Decoding echolocation:
Good practices for studying the sonar of marine animals

Nicolas Deloustal*[1,2,4], *Hervé Glotin[1,2,4], Cláudia Inês Botelho de Oliveira[1,3], Adeline Paiement[1,2,4], Sébastien Paris[1,2,4]*

**PhD student*
1 Centre International d'Intelligence Artificielle en Acoustique Naturelle
2 Laboratoire d'Informatique et des Systèmes, CNRS, Université de Toulon
3 IMAR
4 Chaire IA AID DGA ADSIL ANR-20-CHIA-0014

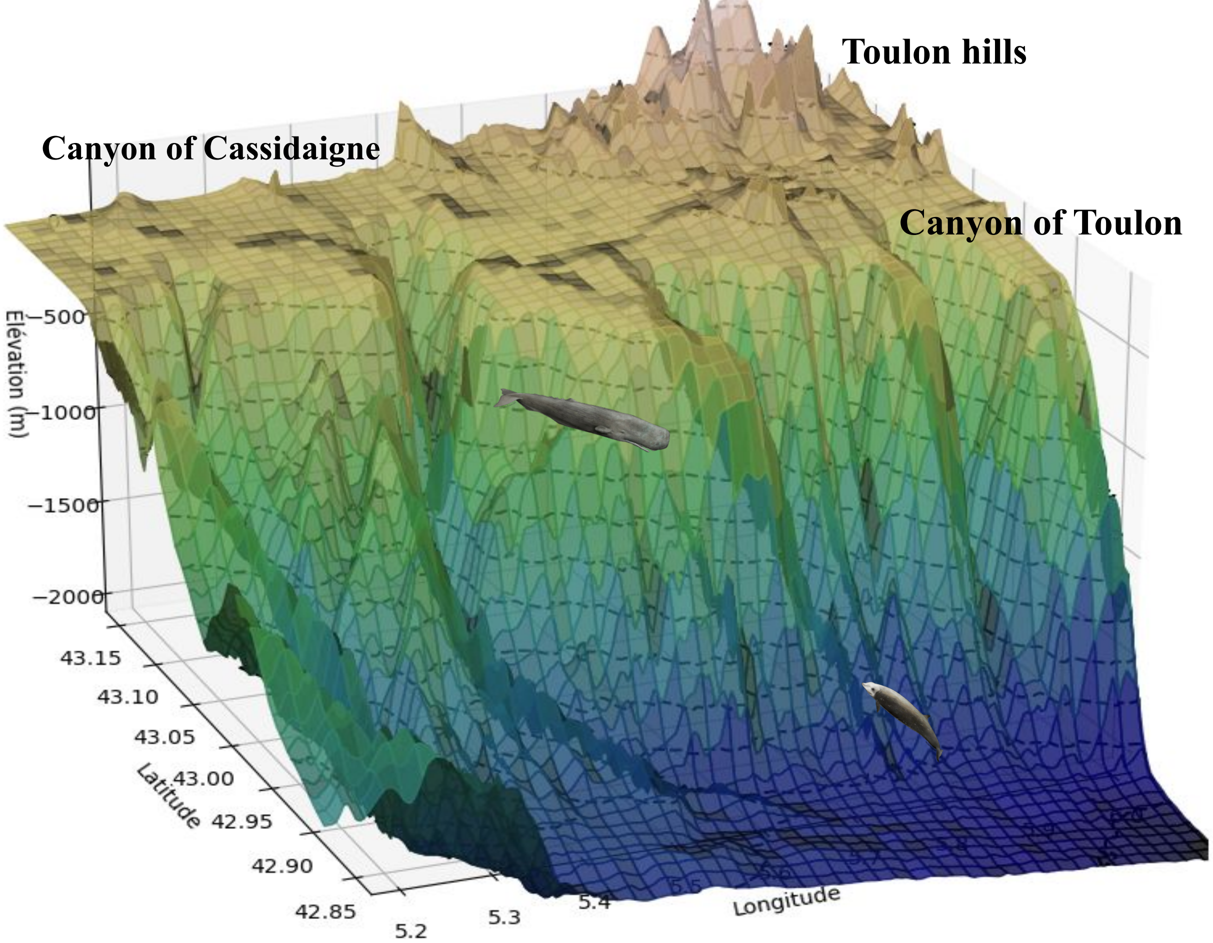
Problem

A dark environment

Navigating without vision

Biosonar

→ Echolocation



Griffin, DR. (1944). Echolocation by blind men, bats and radar. *Science*.
Au, W. (1993). The Sonar of Dolphins Springer, New York, pp. 32, 41–46, 66–70, 148–152.

Echolocation

◿ Detection / Localization

Range measurement :

1 - **Sound emission**
2 - **Echo**
3 - **Echo analysis**

air ≈ 344 m/s
water ≈ 1500 m/s

$$\text{Range}_{(\text{sonar/target})} = \frac{t(\text{Sonar} \rightarrow \text{Target} \rightarrow \text{Sonar})}{2} \times \text{speed of sound}$$

