Cetacean sounds detection with KM3NeT hydrophones

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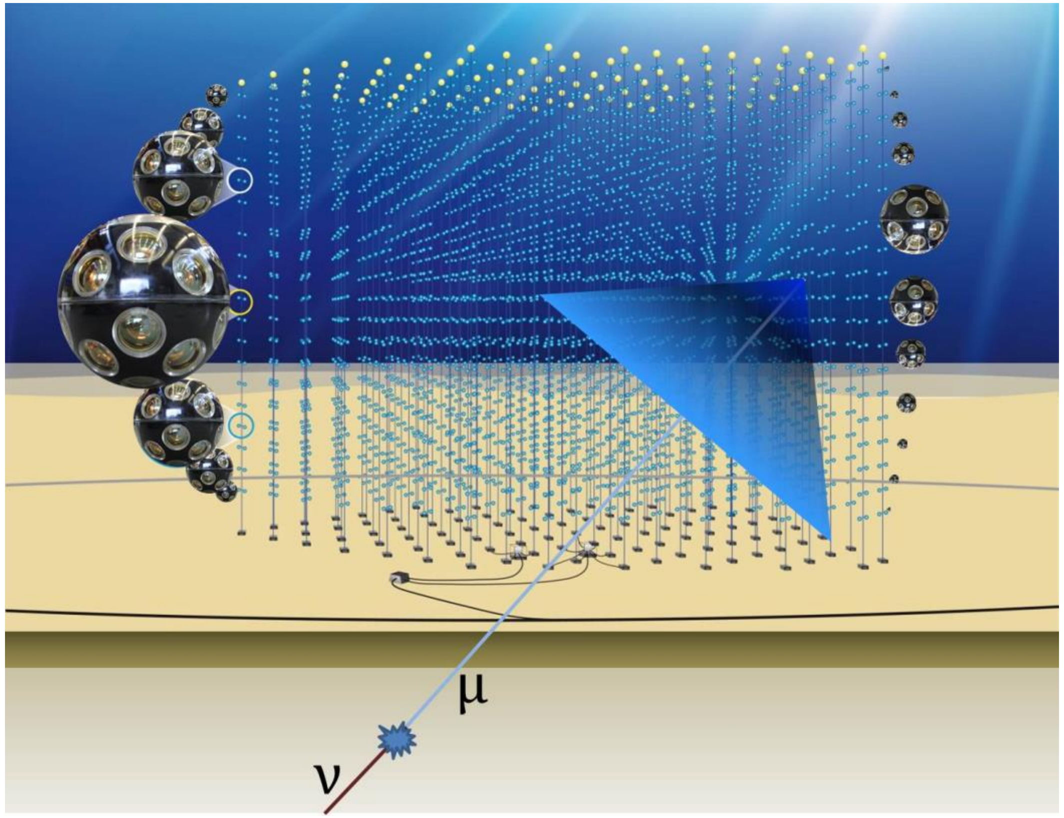
KM3NeT

- KM3Net is a submarine telescope for the detection of cosmic neutrinos.
- Some neutrinos, crossing the earth, interact and produce a muon.
- Photomultipliers detect the light generated by Cherenkov effect of muons traveling in a medium in which their speed is greater than the speed of light in that medium.

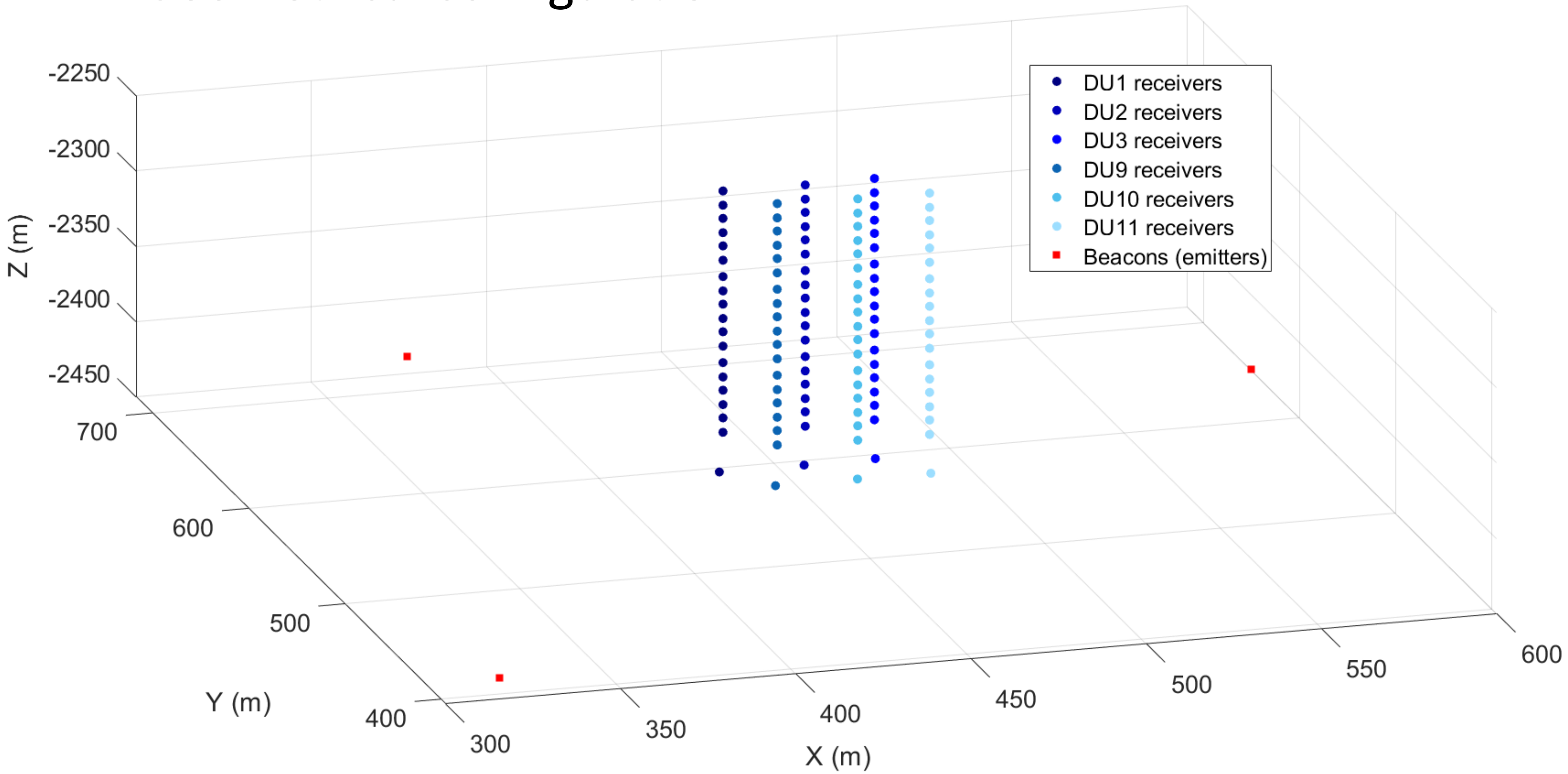


Why do we need a positioning system?

- During deployment, the position of the string bases is determined with an accuracy of $1\ m$
- A submarine current may be present at speeds up to $20\ cm/s$ which tilts the string moving the DOM from the vertical to about $7\ m$ in the most pessimistic case
- The goal is to have a temporal resolution of the order of the nanosecond, in order to reconstruct the tracks of the muons
- The light travels $1\ ns$ in about $20\ cm$ in sea water
- For this reason it is necessary to know with a precision less than $20\ cm$ the position of each DOM

KM3NeT Acoustic Positioning System

Geometrical configuration:

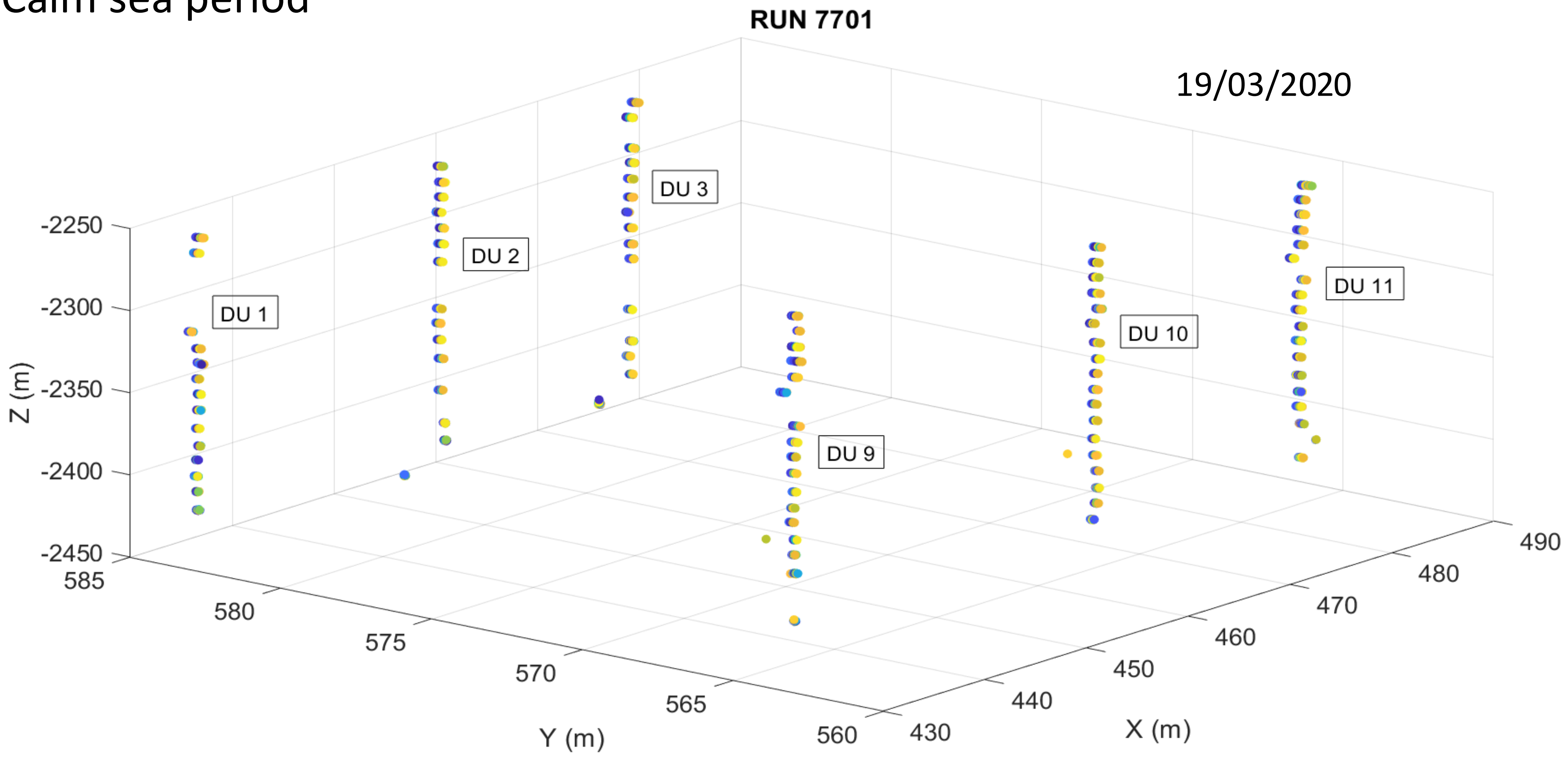


In principle the three beacons emit 11 pulses every 10 minutes

Currently Beacon 1 is not working

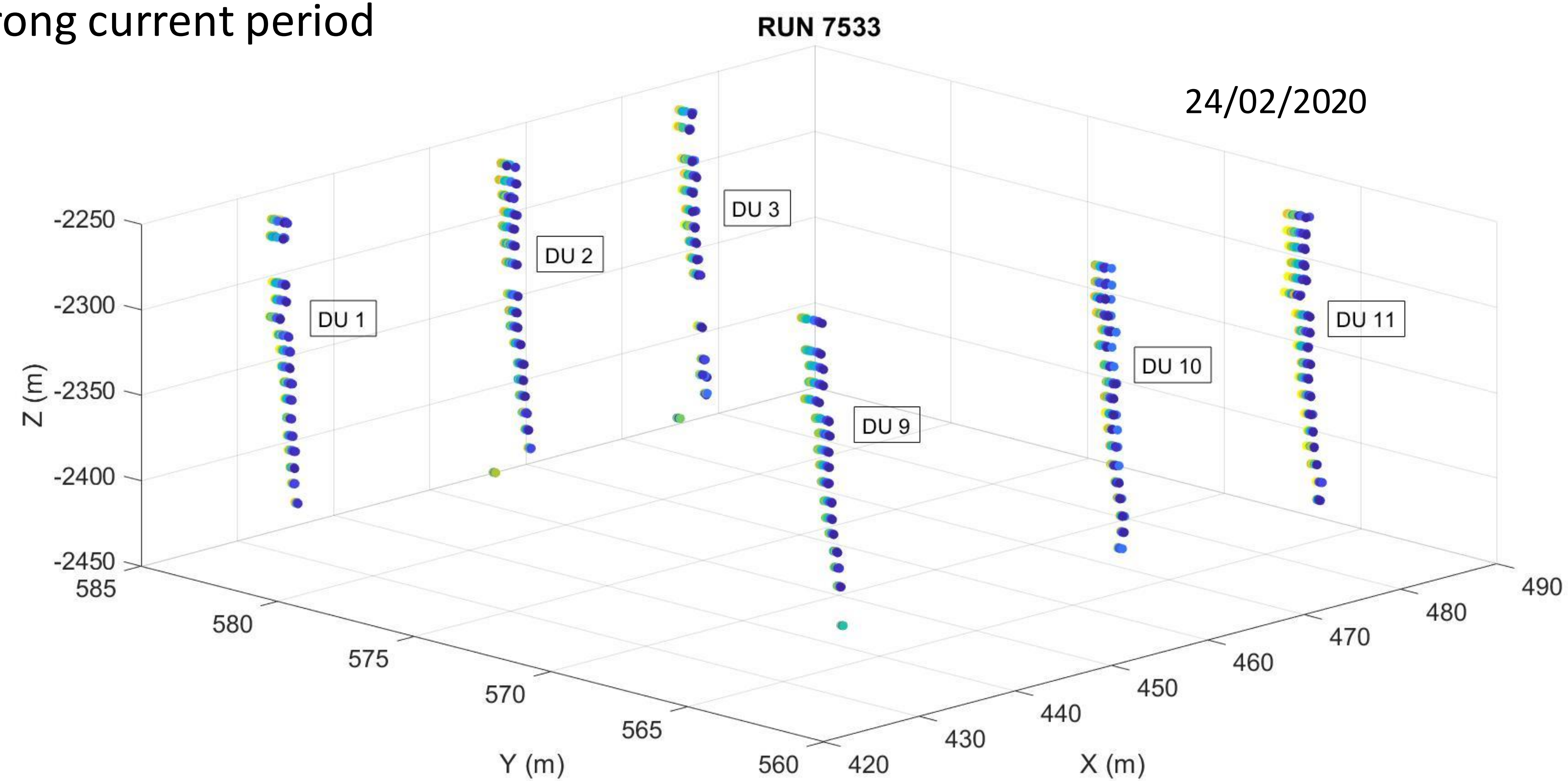
ACOUSTIC POSITIONING SYSTEM APPLIED TO REAL DATA

Calm sea period



ACOUSTIC POSITIONING SYSTEM APPLIED TO REAL DATA

Strong current period

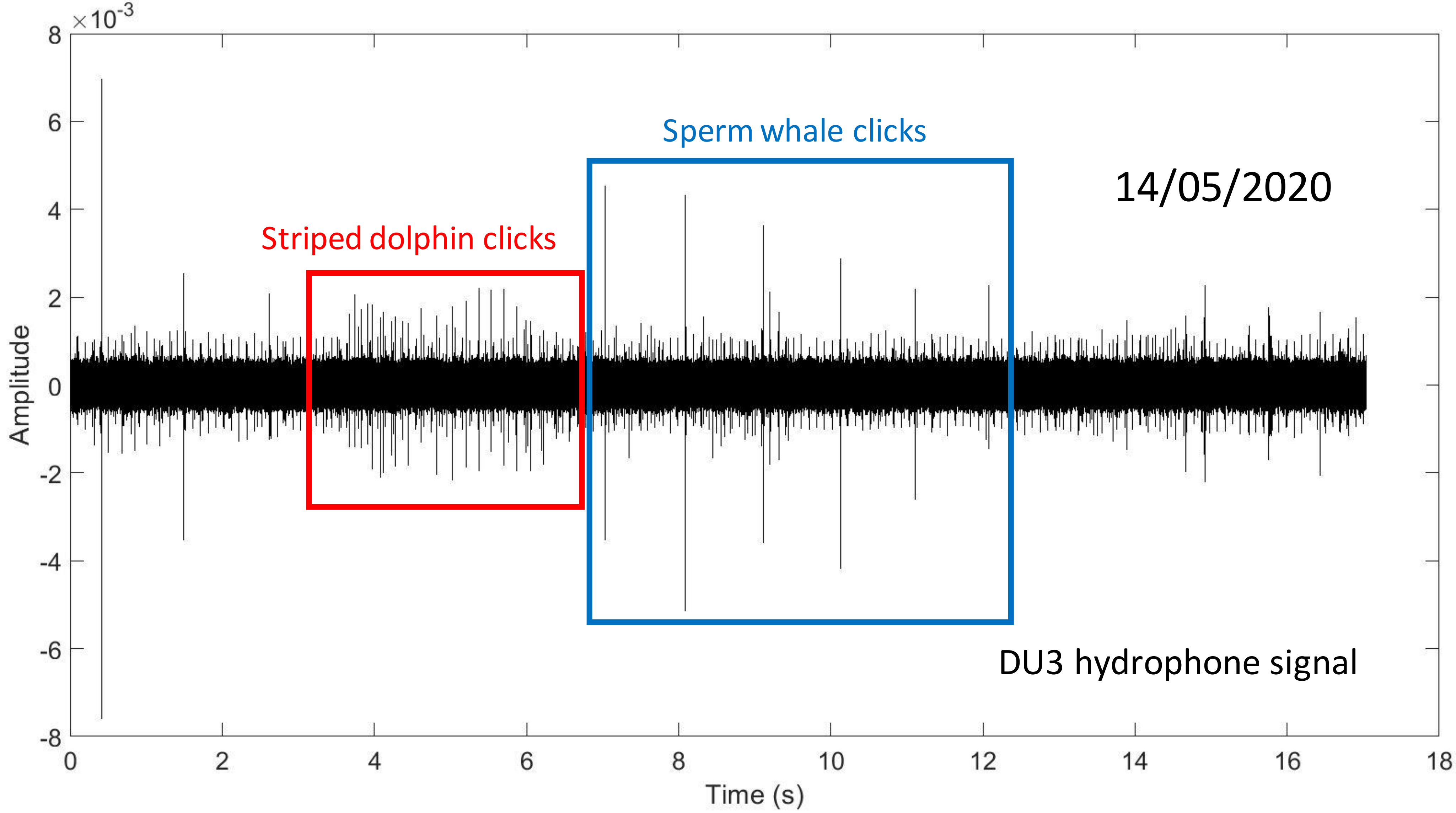


Cetacean detection – possible studies:

- Classification of cetaceans’ sounds
- Study on the behaviour of marine mammals
- Study on the presence and passage of cetaceans in the area
- Effect of anthropic activity on the marine ecosystem
- **Localization and tracking of cetaceans that emit clicks (in particular sperm whales)**

SIGNALS FROM DU3 KM3NeT HYDROPHONE

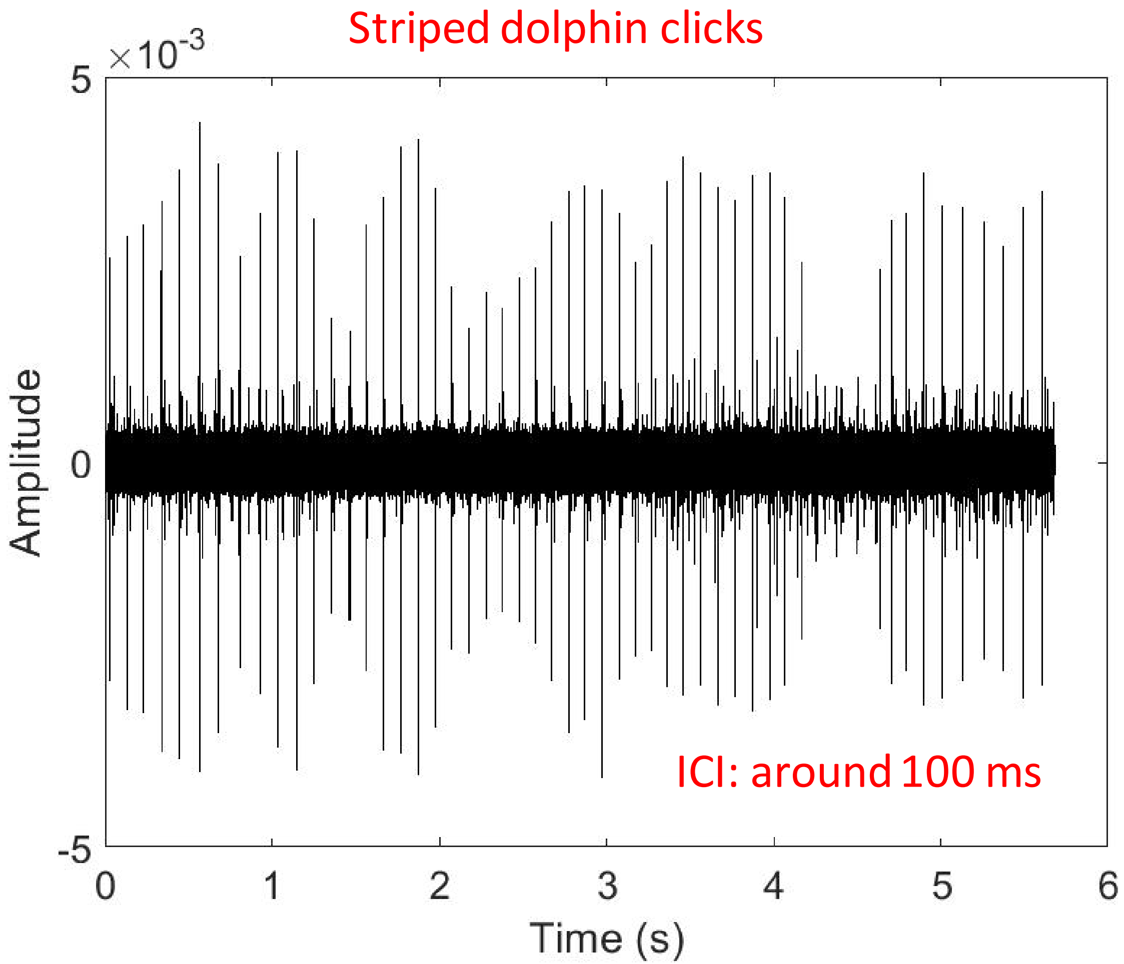
Two different kind of clicks have been detected

