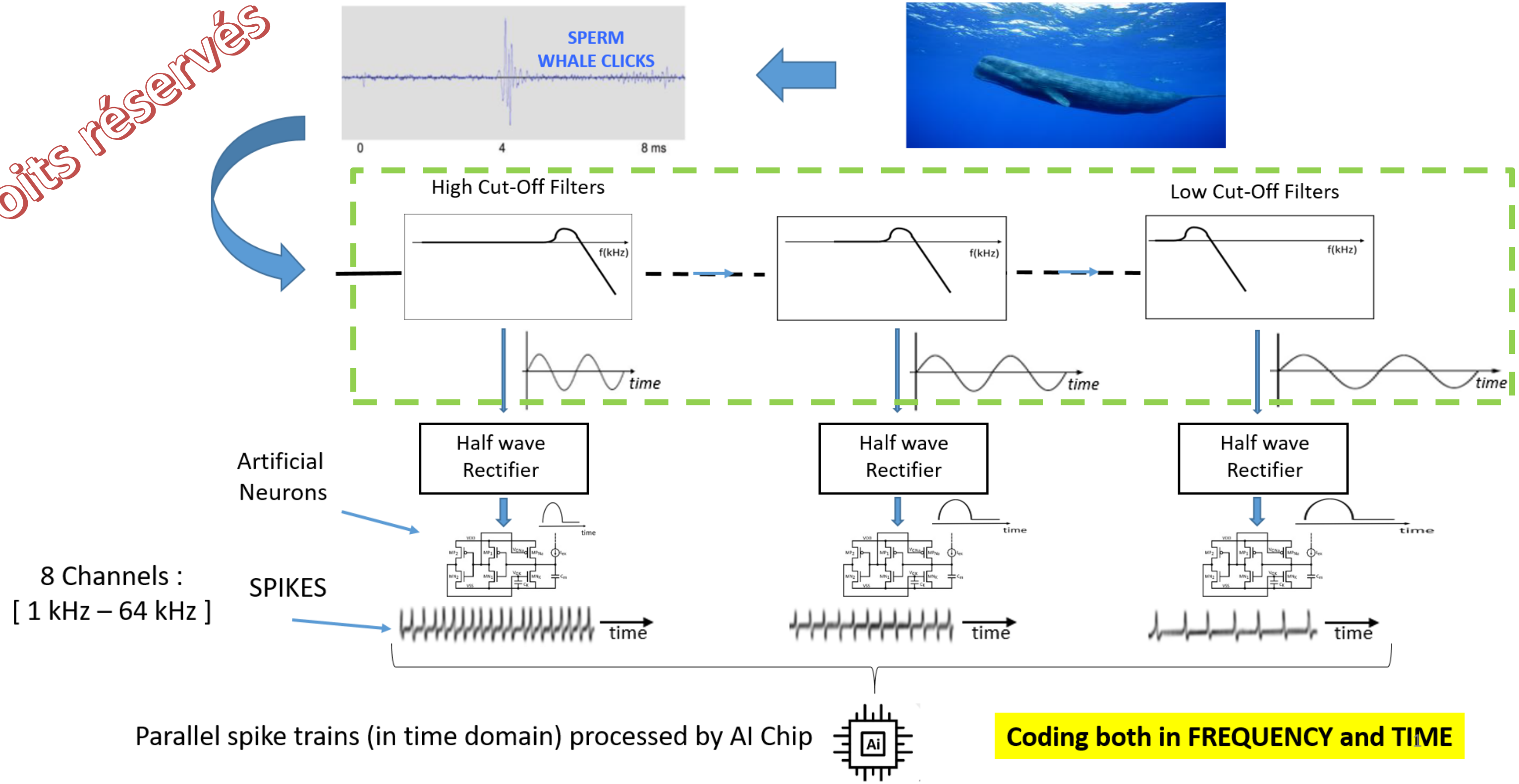

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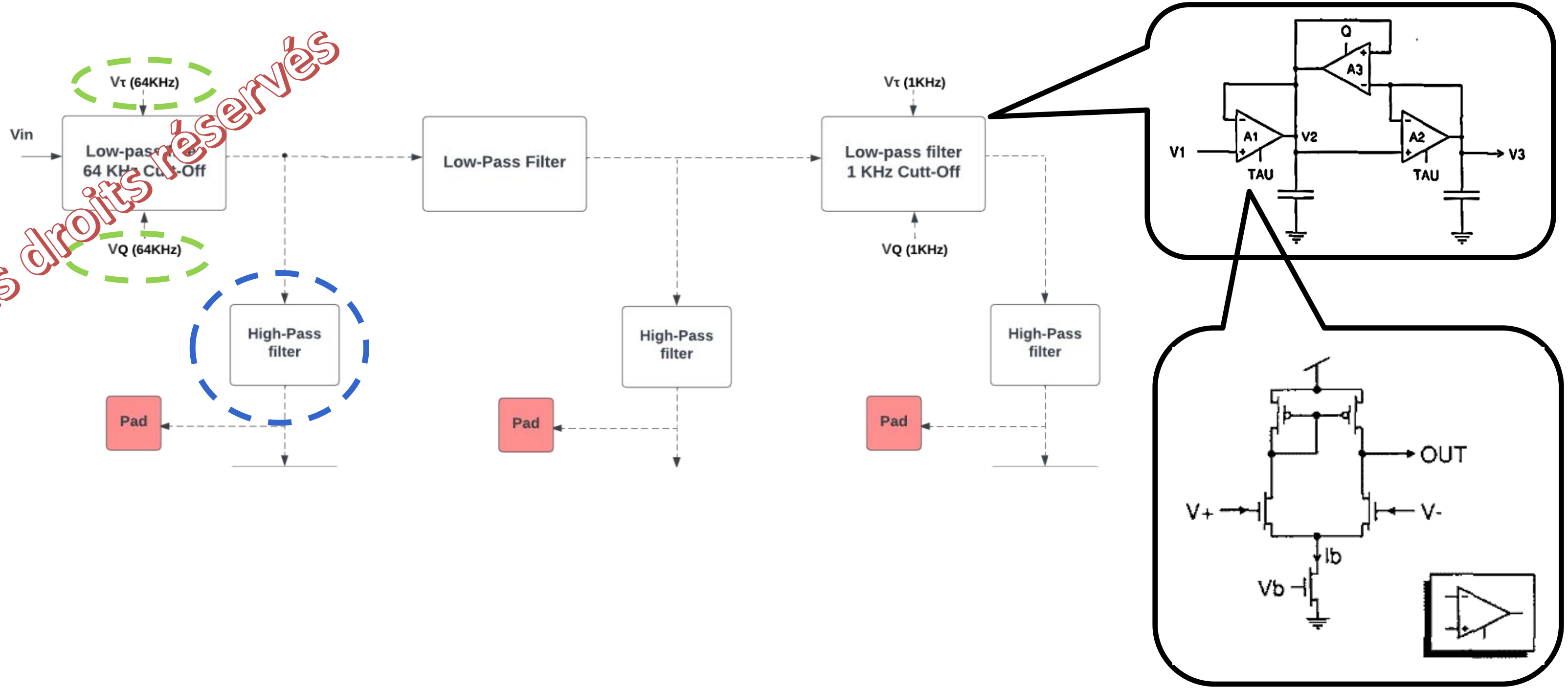
Artificial Cochlea

Cascade of Filters



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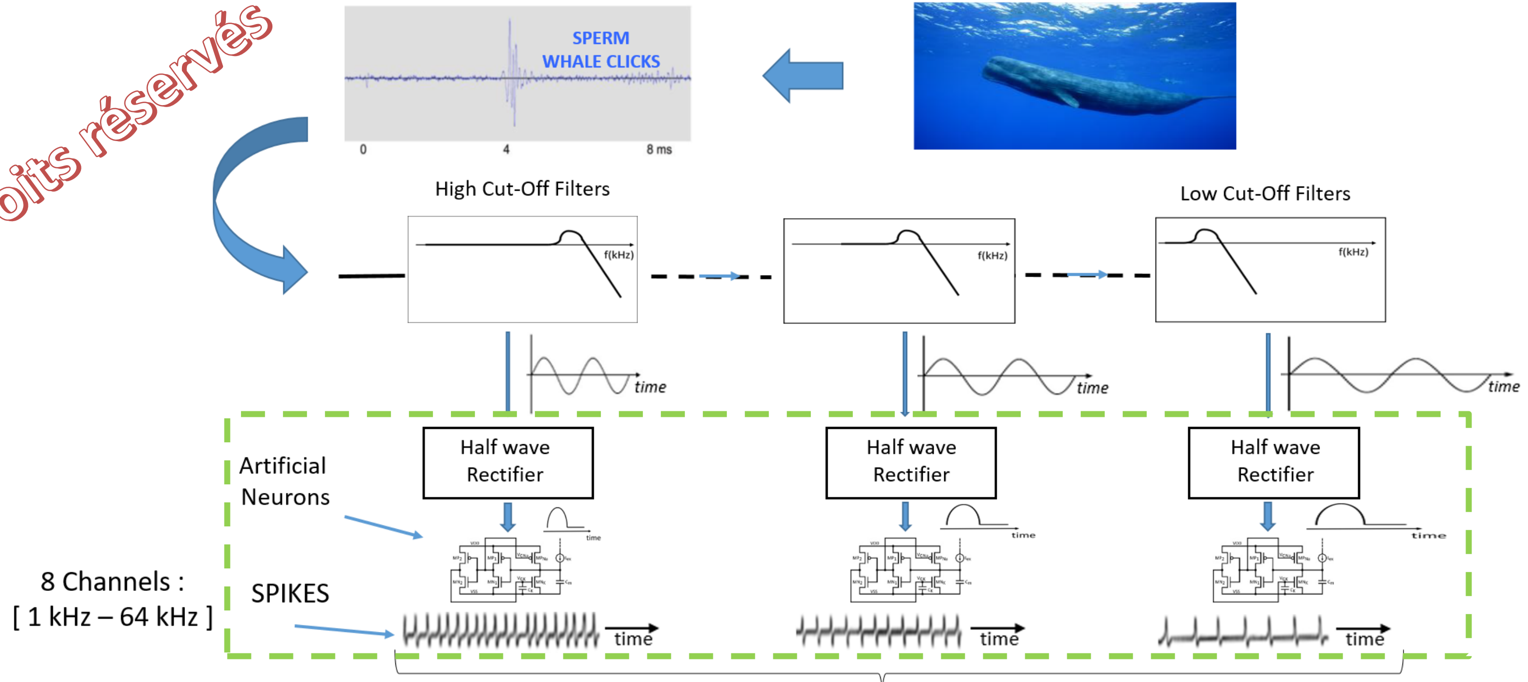
Artificial Cochlea

Conversion to spikes ?



