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MERMAIDs:
First observations of seismic *P* waves with freely floating submarine robots

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Motivation

CURRENT PROBLEM

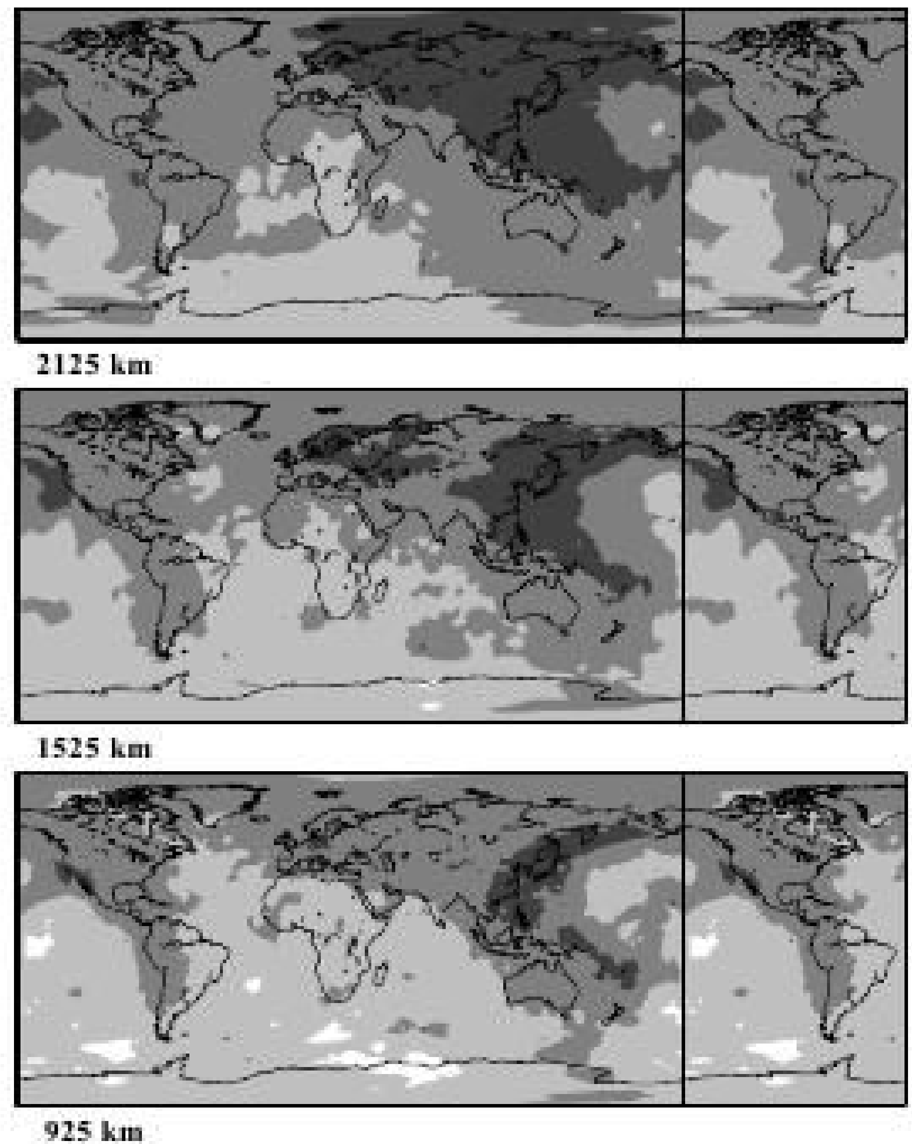
A lack of seismic data from **oceanic** domains

• a significant impediment to the global seismic tomography

• especially severe for southern hemisphere which contains most of the known plumes

RAY DENSITY

(adopted from Montelli *et al*., *GJI* **158,** 637, 2004)

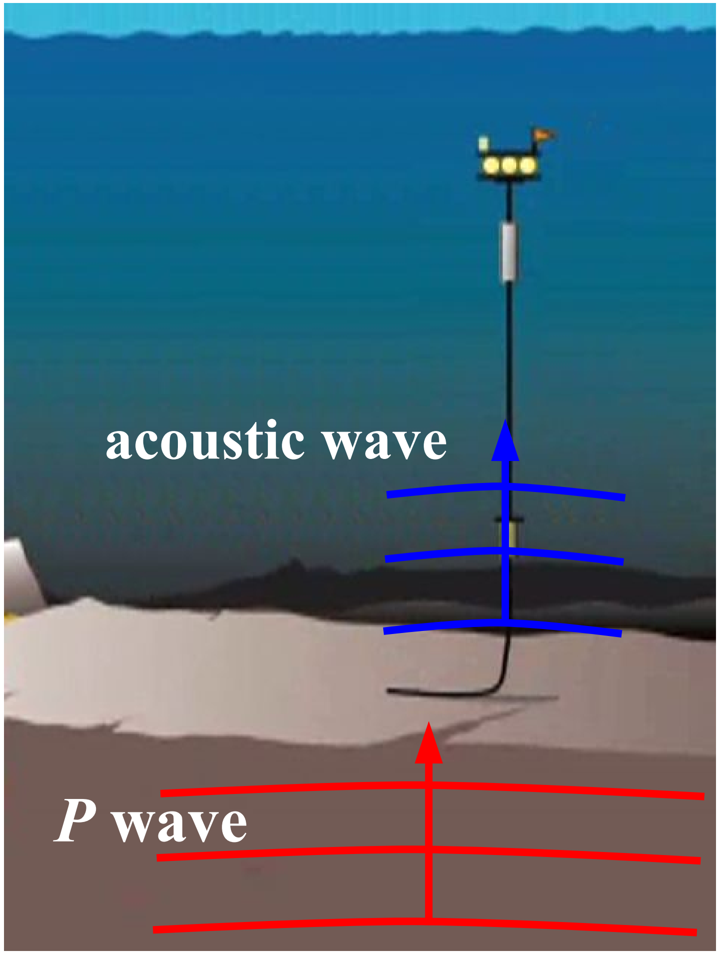


Seismic data collection at sea

Ocean Bottom Seismometers (OBS)

(https://geoazur.oca.eu/spip.php?article62)

Moored Hydrophones



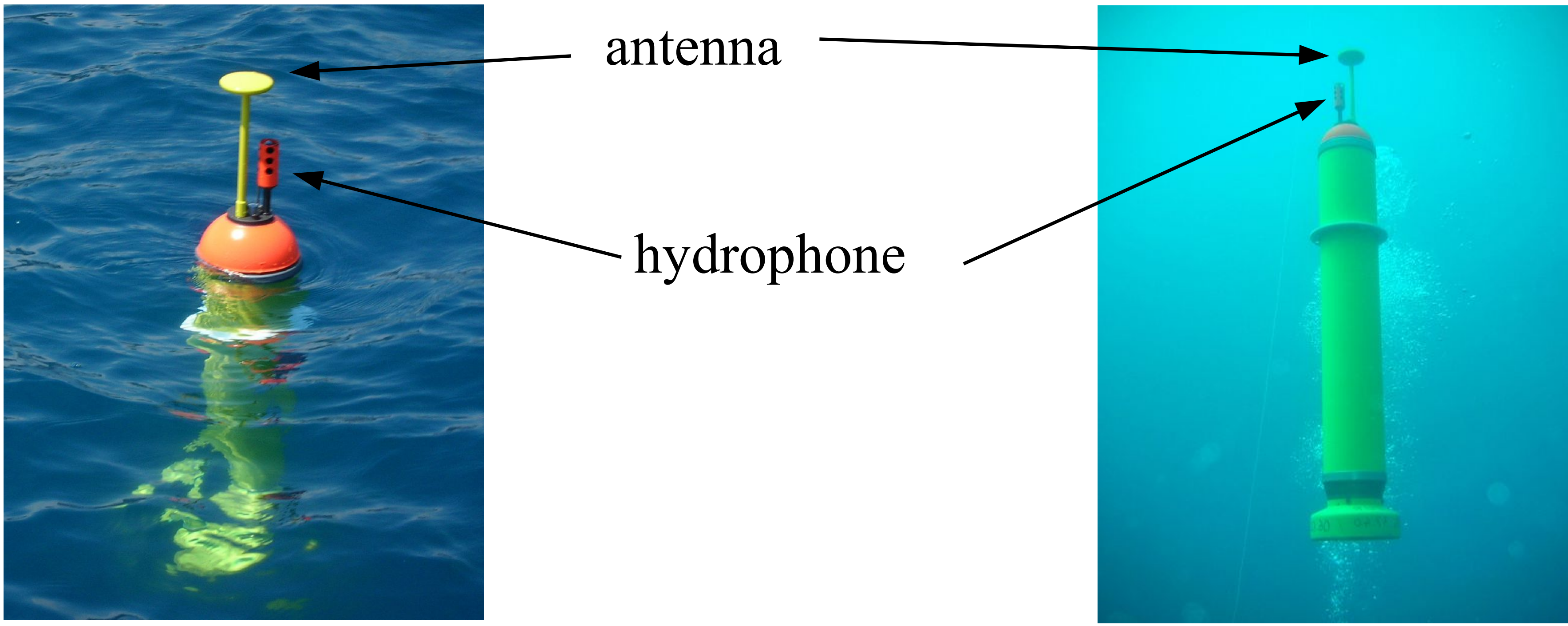
(adopted from *http://www.pmel.noaa.gov/vents/acoustics/haru_system.html*)

DRAWBACK : high installation&recuperation costs preclude ocean coverage dense enough for seismic tomography

MERMAID

SOLUTION : new detecting instrument **MERMAID**

Mobile **E**arthquake **R**ecording in **M**arine **A**reas by **I**ndependent **D**ivers



- freely drifting underwater robot of variable buoyancy which can dive to and remain at certain depth
- records acoustic waves generated by seismic events and transmits the recorded data via satellite
- Advantages : **LOW COST** and **MOBILITY**

MERMAID first prototype

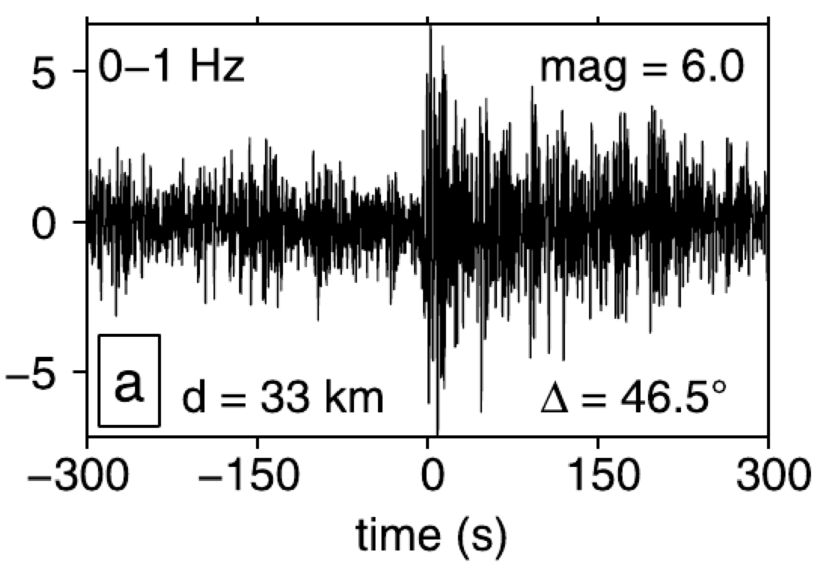
Pioneering experiments by Simons *et al.** in 2003-2007:

• **S**ounding **O**ceanographic **L**agrangian **O**bserver (SOLO) equipped with a hydrophone and recording system

• 120-hour-long continuous records gathered at the depth of 700 m offshore San-Diego

• several acoustic signals generated by the seismic events are detected, among which a teleseismic one:

2003-11-05, LAT = 5.07, LON=-77.69, 5.7mb,
NEAR WEST COAST OF COLOMBIA (Simons et al., 2009)



MERMAID prototype
(Simons et al., 2009)

* Simons *et al*., On the potential of recording earthquakes for global seismic tomography by low-cost autonomous instruments in the oceans, JGR, 2009

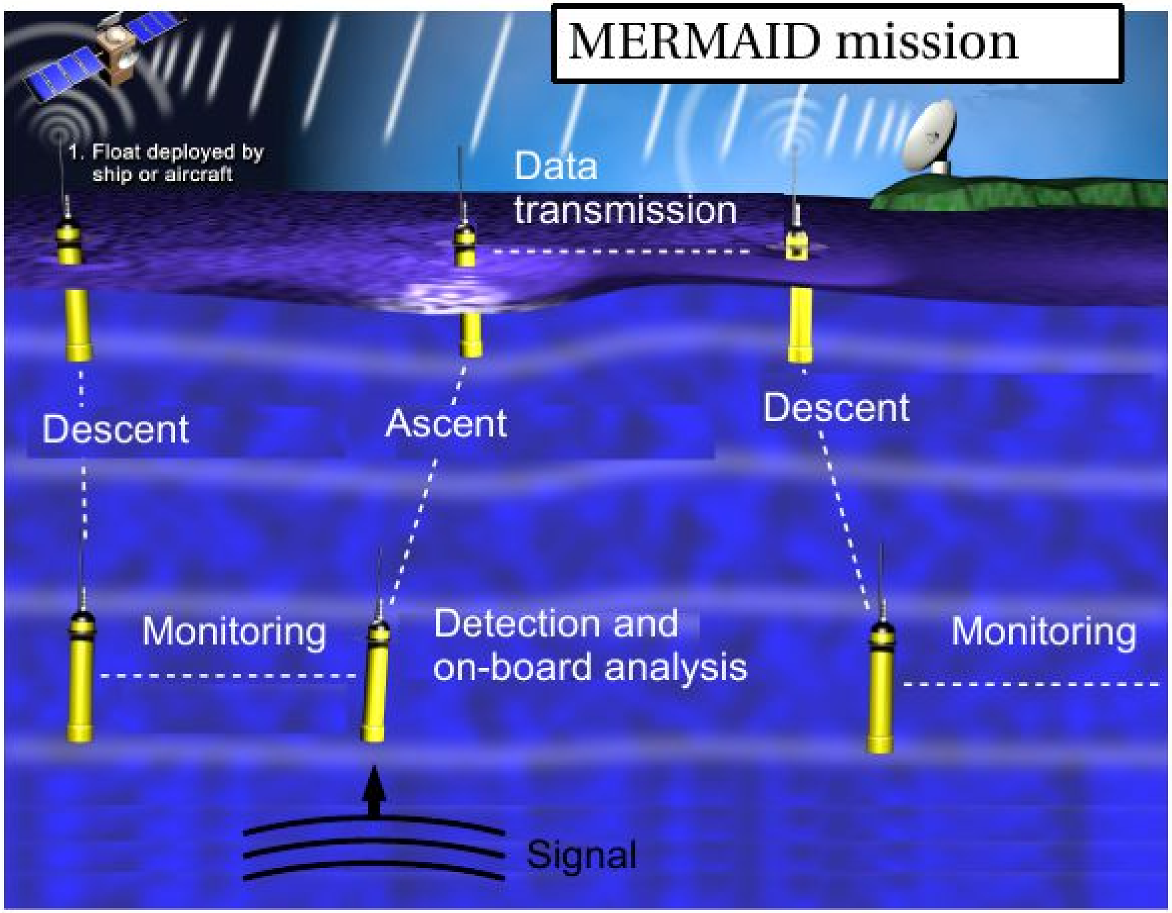
MERMAID's typical mission

- descent to a programmed depth

- *continuous* monitoring of the pressure variation and on-board analysis of the detected signal

- *rapid* ascent if a teleseismic *P* wave detected → data transmission and MERMAID localization (the place of detection is as important as the arrival time!)