Echolocation

Detection / Localization

<u>Speed measurement :</u>

Doppler effect

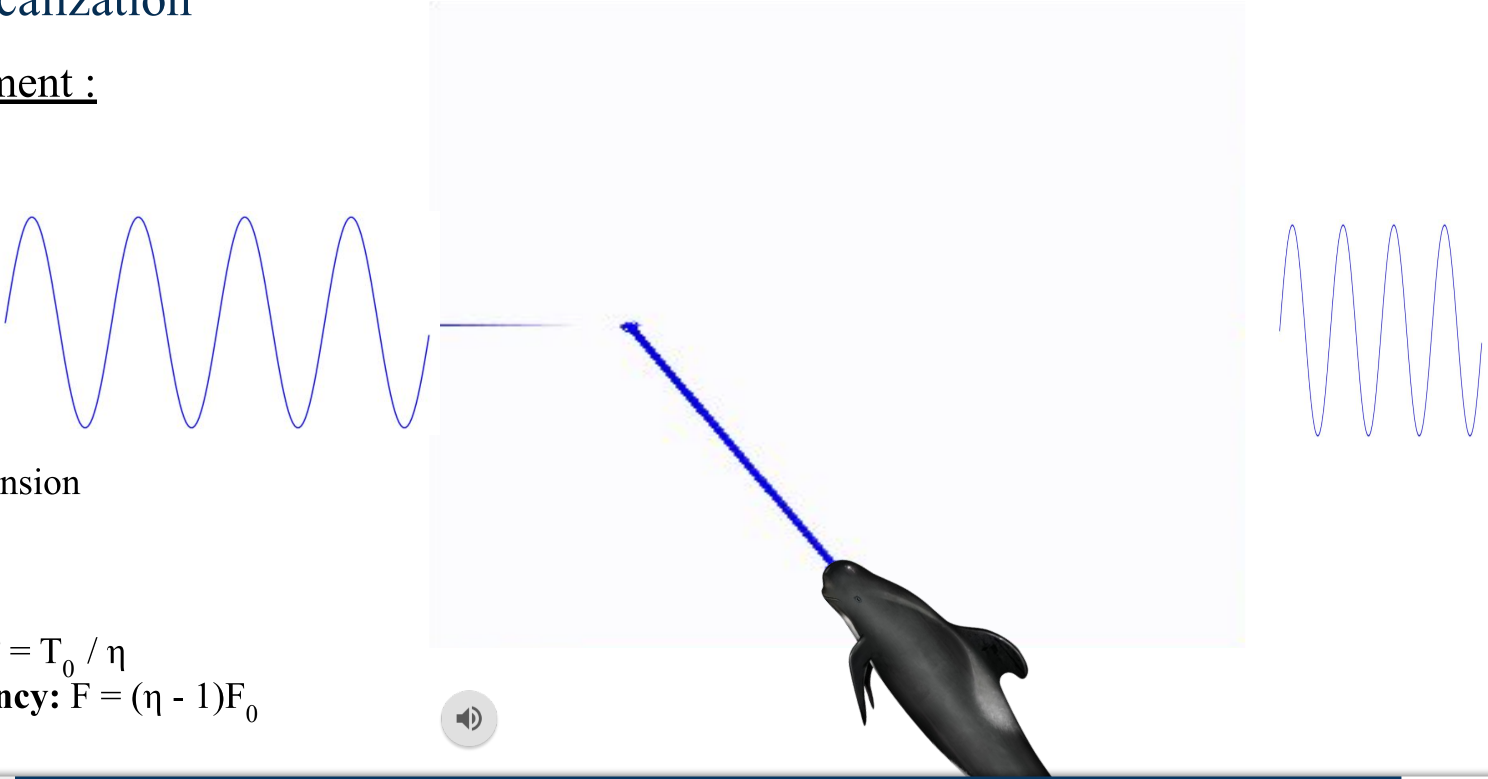
Distance variation

↓

Compression or expansion

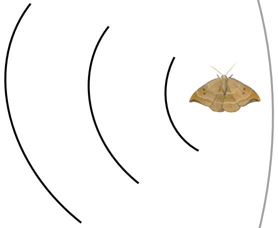
↓

Changes **duration**: $T = T_0 / \eta$
and therefore **frequency:** $F = (\eta - 1)F_0$



Echolocation and behavior

Foraging



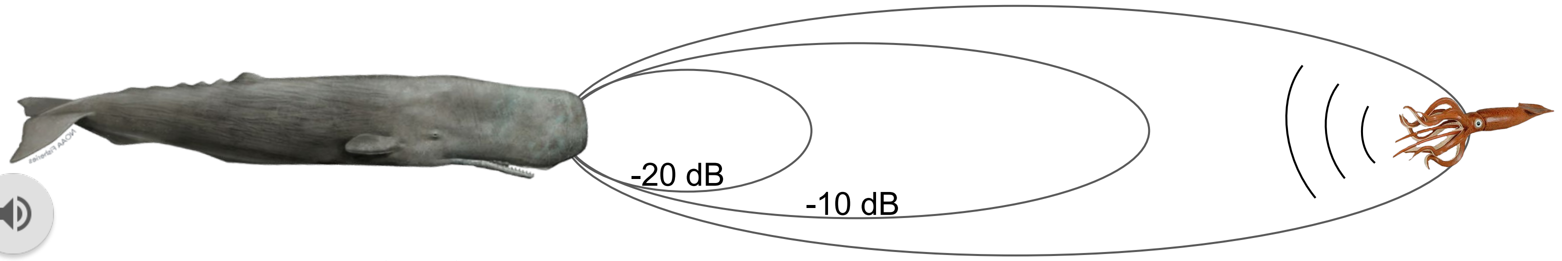
Detection :

- Perceiving movement / velocity
- Finding obstacles and speed in a stationary space

Low frequency, high energy	
Very good propagation	Low spatial resolution

Echolocation and behavior

Foraging



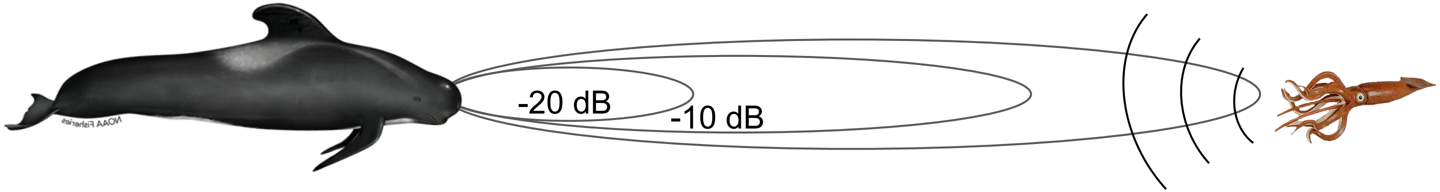
Localization :