Parallel spike trains (in time domain) processed by AI Chip

Coding both in FREQUENCY and TIME

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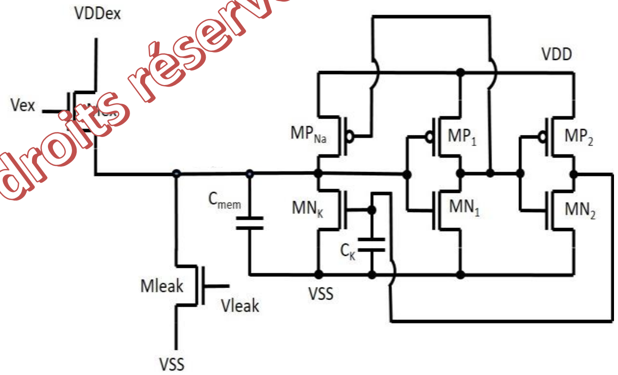
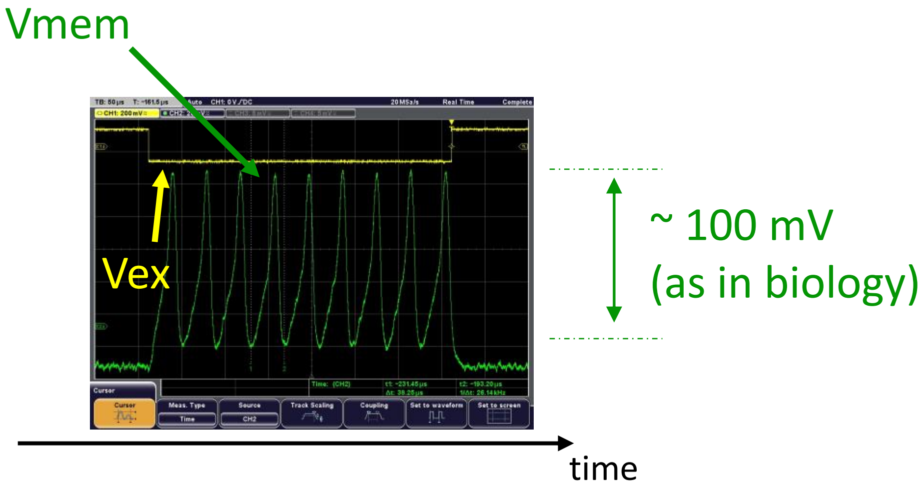
Artificial Cochlea

Artificial Neuron*

Silicon transistor circuit





Power Consumption < 100 pW

* *Patent, FR3050050 A1, 13/10/2017 (INPI)*

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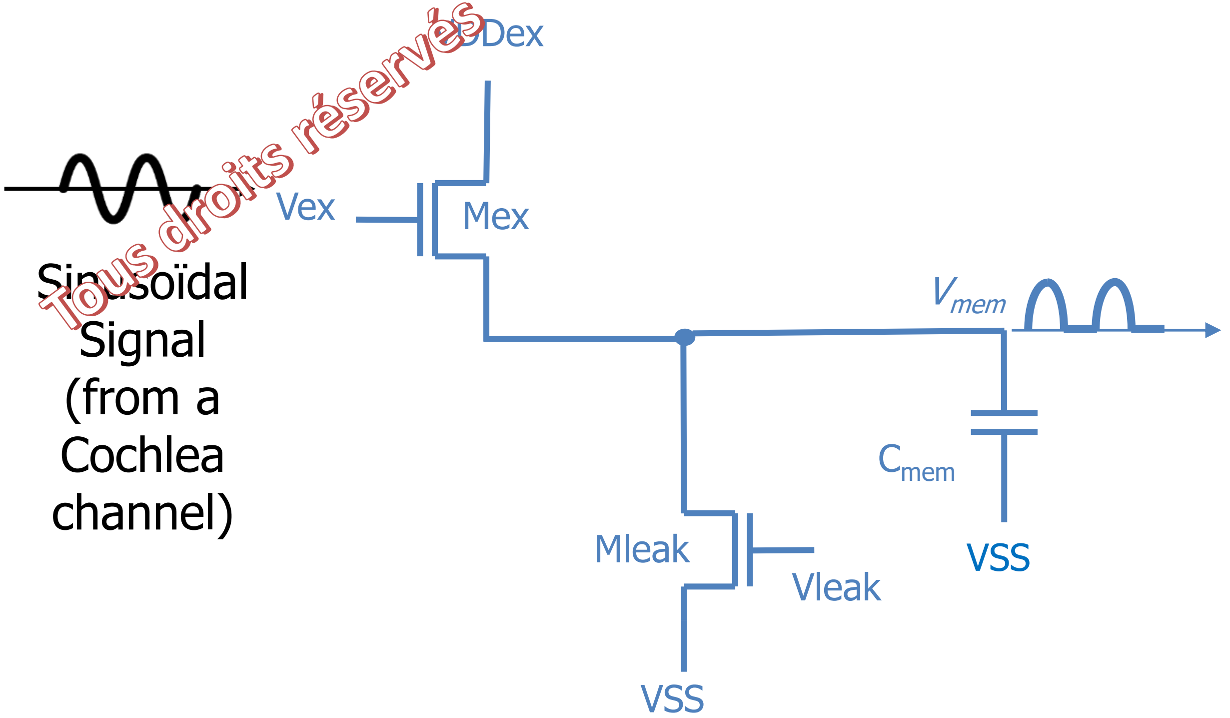
Artificial Cochlea

Half Wave Rectifier ?



V_{mem} turns to be a half wave signal

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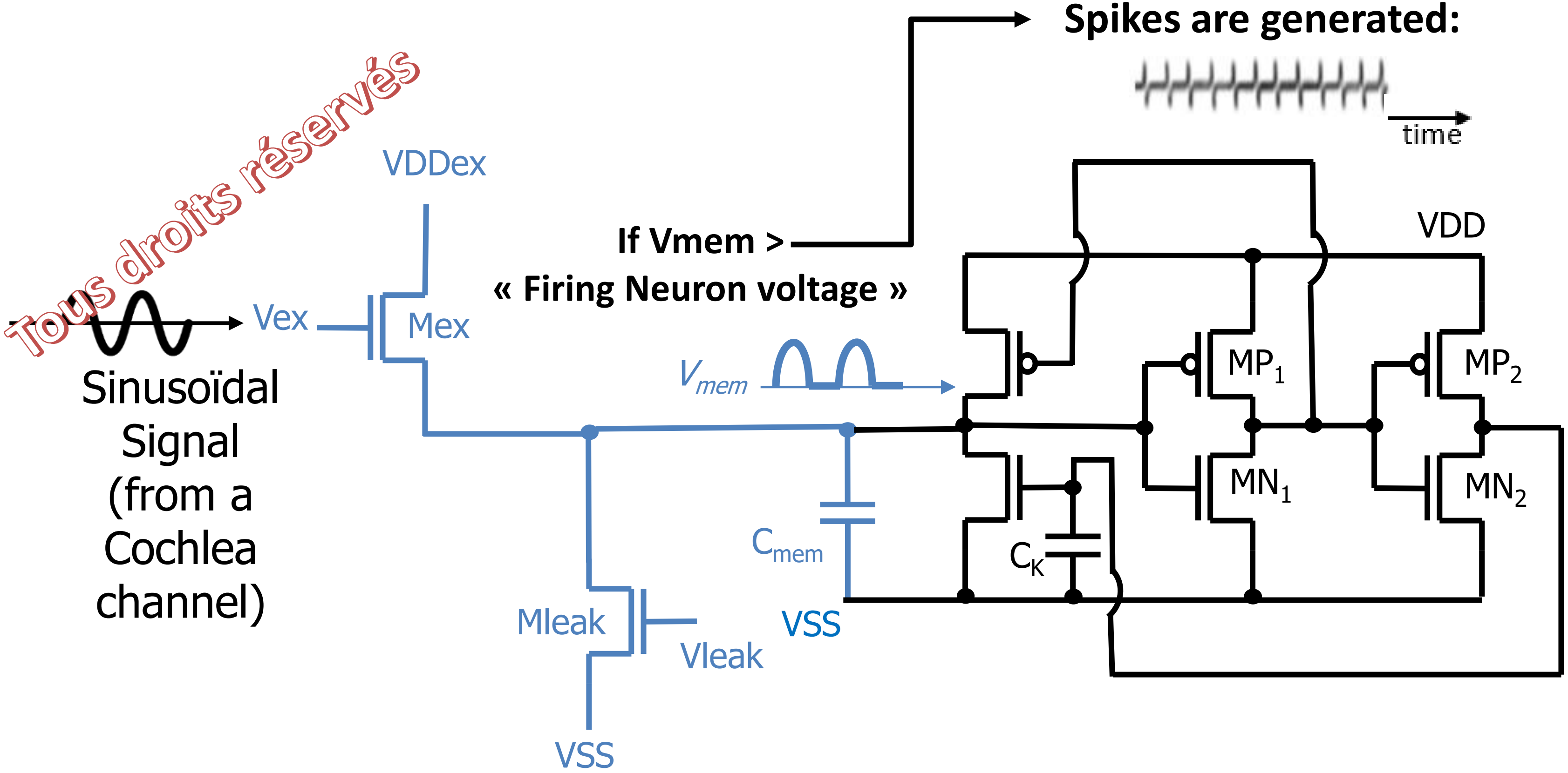
Artificial Cochlea

Conversion to spikes ?



Implementation in CMOS TSMC 65nm Technology

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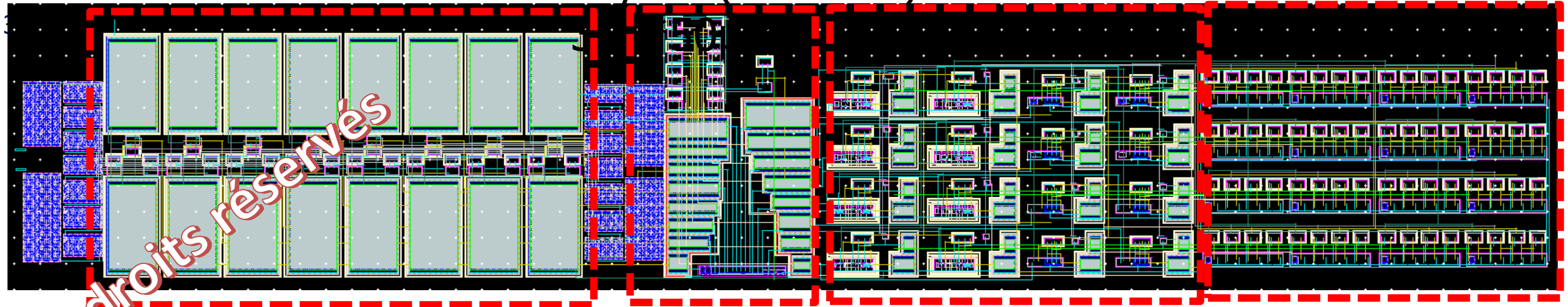
Layout (Cadence)



Low-Pass filters

High-Pass filters

HWR / Output Neurons

Buffers

CMOS Microchip 1500*250µm²

8 Output Channels

Artificial Cochlea

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Simulated results

Artificial Cochlea

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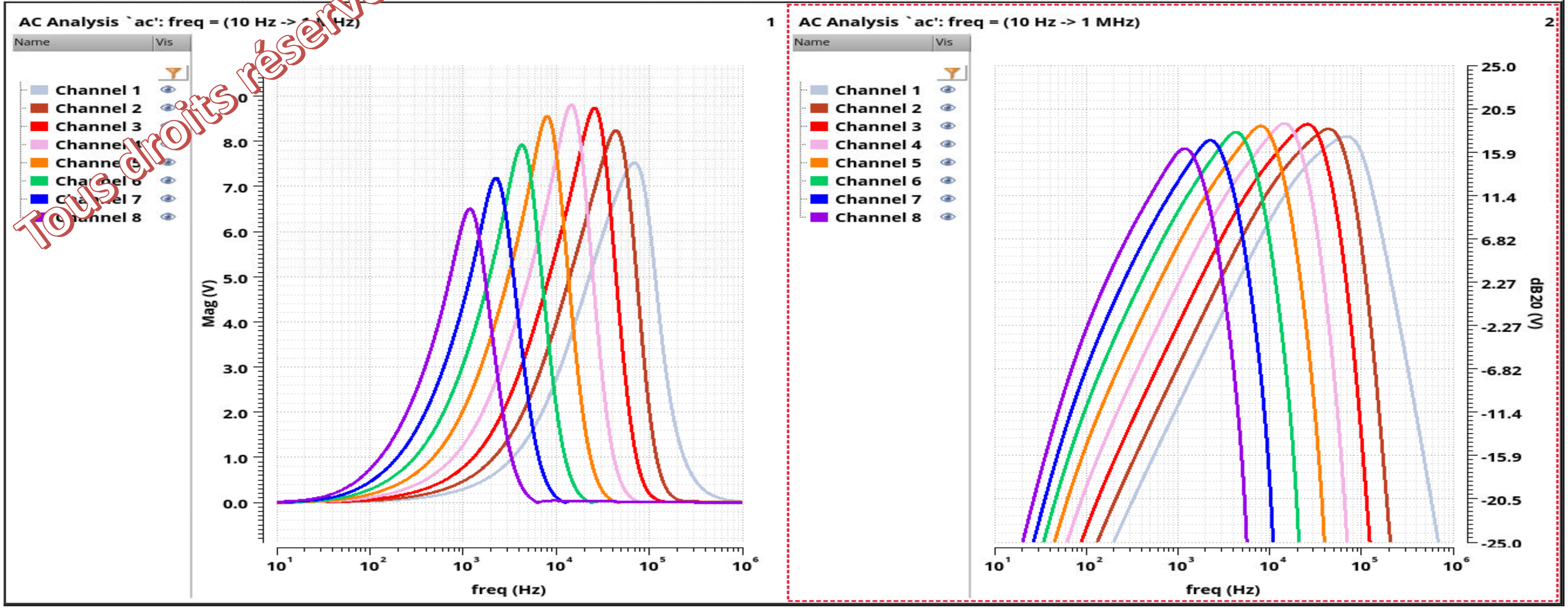
Cascade of Filters:

Frequency Channels (kHz) : 0.5-1-2-4-8-16-32-64



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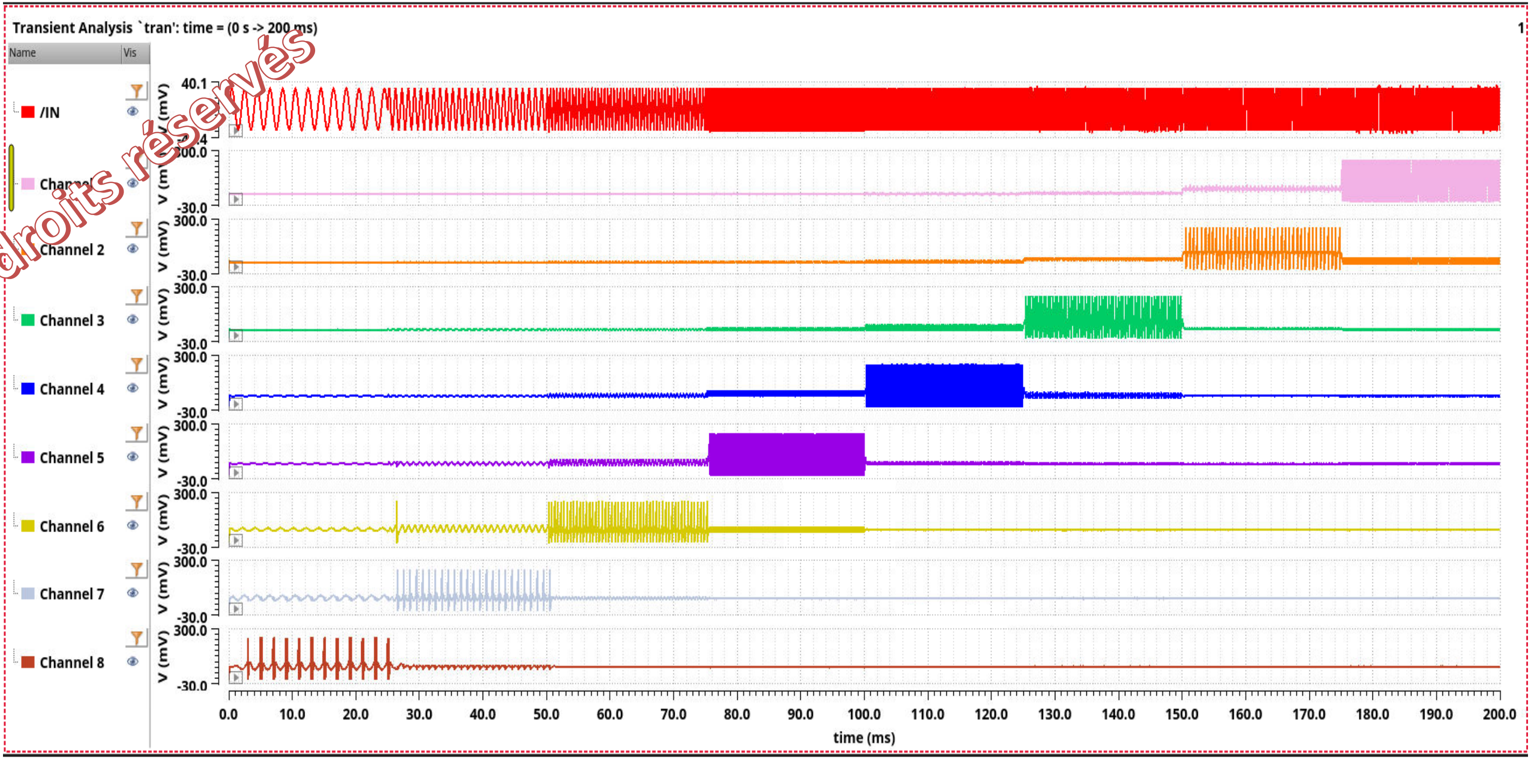
Artificial Cochlea

Conversion to spikes



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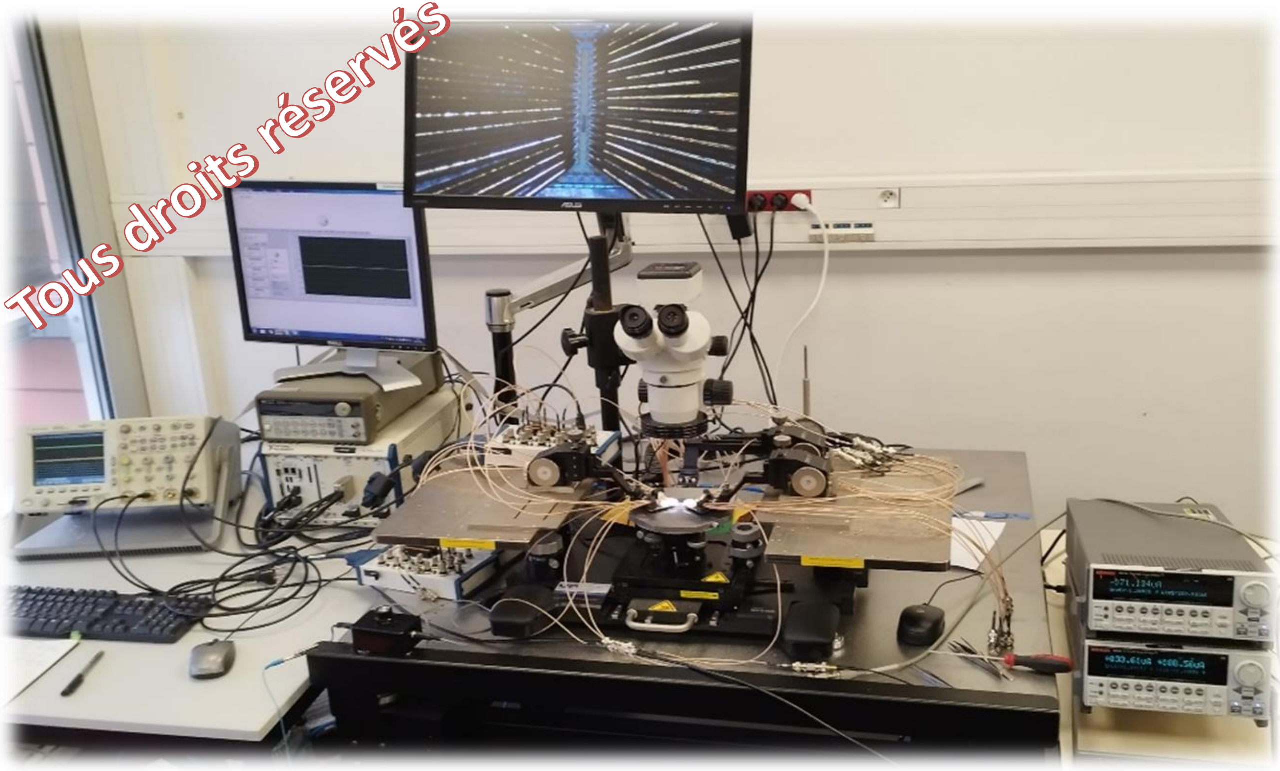
Artificial Cochlea:
Simulation / Experimental results



Characterization :
Use of a probe station

Acoustic (natural) Signal of two Ceteceans

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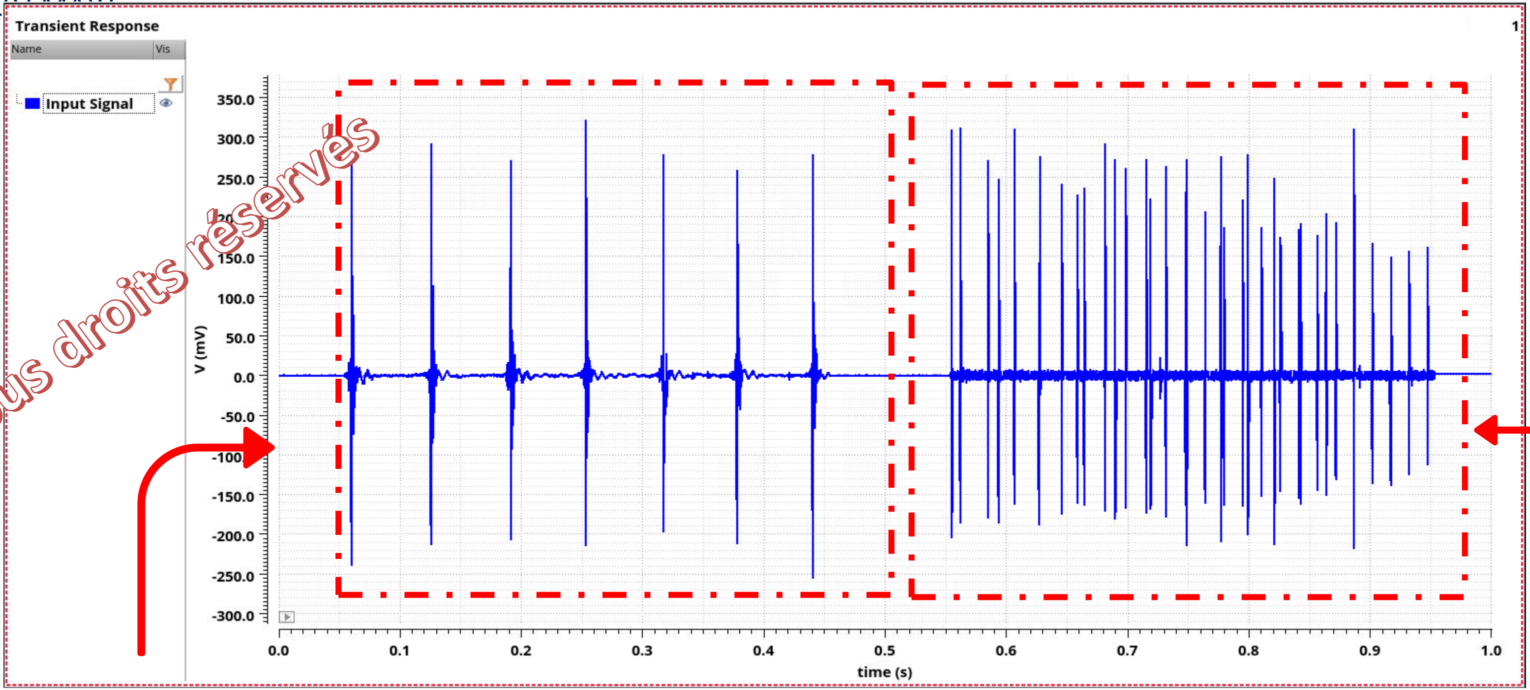
Sperm Wale clicks : Discovery of Sound in the Sea
https://dosits.org/galleries/audio-gallery/marine-mammals/toothed-whales/sperm-whale

Rough-toothed Dolphin clicks : DCLDE Oahu
https://www.soest.hawaii.edu/ore/dclde/

Acoustic (natural) Signal of two Ceteceans

UL
3D



Sperm Whale
(Physeter
macrocephalus)

The rough-toothed
dolphin
(Steno
bredanensis)