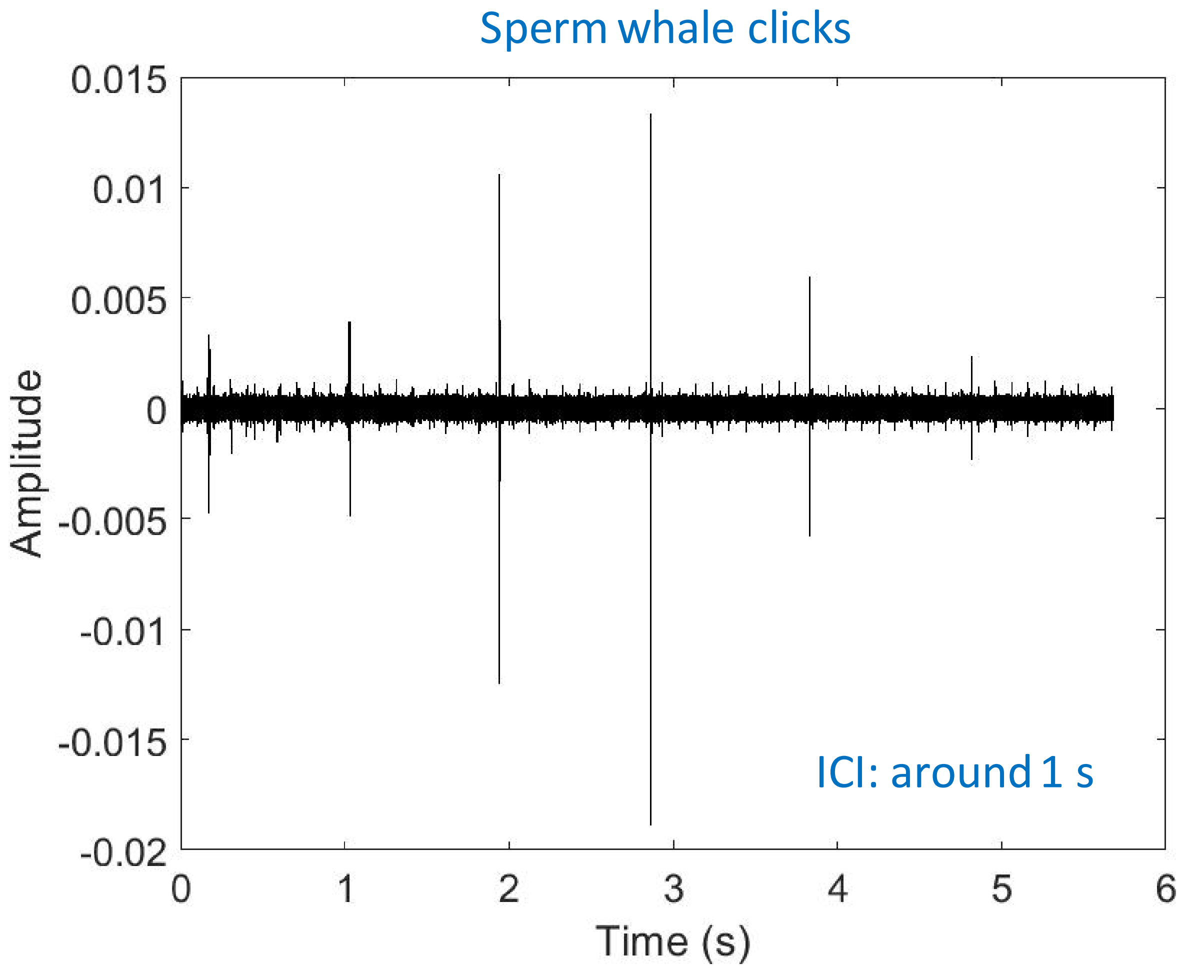


Main differences between Striped Dolphin and Sperm Whale clicks

- ❖Inter Click Interval
- ❖Click Shape
- ❖Frequency Range

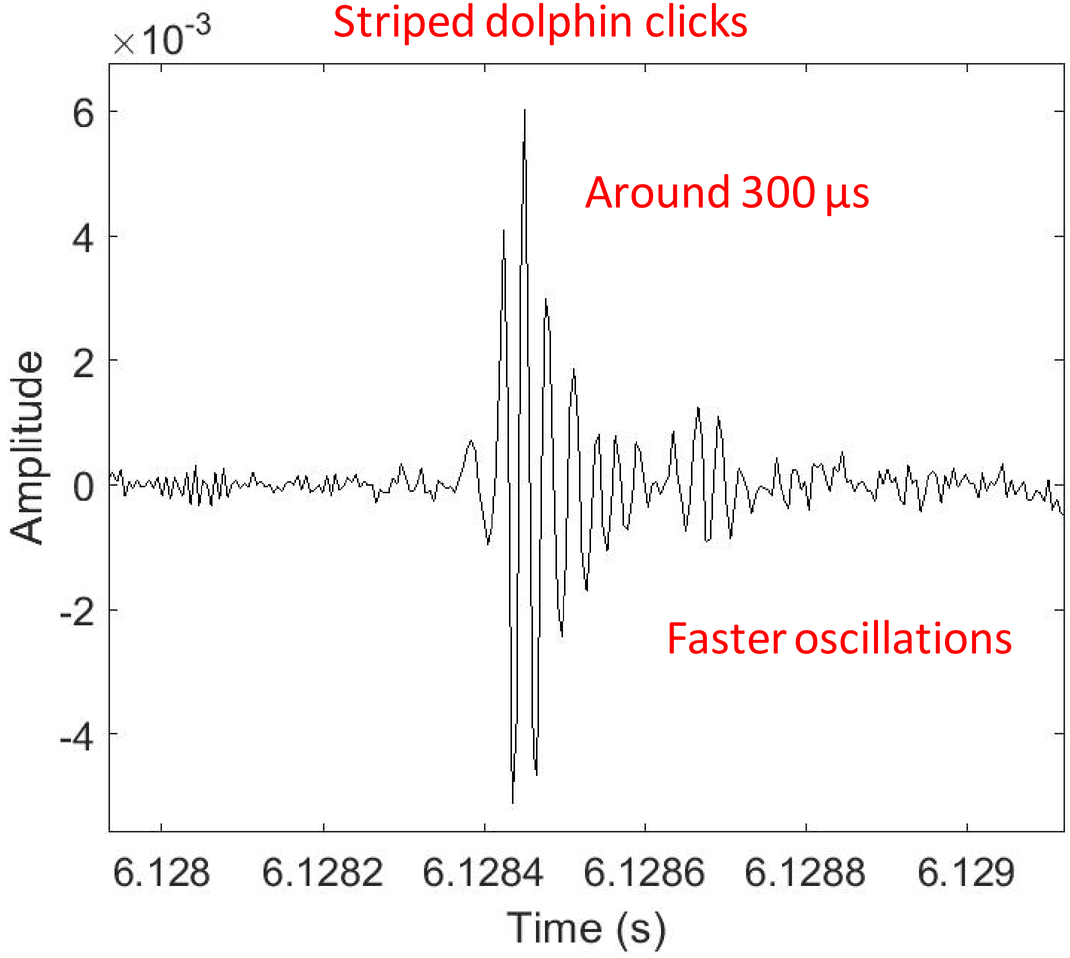
Inter Click Interval



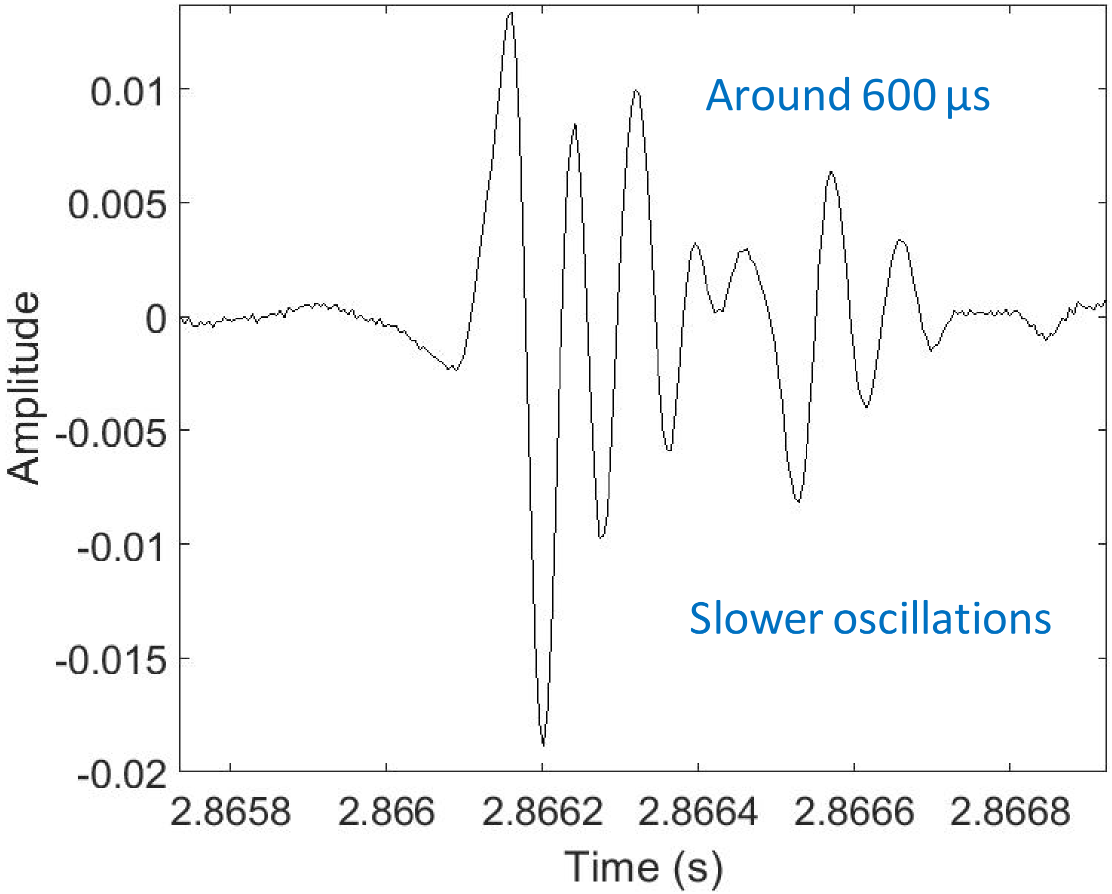


Click shape

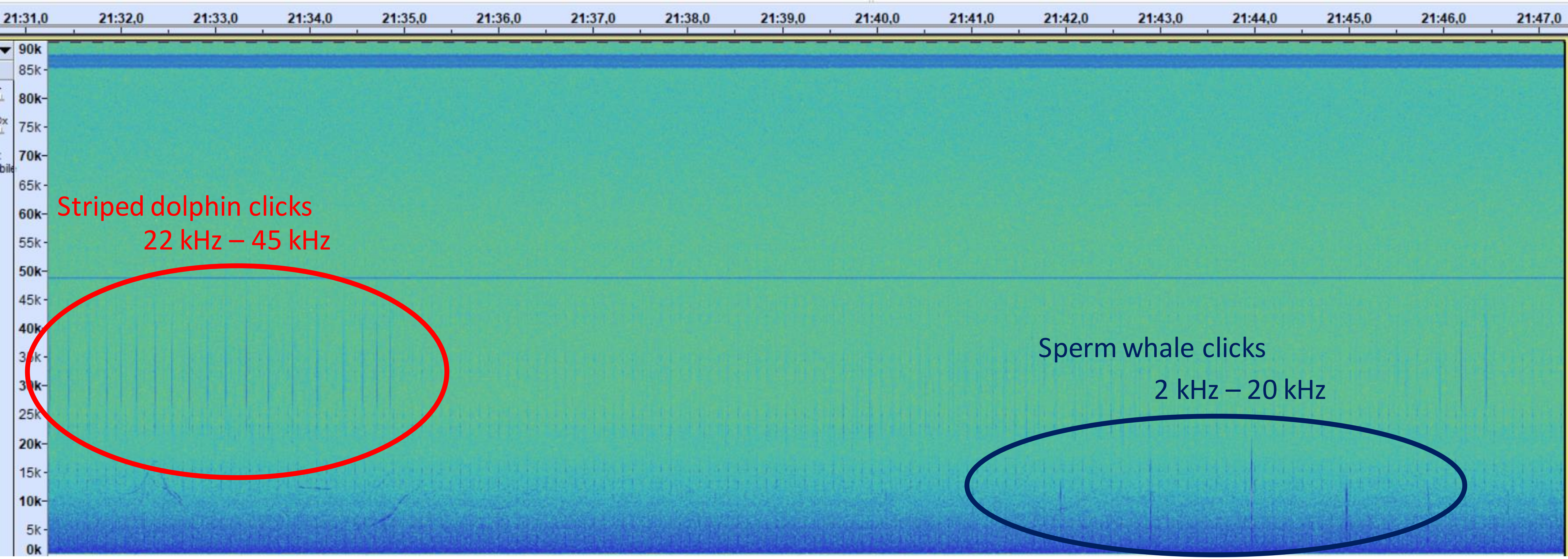
Striped dolphin clicks



Sperm whale clicks



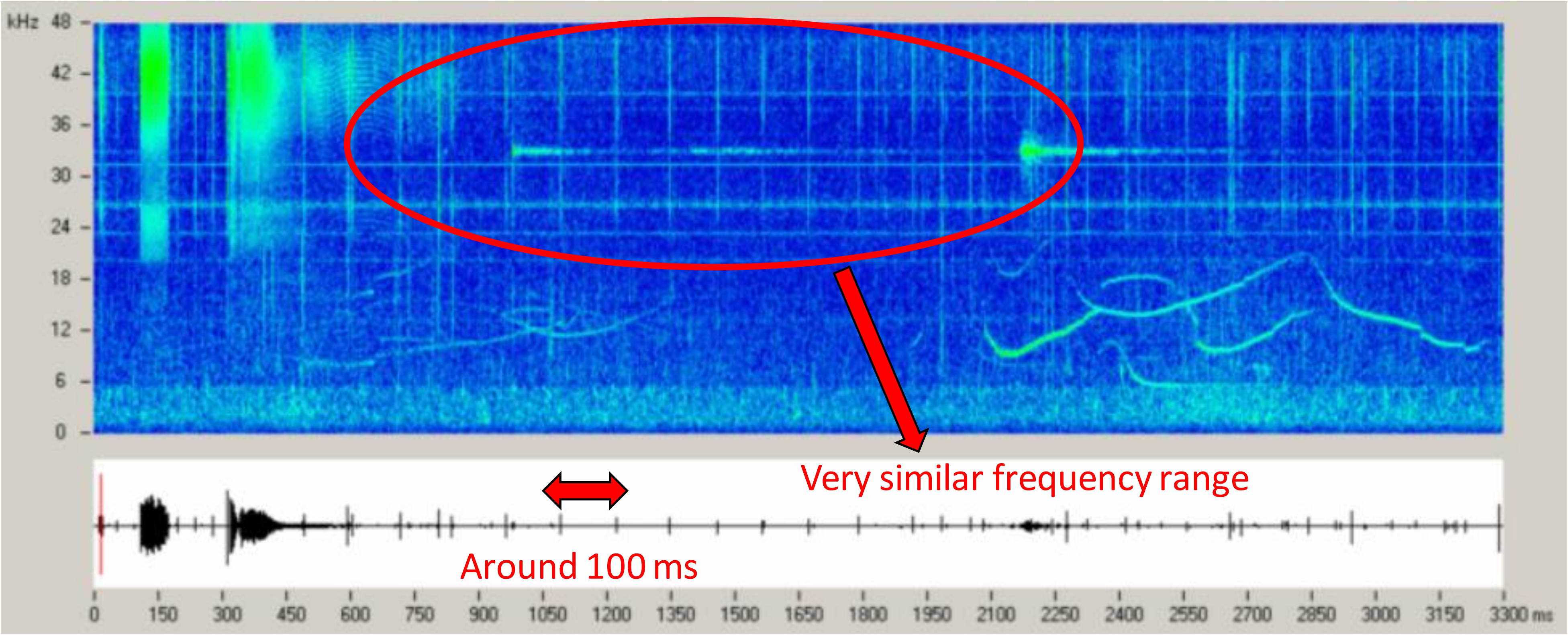
Frequency range



Comparison with CIBRA sounds

http://www-3.unipv.it/cibra/edu_dolphins_uk.html

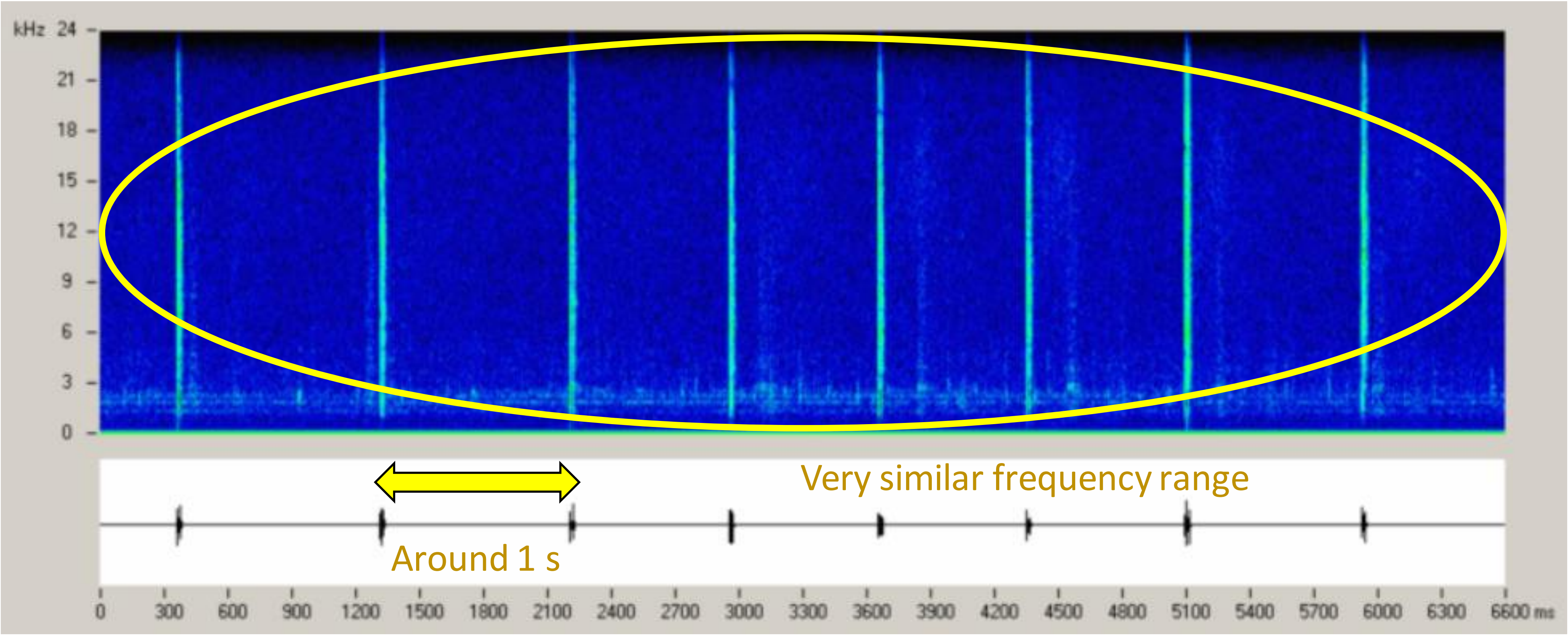
Striped dolphin



Comparison with CIBRA sounds

http://www-3.unipv.it/cibra/edu_spermwhale_uk.html

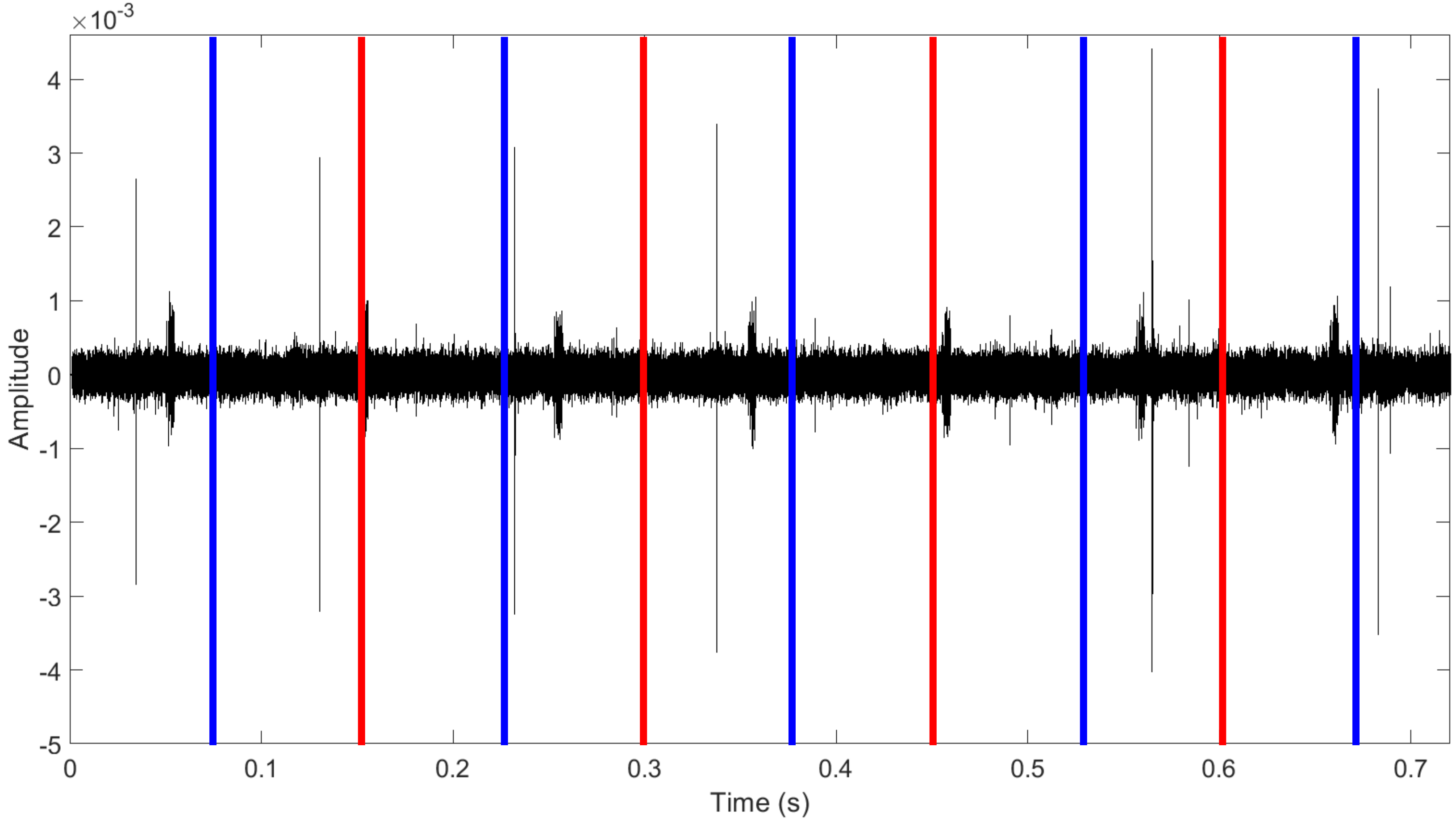
Sperm whale



CLICK IDENTIFICATION

- Application of an high pass filter (2 kHz or 5 kHz) to mitigate the low frequency noise

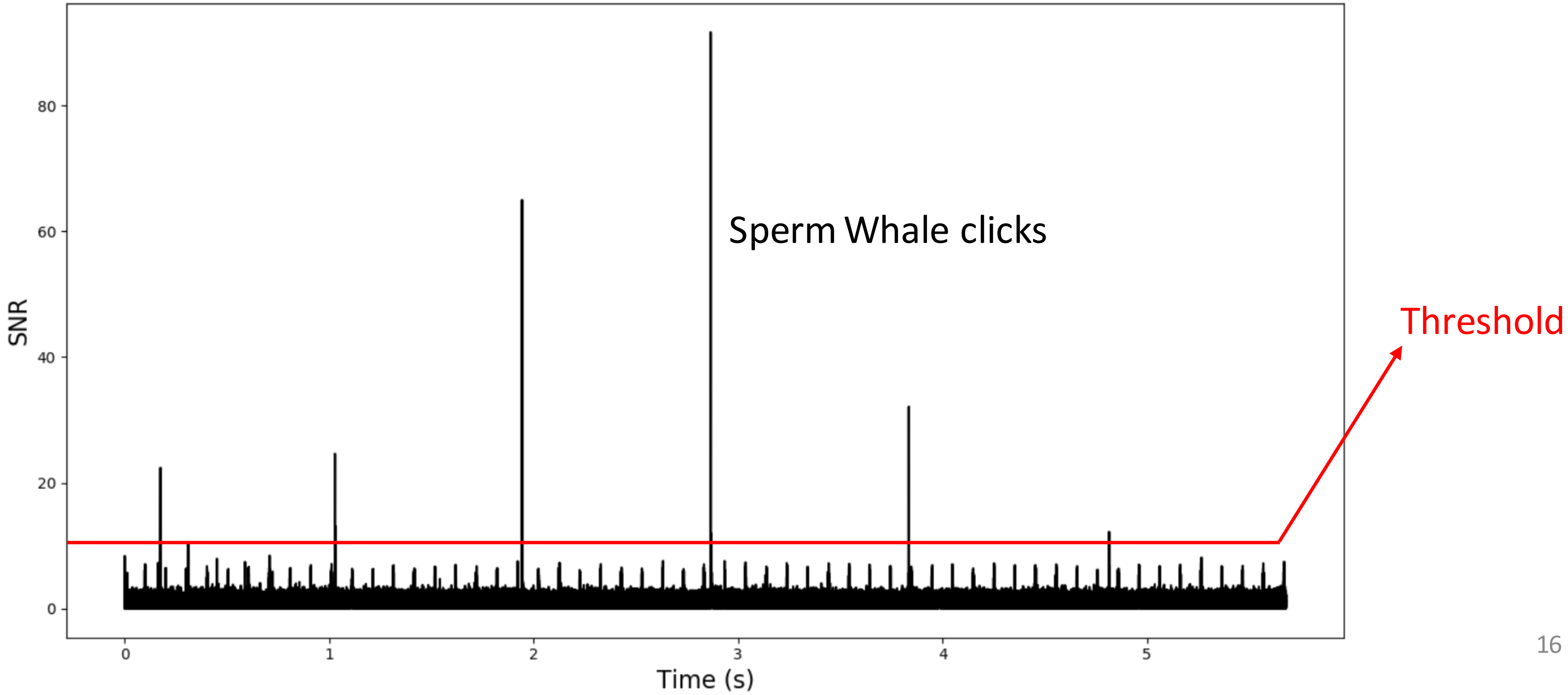
- Division of the audio file into time windows of a certain duration (0.15 s) with an overlap of 50% to be sure not to skip some clicks.



CLICK IDENTIFICATION

- For each time window calculation of the Signal to Noise Ratio (SNR) as a function of time, taking as a reference noise the median of the absolute value of the envelope (Hilbert function) of the signal.

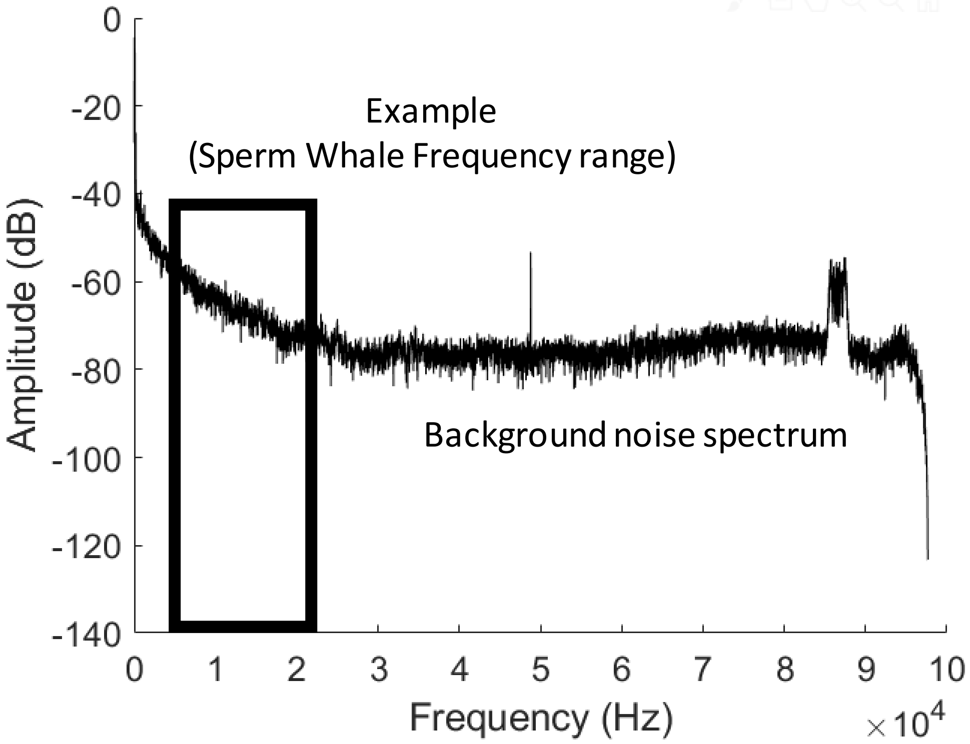
- In each time window there is a click if there is a value of SNR greater than 10 times the median of all the SNR values in that time window (SNR threshold). The value of the threshold is empirical.