- Determine the position of a target (regardless of speed)

Greater frequency bandwidth	
Good spatial resolution, resistant to Doppler effect	Requires close target distance

Echolocation and behavior

Foraging



Characterization :

- Identify the nature of a target (size / shape / texture)

High frequency	
Excellent spatial resolution	Requires close distance to target

Echolocation and behavior

Foraging

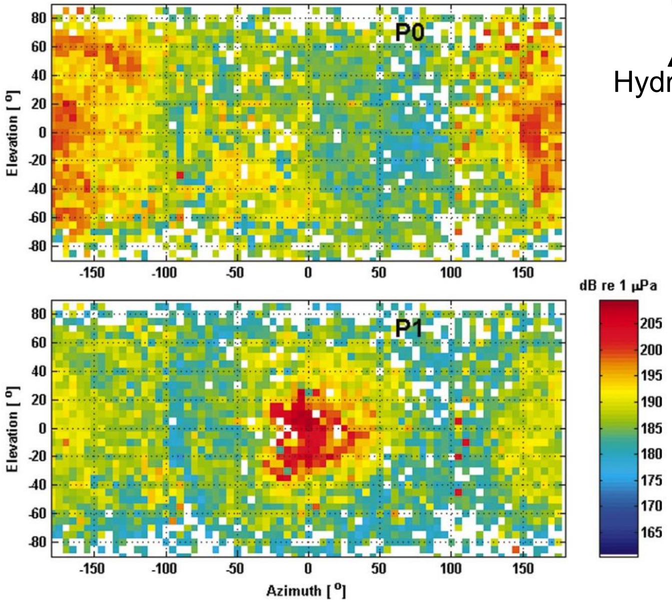
Buzz :

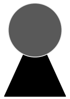
- Estimate the most precise **distance** possible