Sperm Whale clicks

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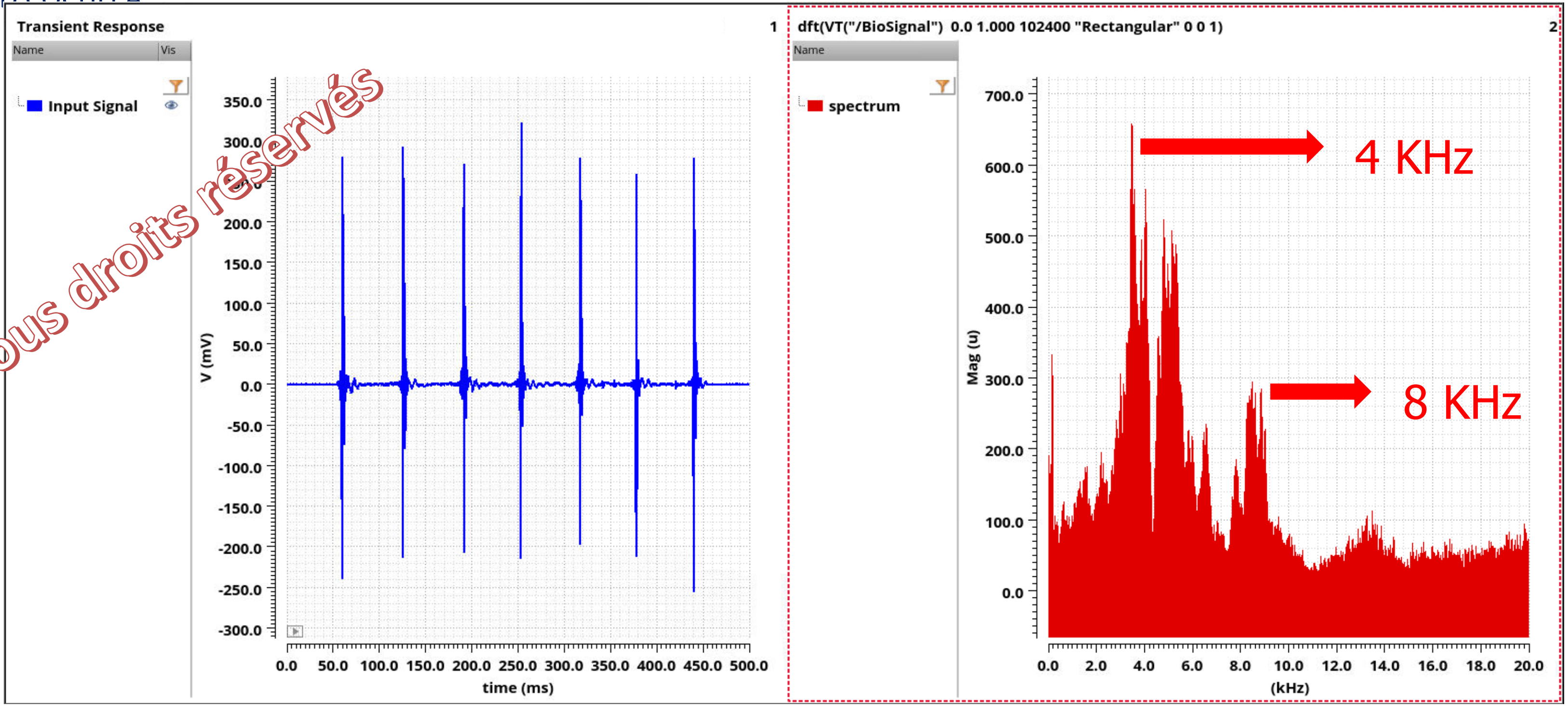

Sperm whale clicks : spectrum

Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)

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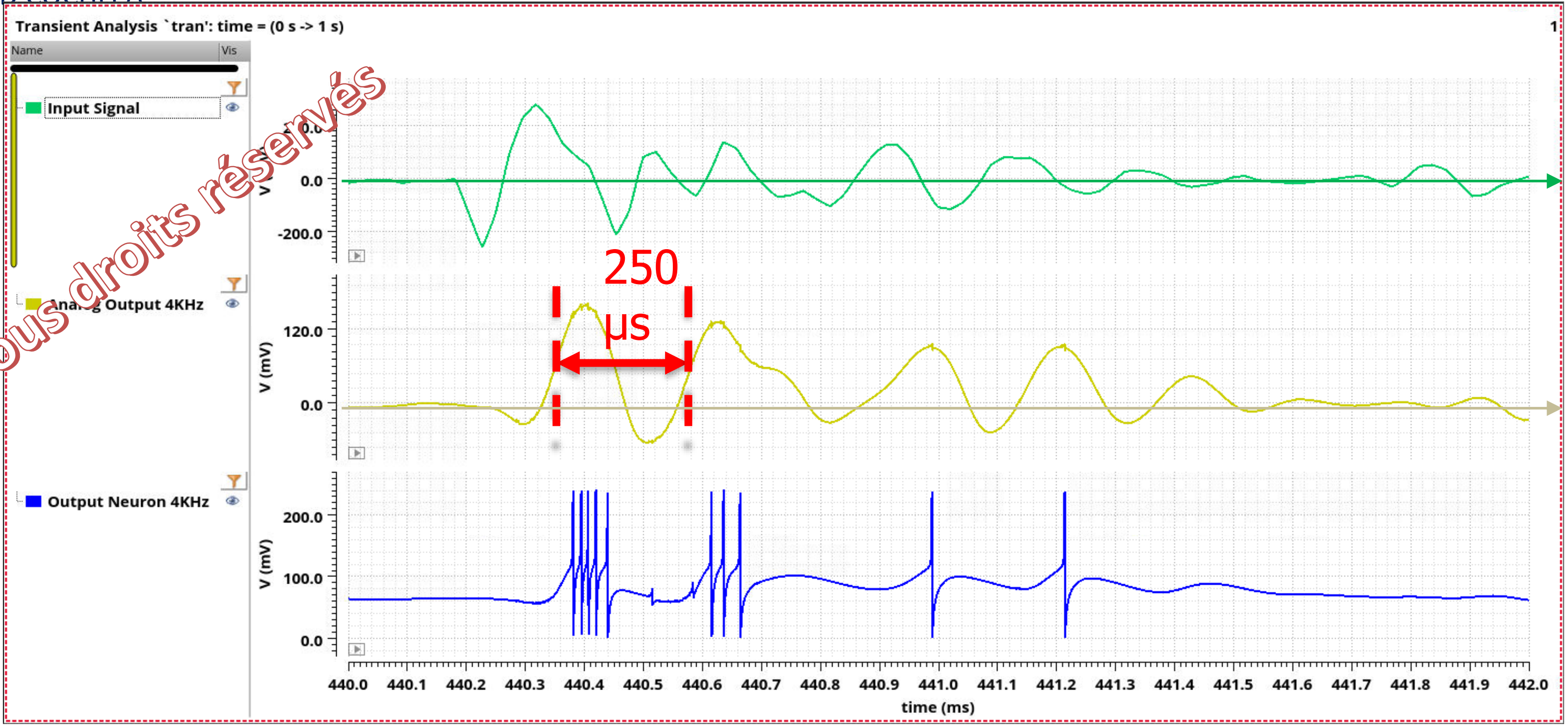

Transient response of the cochlea to a single Sperm Whale click (4KHz Channel)

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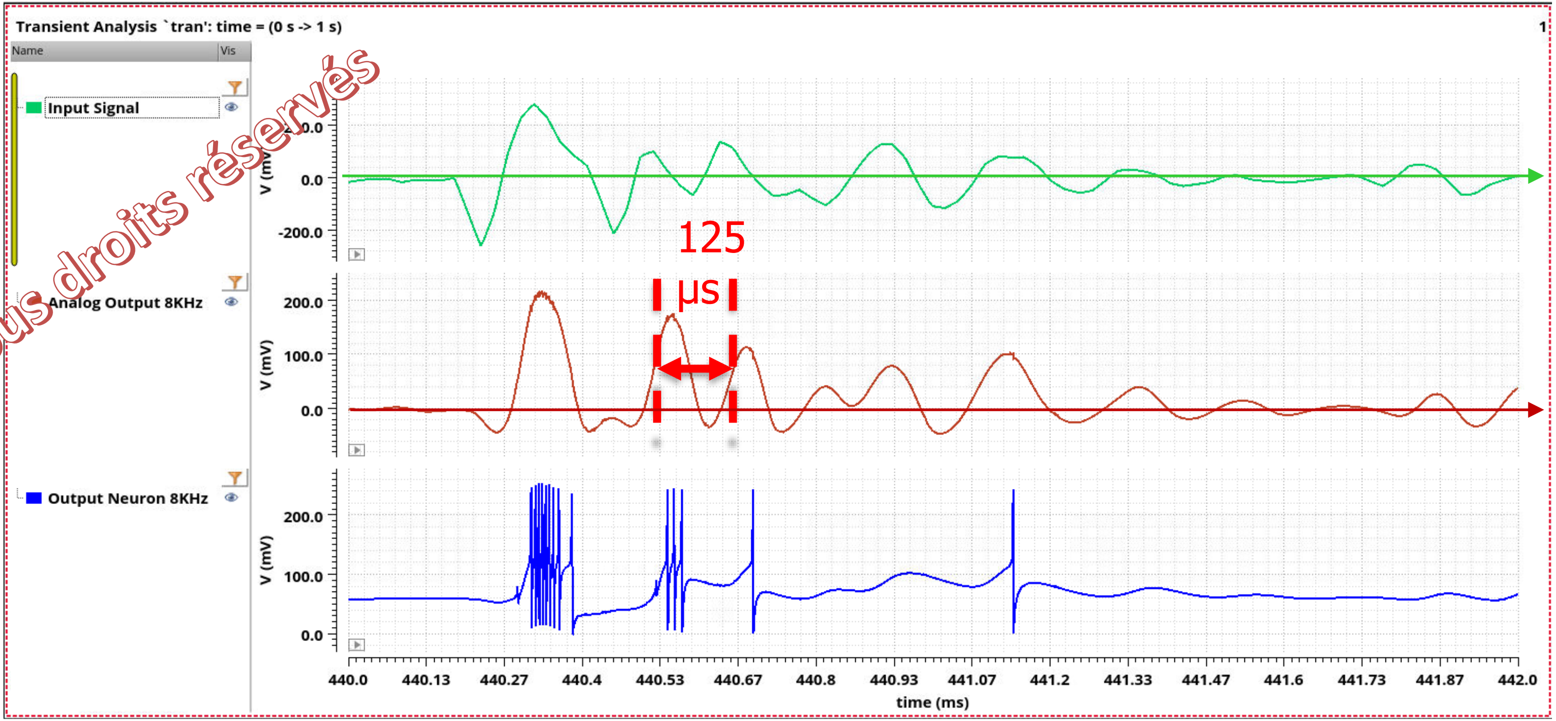
Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)



Transient response of the cochlea to a single Sperm Whale click (8KHz Channel)