CLICK IDENTIFICATION

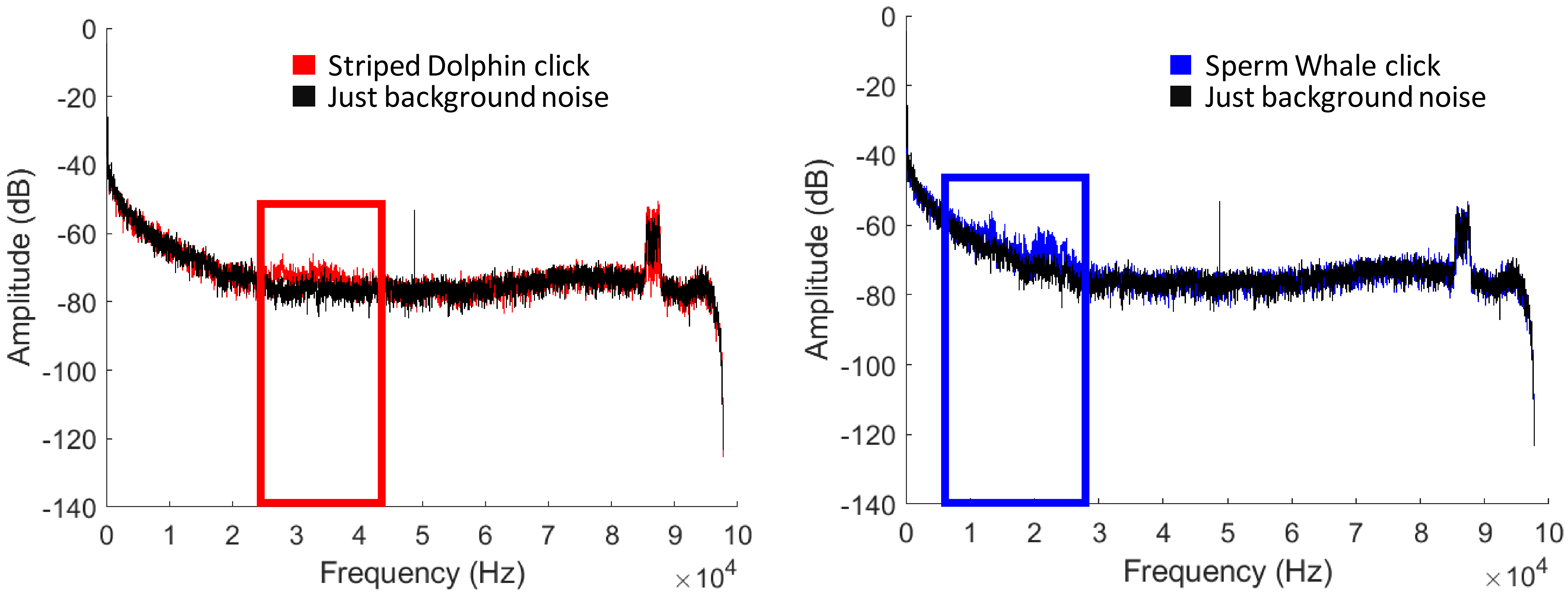
- Isolation of a segment of the same duration of the time windows in which I know there is only background noise and I calculate the FFT.

- Take the amplitude of the FFT at the frequencies between 2 kHz and 20 kHz (typical sperm whale frequencies), 20 kHz and 50 kHz (typical striped dolphin frequencies) and between 2 kHz and 50 kHz (generic click) and save those values in different arrays (noise thresholds).



If at least 20% of the values are greater than the noise threshold at the different frequencies, I assign a value 1 to the time window (possible click), otherwise I assign the value 0 (no clicks).

Spectrums



If a cetacean click is present, at least 20% of the frequency bins of the spectrum is greater than the same frequency bins of the pure background noise

Click Identifier – Best Configuration

General parameters

- High Pass Filter Frequency: $2\ kHz$
- SNR threshold: $Median_{SNR} \cdot 8$
- Frequency bin percentage: $20\ \%$

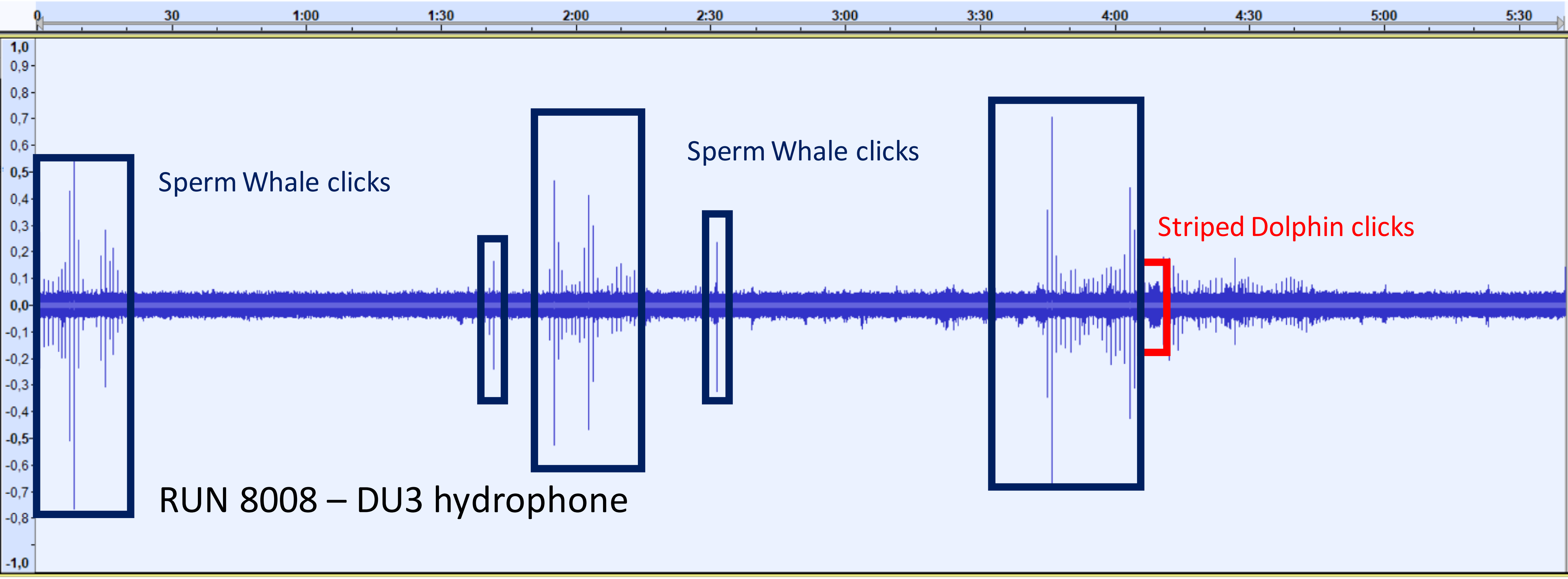
Striped Dolphin parameters

- Striped Dolphin clicks Frequency Limits: $30kHz \leq f_{SW} \leq 50\ kHz$
- Striped Dolphin clicks in a file: $N_{SD} \geq 3$
- Striped Dolphin Inter Click Interval: $ICI_{SD} > 0.05\ s$