Low energy, short pulse	
Near real-time target estimation	Short range

Data acquisition - Directivity effect

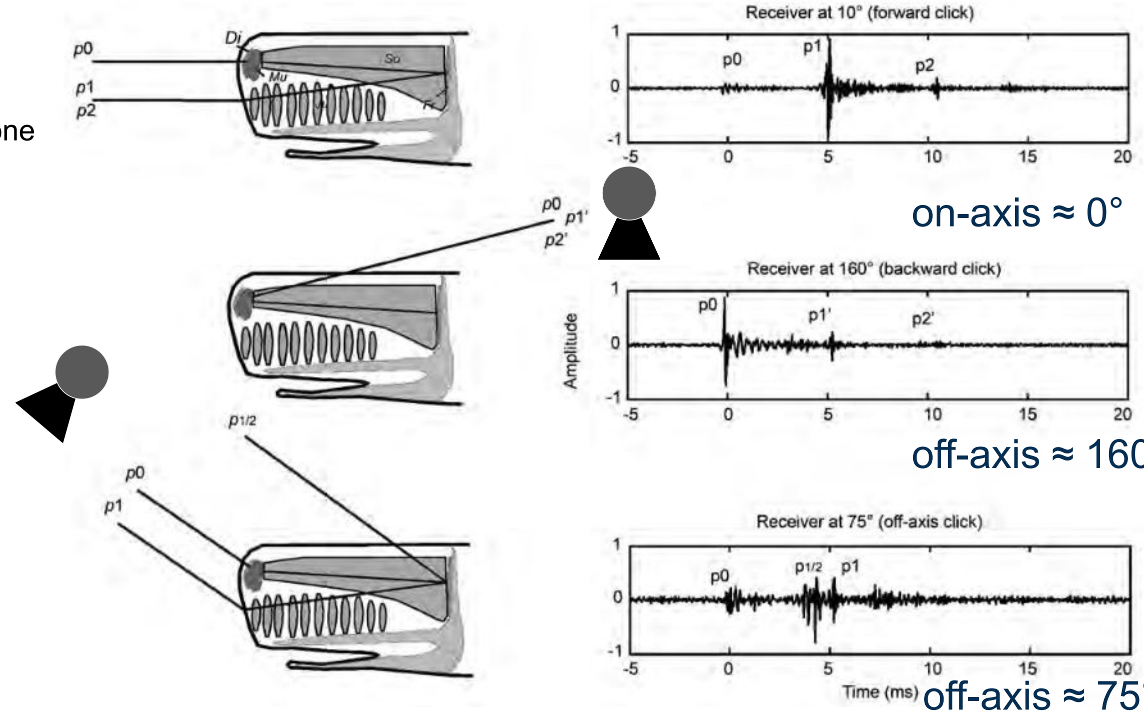
Hydrophone position





Hydrophone

Sperm whale example



p1 = localization

p0 = orientation cues

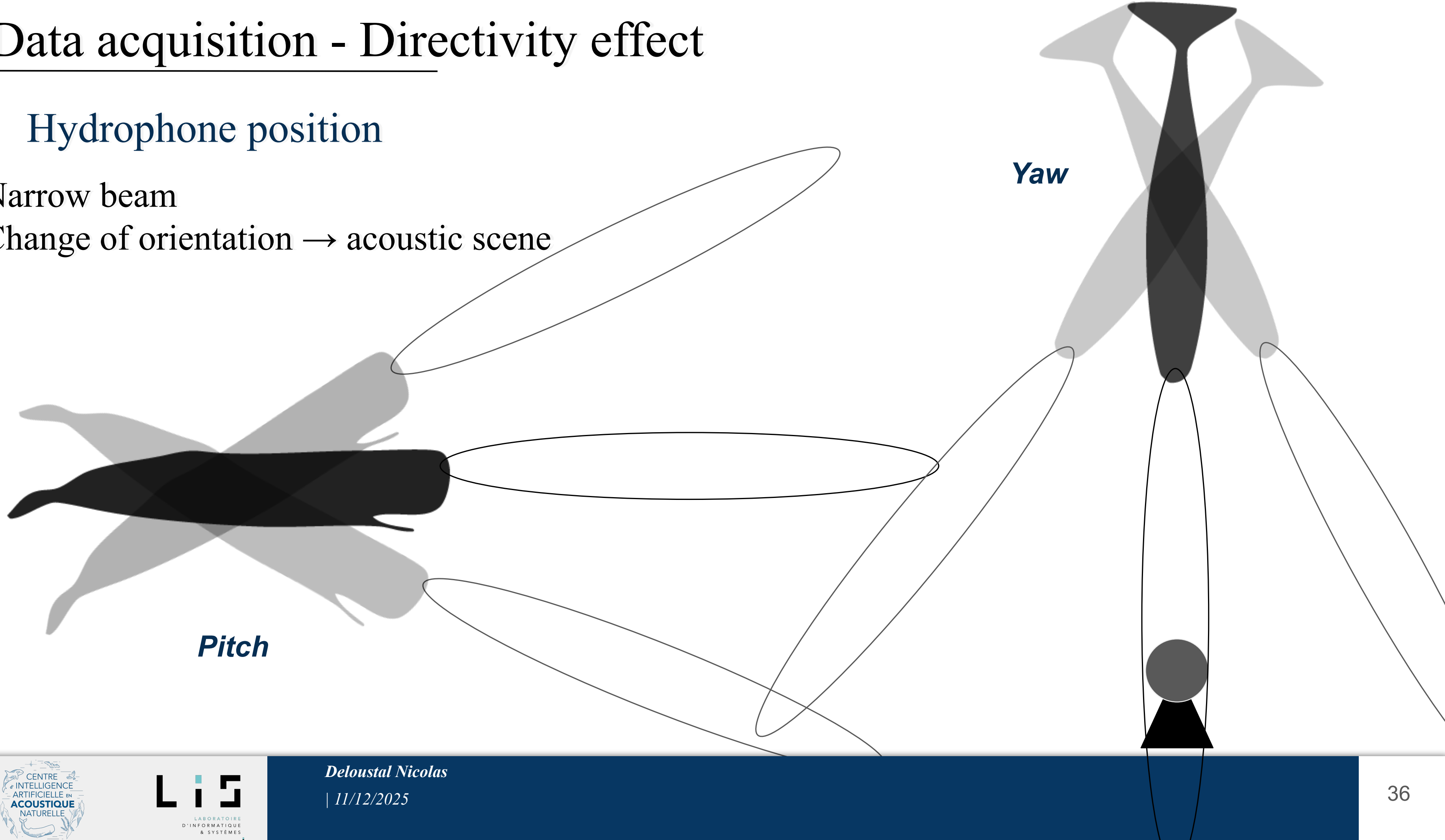
→ Must be on-axis

Zimmer, W. M., Tyack, P. L., Johnson, M. P., & Madsen, P. T. (2005). Three-dimensional beam pattern of regular sperm whale clicks confirms bent-horn hypothesis. The Journal of the Acoustical Society of America, 117(3 Pt 1), 1473–1485.
Teloni, V., Zimmer, W. M., WAahlberg, M., & Madsen, P. (2007). 127 consistent acoustic size estimation of sperm whales using clicks recorded from unknown aspects. *J. Cetacean Res. Manage*, *9*(2), 127-136.