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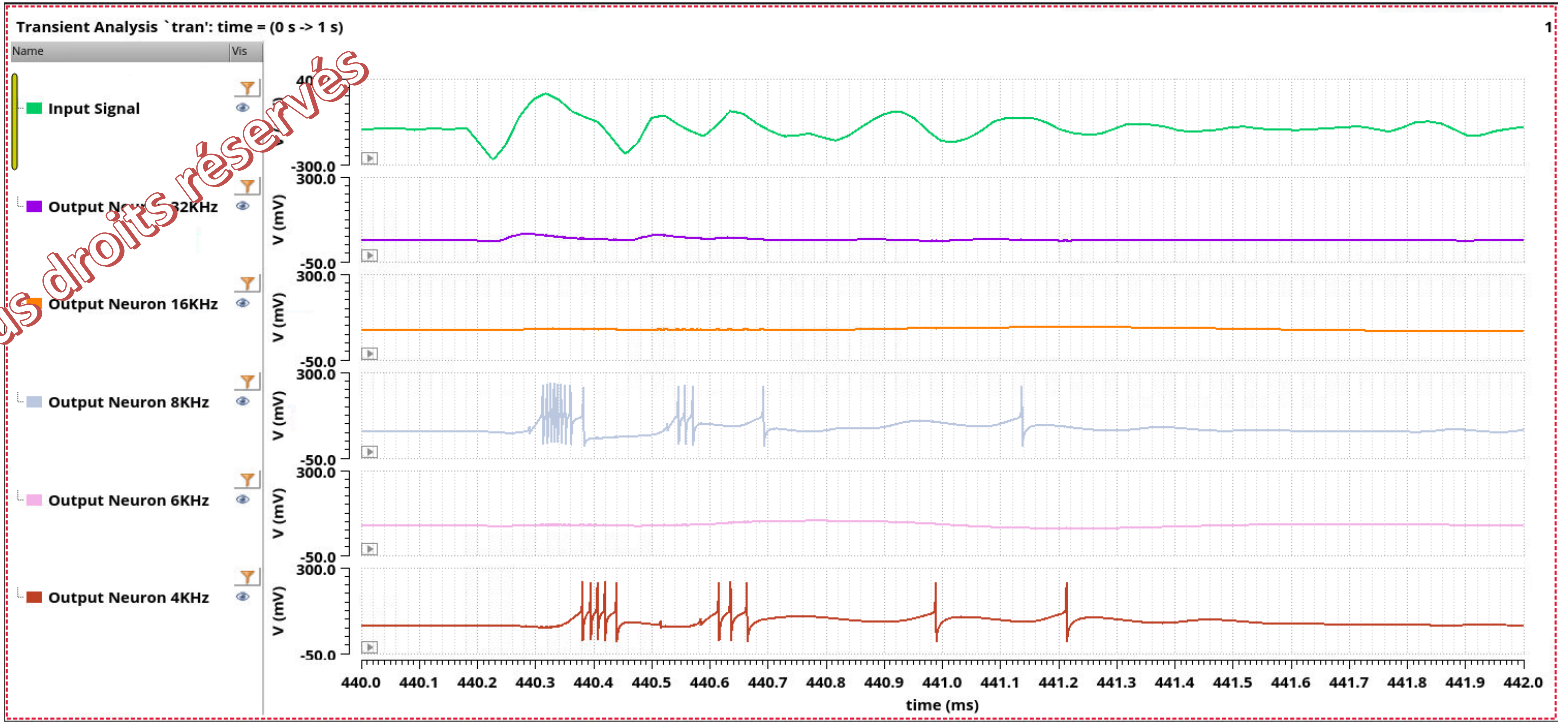
Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)



Transient response of the cochlea to a single Sperm Whale click (All Channels)

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Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)

Transient response of the cochlea to a train of Sperm Whale clicks (All Channels)

Response of the Cochlea to Sperm Whale Clicks (Experimental results)

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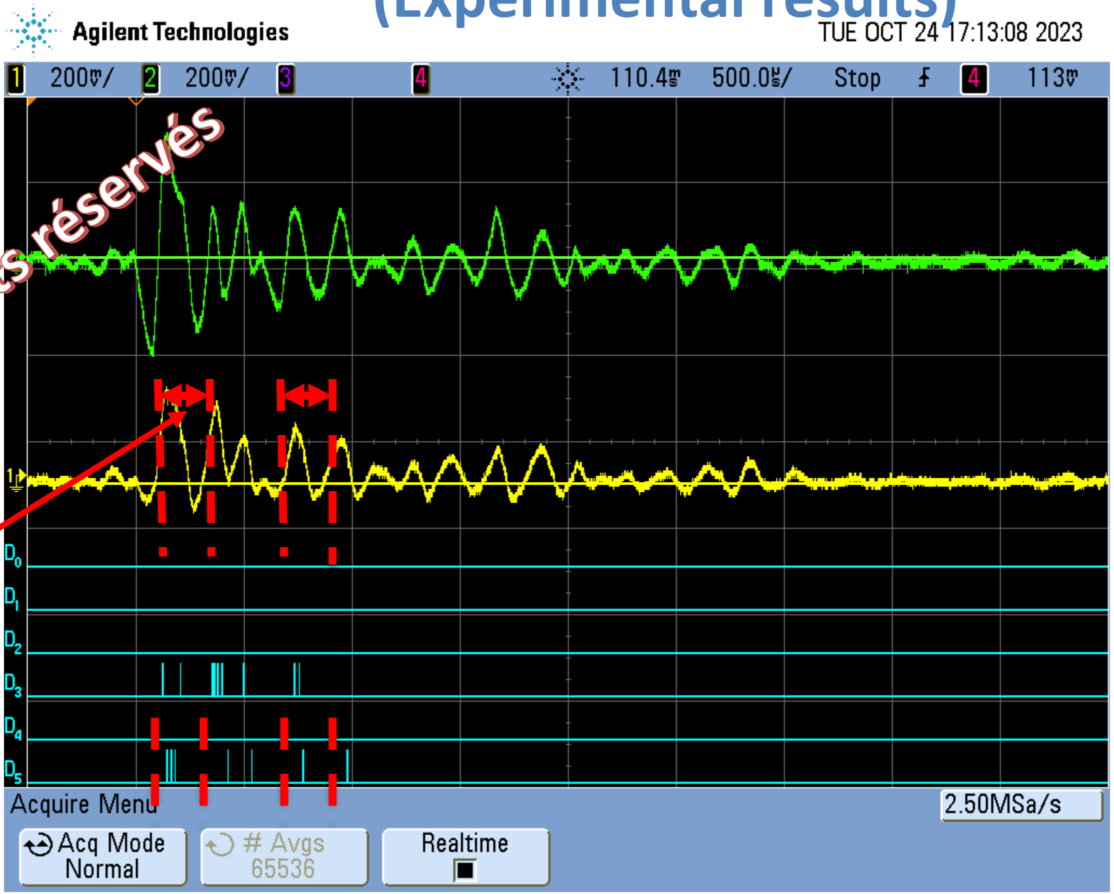

250µs

Sperm Whale click

Single output of
Filters bank available

Analog output
4KHz

32KHz Channel

8KHz Channel

4KHz Channel

Response of the Cochlea to Sperm Whale Clicks (Experimental results)

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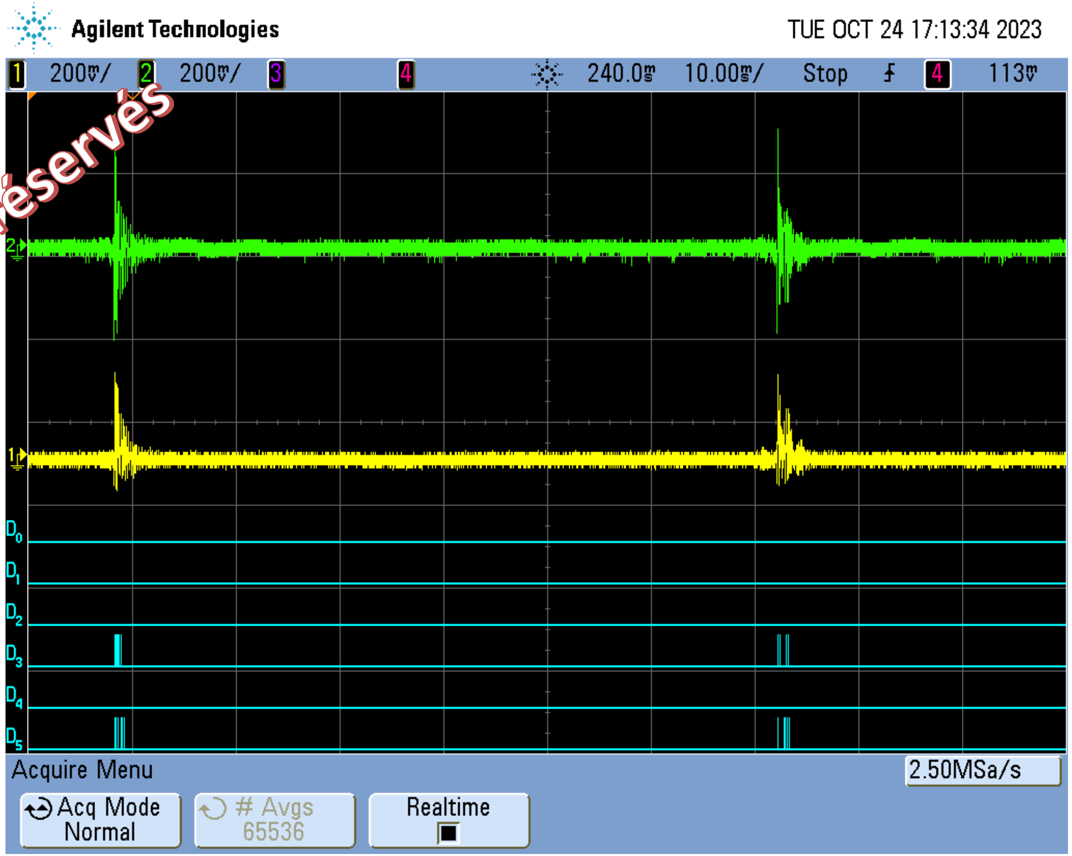

Sperm Whale click

Analog output 4KHz

32KHz Channel

8KHz Channel

4KHz Channel

Dolphin clicks

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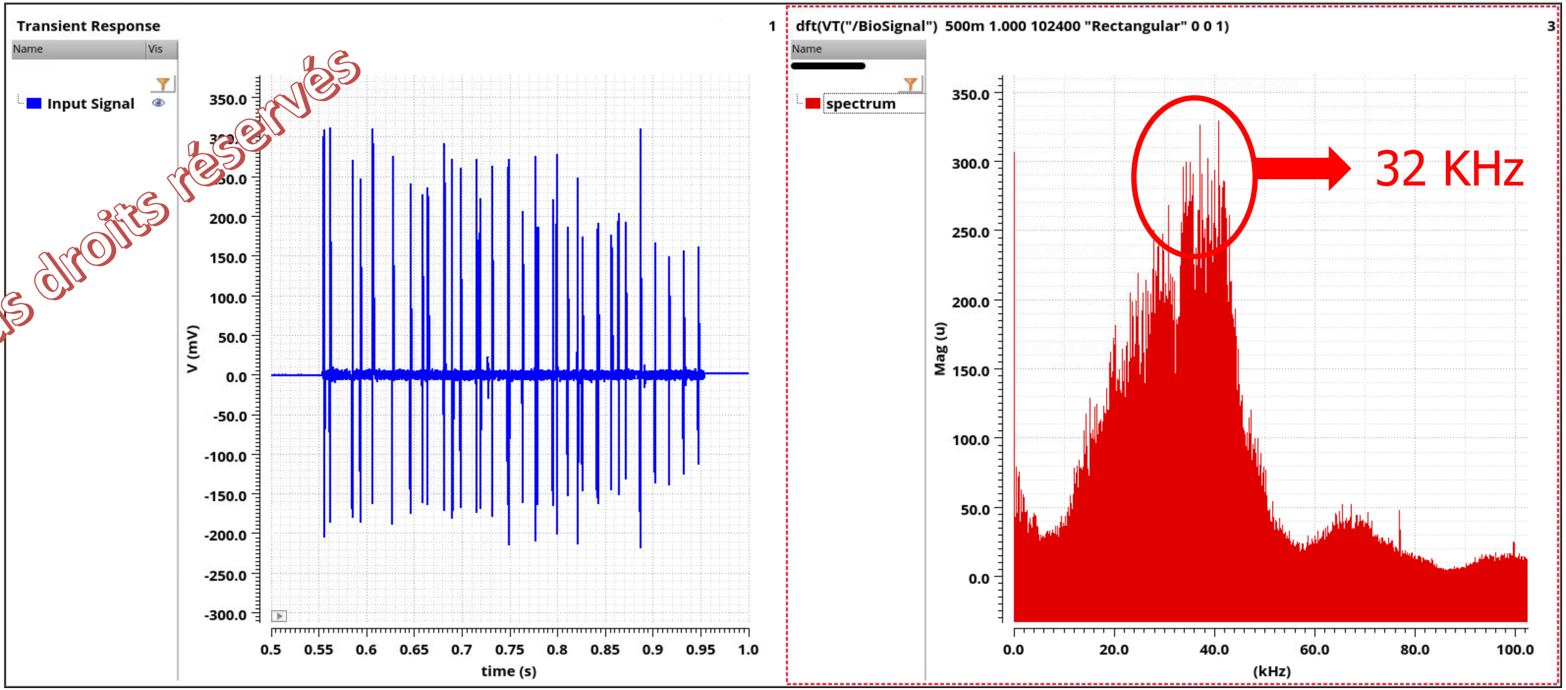