Sperm Whale parameters

- Sperm Whale clicks Frequency Limits: $2\ kHz \leq f_{SD} \leq 22\ kHz$
- False Positive clicks Frequency Limits: $2\ kHz \leq f_{SW} \leq 6\ kHz$
- False Positive/True Positive Ratio: $R_{amp_{FP}/amp_{sw}} < 4$
- Sperm Whale clicks in a file: $3 \leq N_{SW} \leq 7$
- Sperm Whale Inter Click Interval: $ICI_{SW} > 0.4\ s$
- Standard Deviation of Sperm Whale ICIs: $\sigma_{ICI_{SW}} < 0.1$

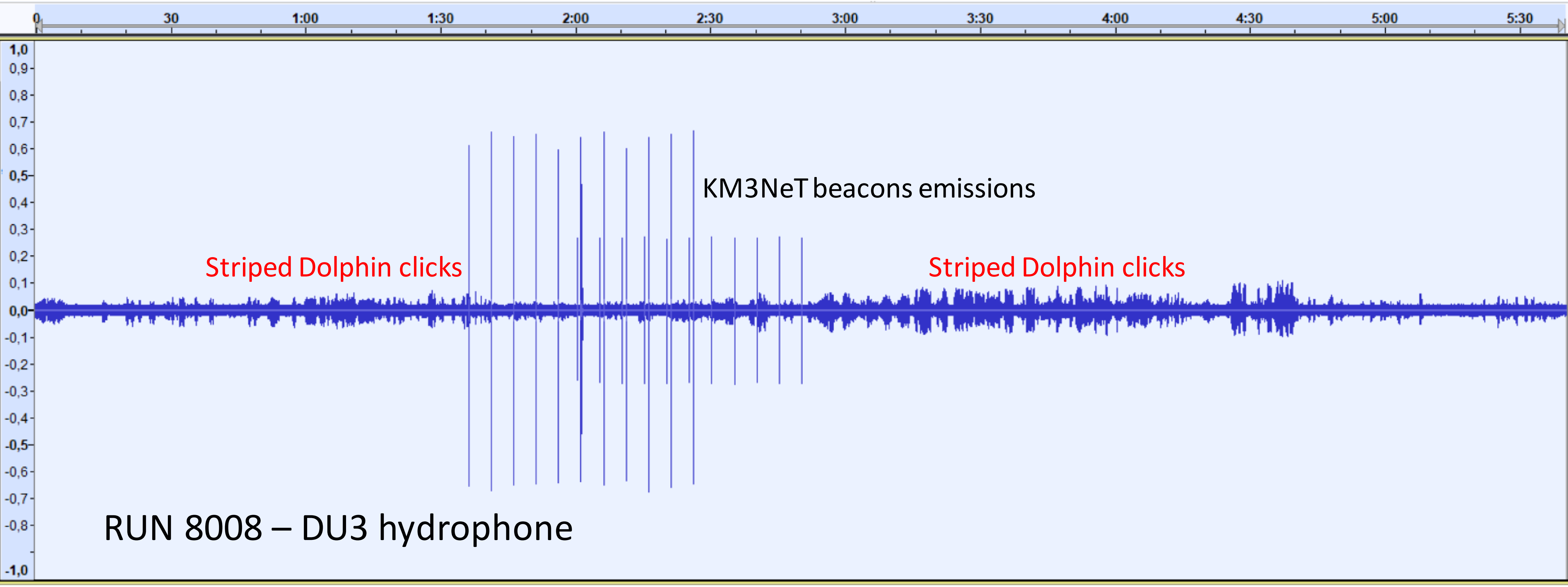
Application of the Click Identifier (example 1)



Sperm Whale clicks: 64

Striped Dolphin clicks: 14

Application of the Click Identifier (example 2)



Sperm Whale clicks: 0

Striped Dolphin clicks: 1966

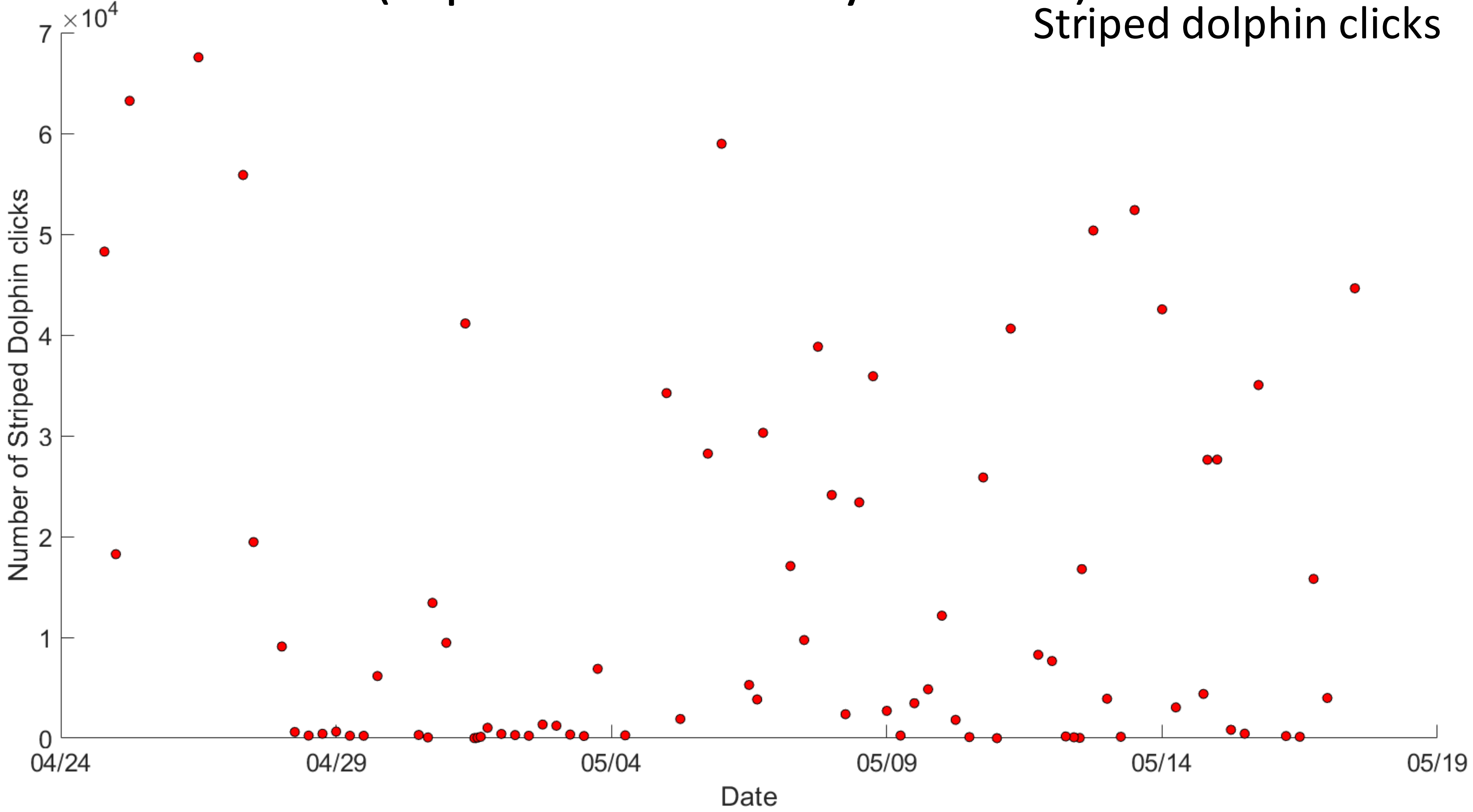
Application of the Click Identifier (example 3)

Sperm Whale clicks: 0

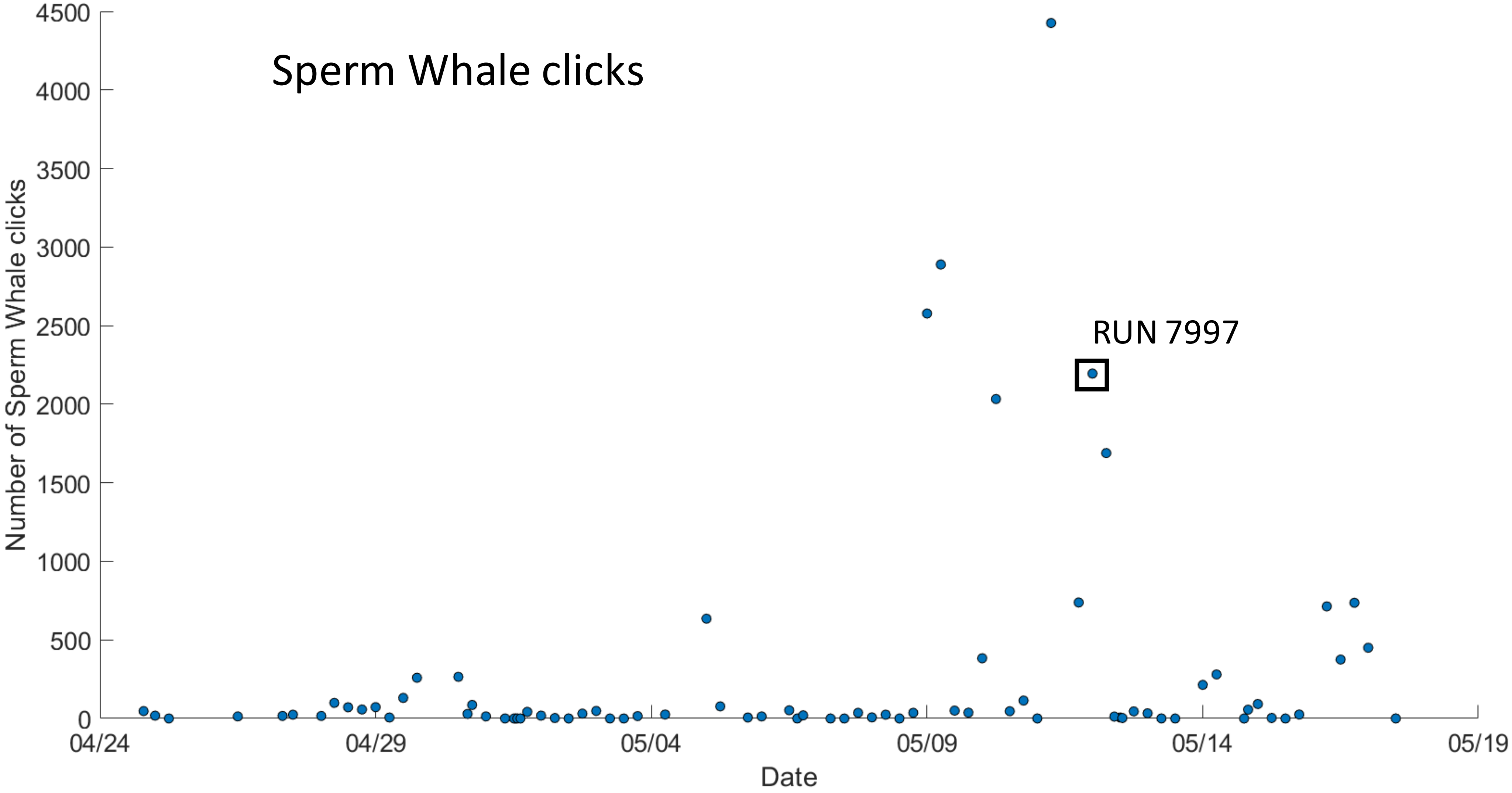
Striped Dolphin clicks: 0

Application of the Click Identifier to 100 RUNs (April and May 2020)