Data acquisition - Directivity effect

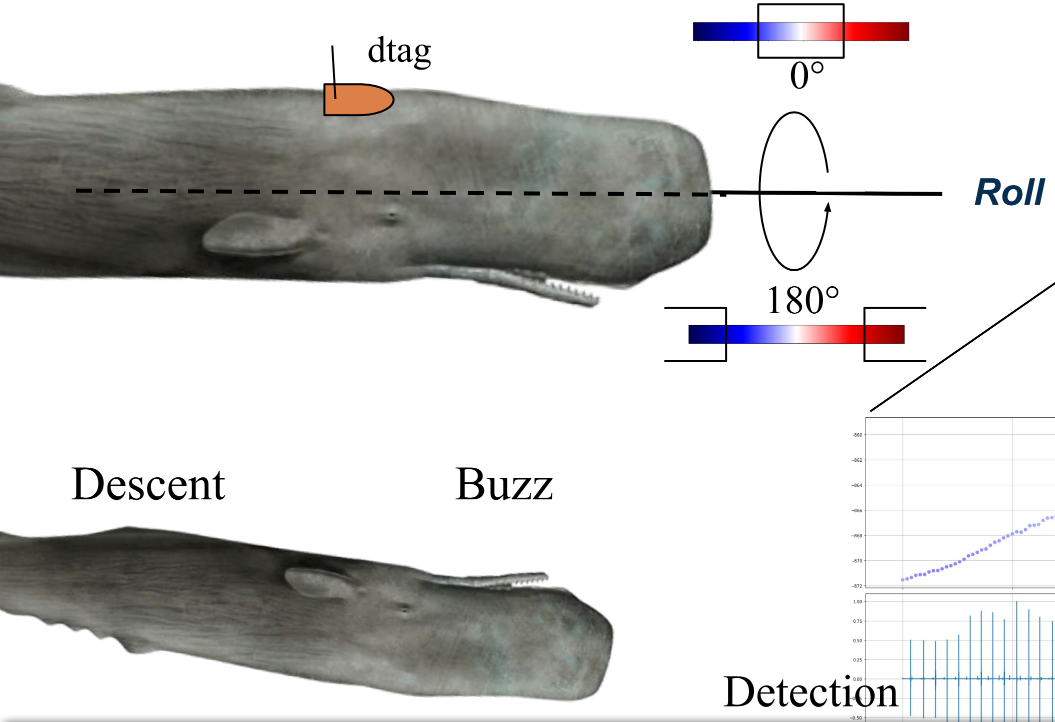
Hydrophone position

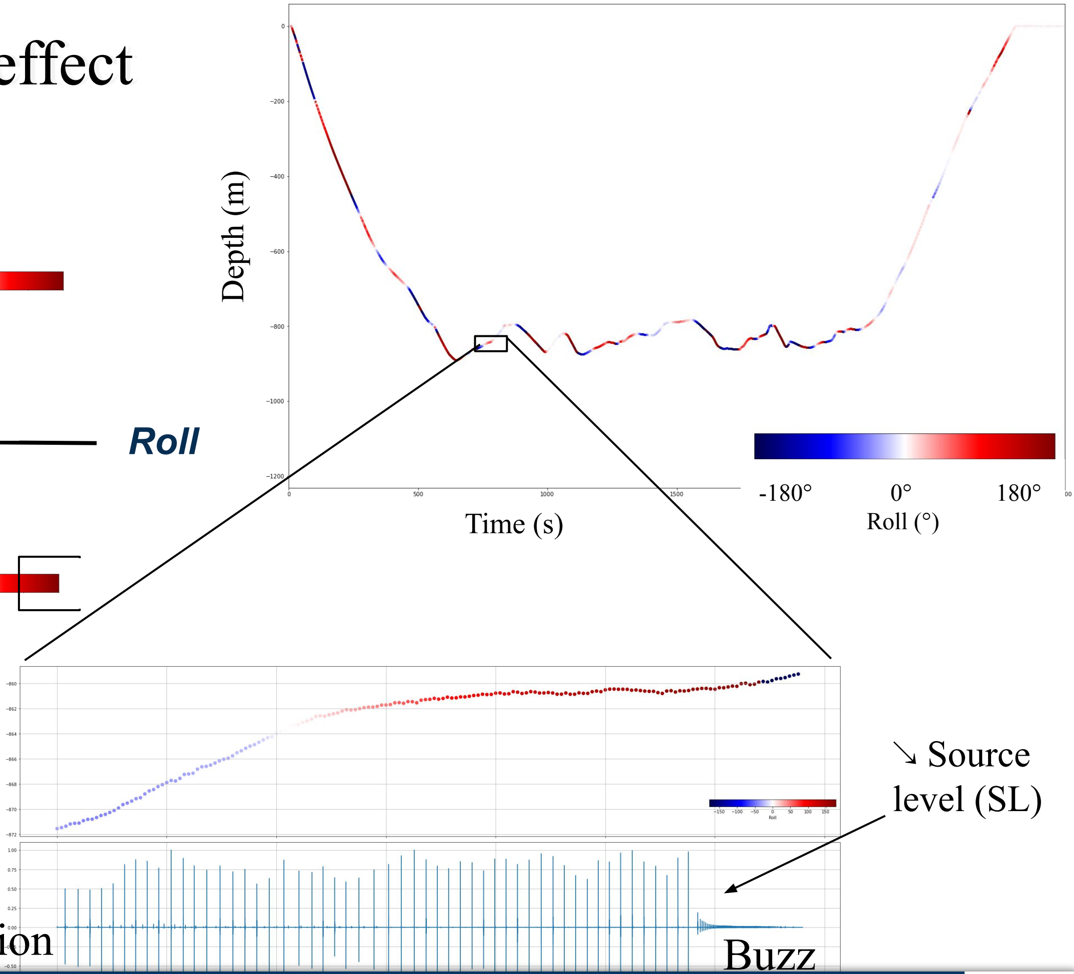
Narrow beam
Change of orientation → acoustic scene



Data acquisition - Directivity effect

Hydrophone position





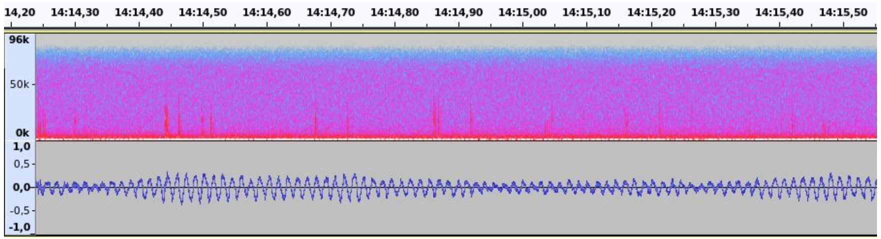
Oliveira, C., Wahlberg, M., Silva, M. A., Johnson, M., Antunes, R., Wisniewska, D. M., Fais, A., Gonçalves, J., & Madsen, P. T. (2016). Sperm whale codas may encode individuality as well as clan identity. The Journal of the Acoustical Society of America, 139(5), 2860.

Data acquisition

Noise

Anthropophony

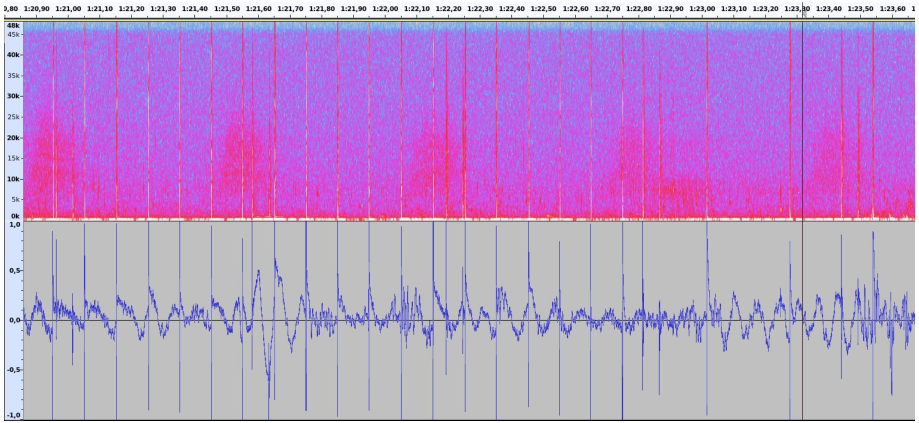
- Boat



Time (s)

Solution: Filtering

- Echosounder



Time (s)

Biophony

- Snapping shrimp

Zimmer, W. M., Tyack, P. L., Johnson, M. P., & Madsen, P. T. (2005). Three-dimensional beam pattern of regular sperm whale clicks confirms bent-horn hypothesis. The Journal of the Acoustical Society of America, 117(3 Pt 1), 1473–1485.
Teloni, V., Zimmer, W. M., WAahlberg, M., & Madsen, P. (2007). 127 consistent acoustic size estimation of sperm whales using clicks recorded from unknown aspects. *J. Cetacean Res. Manage*, *9*(2), 127-136.