Dolphin clicks: spectrum

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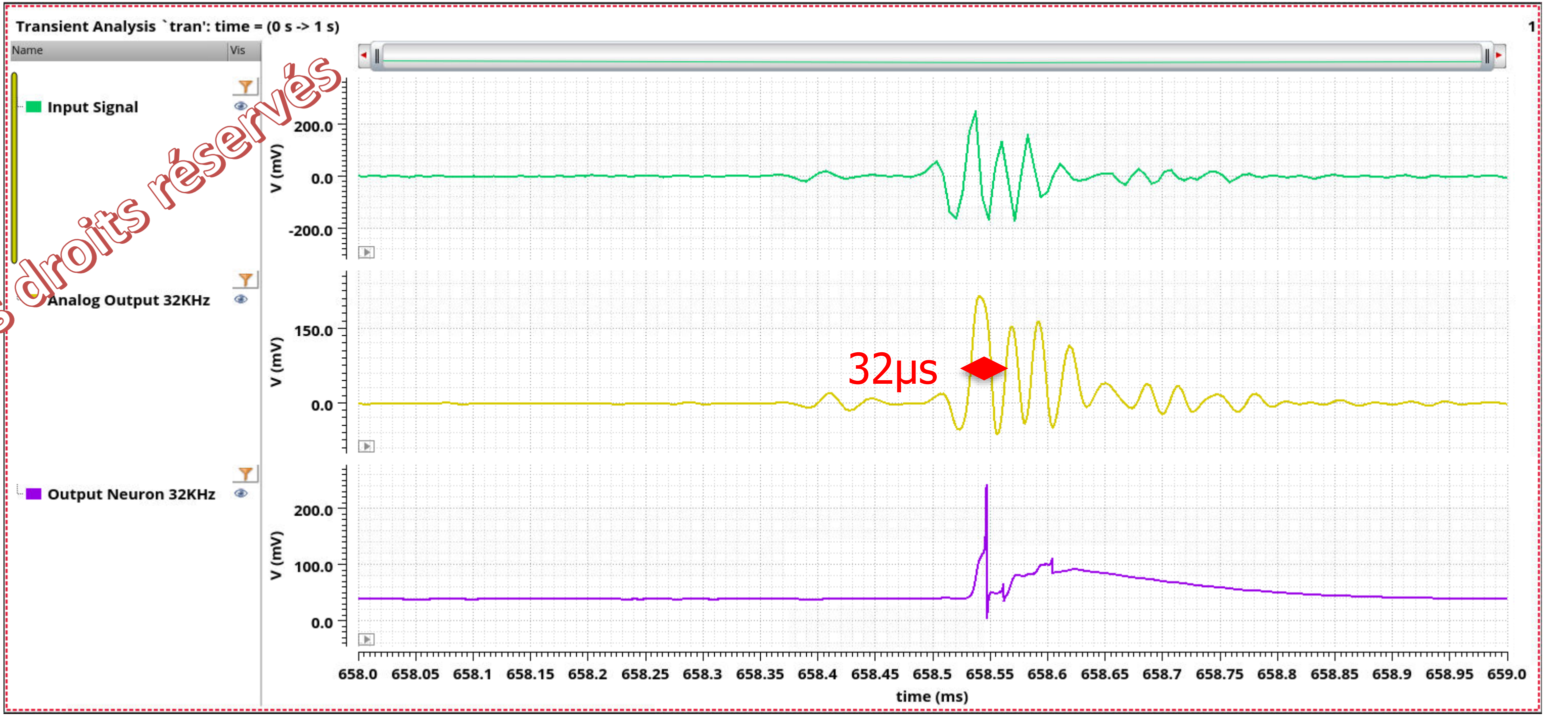
Response of the Cochlea to Dolphin Clicks (simulation in CADENCE)



Transient response of the cochlea to a single Dolphin click (32KHz Channel)

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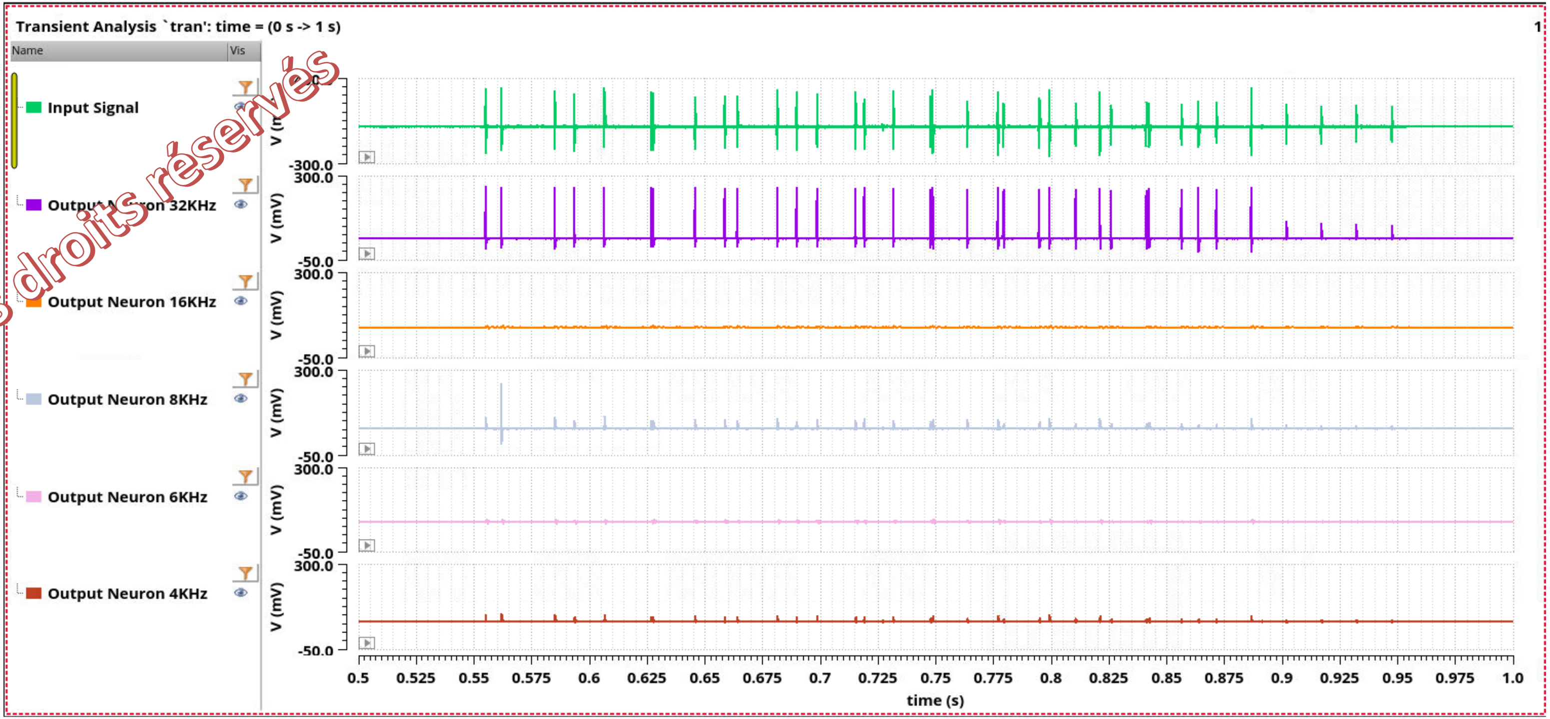
Response of the Cochlea to Dolphin Clicks (simulation in CADENCE)



Transient response of the cochlea to a train of Dolphin clicks (ALL KHz Channel)

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Response of the Cochlea to Dolphin Clicks (Experimental results)

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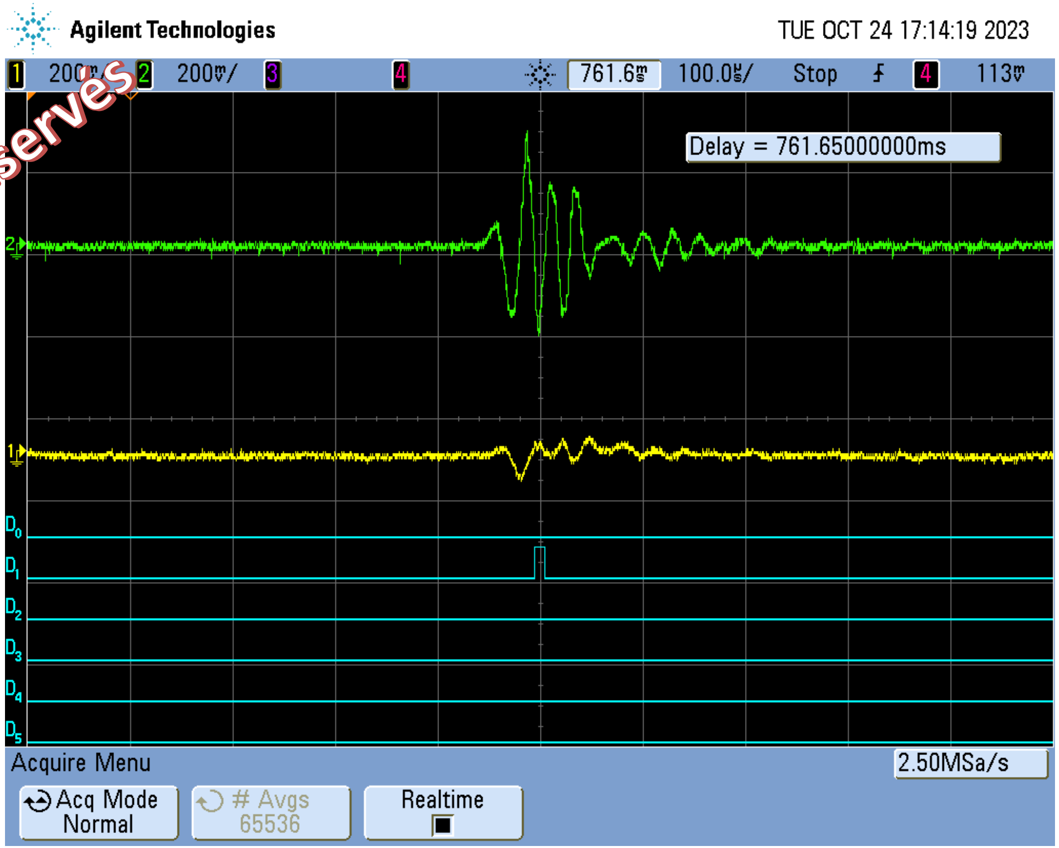