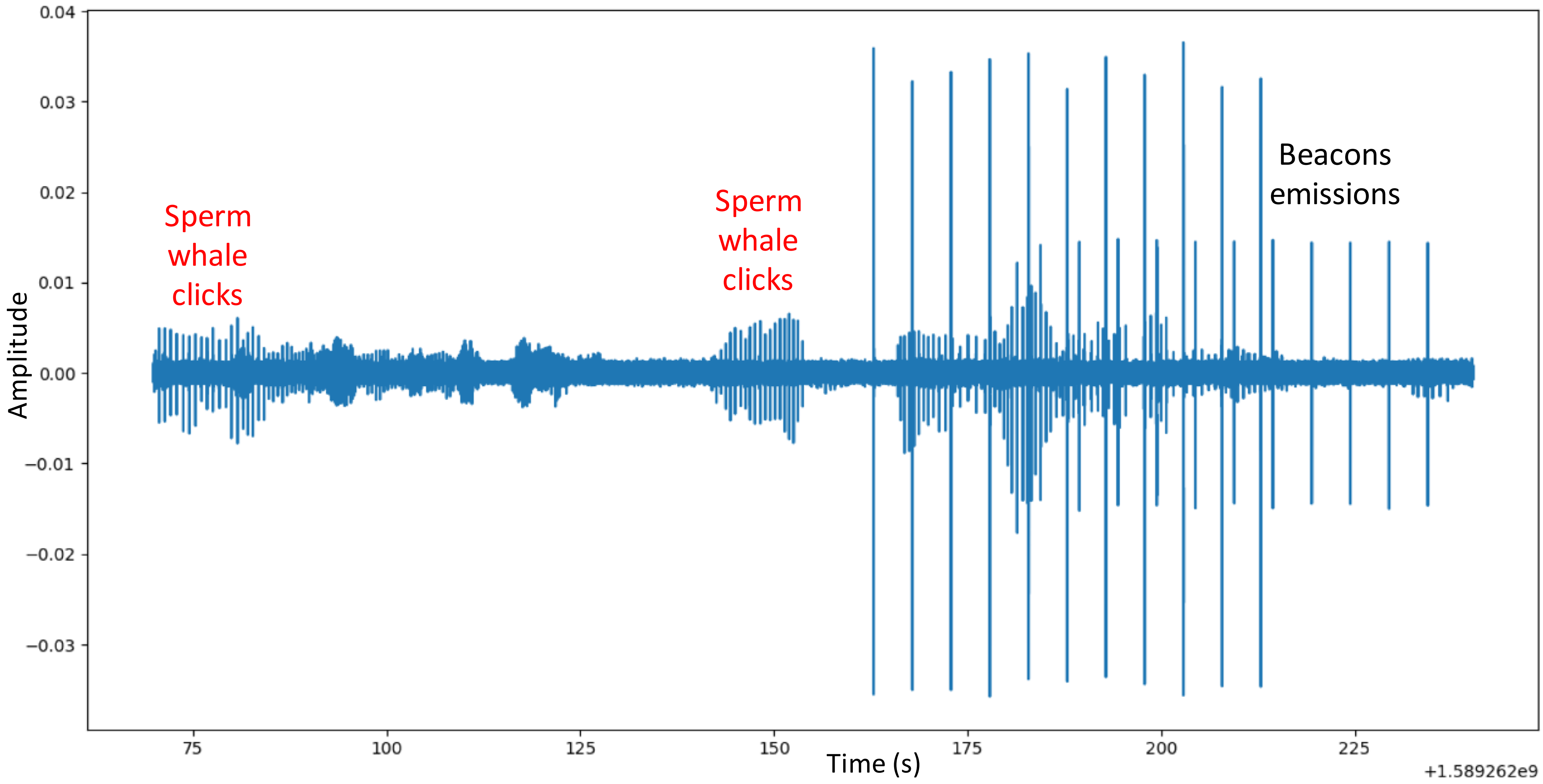
Striped dolphin clicks



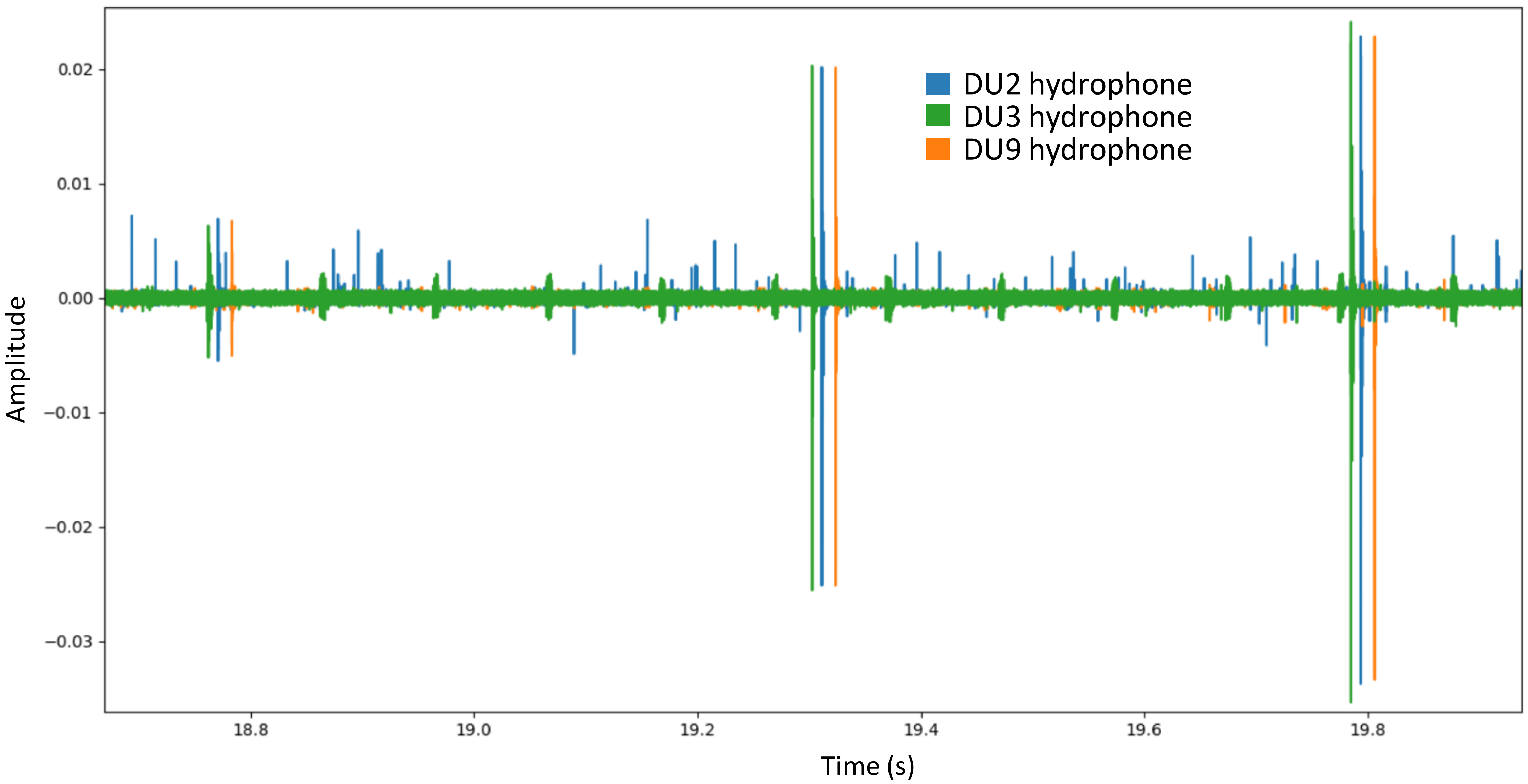
Application of the Click Identifier to 100 RUNs (April 2020)



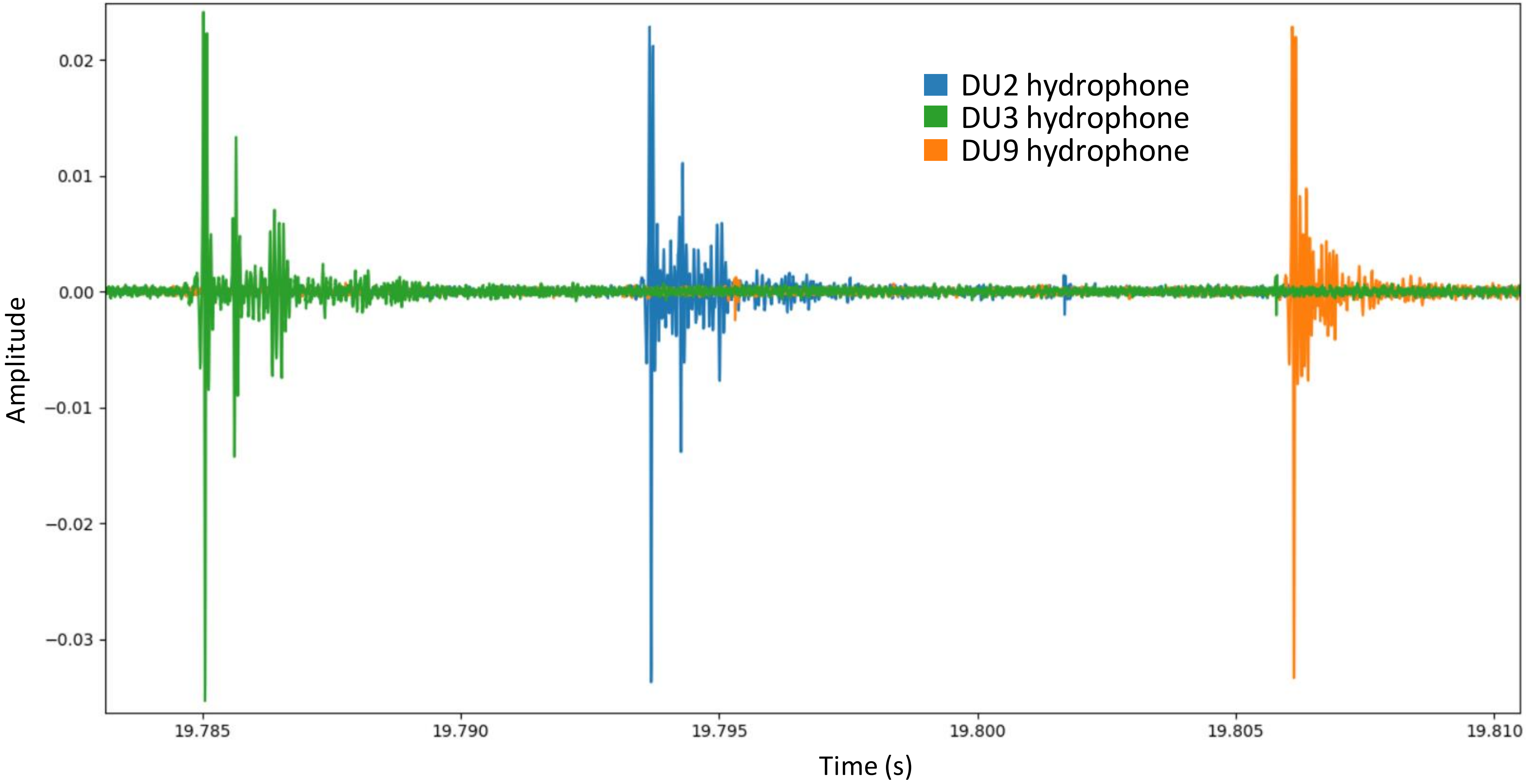
RUN 7997
DU3 hydrophone



Sperm Whale clicks in Three hydrophones



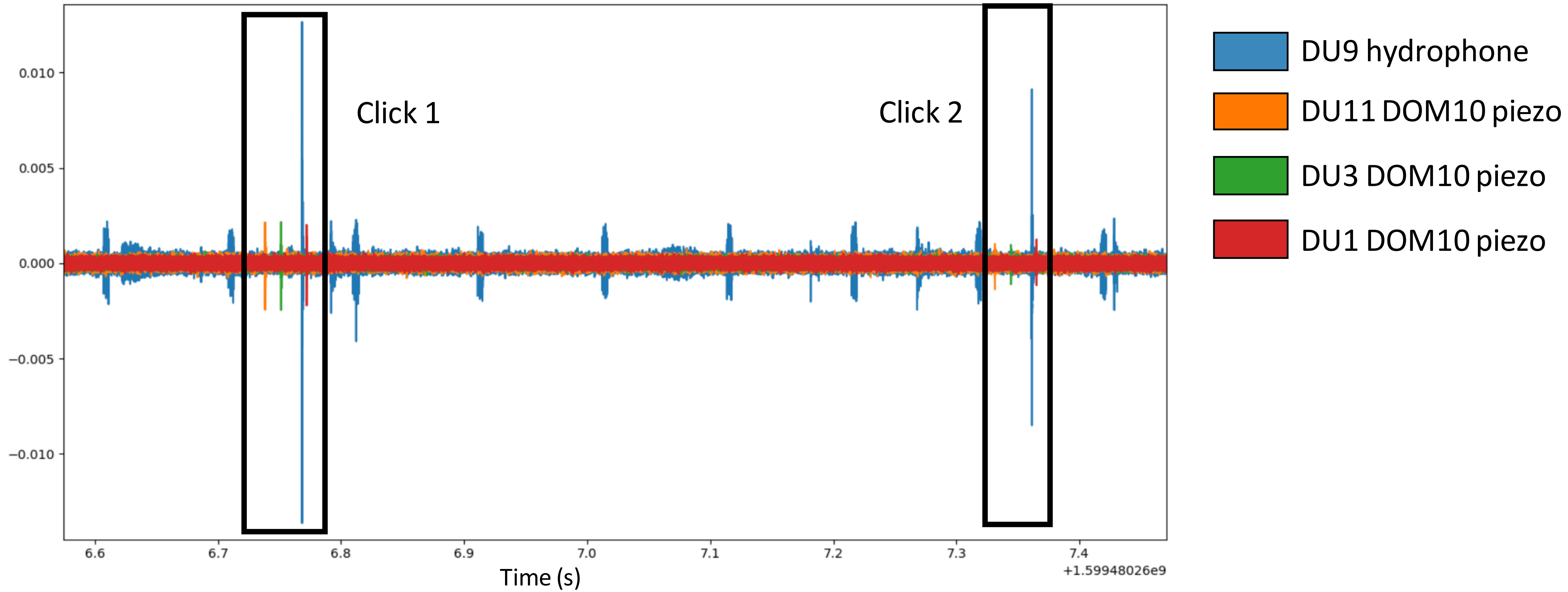
Sperm Whale clicks in Three hydrophones



Other example

RUN 8584 (10 minutes)

Receivers: DU9 hydrophone, DU1 DOM10, DU3 DOM10, DU11 DOM10 piezos



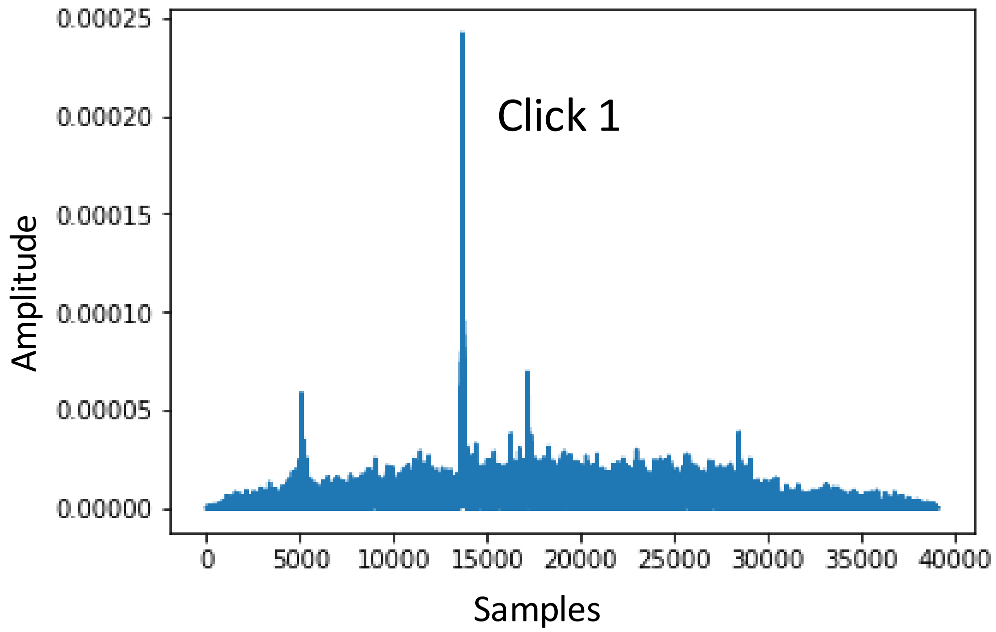
Application of the method

Examples

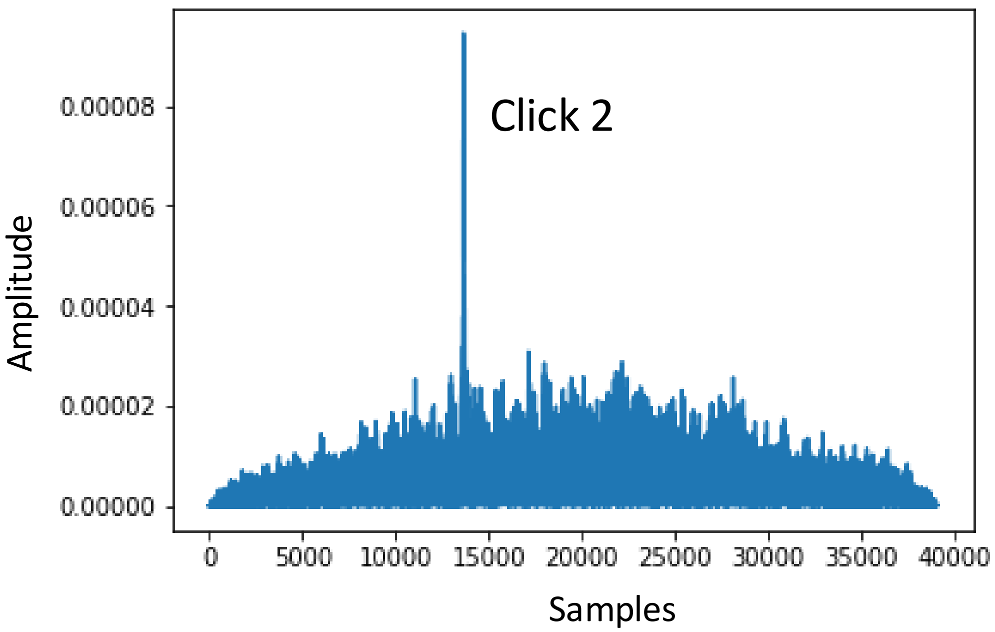
DU9 hydrophone

DU11 DOM10

ABS of Cross correlation



QF: 6626
Delay Time: 0.030046 s



QF: 2906
Delay Time: 0.030049 s

1 μs uncertainty?