Data acquisition - Acoustic masking

Propagation

TL: transmission loss

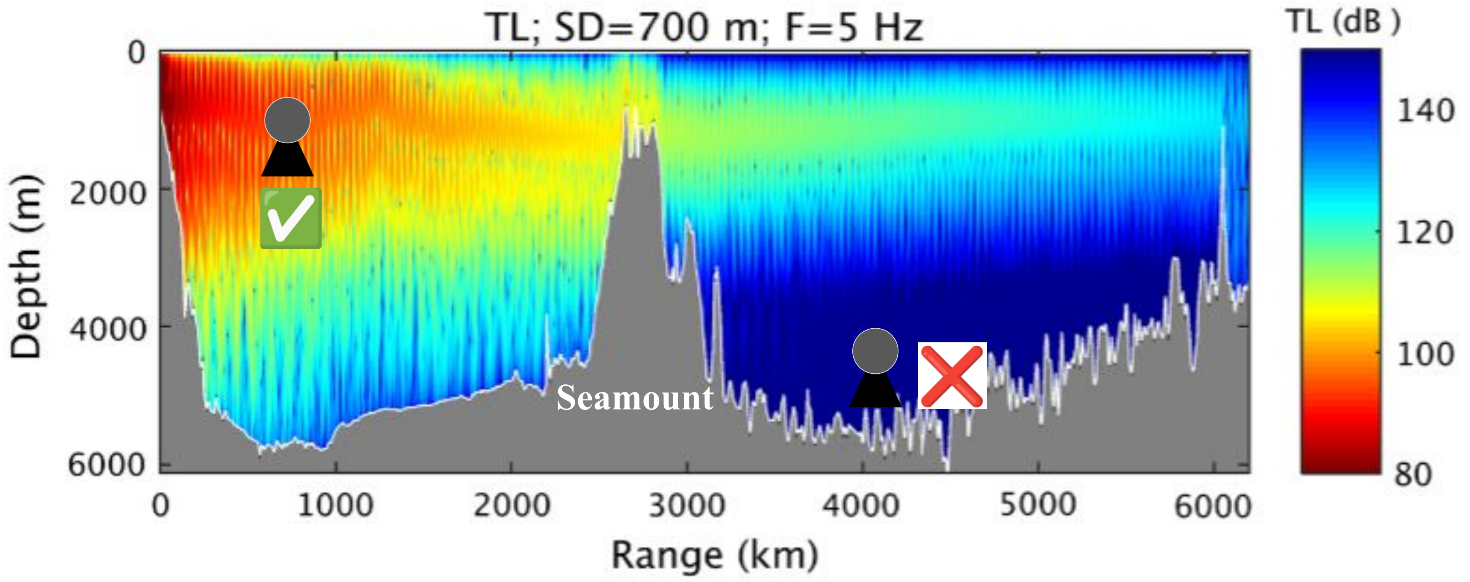
→ affects **spectral** & **temporal** properties,

Factors:

Mixing layers

Acoustic masking

Distance



Functional Convergence in Bat and Toothed Whale Biosonars (2013) P. T. Madsen and A. Surlykke Physiology, 28:5, 276-283
Nielsen, Peter et al., (2021). CTBTO's Data and Analysis Pertaining to the Search for the Missing Argentine Submarine ARA San Juan. Pure and Applied Geophysics.

Signal processing : Quantify information

Ambiguity function

$$\chi(\tau,\eta) = \sqrt{\eta}\int_{-\infty}^{+\infty} s(t)s^*(\eta(t-\tau))dt$$

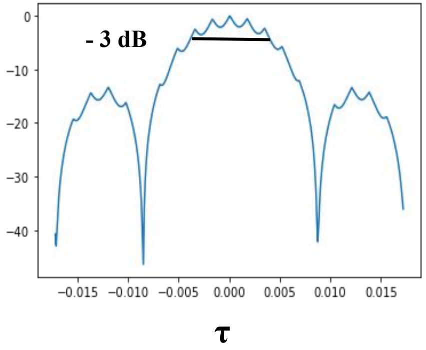
s(t) : biosonar,
s*(η(t-τ)) : echo reflected by targets,
τ : delay,
η : Doppler scaling factor

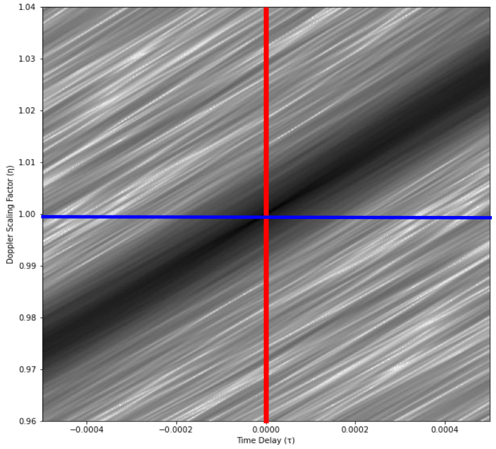
→ Sonar performance measurements

surface $|\chi(\tau, \eta)|^2$

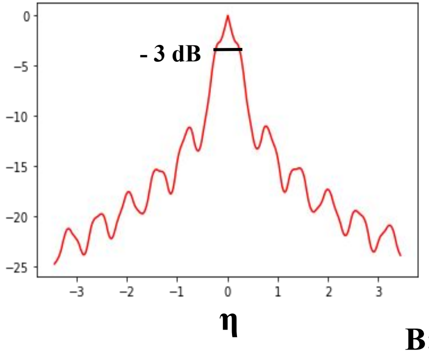
Range Resolution (RR)