- return to the monitoring state if the signal is not a teleseismic *P* wave



(adopted from www.argo.ucsd.edu)

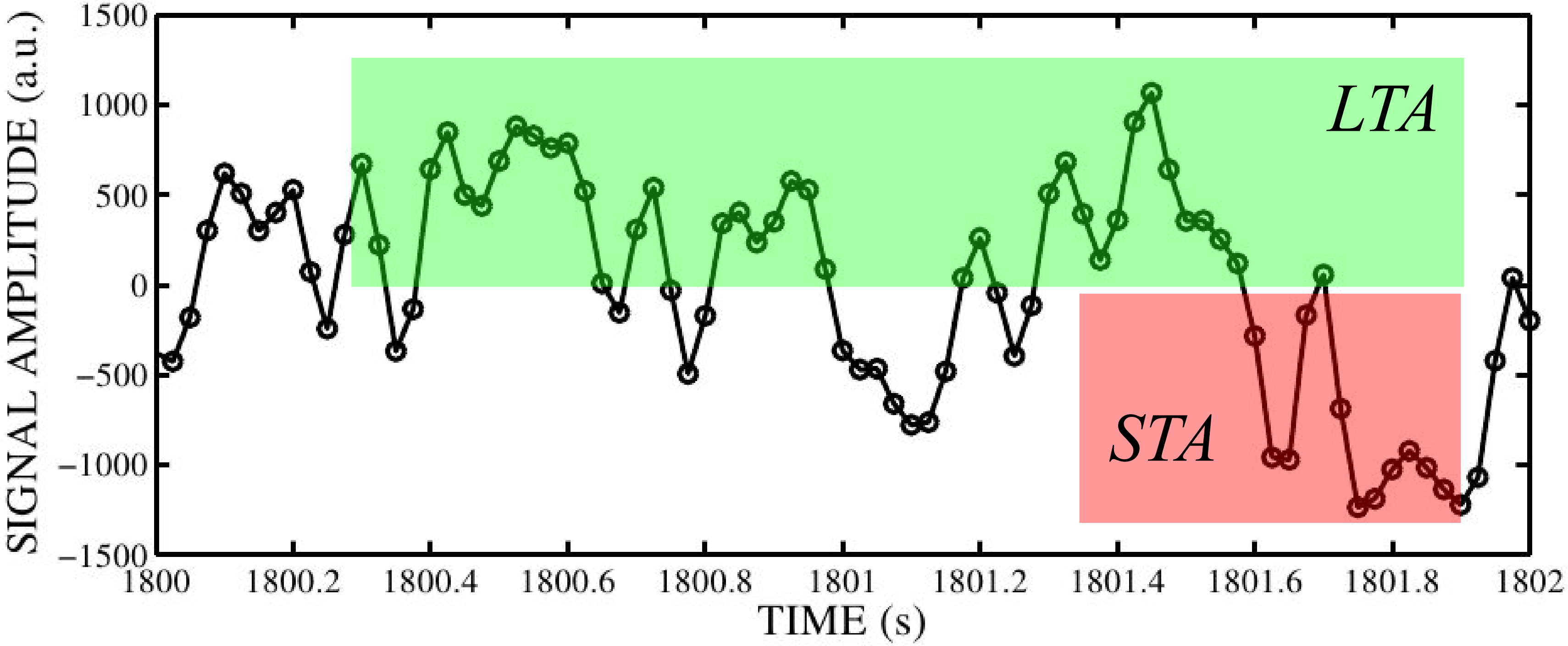
Note that ascents and descents are two phases with major power consumption

Signal Detection (STA/LTA)

Detection of an arriving signal is ensured by continuous calculation of the ratio of the short-term to long-term moving averages (**STA/LTA** algorithm)*

For a given record s_i

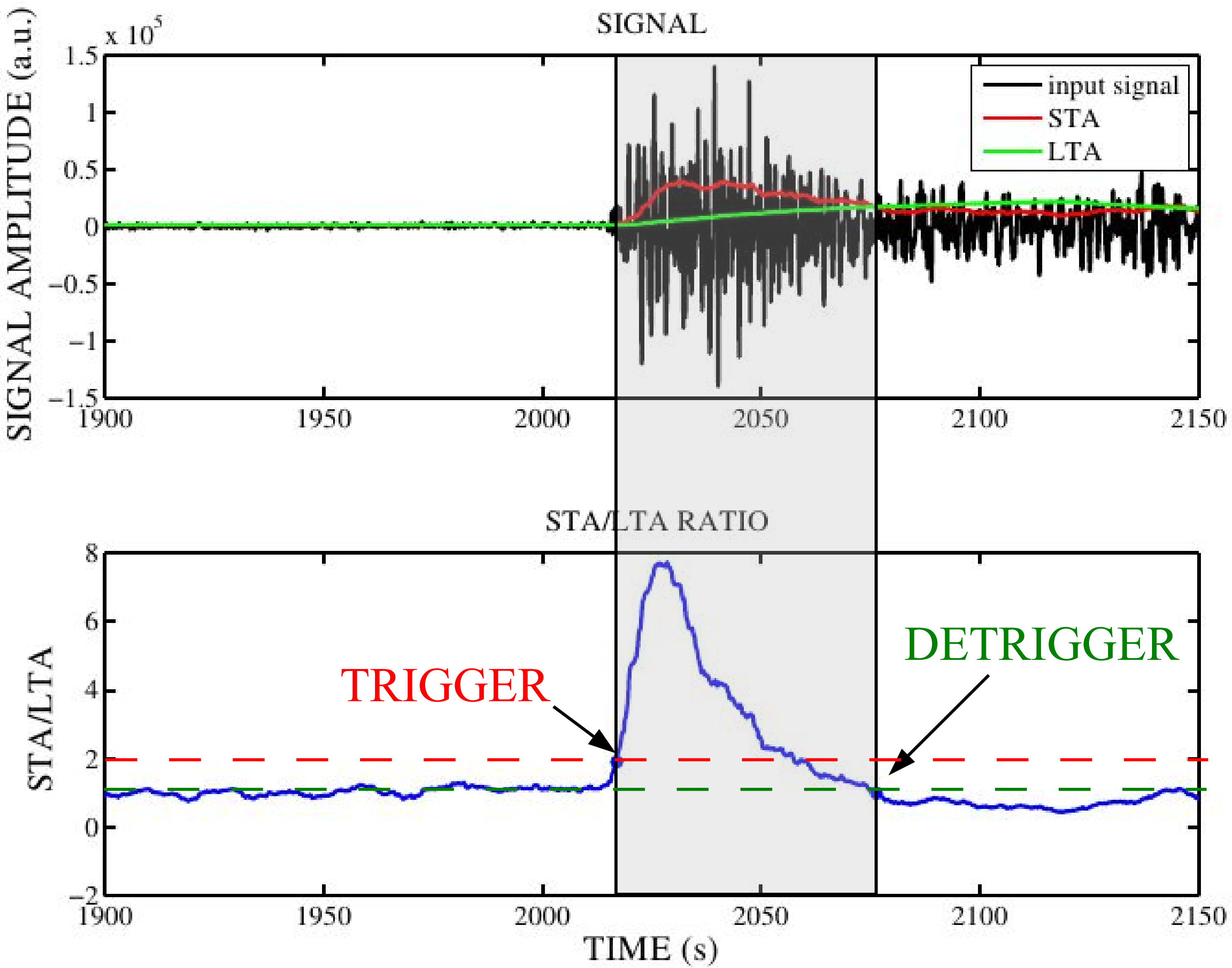
$$STA = \frac{1}{N}\sum_{i=j}^{j+N-1} \left| s_j \right| \quad \text{and} \quad LTA = \frac{1}{M}\sum_{i=j}^{j+M-1} \left| s_j \right| \quad (M > N)$$



*Allen, R. V. (1978), Automatic earthquake recognition and timing from single traces, Bull. Seismol. Soc. Am.

Signal Detection (STA/LTA)

Detection of an arriving signal is ensured by continuous calculation of the ratio of the short-term to long-term **moving** averages (**STA/LTA** algorithm):



Acoustic contaminants

ACOUSTIC CONTAMINANTS (for us)

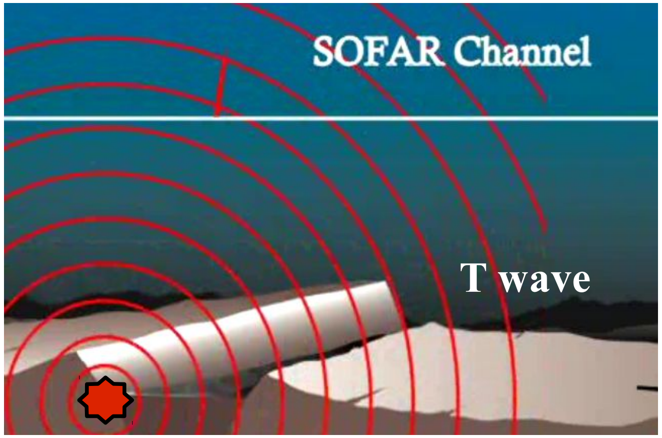
SHIPS

MARINE ANIMALS

ICE CALVING

EXPLORATION CAMPAIGNS

***T* WAVES**



ETC ...

Need an **AUTOMATIC DISCRIMINATION** of STA/LTA detected signals

Signal discrimination algorithm*

STATISTICAL APPROACH

1. Analyze as many signals of the **same origin** as possible

STATISTICAL MODEL
describes how *on average* the total power of the signals of this type is distributed among different frequency bands

2. Compare an unknown signal with the statistical model

Recognition criterion *C*

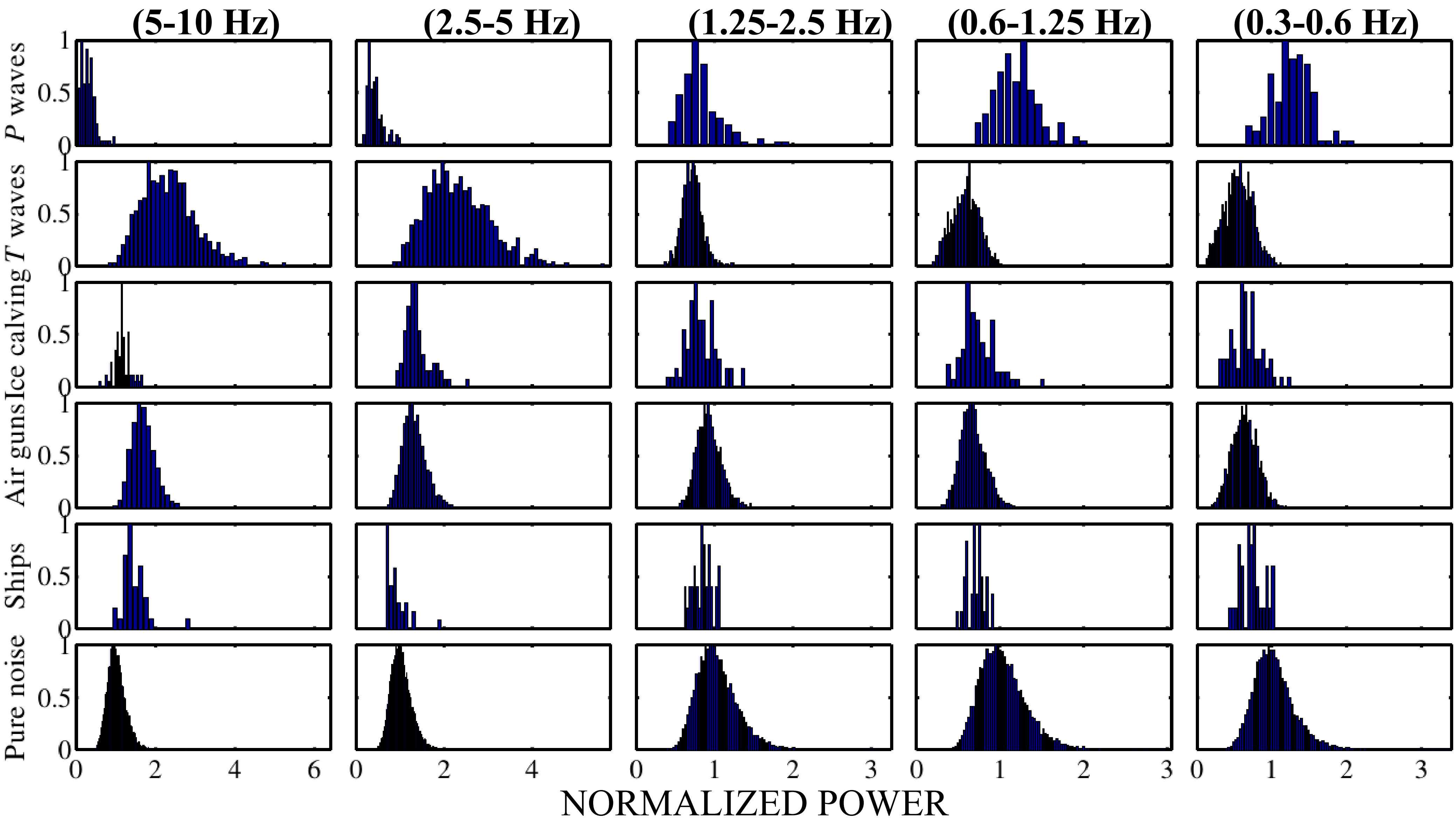
(quantifies the probability for the signal to belong to the model)

The signal belongs to the model when $C > C_0$

*Sukhovich *et al*., GRL **38**, L18605, 2011

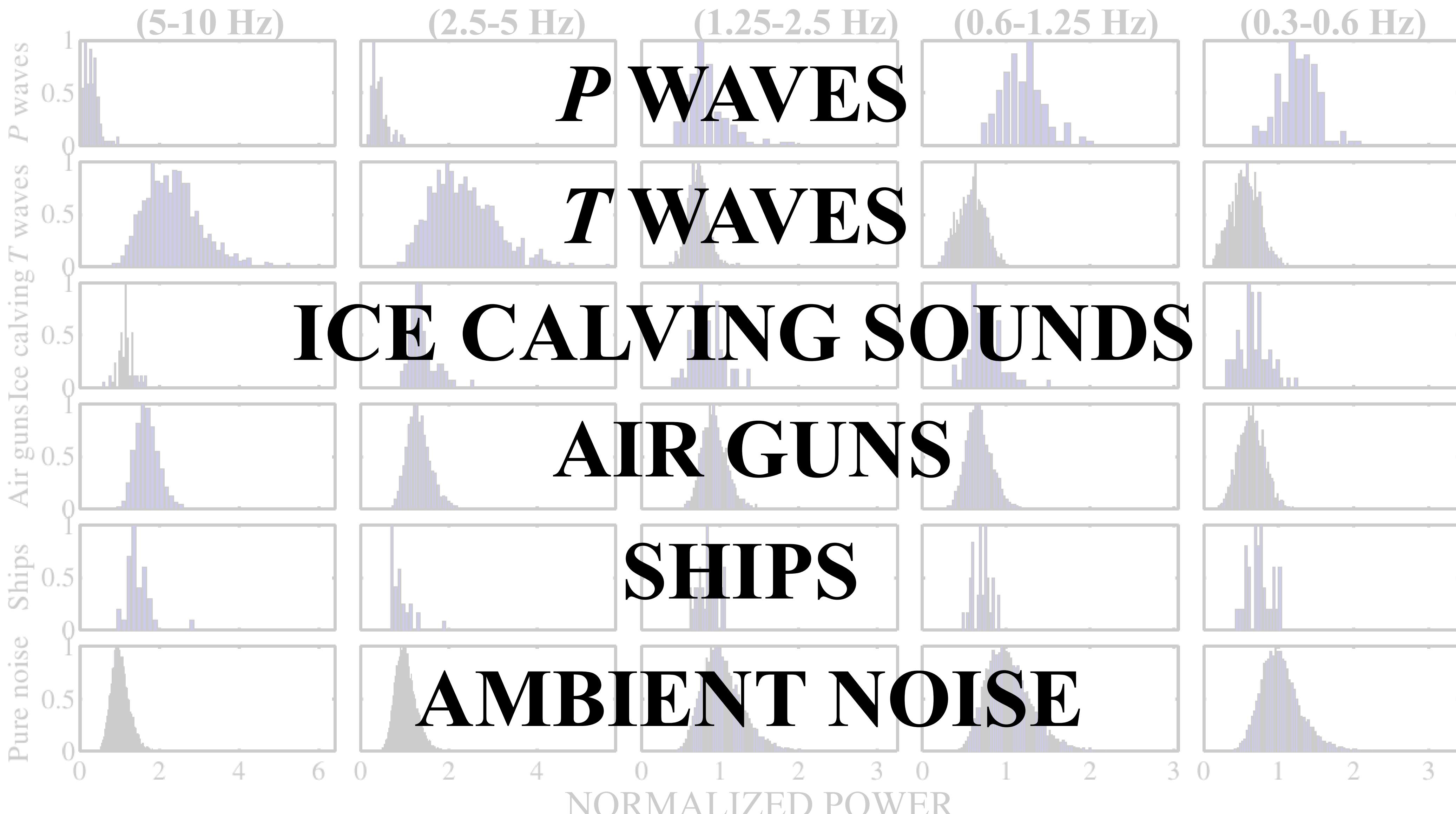
Statistical models

STATISTICAL MODEL : average repartition of the total power of signals' of the same origin among frequency bands



Statistical models

STATISTICAL MODEL : average repartition of the total power of signals' of the same origin among frequency bands