Dolphin click

Analog output 4KHz

32KHz Channel

8KHz Channel

4KHz Channel

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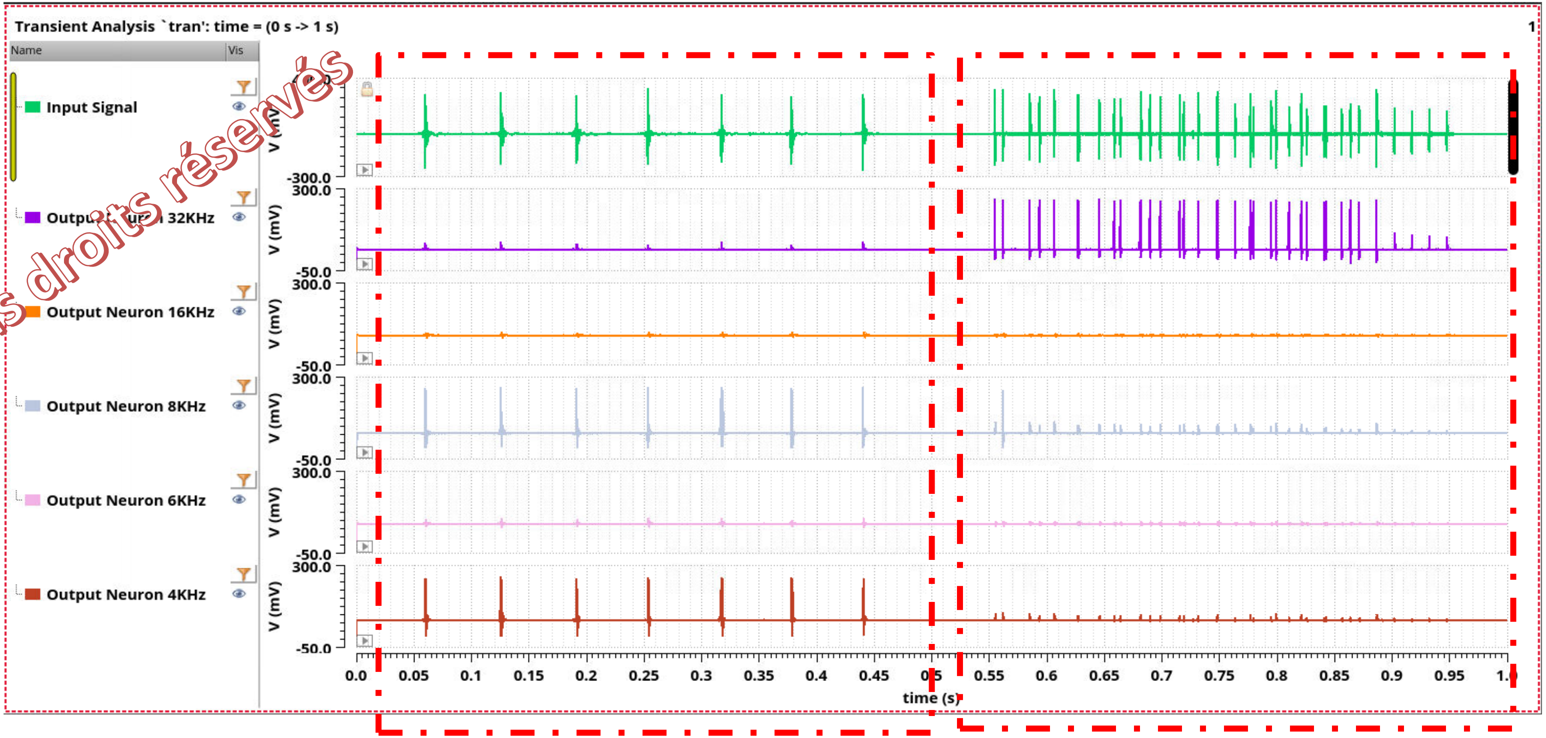
Response of the Cochlea to Dolphin and Sperm Whale clicks (simulation in CADENCE)



Sperm Whale

Dolphin

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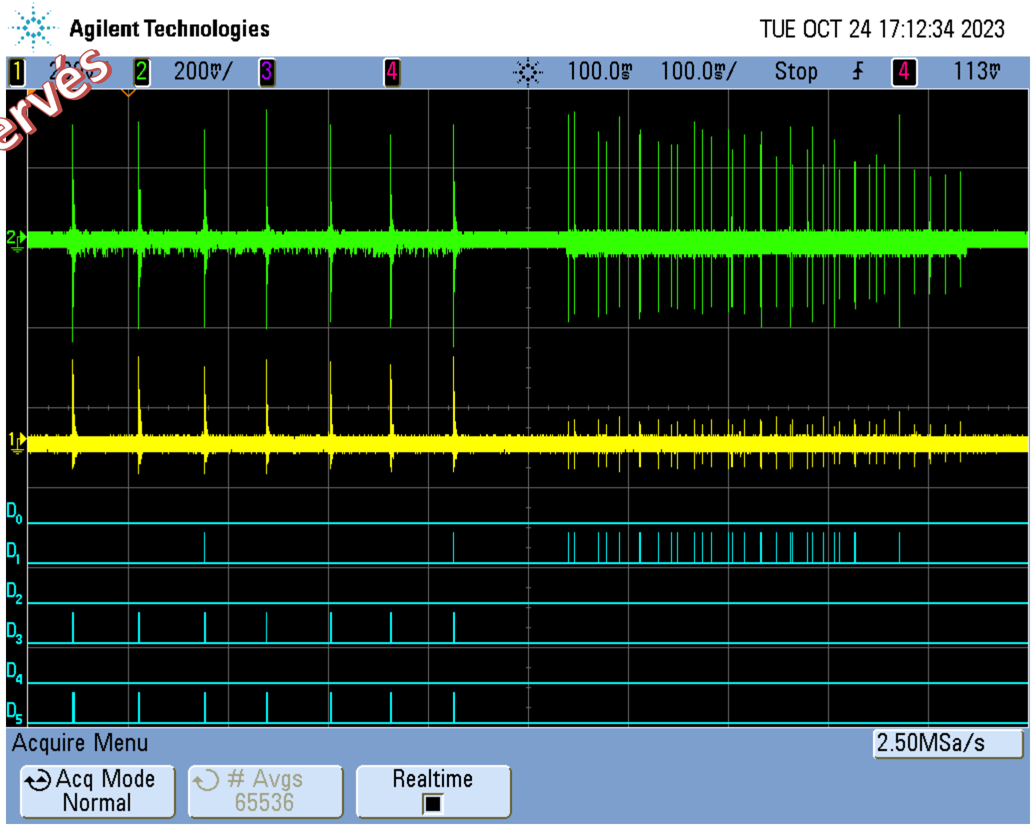
Response of the Cochlea to Dolphin and Sperm Whale Clicks (Experimental results)



Acoustic Signal

Analog output
4KHz

32KHz Channel

8KHz Channel

4KHz Channel

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Power consumption ?

CMOS Microchip 1500*250µm²

8 Channels

With buffers (required for characterization) :
~ few microWatts / channel

Without buffers (required for characterization) :
100 nanoWatts / channel

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NEXT ?

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Dataset

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Dataset

10 species selected from the dataset

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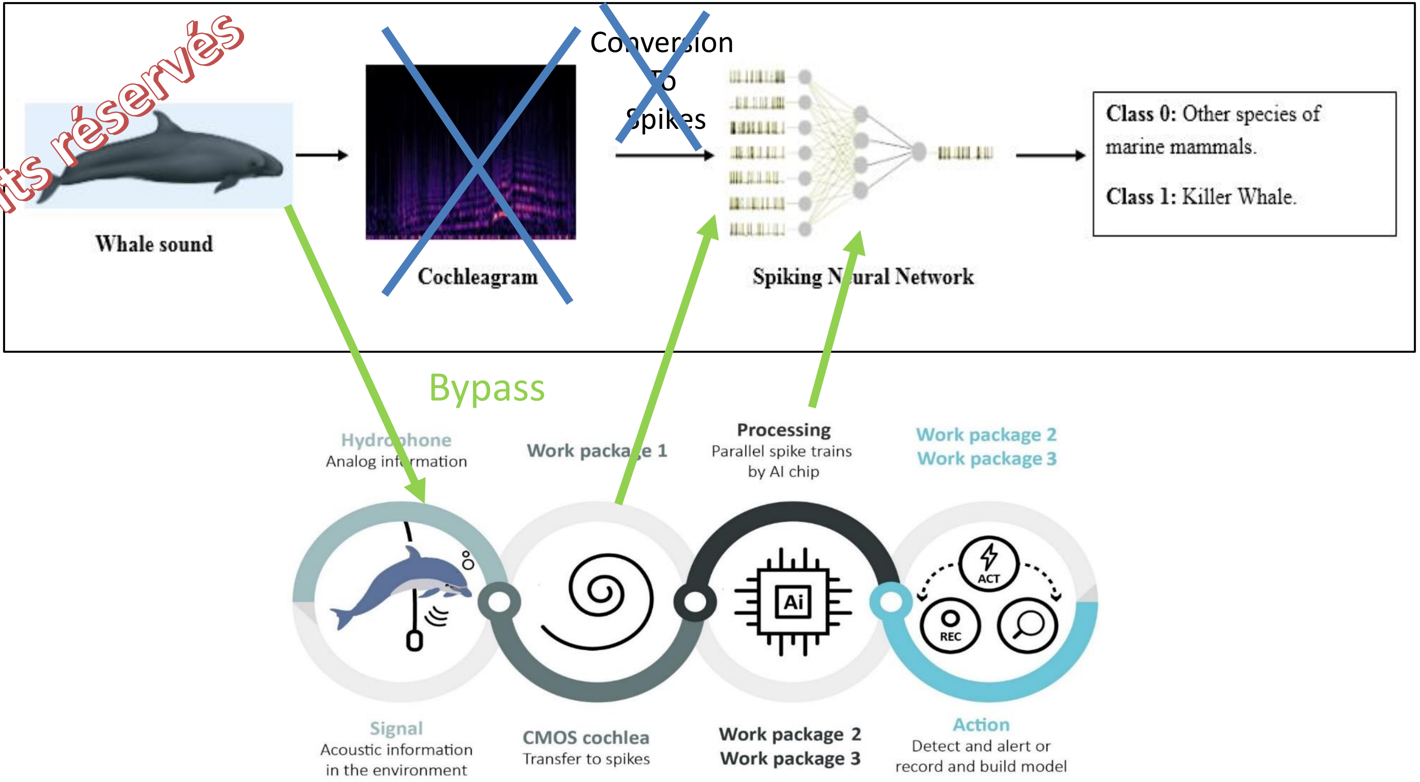
Binary Classification : Two classes are used the first class contains several species of marine mammals and the second class corresponds to the killer whale species.



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ULP COCHLEA

ANR ULP SMART COCHLEA

LOCALIZATION ?

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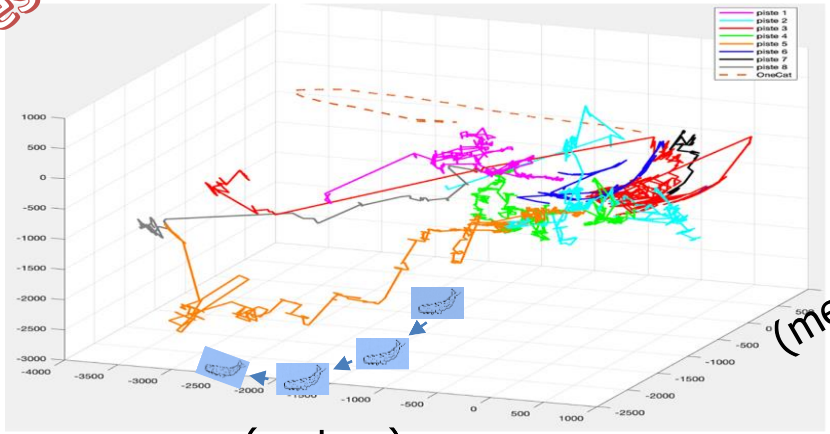
Hi!, where are you located ?