$$RR \propto \frac{c}{2B}$$





Velocity Resolution (VR)



$$VR \propto \frac{c}{2 \cdot f_c \cdot T}$$

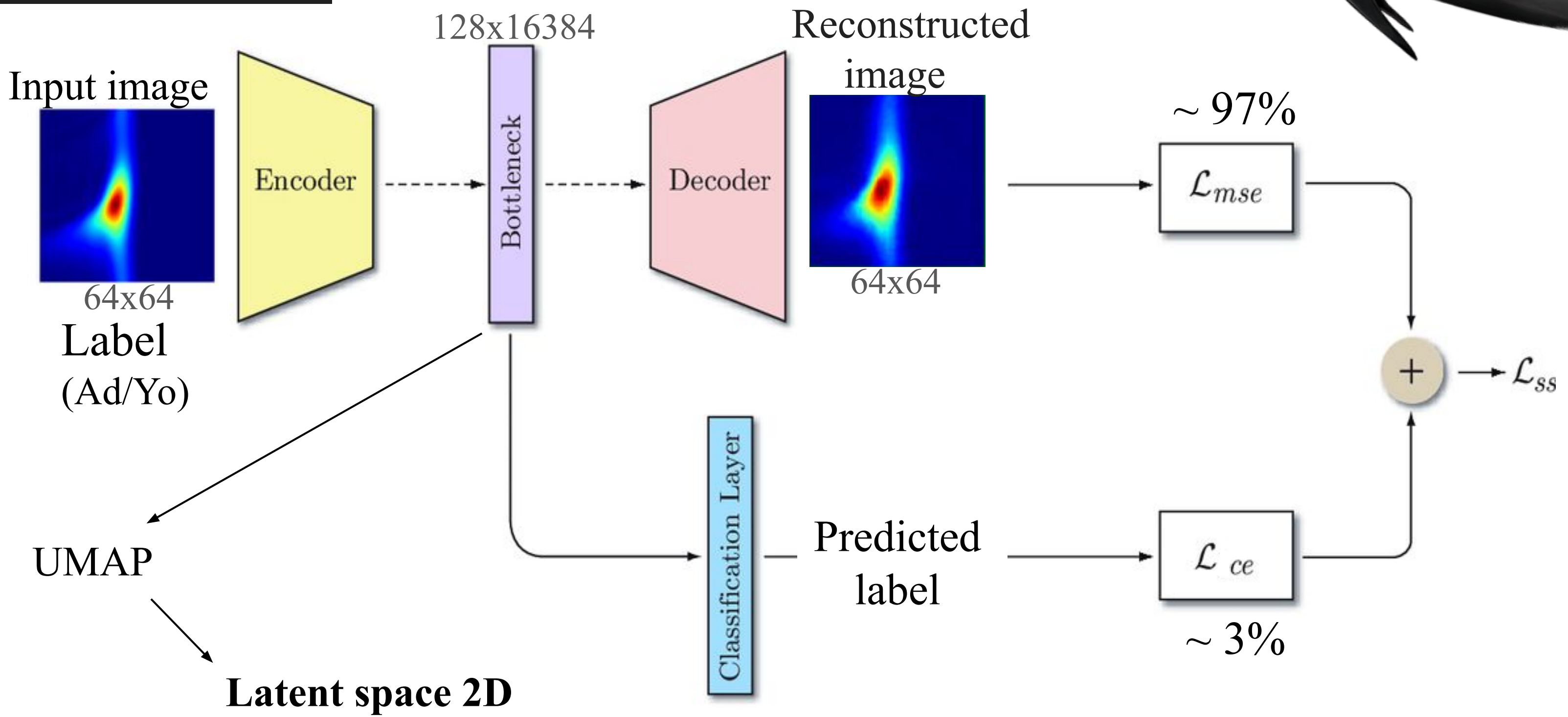
→ Performance = Intentions = Behavior

B: bandwidth
fc: center frequency
T: effective duration
c: speed of sound

Kelly, E. J., and Wishner, R. P. (1965). "Matched-filter theory for high-velocity, accelerating targets," IEEE Transactions on Military Electronics 9, 56–69