Statistical models

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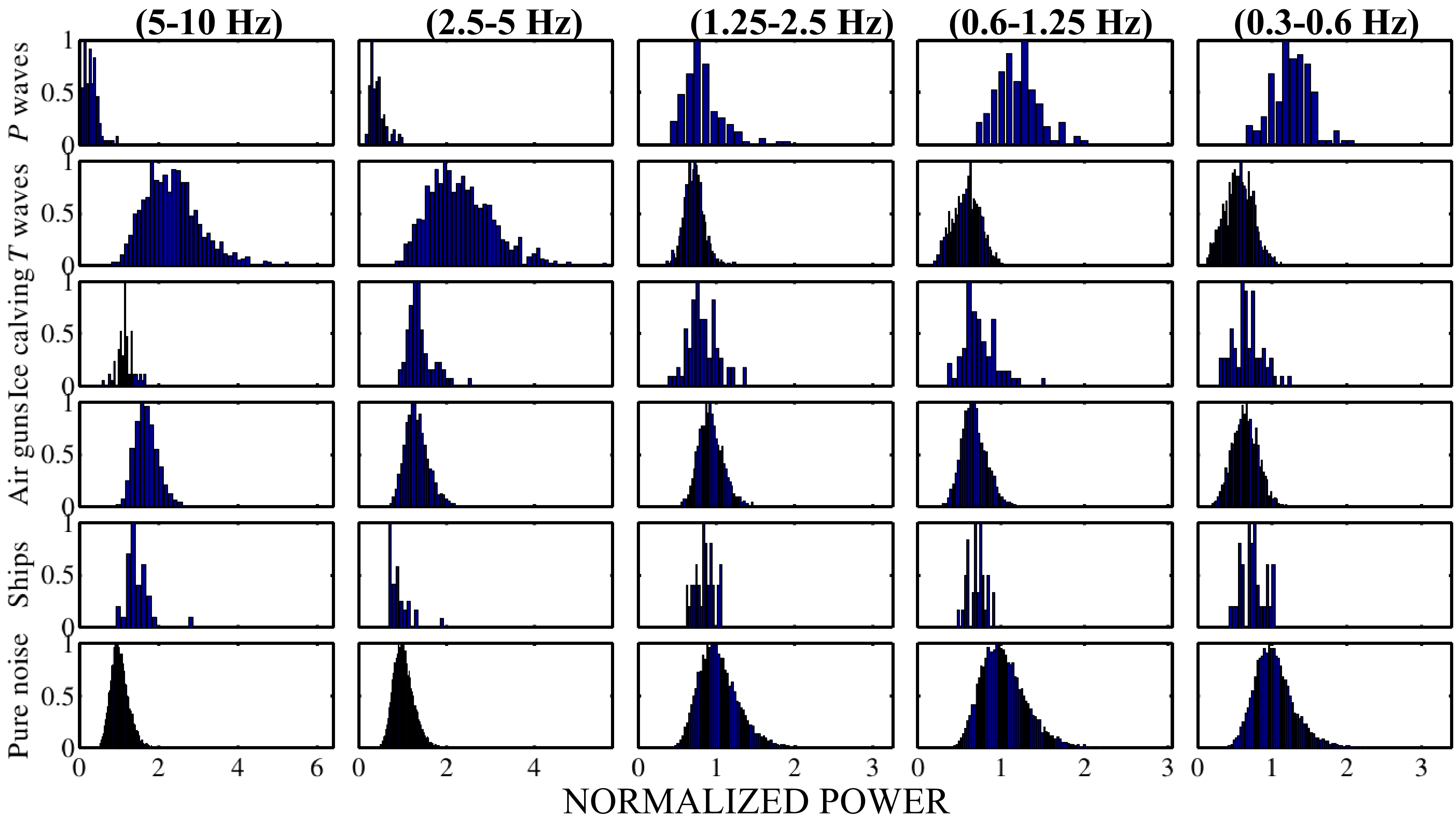

Statistical models

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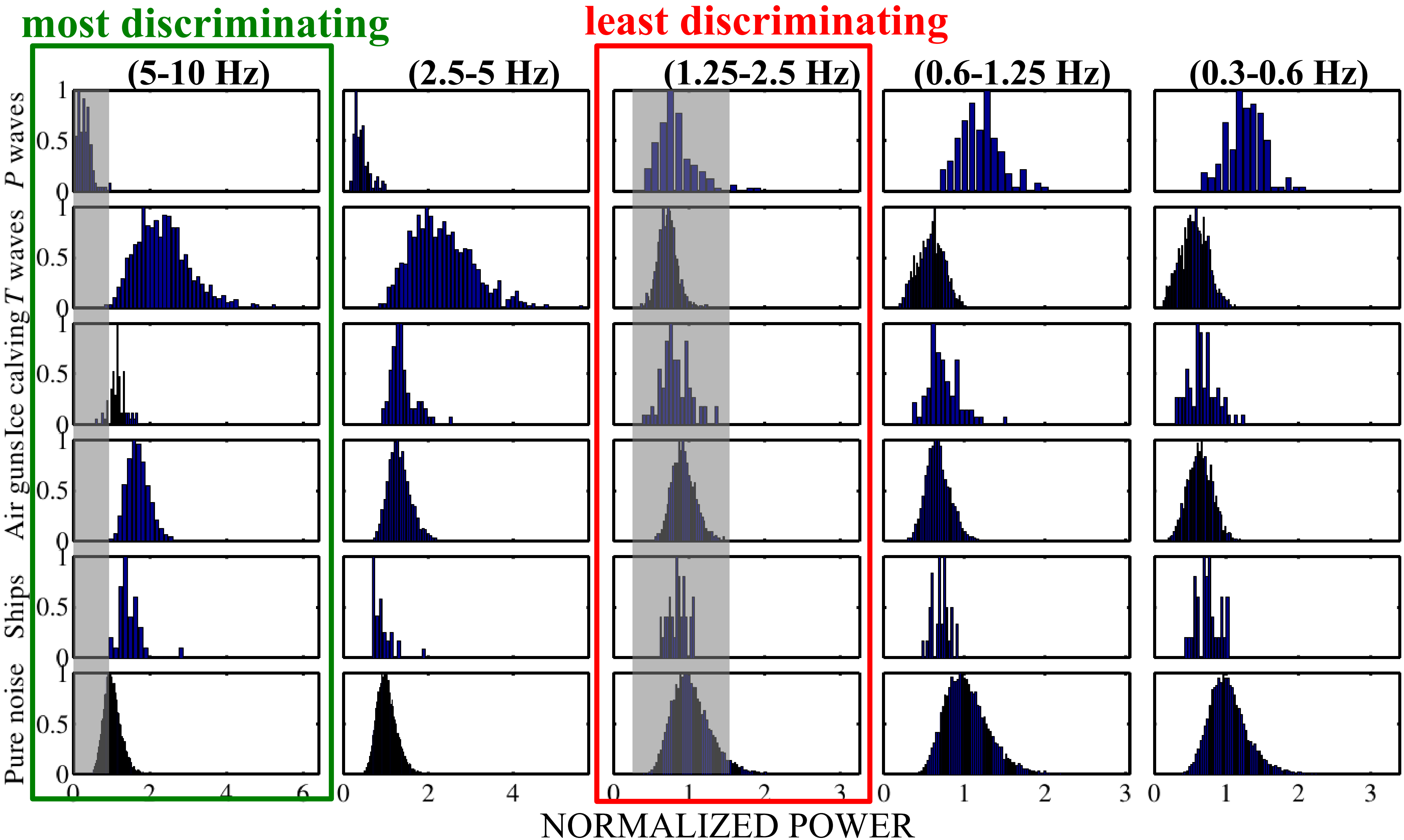
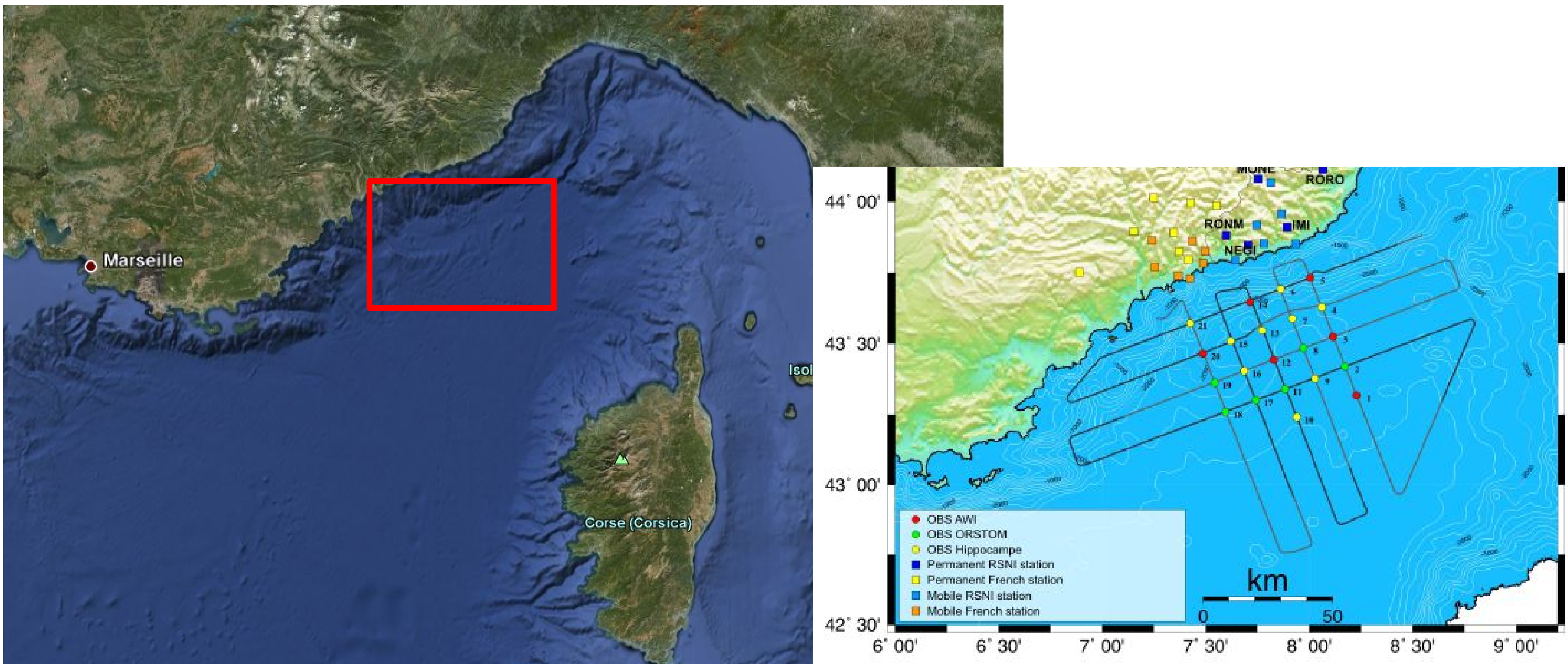


Evaluation of statistical models

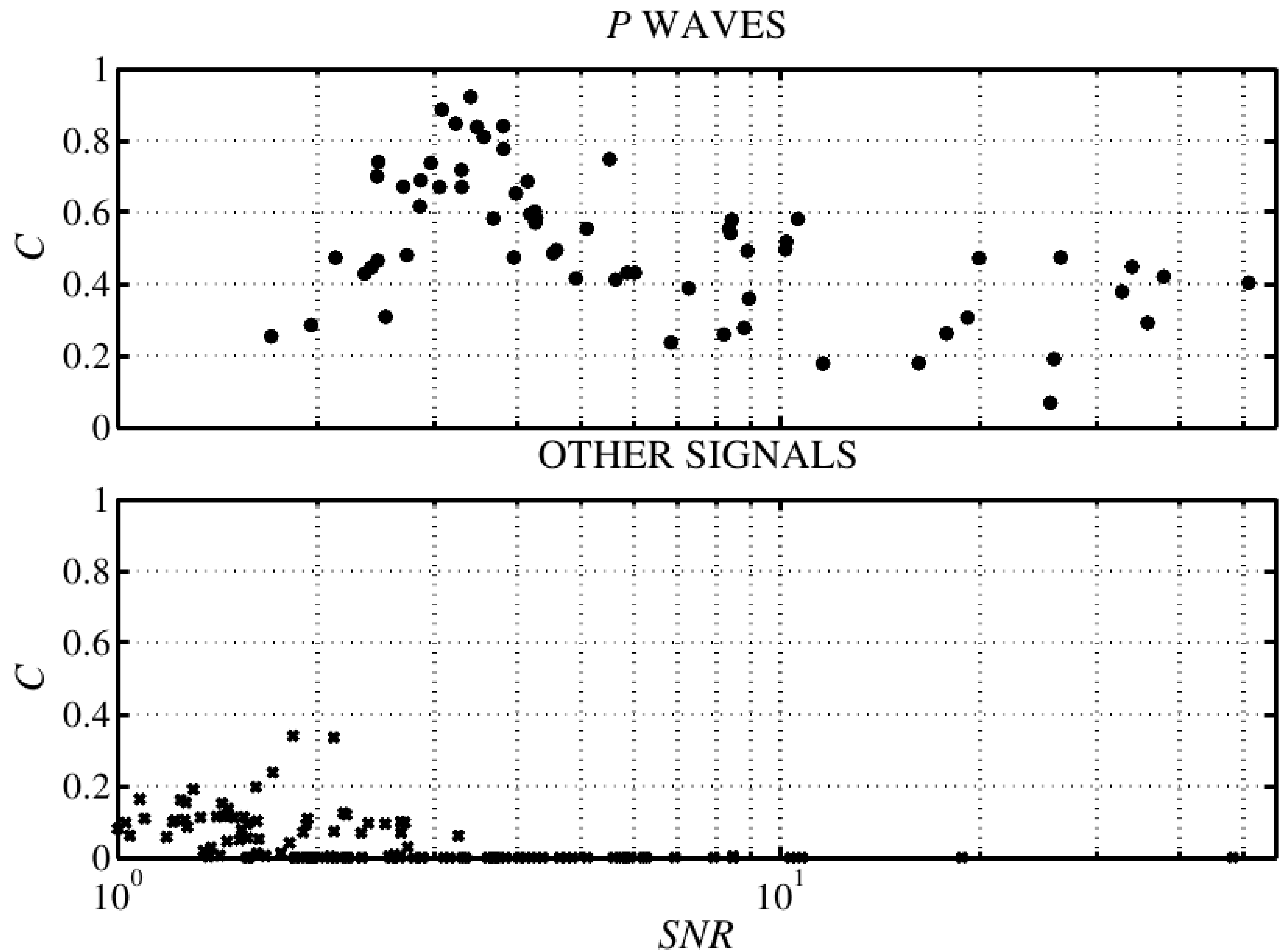
Continuous records of 7 Ocean Bottom Hydrophones (OBHs) recorded during 6-months-long “Grosmarin” experiment* conducted in Ligurian Sea (Mediterranean):

STUDY AREA OF GROSMARIN EXPERIMENT

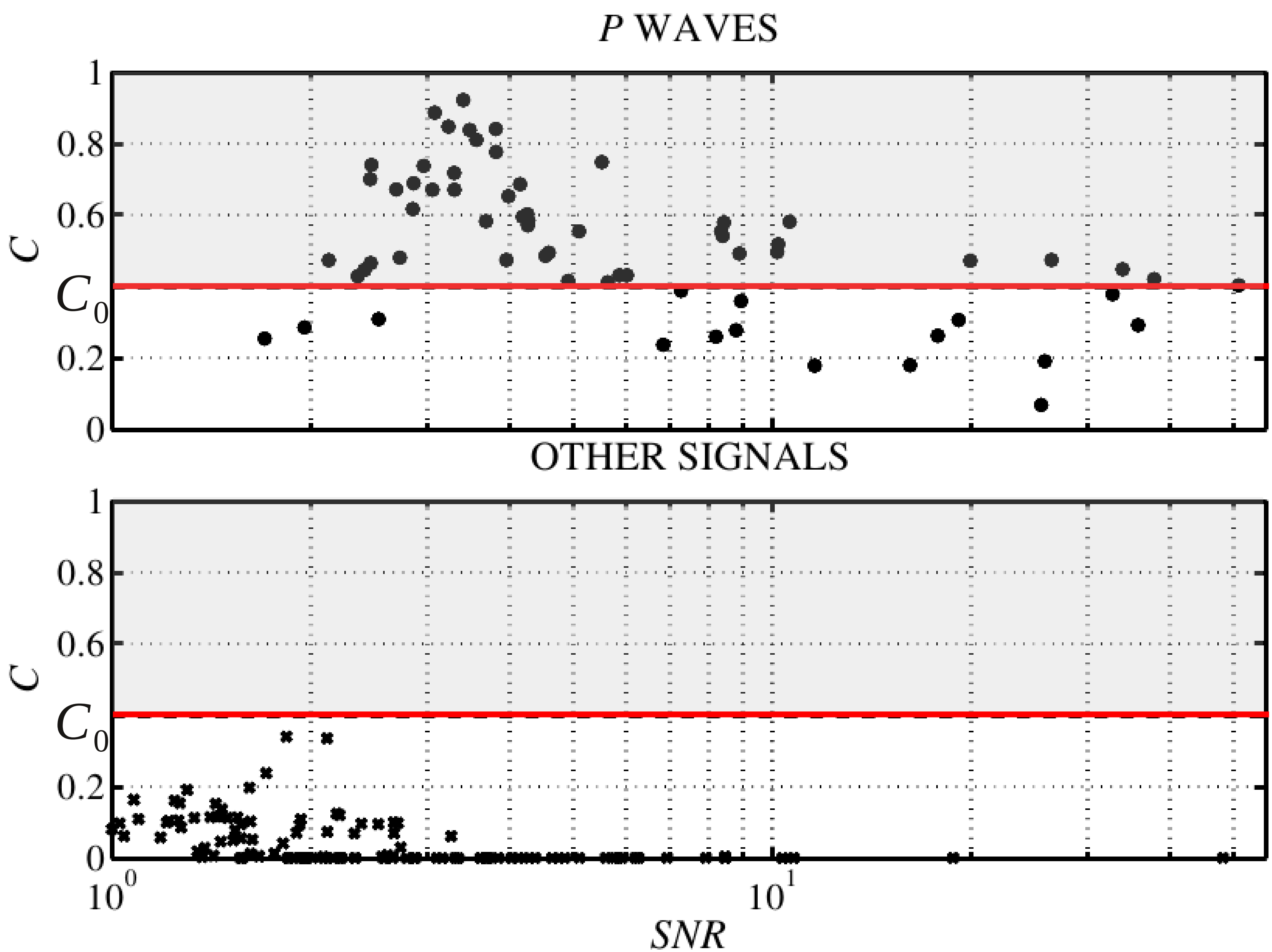


* Dessa *et al*., Bull. Soc. Geol. Fr., 182(4), 305–321 (2011)