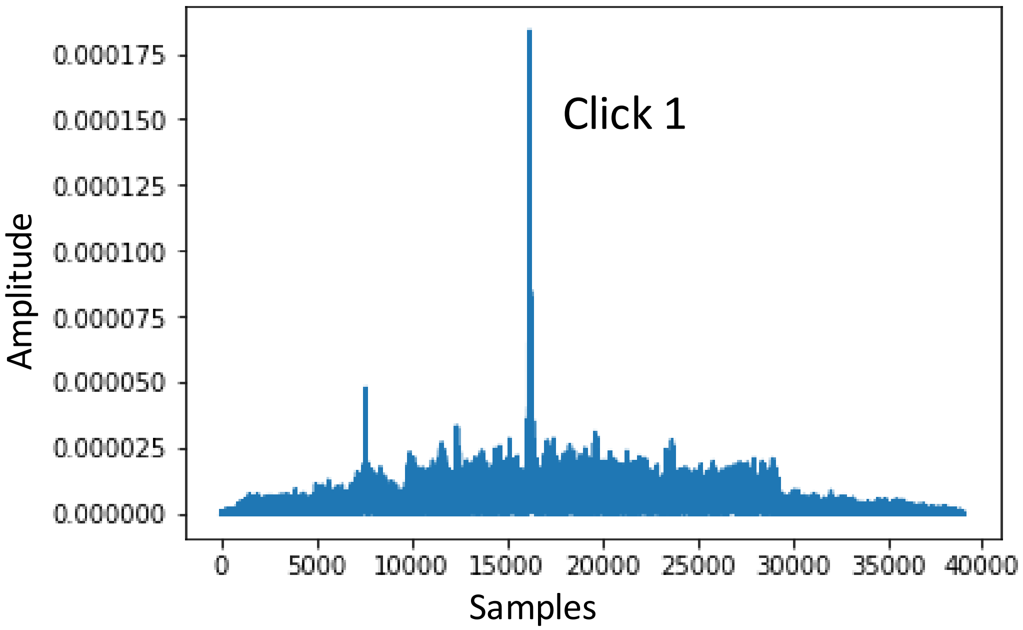
Application of the method

Examples

DU9 hydrophone

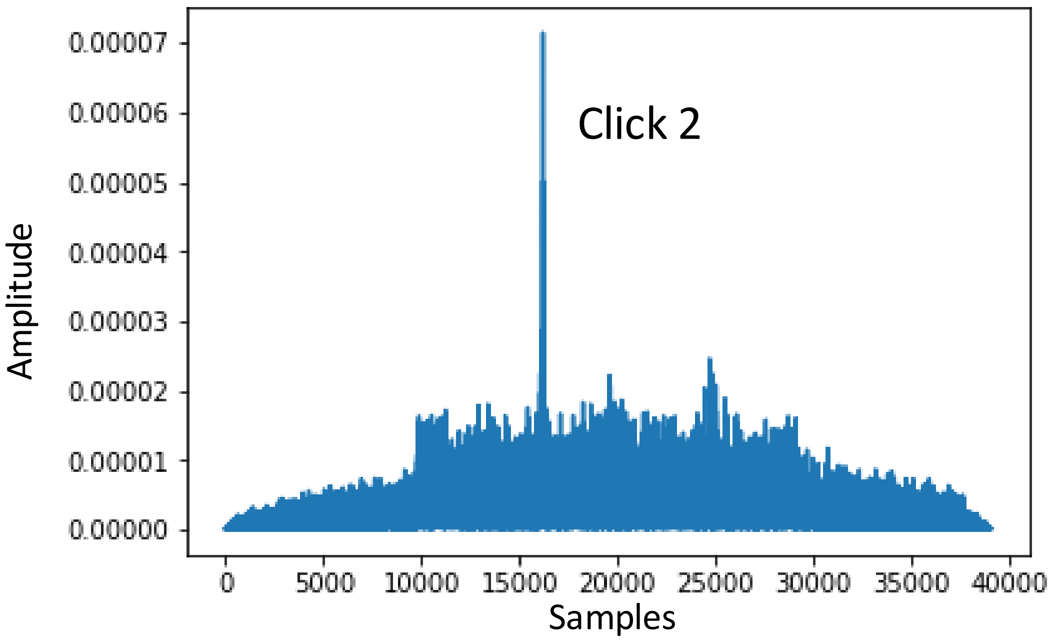
DU3 DOM10

ABS of Cross correlation



QF: 6759

Delay Time: 0.017047 s



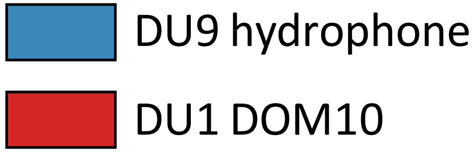
QF: 3270

Delay Time: 0.017049 s

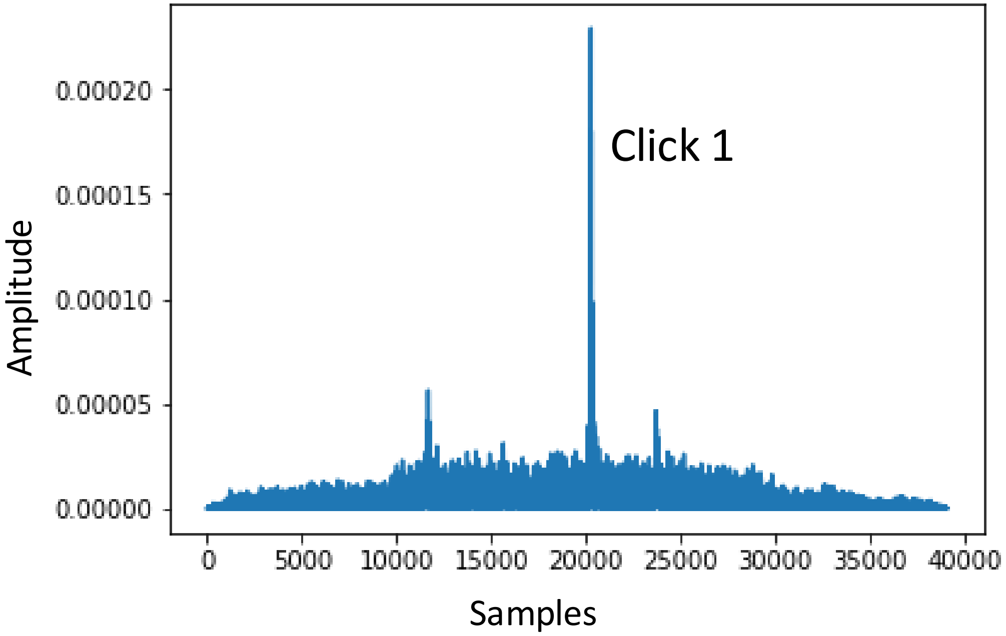
1 μs uncertainty?

Application of the method

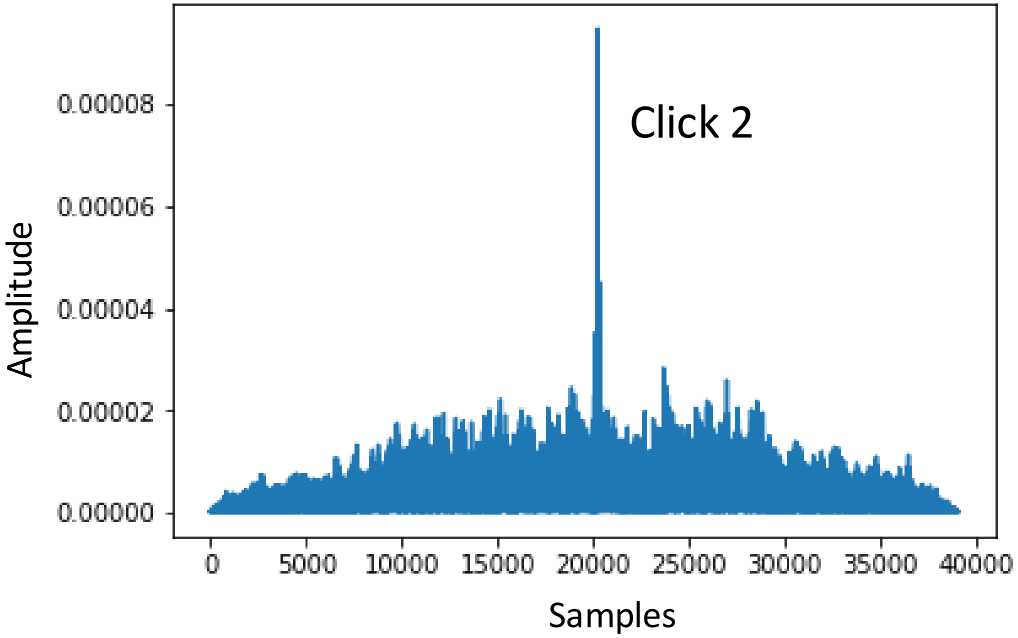
Examples



ABS of Cross correlation



QF: 7583
Delay Time: -0.003735 s



QF: 3436
Delay Time: -0.003732 s

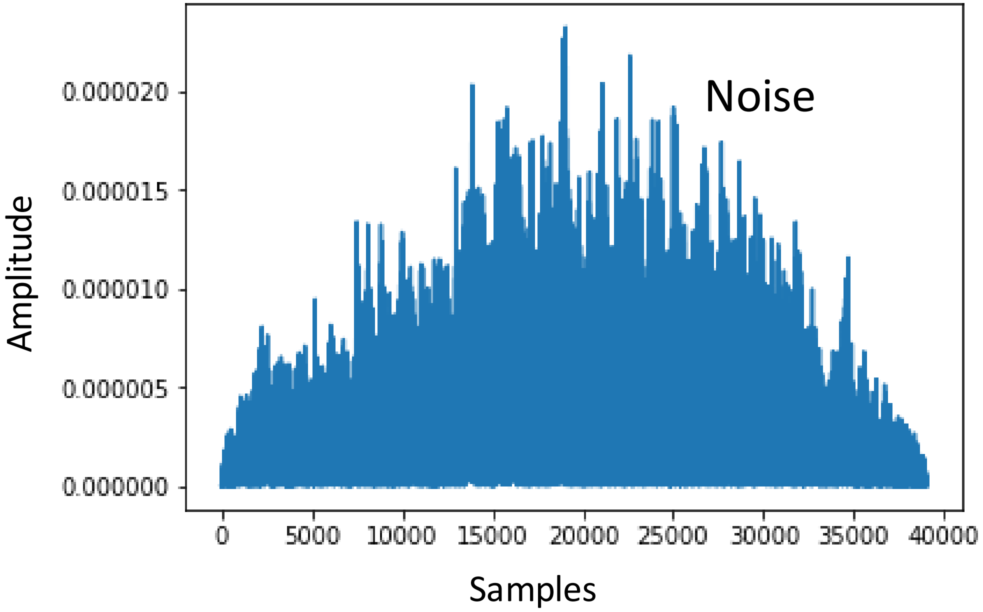
1 μs uncertainty?

Application of the method
Examples

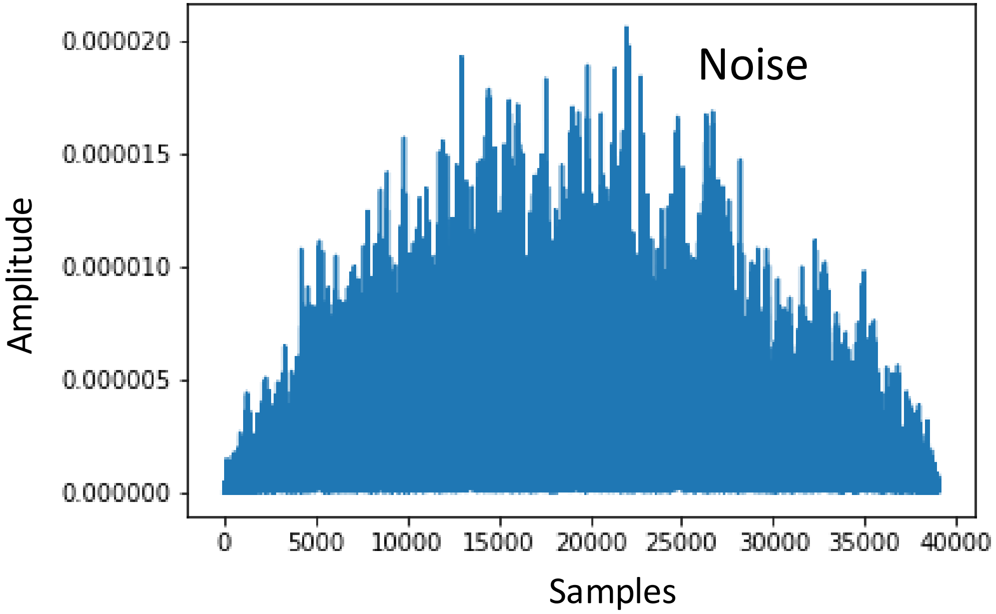
ABS of Cross correlation

DU9 hydrophone

DU1 DOM10



QF: 847
Delay Time: ~~0.015744 s~~



QF: 868
Delay Time: ~~0.012508 s~~

POSITION RECONSTRUCTION ALGORITHM

Set of hydrophones: $h_i, i = 1, \dots M$ at positions (x_i, y_i, z_i)