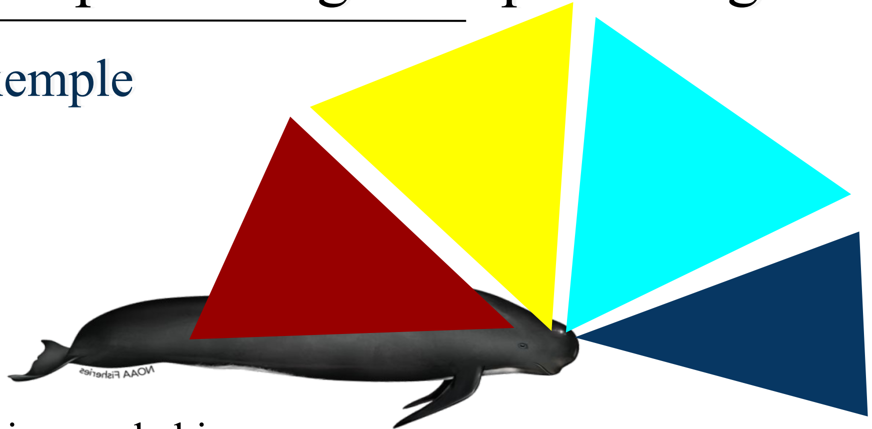
Signal processing : Deep learning

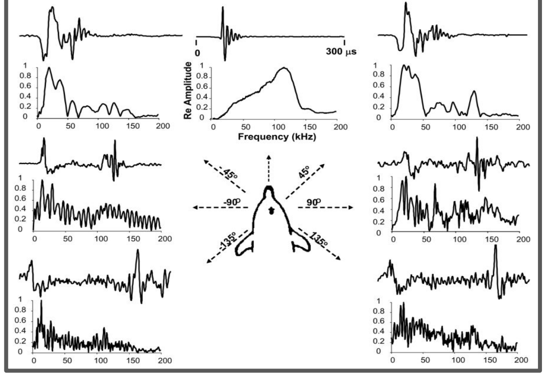
Supervised AE + Classifier



Signal processing : Deep learning

Exemple



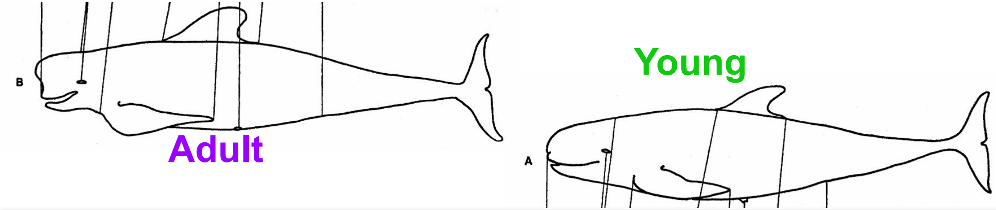


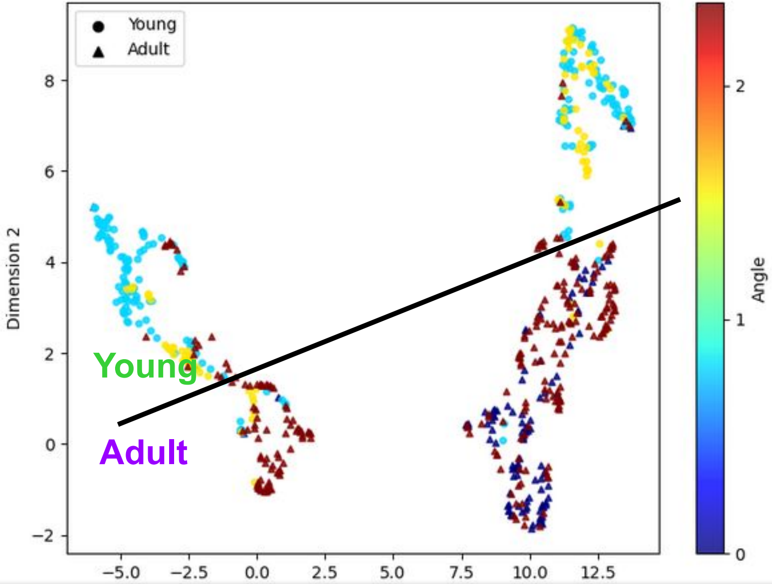
Biosonar click at different angles (horizontal plane)

- Emission angle bias :

Side = Young **Front and Back = Adult**

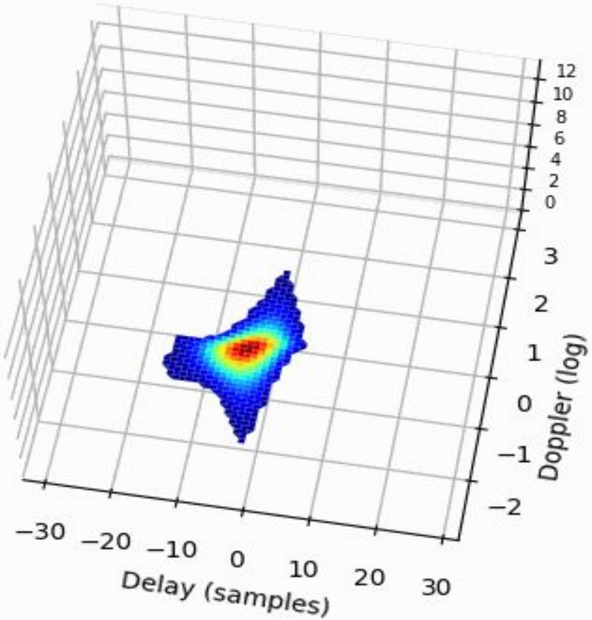
- Visual differentiation between young and adults :



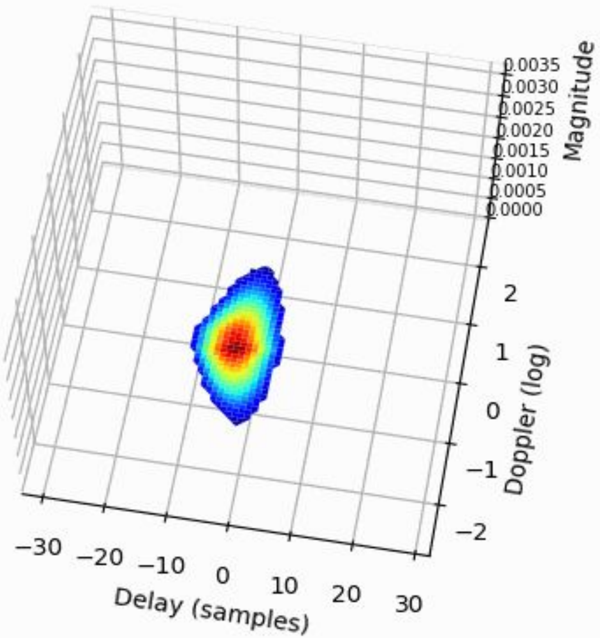


Au WW, et al,. The biosonar field around an Atlantic bottlenose dolphin (Tursiops truncatus). J Acoust Soc Am. 2012 Jan;131(1):569-76

Dynamic patterns : Different Behaviour / biosonar tactic ?



Adult



Young

Thank you for listening