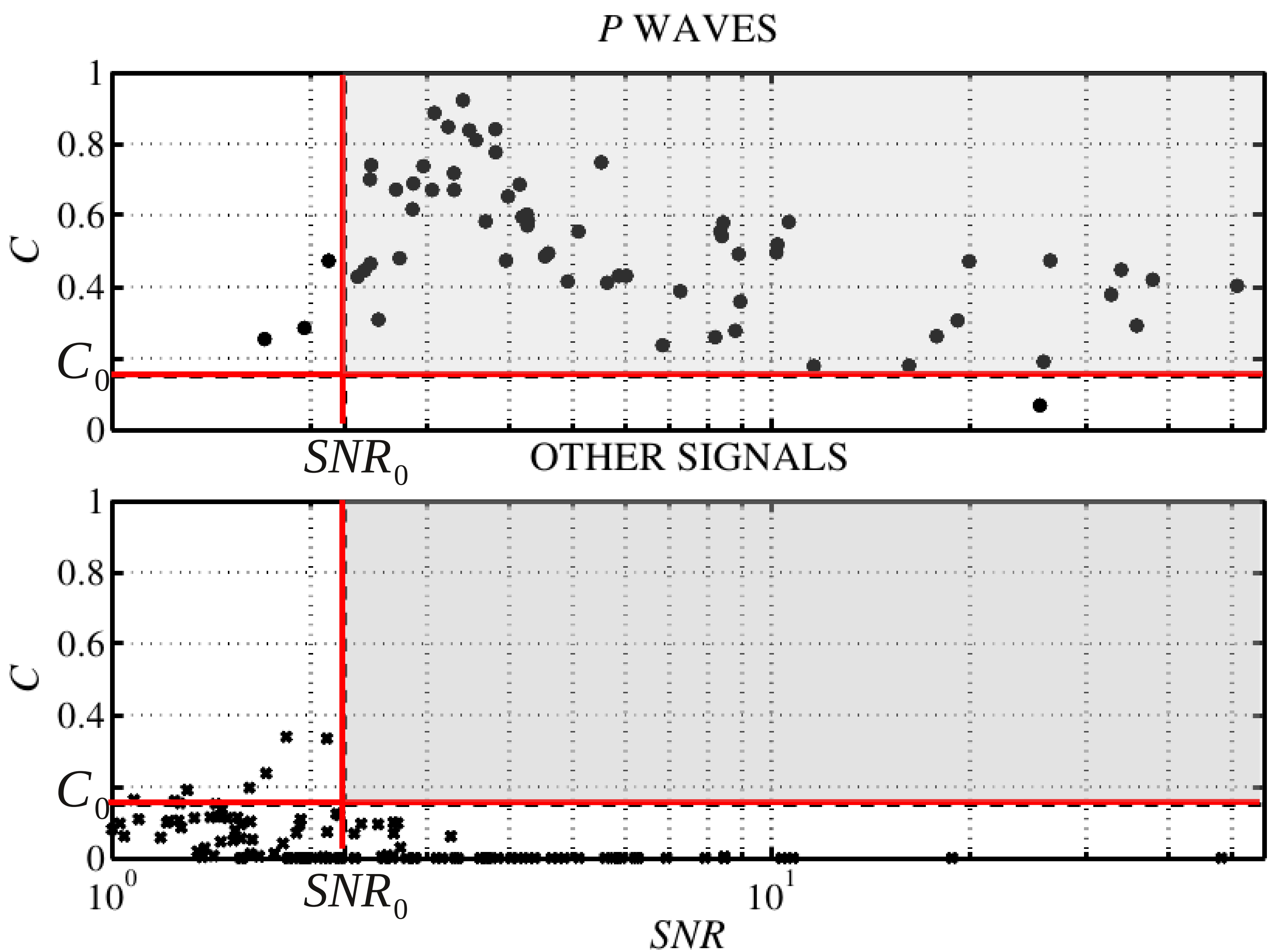
Auto-Discrimination: Grosmarin data



Auto-Discrimination: Grosmarin data



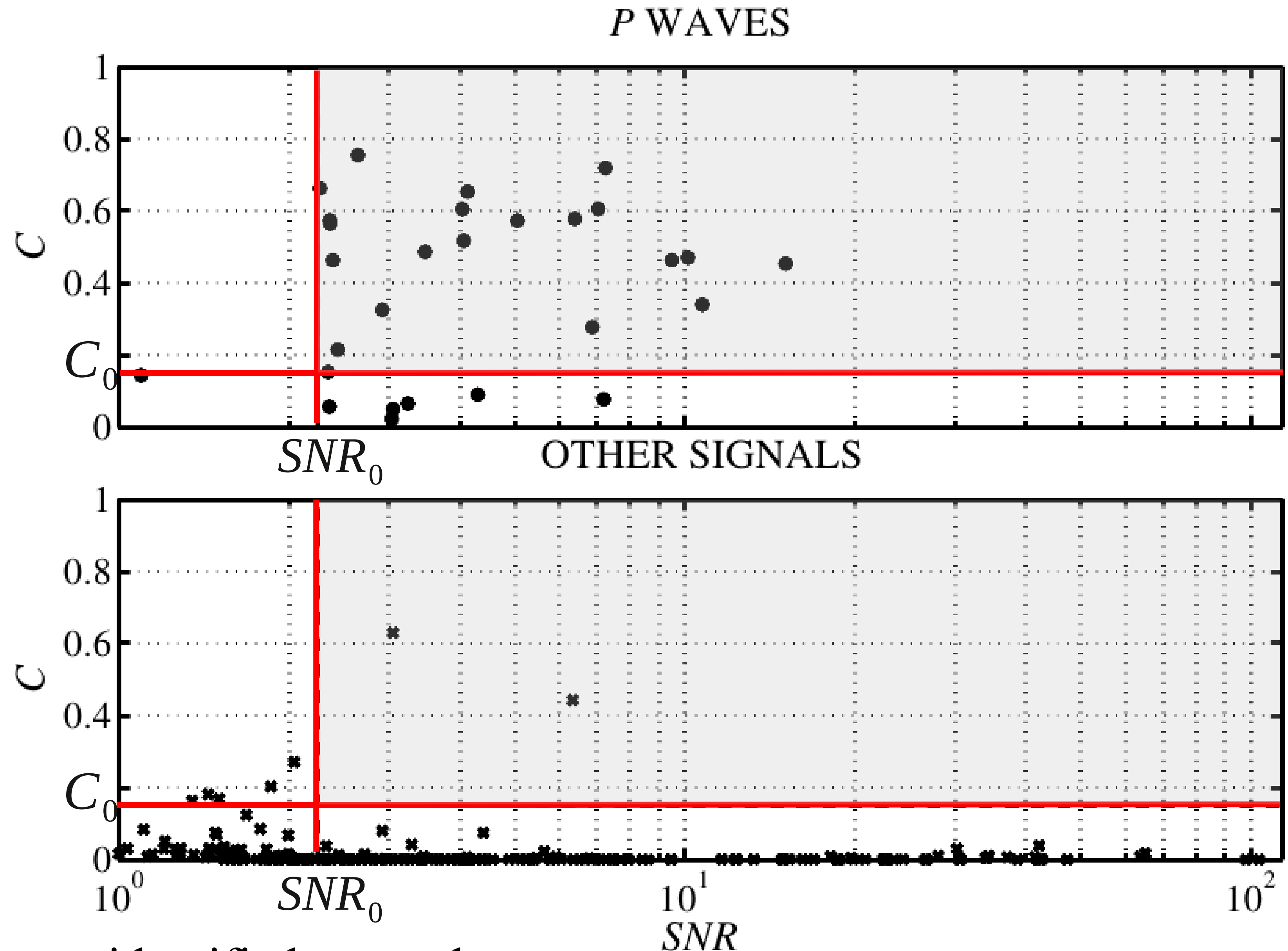
Auto-Discrimination: Grosmarin data



With $C_0 = 0.15$ and $SNR_0 = 2.25$: 94% of *P* waves are identified correctly

Discrimination: Haiti data

Independent data set by two OBHs from 4-month-long experiment at large of Haiti



$C_0 = 0.15$

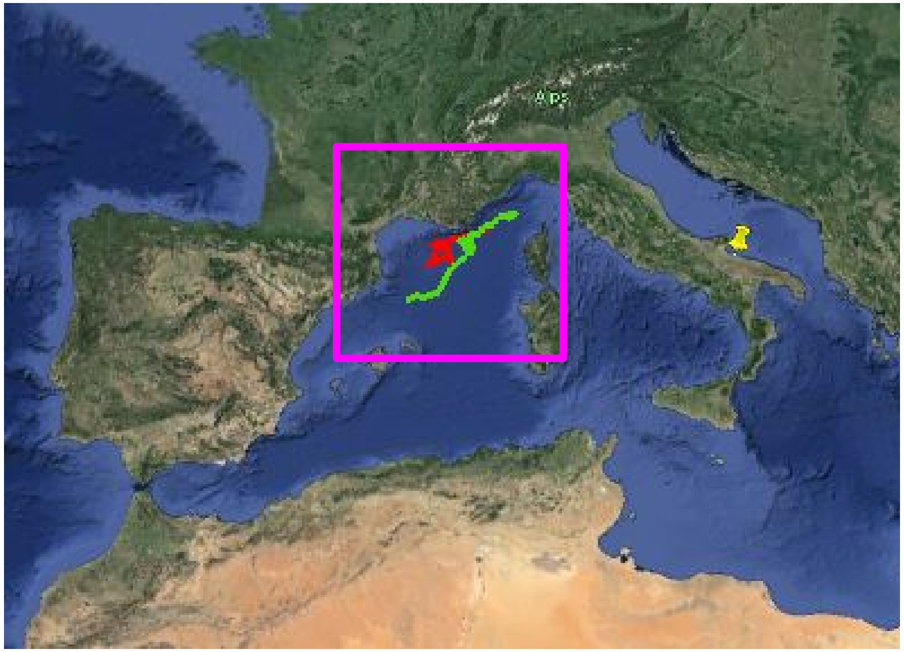
$SNR_0 = 2.25$:

75% of *P* waves are identified correctly

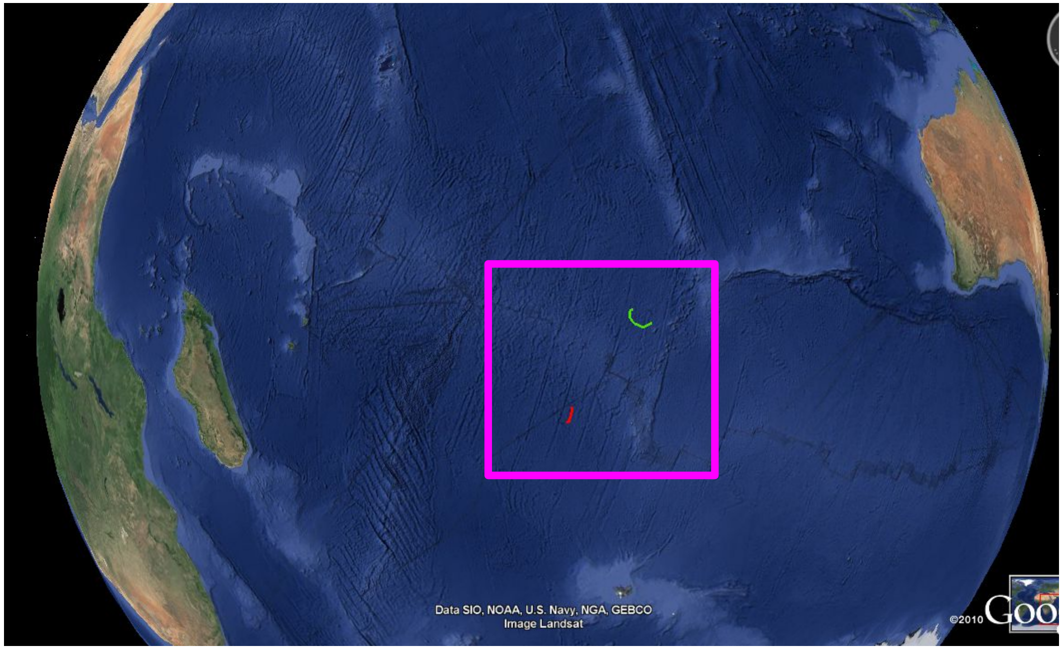
Ongoing missions

4 MERMAIDS

MEDITERANEAN



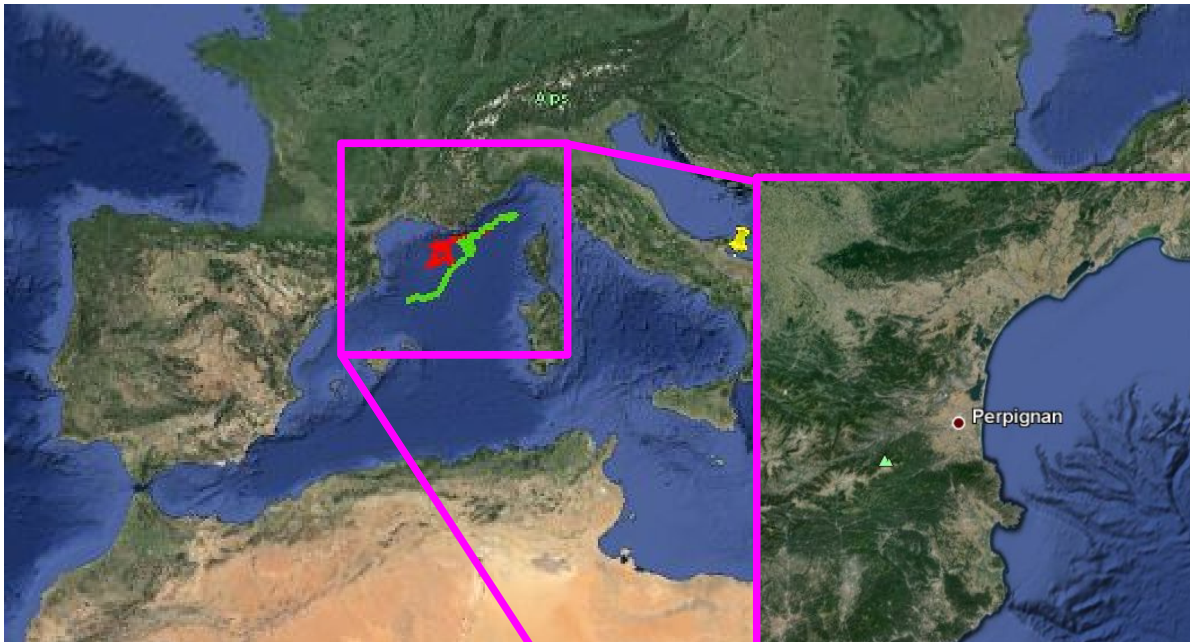
SOUTH INDIAN OCEAN

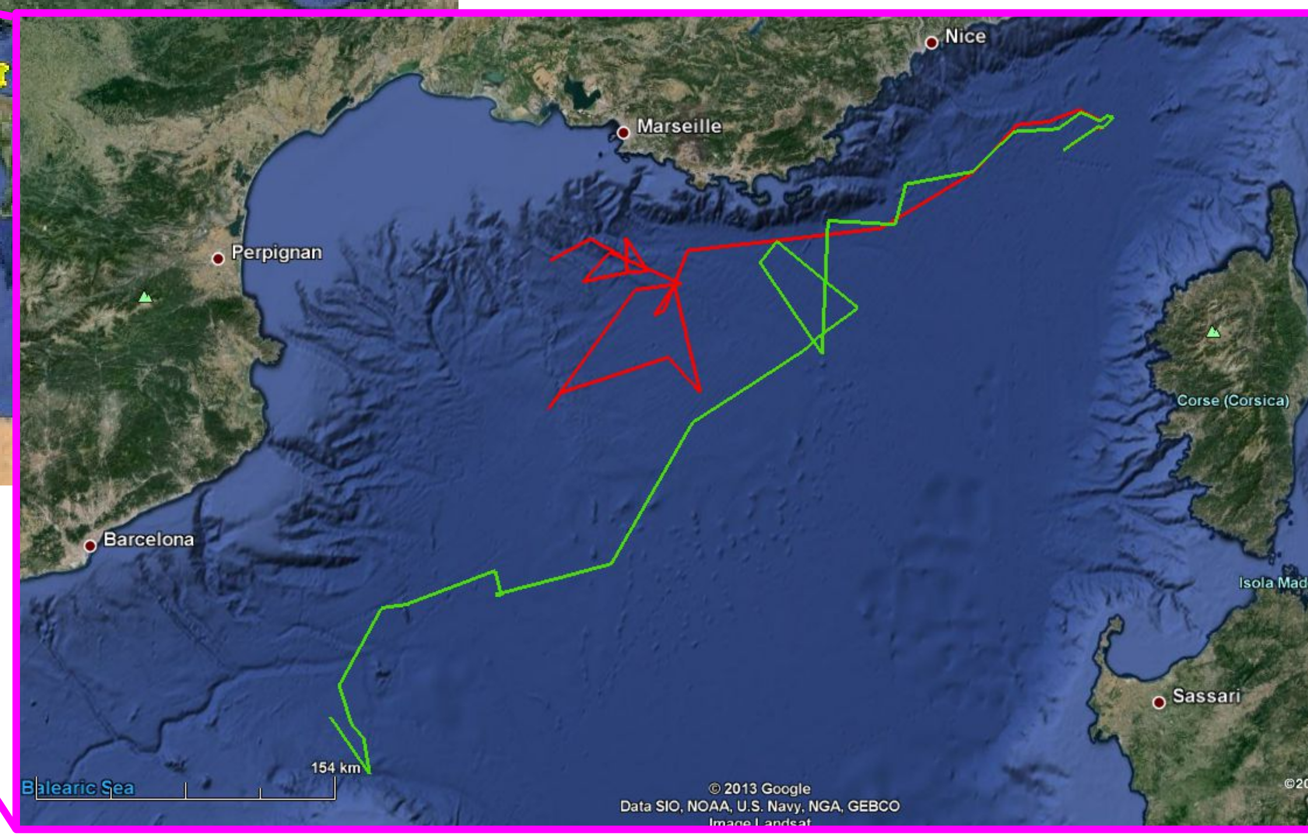


Ongoing mission: Mediterranean

2 MERMAIDs

POSITIONS AT THE SURFACE
December 2012 – June 2013



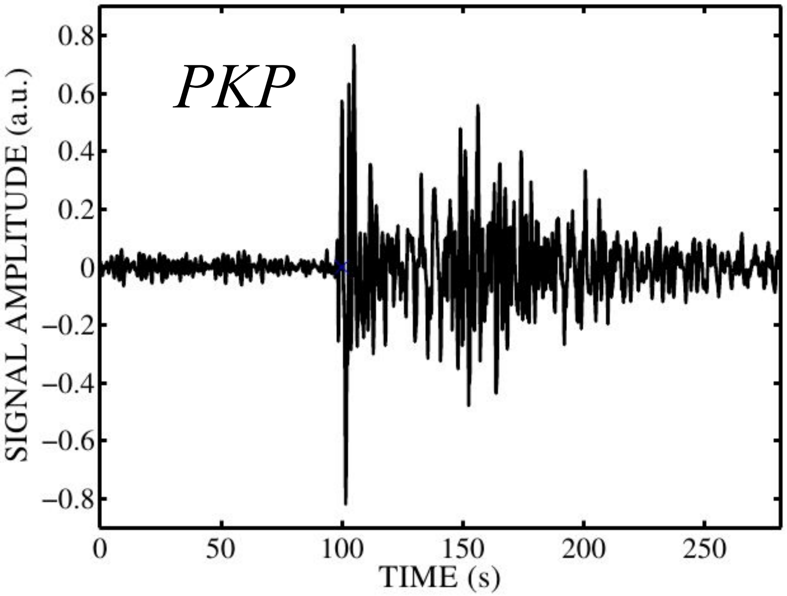


Mission start: End of December 2012

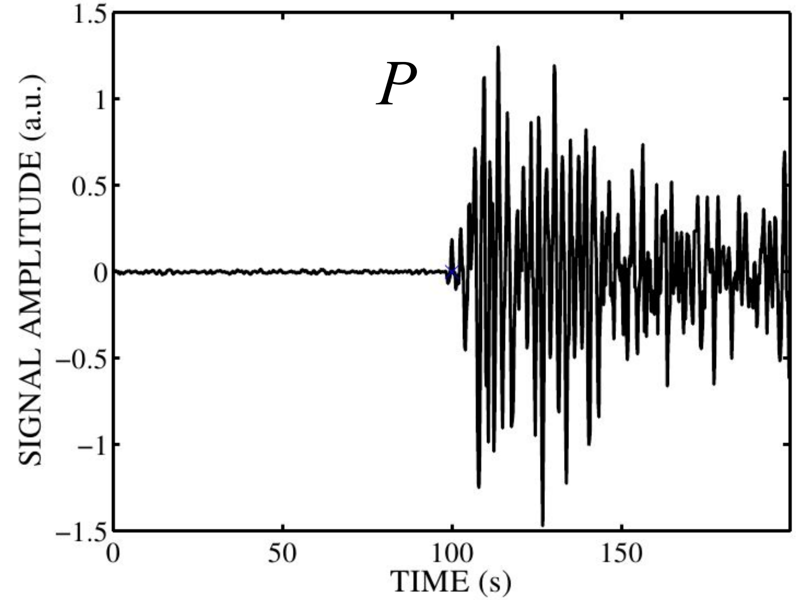
Total number of events detected by July 19, 2013: **27**

Sample seismograms

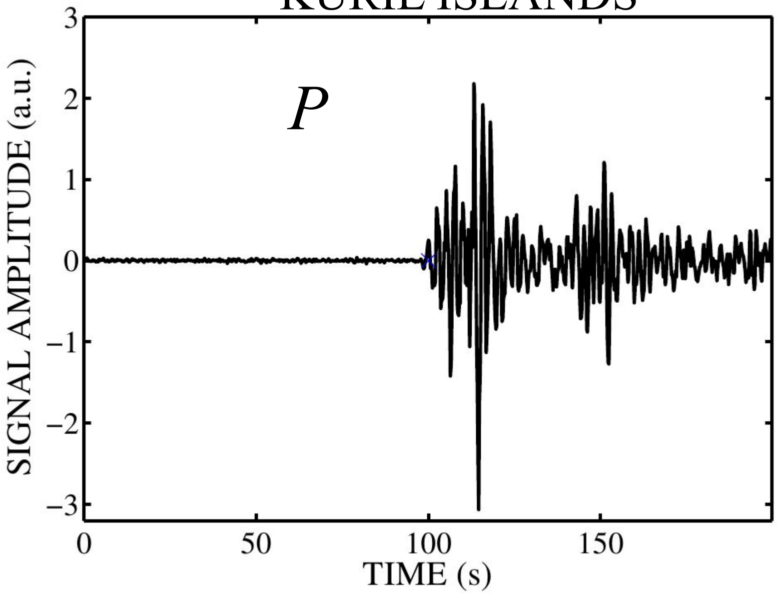
2012-12-21 DELTA: **146.07**; MAGN: **6.7** MW ; VANUATU ISLANDS



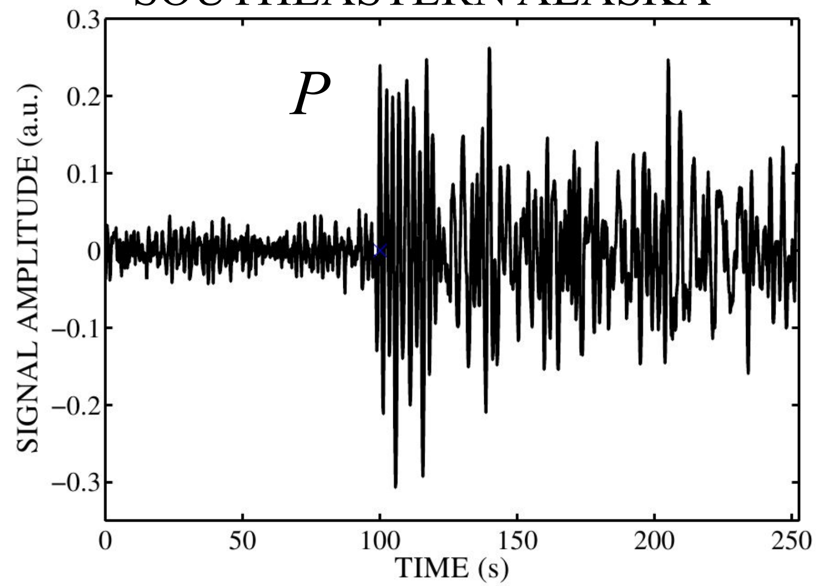
2013-04-16 DELTA: **46.73**; MAGN: **7.7** MW; SOUTHWESTERN PAKISTAN



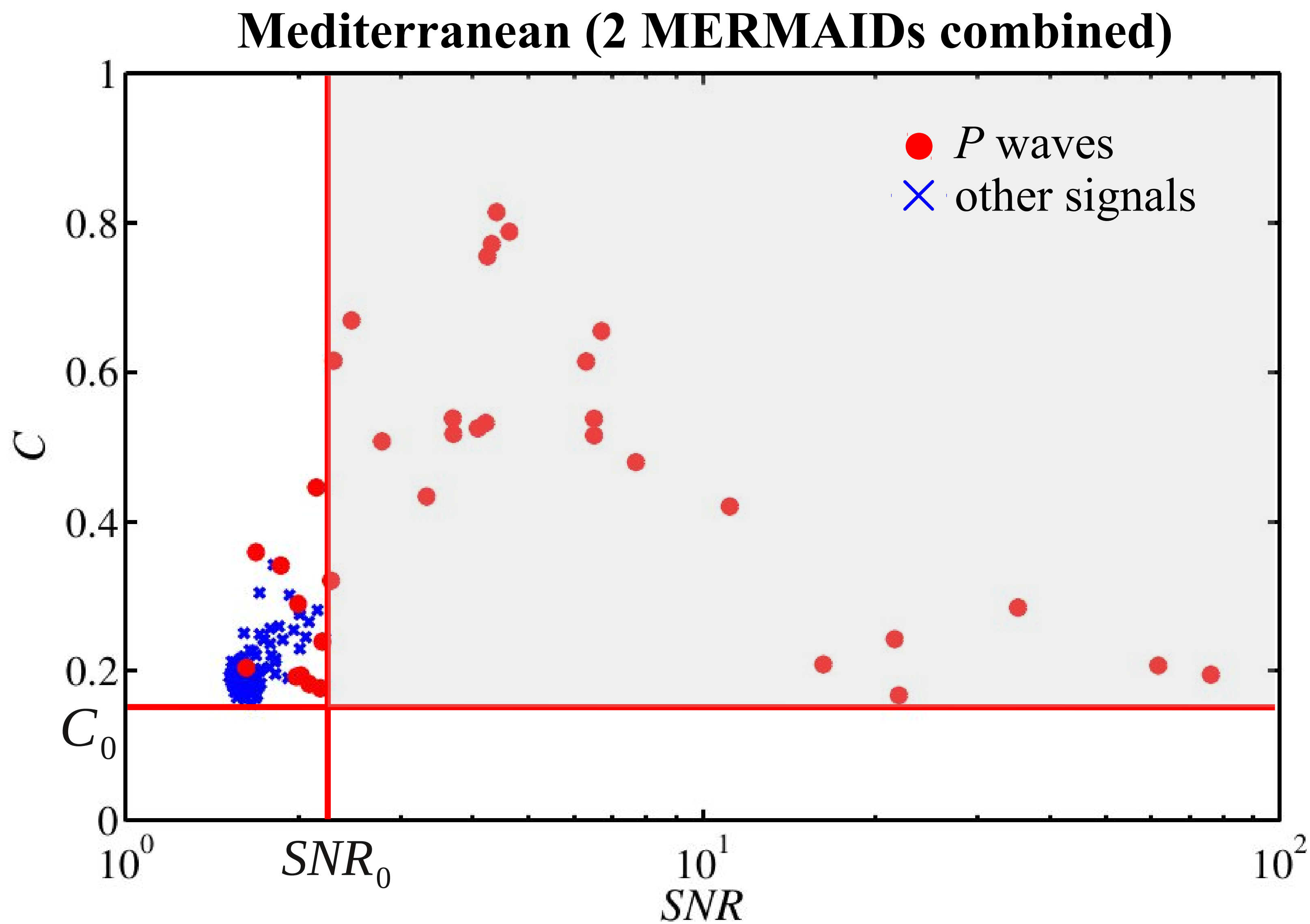
2013-04-19 DELTA: **86.11**; MAGN: **7.3** MW; KURIL ISLANDS



2013-01-05 DELTA: **76.7**; MAGN: **7.5** MW; SOUTHEASTERN ALASKA



Ongoing mission: Mediterranean

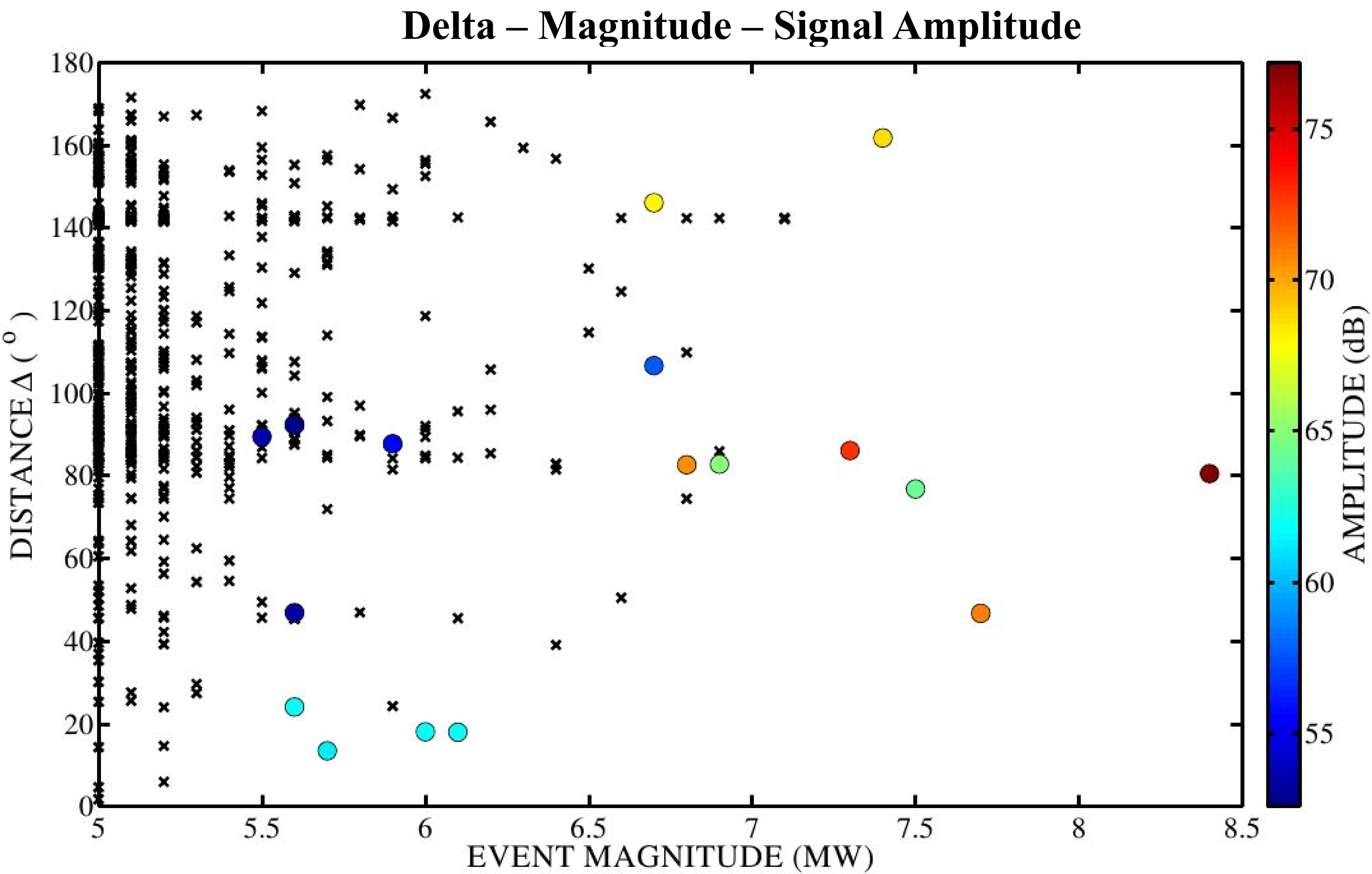


With $C_0 = 0.15$ and $SNR_0 = 2.25$:

21 (**78%**) distinct events identified correctly

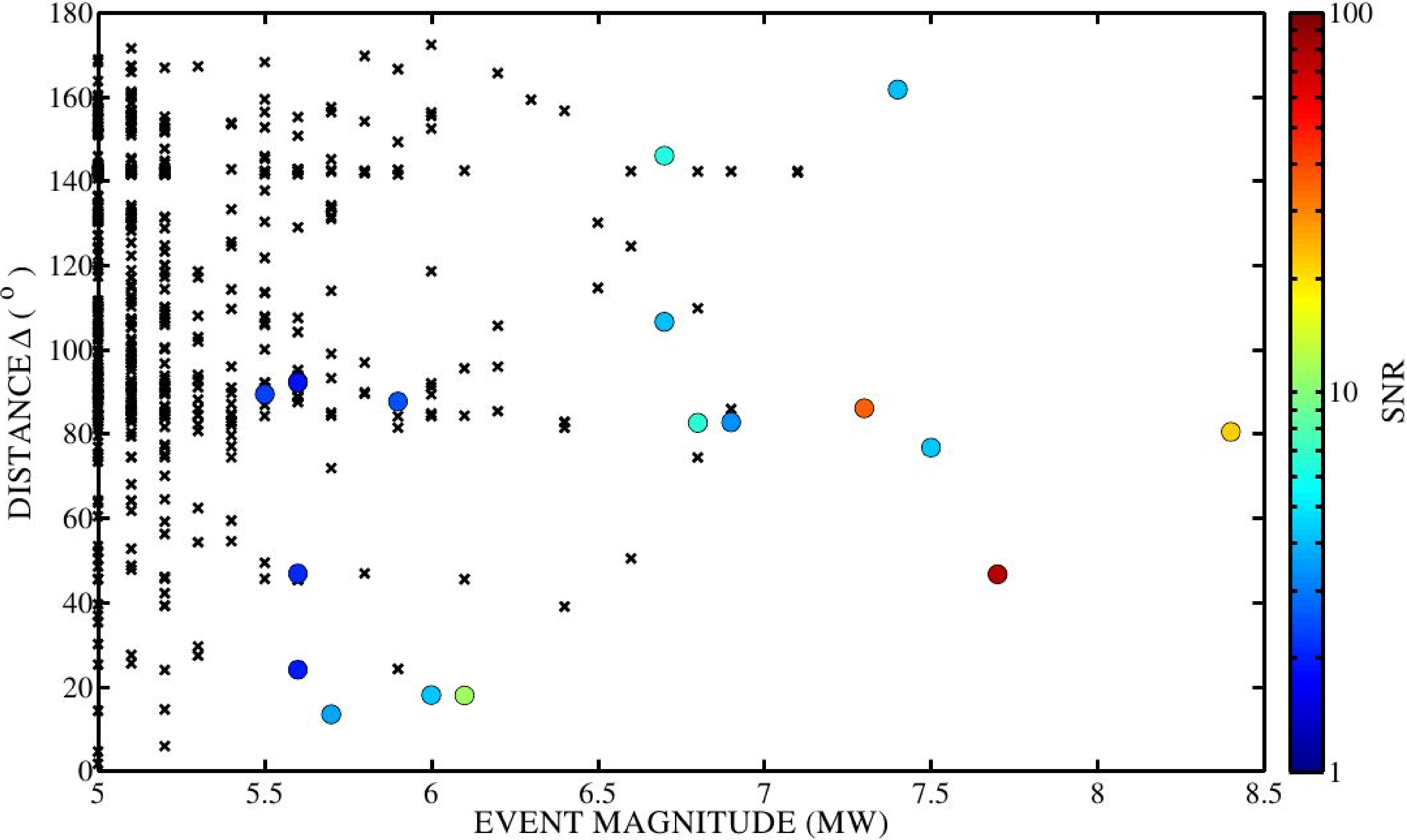
6 false negatives and 0 false positives

Ongoing mission: Mediterranean



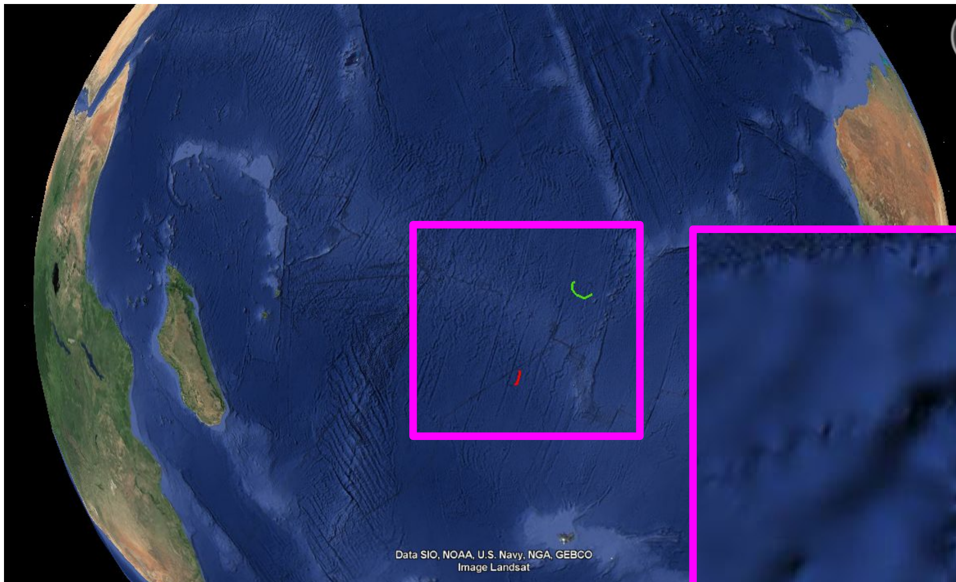
Ongoing mission: Mediterranean

Delta – Magnitude - SNR

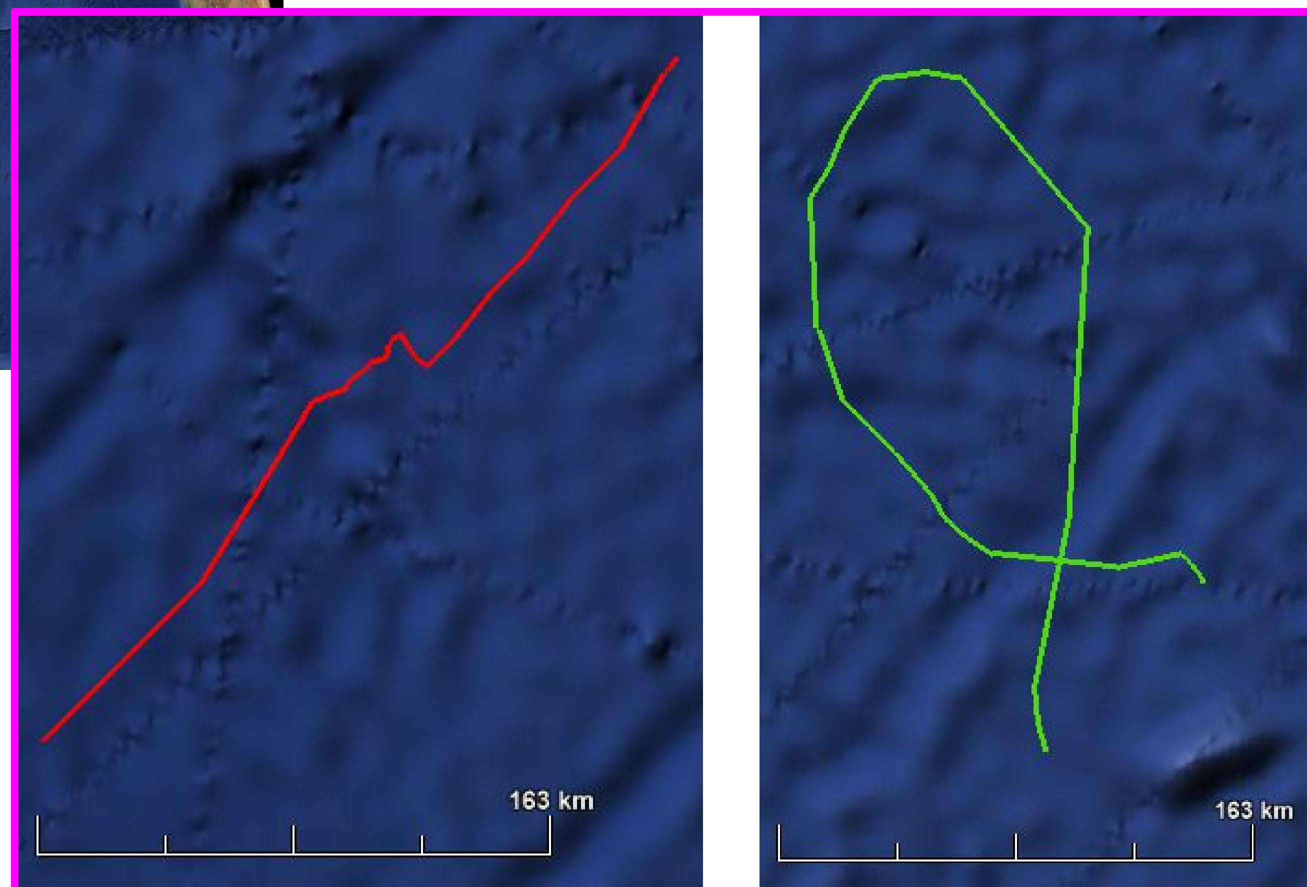


Ongoing mission: South Indian ocean

2 MERMAIDs

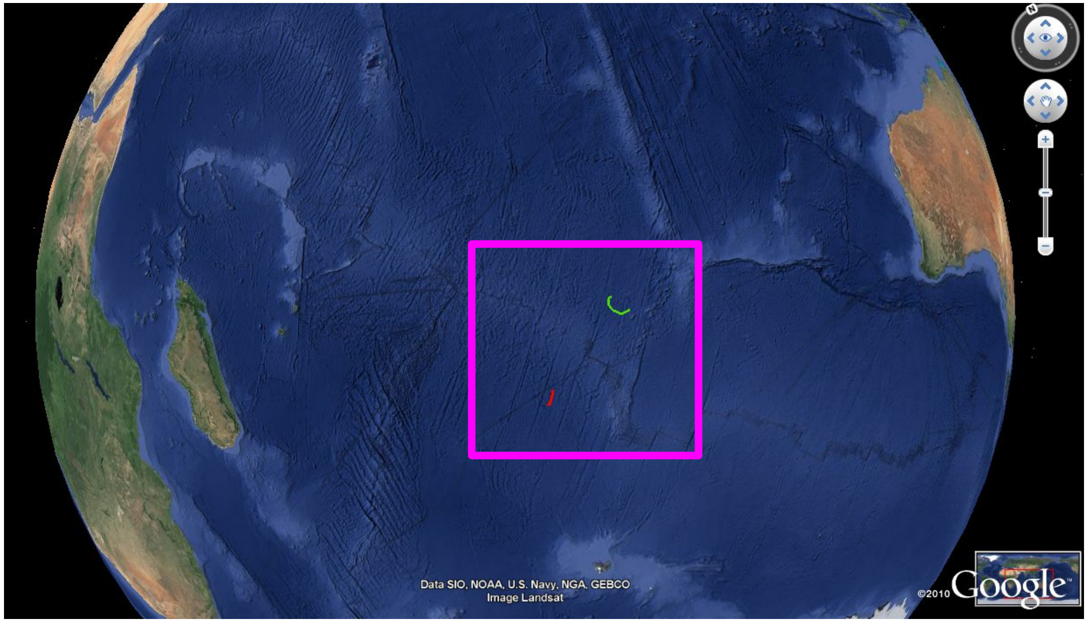


POSITIONS AT THE SURFACE
March 2013 – June 2013



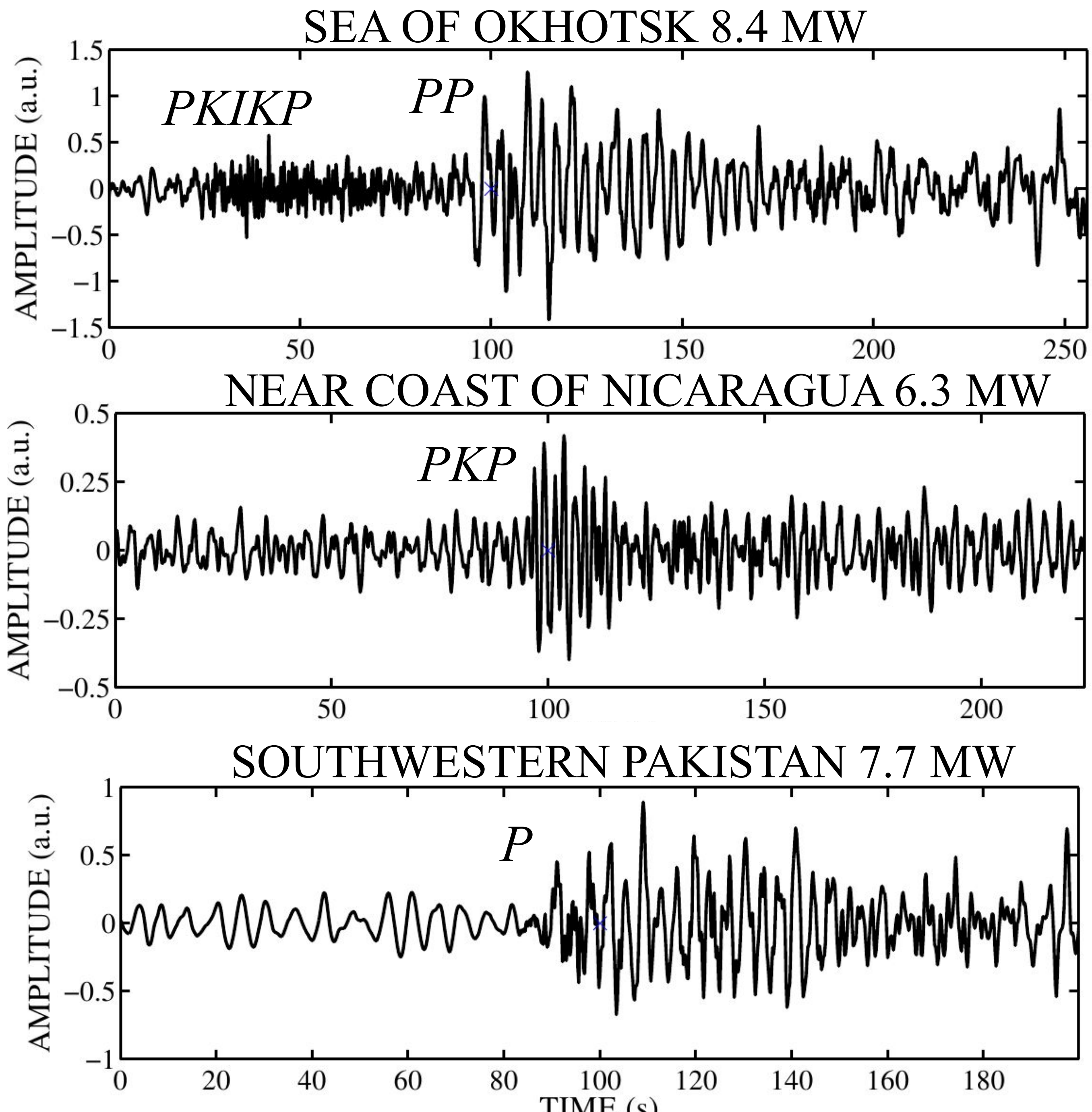
Mission start: beginning of March 2013
Number of events detected by July 19, 2013: **5**

Ongoing mission: South Indian ocean

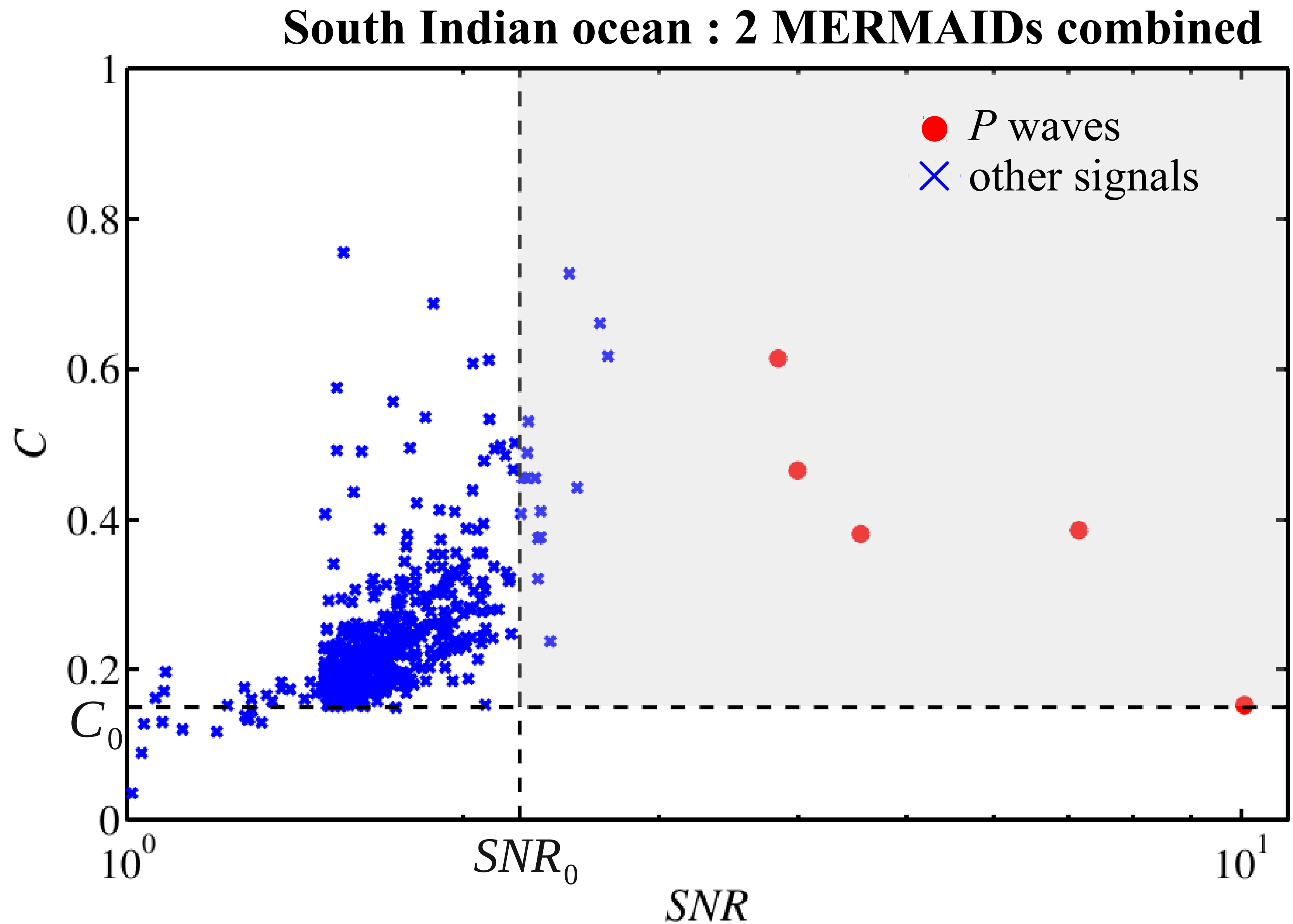


TIME	DELTA	DEPTH	MAG TYPE	REGION
2013-05-24 05:44:49	113.60	608.90	8.4 MW	SEA OF OKHOTSK
2013-04-16 10:44:20	62.10	82.00	7.7 MW	SOUTHWESTERN PAKISTAN
2013-06-15 17:34:29	149.40	44.80	6.3 MW	NEAR COAST OF NICARAGUA
2013-07-07 18:35:30	82.53	386.30	7.3 MW	NEW IRELAND REGION, P.N.G.
2013-07-15 14:03:42	69.93	26.80	7.3 MW	SOUTH SANDWICH ISLANDS REGION