3D localisation of sperm whales (in the abyss) possible, using specific algorithms



Courtesy: Prof. H. Glotin
Univ. Toulon

Sphyrna Odyssey 2019-2020 : 3D tracks of 7 sperm whales off Monaco coast, during 2 hours, hunting in collaboration in the abyss (-1000 à -2000m)

https://www.franceinter.fr/emissions/la-terre-au-carre/la-terre-au-carre-29-octobre-2020

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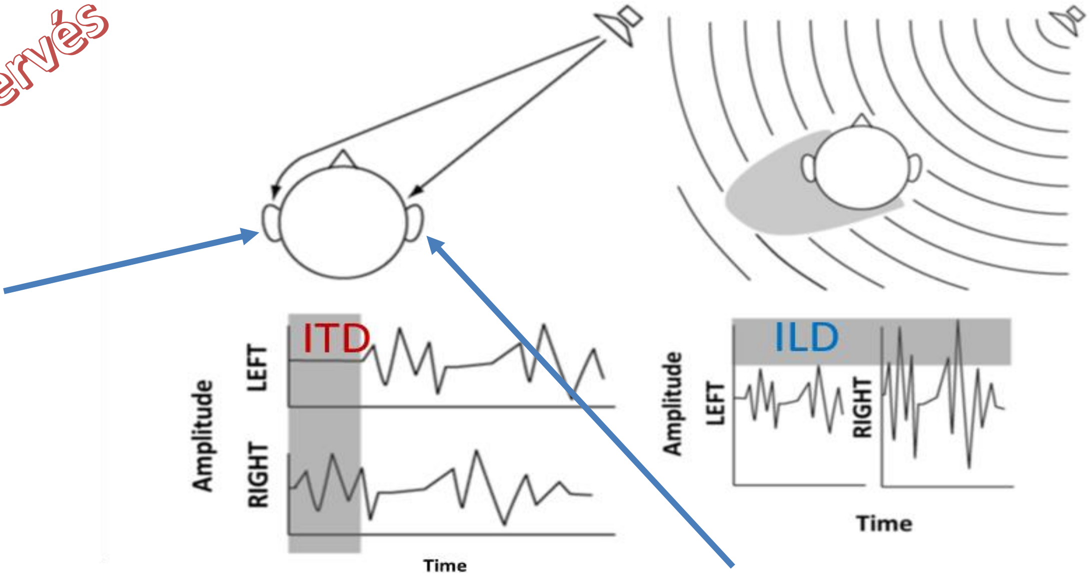
Sound Localization : basics

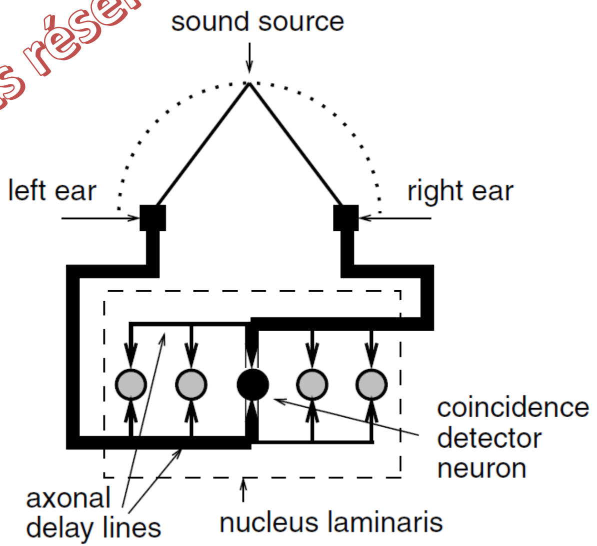


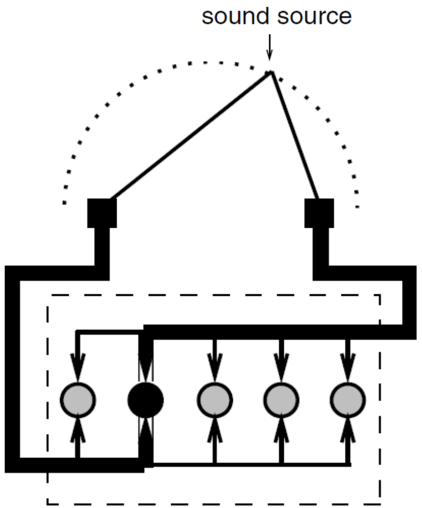
ITD : Interaural Time Difference

ILD : Interaural Level Difference

Sound Localization :
how ITD is encoded in biology* ?

Jeffers model





** J. Leo van Hemmen et al, Problems in Neuroscience, Oxford University Press, USA, 2006*

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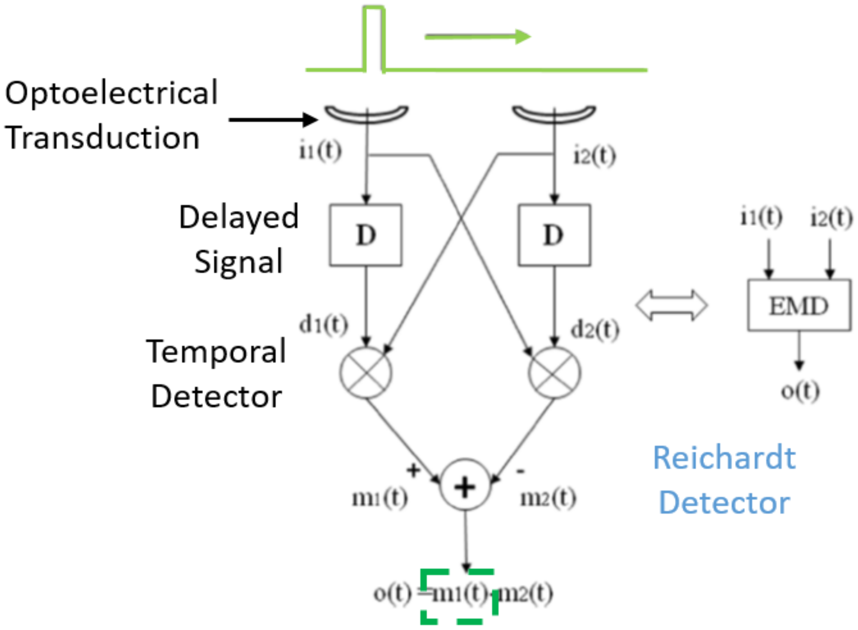
MOTION DETECTOR :
« Hassenstein-Reichardt » detector (1956)

Luminous spot that moves

Luminous spot that moves



m1(t) detected

Coincidence Detector*: coding interaural time difference (ITD), by (simply) counting spikes

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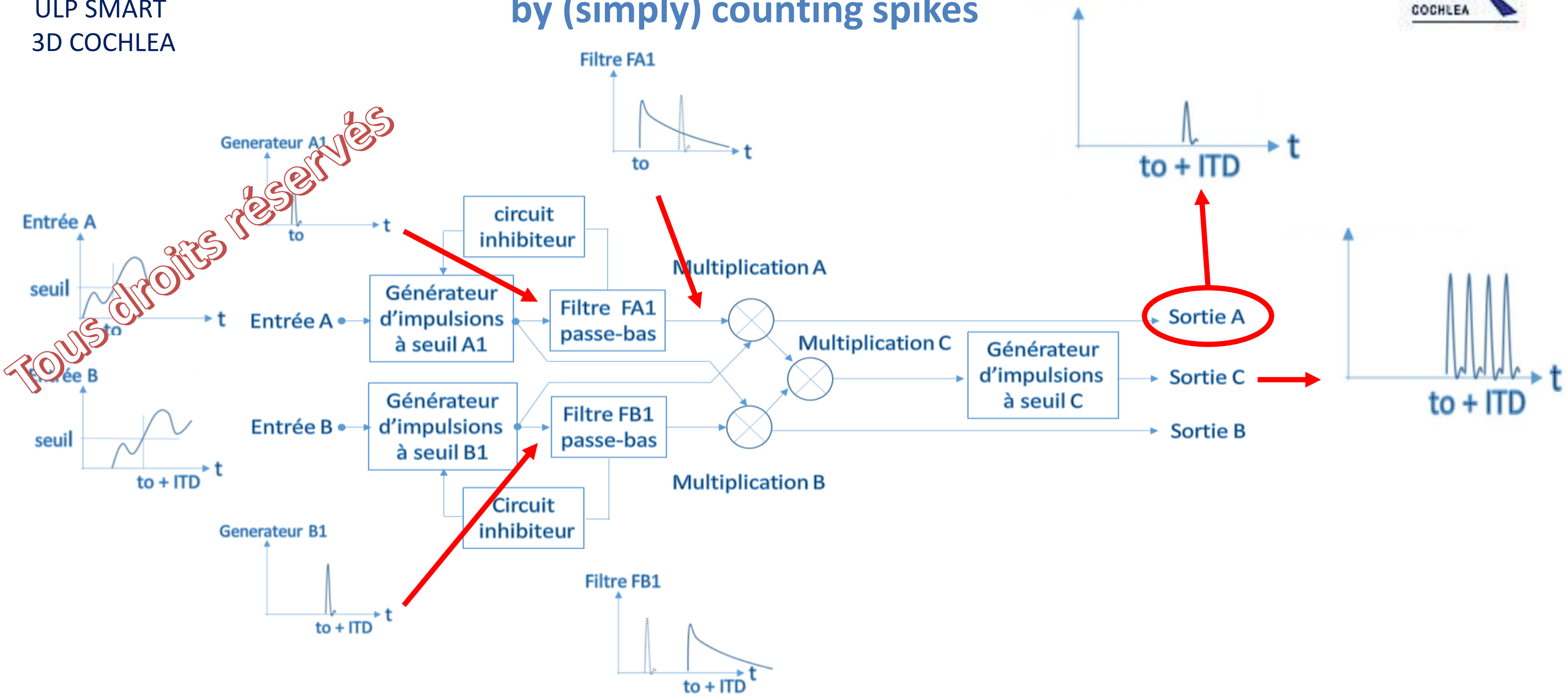

* Patent, *FR2112849, 02/12/2021 (INPI)*

2D LOCALIZATION ?

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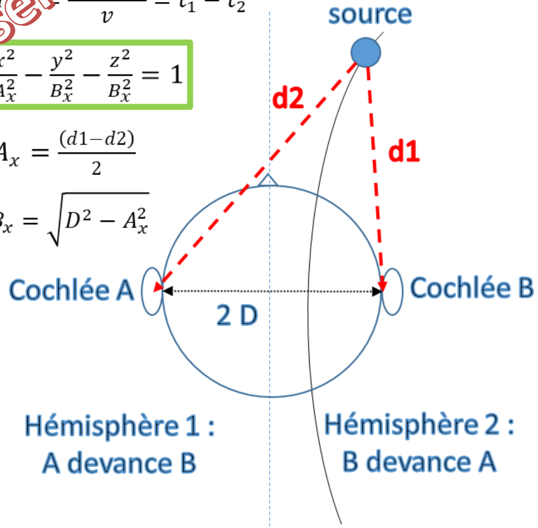
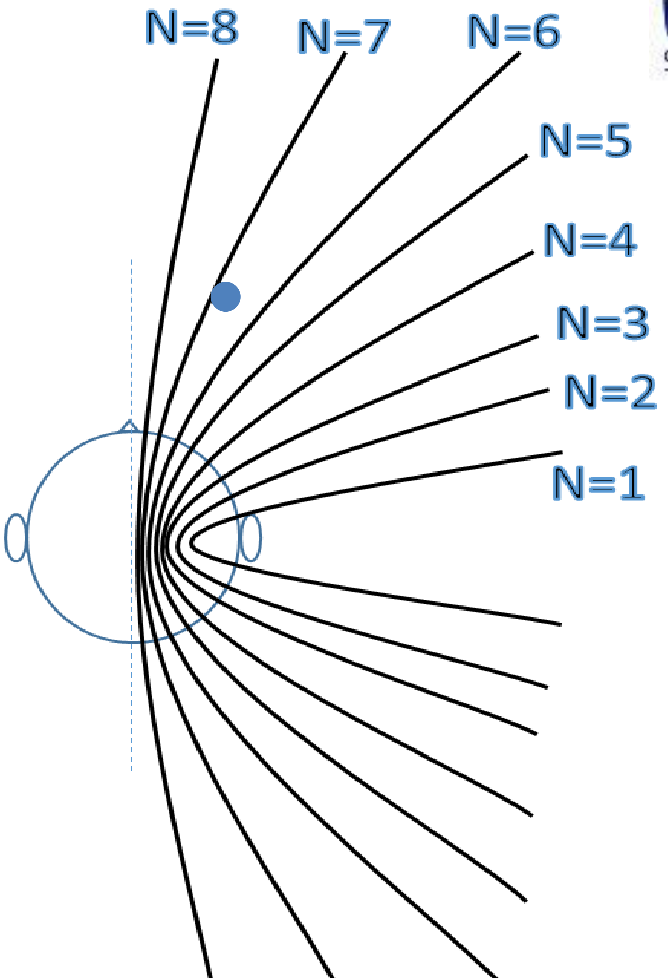
$$ITD = \frac{d_1 - d_2}{v} = t_1 - t_2$$

$$\boxed{\frac{x^2}{A_x^2} - \frac{y^2}{B_x^2} - \frac{z^2}{B_x^2} = 1}$$

$$A_x = \frac{(d1 - d2)}{2}$$

$$B_x = \sqrt{D^2 - A_x^2}$$





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3D COCHLEA

Conclusion

ULP COCHLEA

- ULP Artificial cochlea presented :
  - 100 nW / Channel (w/o buffer)

- Challenges :
  - Biodiversity monitoring (Ceteceans, not only)
  - Digital transition (Data deluge ↓)

- Key applications (biodiversity monitoring) :
  - Classification
  - Tracking
  - Anthropogenic noise impact ? (human activities)