Whale at the position (x_w, y_w, z_w)

Individual ranges: $R_i = R_0 + \delta R_i$ with $\delta R_i = c\delta T_i$ (1)

Distances between the whale and the hydrophones: $R_{wi}^2 = (x_i - x_w)^2 + (y_i - y_w)^2 + (z_i - z_w)^2$ (2)

$$R_0^2 = x_0^2 - 2x_0x_w + x_w^2 + y_0^2 - 2y_0y_w + y_w^2 + z_0^2 - 2z_0z_w + z_w^2 \quad (3)$$

$$R_0^2 + 2R_0\delta R_i + \delta {R_i}^2 = x_i^2 - 2x_ix_w + x_w^2 + y_i^2 - 2y_iy_w + y_w^2 + z_i^2 - 2z_iz_w + z_w^2 \quad (4)$$

Subtracting equation (3) from equation (4):

$$2R_0\delta R_i + \delta {R_i}^2 = x_i^2 - x_0^2 - 2(x_i - x_0)x_w + y_i^2 - y_0^2 - 2(y_i - y_0)y_w + z_i^2 - z_0^2 - 2(z_i - z_0)z_w$$

POSITION RECONSTRUCTION ALGORITHM

$$2R_0\delta R_i + \delta {R_i}^2 = x_i^2 - x_0^2 - 2(x_i - x_0)x_w + y_i^2 - y_0^2 - 2(y_i - y_0)y_w + z_i^2 - z_0^2 - 2(z_i - z_0)z_w$$

4 unknowns (R_0, x_w, y_w, z_w) -> With 5 hydrophones we may form 4 equations

$$\begin{pmatrix} (x_1^2 - x_0^2) + (y_1^2 - y_0^2) + (z_1^2 - z_0^2) - (\delta R_1)^2 \\ (x_2^2 - x_0^2) + (y_2^2 - y_0^2) + (z_2^2 - z_0^2) - (\delta R_2)^2 \\ (x_3^2 - x_0^2) + (y_3^2 - y_0^2) + (z_3^2 - z_0^2) - (\delta R_3)^2 \\ (x_4^2 - x_0^2) + (y_4^2 - y_0^2) + (z_4^2 - z_0^2) - (\delta R_4)^2 \end{pmatrix} = 2 \begin{pmatrix} \delta R_1 & (x_1 - x_0) & (y_1 - y_0) & (z_1 - z_0) \\ \delta R_2 & (x_2 - x_0) & (y_2 - y_0) & (z_2 - z_0) \\ \delta R_3 & (x_3 - x_0) & (y_3 - y_0) & (z_3 - z_0) \\ \delta R_4 & (x_4 - x_0) & (y_4 - y_0) & (z_4 - z_0) \end{pmatrix} \begin{pmatrix} R_0 \\ x_w \\ y_w \\ z_w \end{pmatrix}$$

If all sensors are at the same depth:

$$\begin{pmatrix} (x_1^2 - x_0^2) + (y_1^2 - y_0^2) + (z_1^2 - z_0^2) - (\delta R_1)^2 \\ (x_2^2 - x_0^2) + (y_2^2 - y_0^2) + (z_2^2 - z_0^2) - (\delta R_2)^2 \\ (x_3^2 - x_0^2) + (y_3^2 - y_0^2) + (z_3^2 - z_0^2) - (\delta R_3)^2 \end{pmatrix} = 2 \begin{pmatrix} \delta R_1 & (x_1 - x_0) & (y_1 - y_0) & (z_1 - z_0) \\ \delta R_2 & (x_2 - x_0) & (y_2 - y_0) & (z_2 - z_0) \\ \delta R_3 & (x_3 - x_0) & (y_3 - y_0) & (z_3 - z_0) \end{pmatrix} \begin{pmatrix} R_0 \\ x_w \\ y_w \end{pmatrix}$$

We can estimate the whale depth z_w by: $z_w = z_0 \pm \sqrt{R_0^2 - (x_w - x_0)^2 - (y_w - y_0)^2}$

GEOMETRICAL CONFIGURATIONS OF THE RECEIVERS

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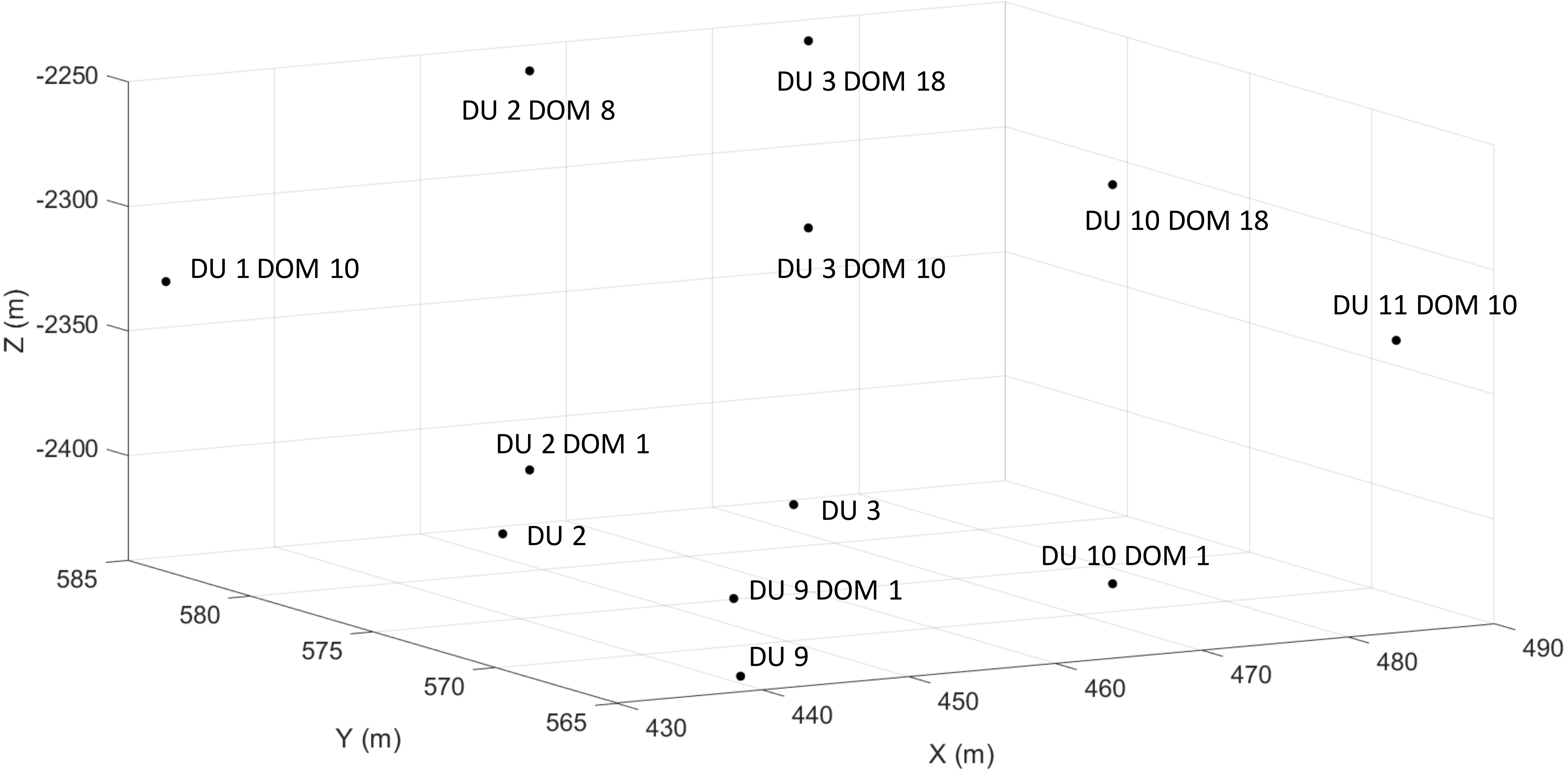

POSITION RECONSTRUCTION SIMULATION

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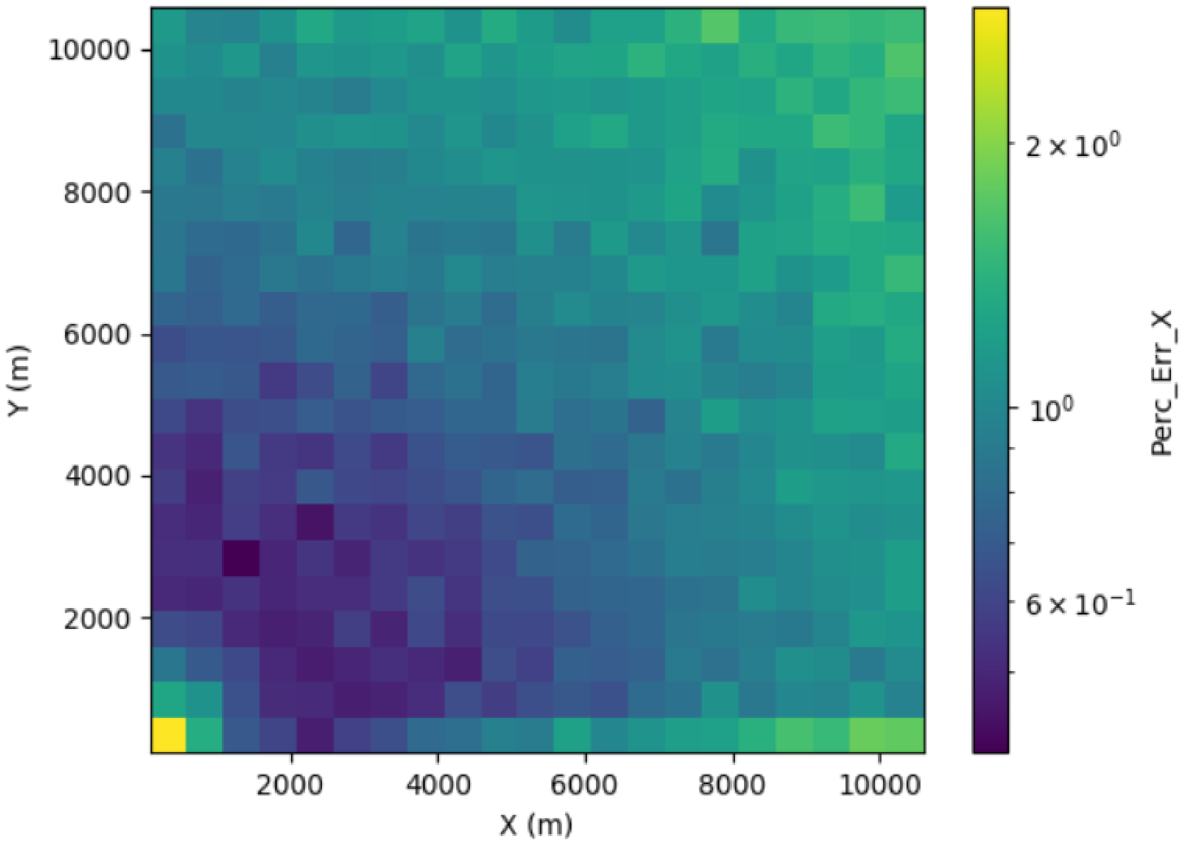
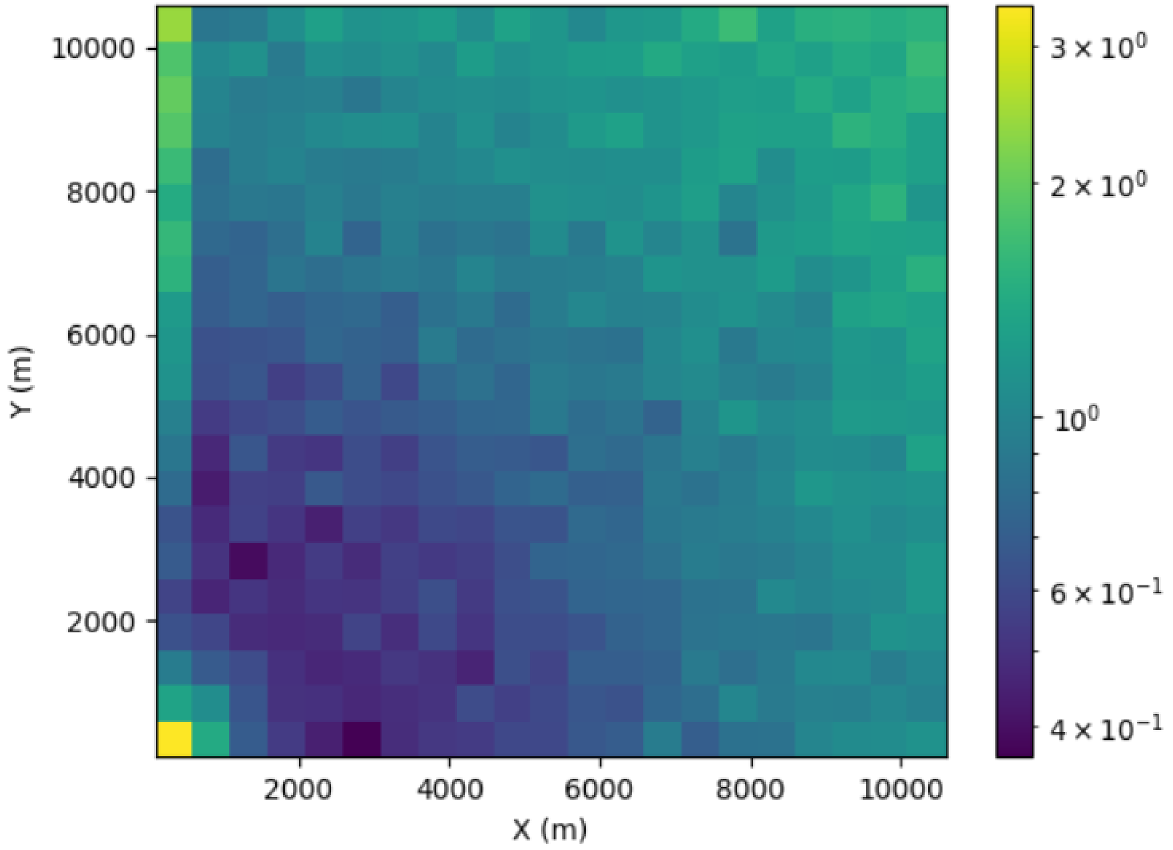
Whale depth: 500 m
Number of measurments: 100
Time delays error: $10\mu s$





Conclusions

- Two different types of clicks have been identified, probably emitted by striped dolphins and sperm whales
- The current version of the click identifier distinguishes the two different clicks.
- We see the cetacean signals in different receivers and we can use this information to improve the accuracy of the detection and calculate the delay times.
- Simulations of the source position reconstruction algorithm have been performed, obtaining good results

Future steps and work in progress

- Begin to reconstruct the position of the acoustic sources using the information of the time delays between the different receivers