South Indian ocean: Seismograms



Ongoing mission: South Indian ocean

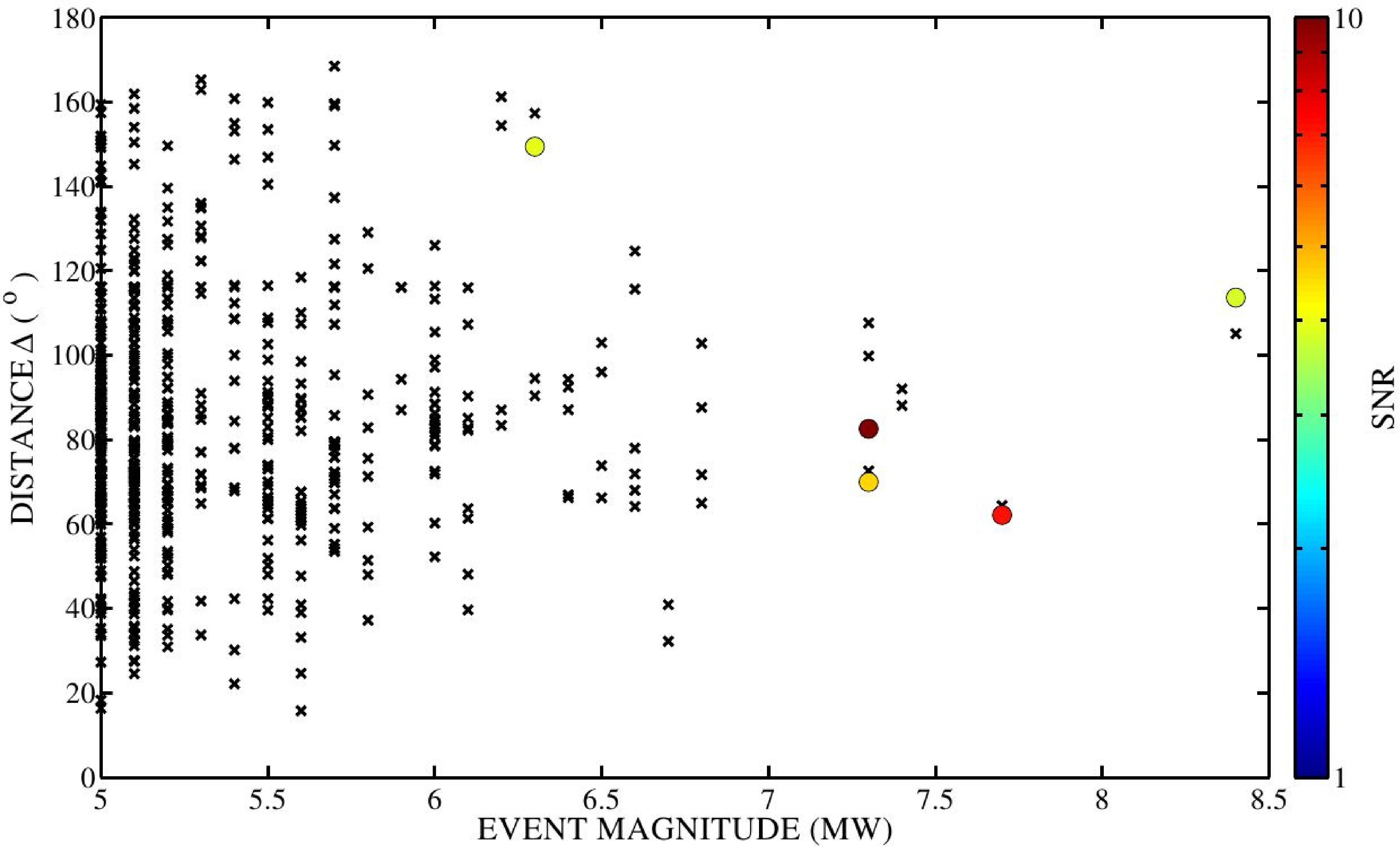


With $C_0 = 0.15$ and $SNR_0 = 2.25$: 5 distinct events are identified correctly

15 false positives

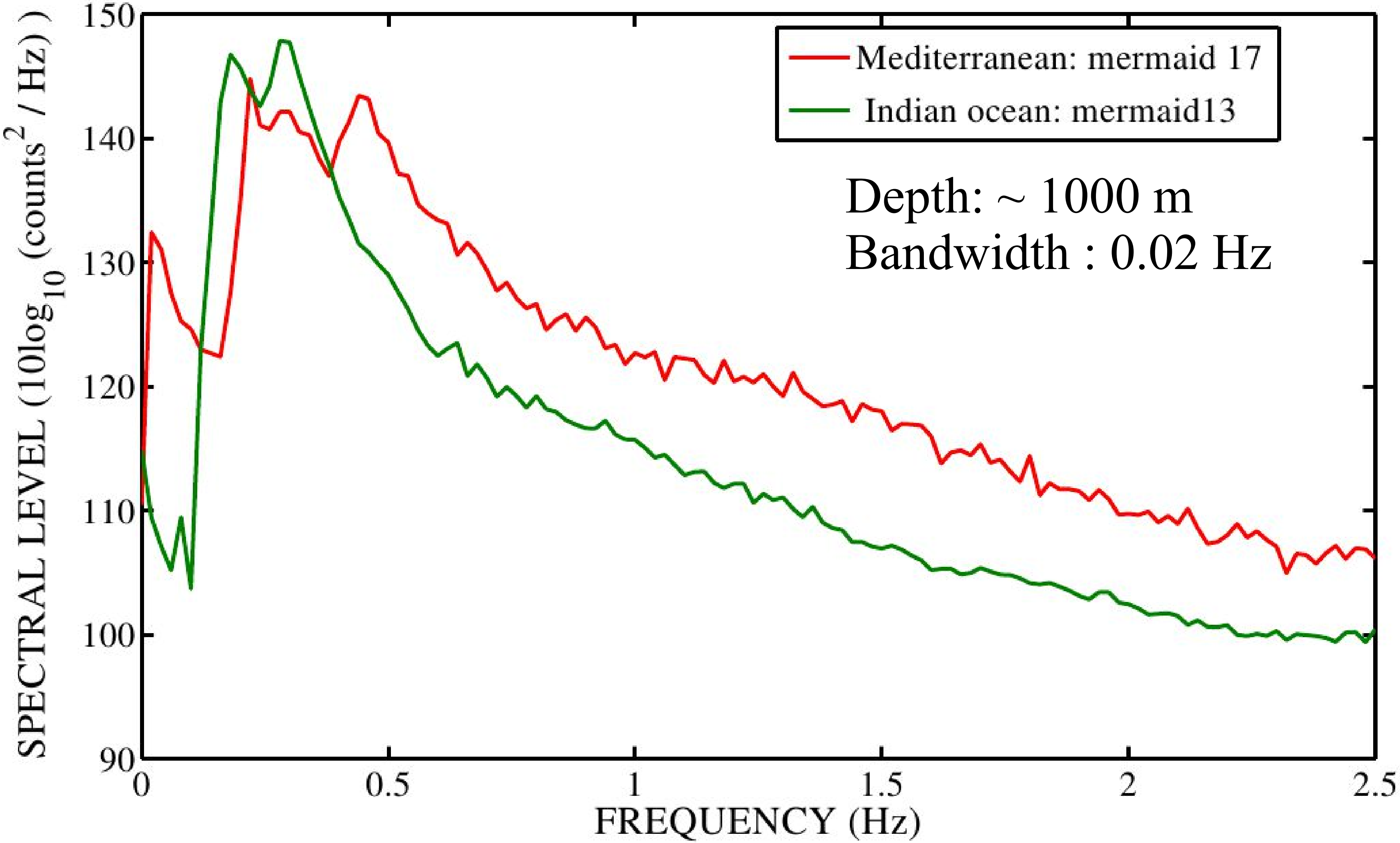
Ongoing mission: South Indian ocean

Delta – Magnitude - SNR



Ambient noise properties

Spectral level of the ambient noise recorded by MERMAIDs



- at lower frequencies (< 0.4 Hz) ambient noise field in stronger in the Indian ocean
- at higher frequencies (> 0.4 Hz) ambient noise field is stronger in the Mediterranean

Conclusions

• MERMAID robots capable to detect acoustic signals generated by seismic *P* waves are developed

• signal discrimination is based on the statistical analysis of the distribution of the signal's total power among different frequency bands

• 23 events recorded in Mediterranean during 6 months

• 5 events recorded in the Indian ocean during 3 months

• Ambient noise spectral level in the Indian ocean is different from that in the Mediterranean and is dominated by lower frequencies (< 0.4 Hz) → the future work includes the adjustment of the detection parameters to the noise conditions in the Indian ocean

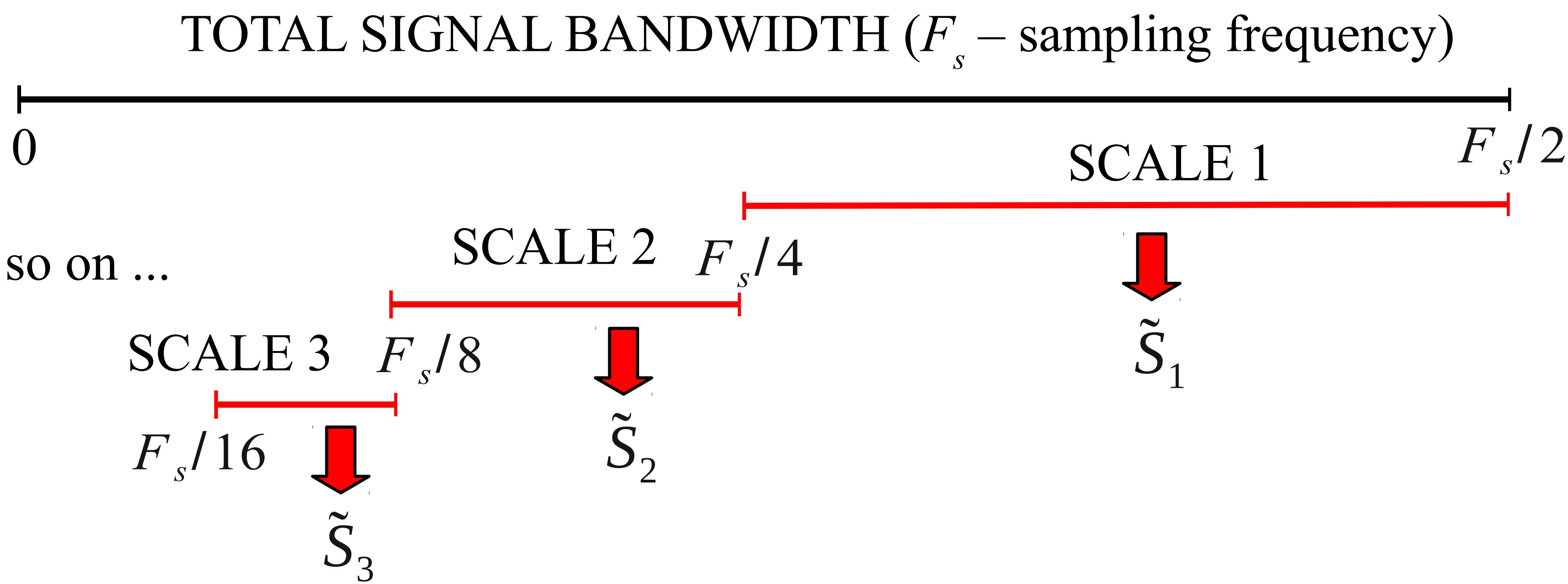
THANK YOU FOR YOUR ATTENTION!

Wavelet transform and power distribution

Signals are analyzed with **WAVELET TRANSFORM :** projection of a function *f(t)* onto a space defined by wavelet functions $\psi(t)$

$$\gamma(s_j, \tau_i) = \int f(t)\, \psi^*\left(\frac{t-\tau_i}{s_j}\right) dt$$

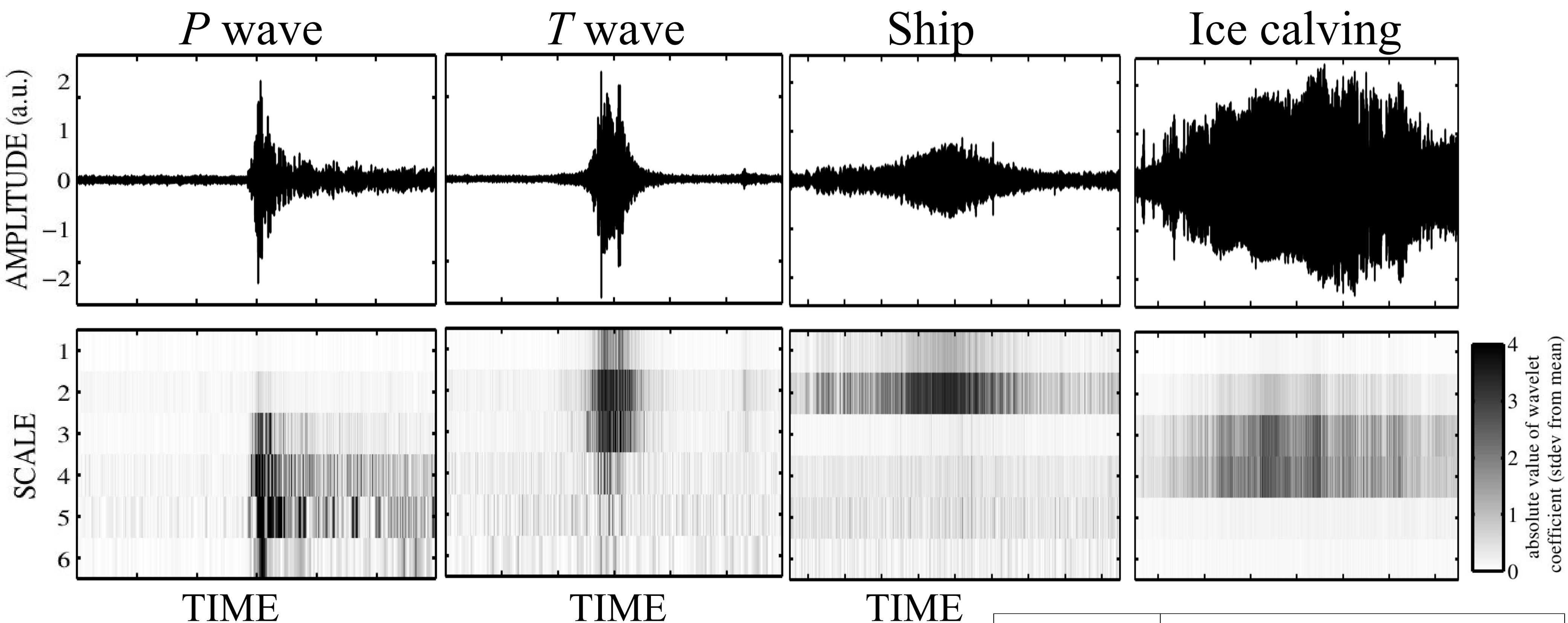
s_j - **scale** ⟺ **frequency band**



SCALE AVERAGES $\tilde{S}_1, \ldots, \tilde{S}_K$ quantify the percentage of the total power concentrated in each scale

Wavelet transform

The DWT is visualized by a **SCALOGRAM** - absolute values of all wavelet transform coefficients $\gamma(s, \tau)$ as a function of s and τ



As a rule of thumb:
scale 1 ↔ [$F_s/4$ $F_s/2$]
scale 2 ↔ [$F_s/8$ $F_s/4$], ...
where F_s is a sampling frequency

In our case (F_s = 40 Hz) :

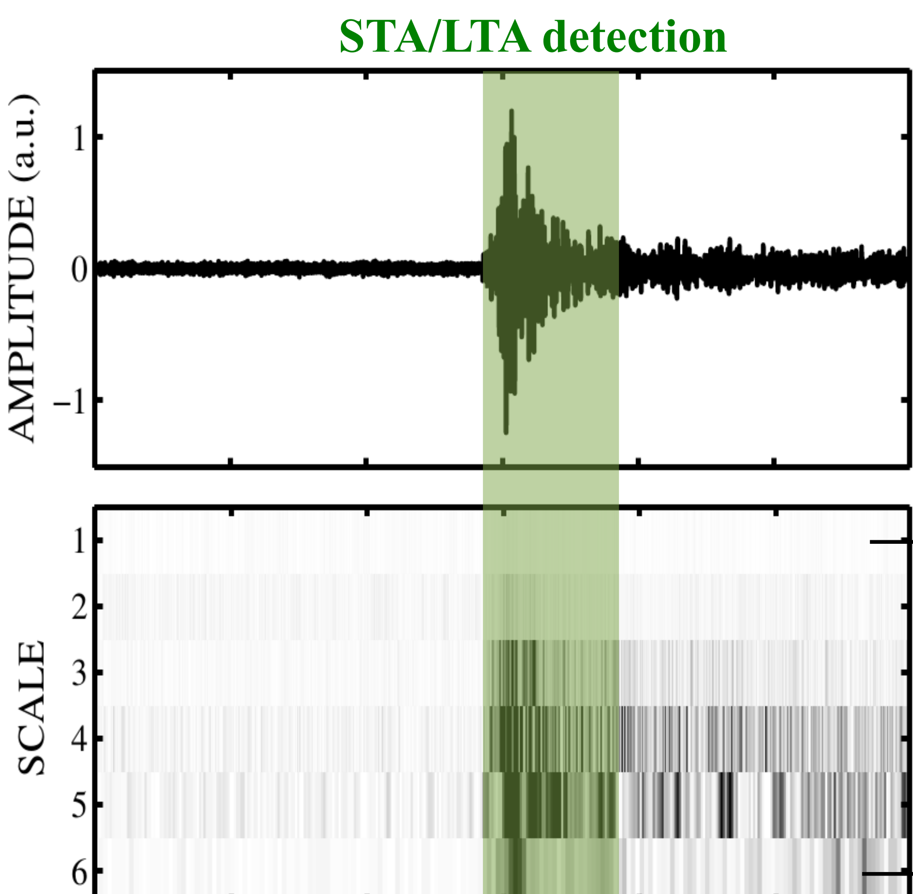
SCALE	FREQUENCY BAND (Hz)
1	10-20
2	5 - 10
3	2.5 - 5
4	1.25 – 2.5
5	0.6 – 1.25
6	0.3 – 0.6

Signal discrimination algorithm

STATISTICAL APPROACH

Compare signal's POWER DISTRIBUTION among wavelet scales with a STATISTICAL MODEL for signals of given origin → Discrimination criterion *C* (measure of probability for a signal to belong to the model)

POWER DISTRIBUTION



Scale averages

$$S_1 = \frac{1}{N_1} \sum_{i=1}^{N_1} \left| w_i^{(1)} \right|$$

...

$$S_K = \frac{1}{N_K} \sum_{i=1}^{N_K} \left| w_i^{(K)} \right|$$

Norm L_1

$$/ \sum_{i=1}^{K} S_i$$

RELATIVE POWER DISTRIBUTION

$\tilde{S}_1$

...

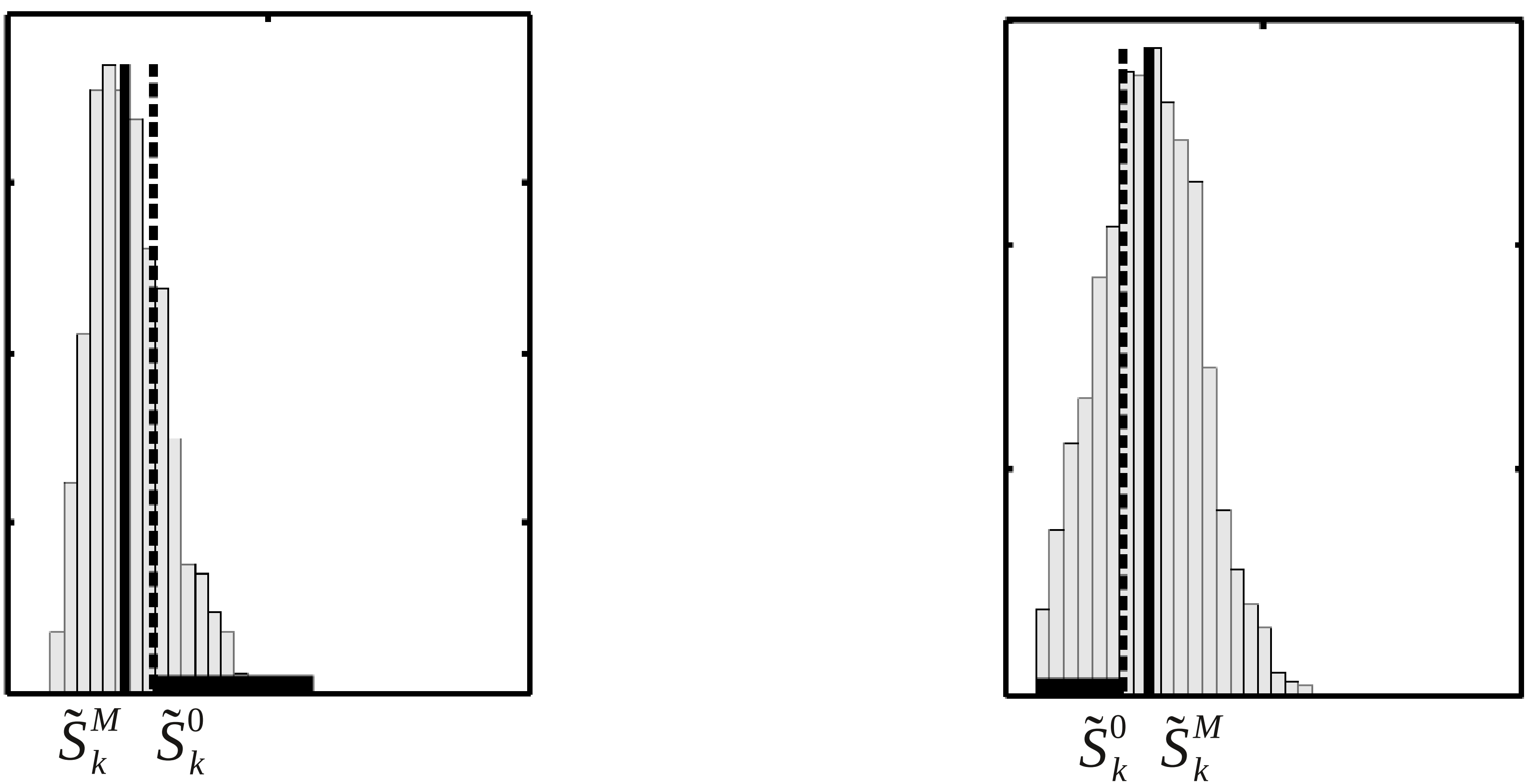
$\tilde{S}_K$

Signal discrimination algorithm

Comparison of signal's scale averages $\tilde{S}_1^0, \ldots, \tilde{S}_K^0$ with the statistical model:

- find proportion p_k of the model's $\tilde{S}_k$ values more extreme than the corresponding signal's value $\tilde{S}_k^0$
  (as a **reference point** we are using **median of the distribution** $\tilde{S}_k^M$)

$\tilde{S}_k > \tilde{S}_k^0$ (when $\tilde{S}_k^0 > \tilde{S}_k^M$) $\tilde{S}_k < \tilde{S}_k^0$ (when $\tilde{S}_k^0 < \tilde{S}_k^M$)



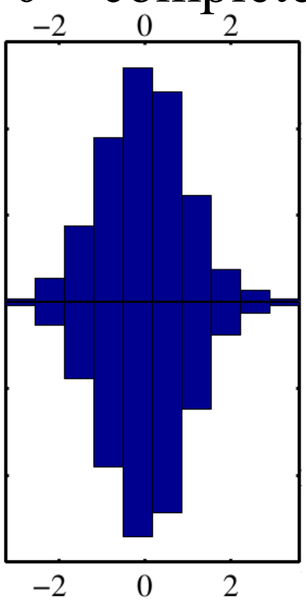
Signal discrimination algorithm

All proportions are combined in a weighted average to get a single discrimination criterion C :

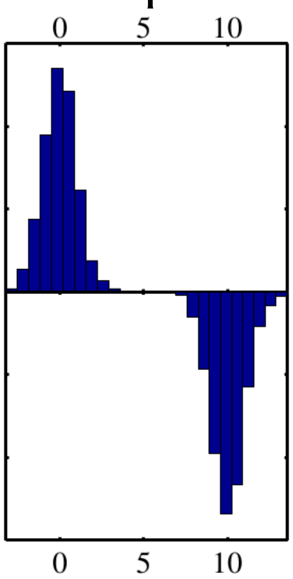
$$C = \sum_k D_k p_k / \sum_k D_k$$

Weights D_k are Kolmogorov-Smirnov statistics. For any two distributions Kolmogorov-Smirnov test gives:

$D = 0$ – complete match



$D = 1$ – complete mismatch

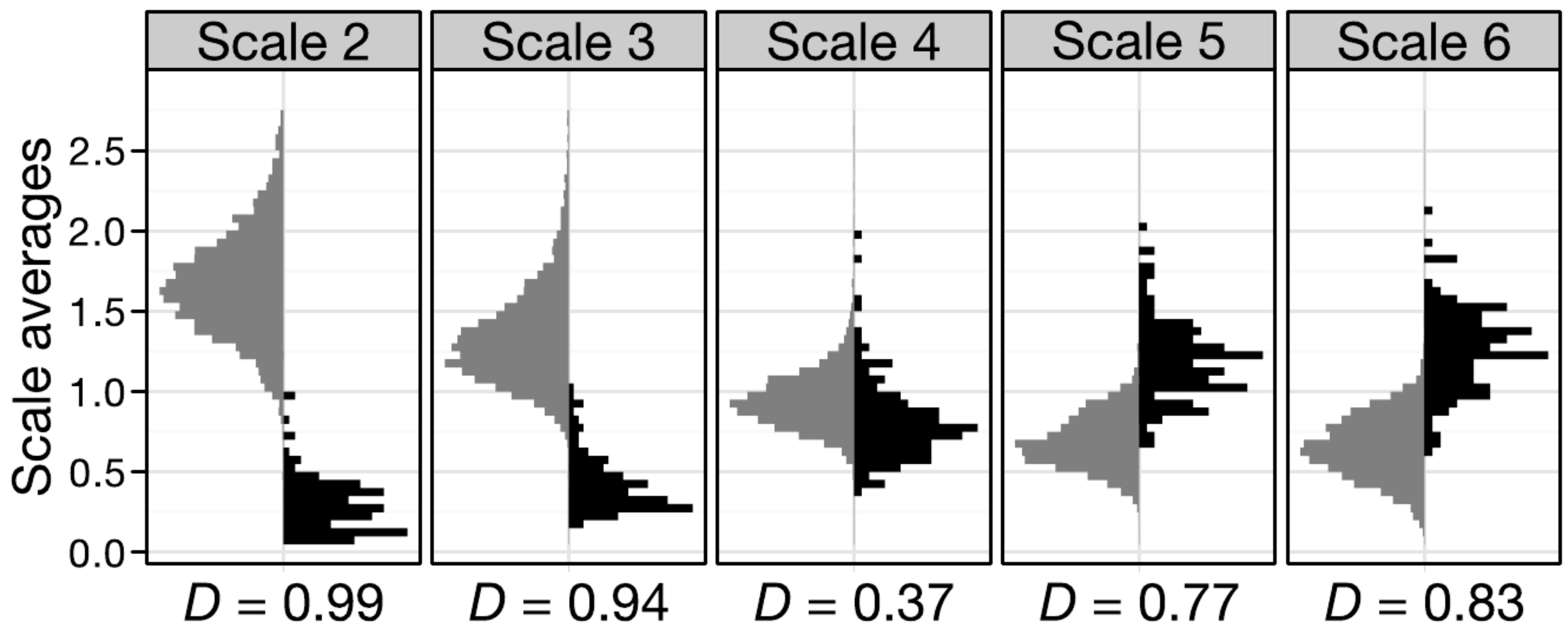


Signal discrimination algorithm

All proportions are combined in a weighted average to get a single discrimination criterion C :

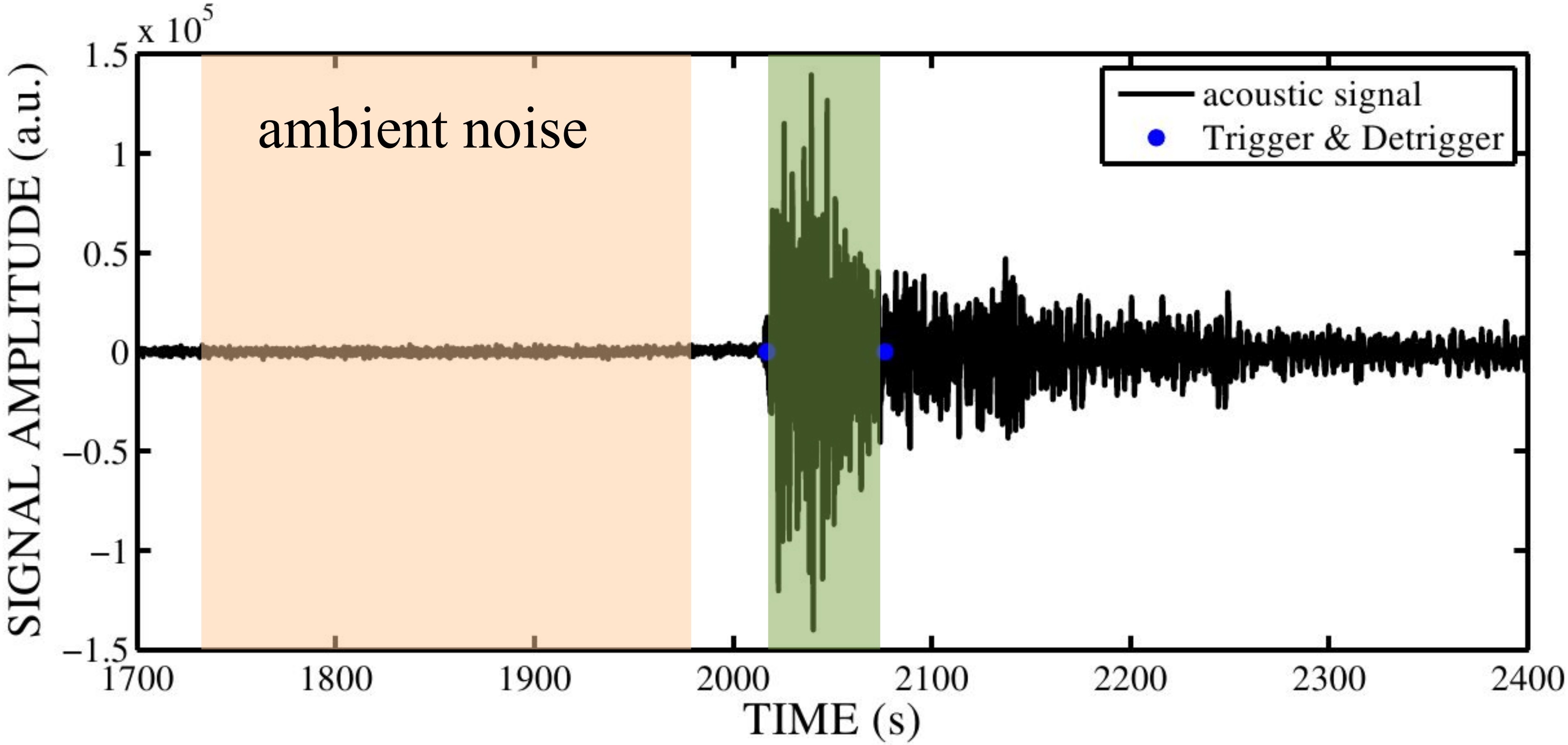
$$C = \sum_k D_k p_k / \sum_k D_k$$

- as we are interested in P waves, weights D_k are obtained by comparing distributions of a P wave model (black) with the distributions of **ALL OTHER** signals (gray) combined



Signal-to-noise ratio (*SNR*)

In addition to *C* we calculate *SNR* of a detected signal defined as ratio of DWT coefficients of the signal and the ambient noise preceding the signal :



$W_1^{(n)}, \dots, W_K^{(n)}$

$W_1^{(s)}, \dots, W_K^{(s)}$

$$SNR = \frac{\sum_{k=1}^{K} W_k^{(s)}}{\sum_{k=1}^{K} W_k^{(n)}}$$

SNR is used as an **ADDITIONAL DISCRIMINATION CRITERION**