15 years of acoustic detection studies at INFN

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8th international workshop on Acoustic and Radio EeV Neutrino Detection Activities

Underwater acoustics at INFN

The interest in underwater acoustics at INFN began in the early 2000's

Goals:

- development of an acoustic positioning system for a km3-scale Cherenkov neutrino telescope

- measurement of the underwater background noise in the Mediterranean Sea taking advantages of the underwater infrastructures already deployed for the NEMO (NEutrino Mediterranean Observatory) project.

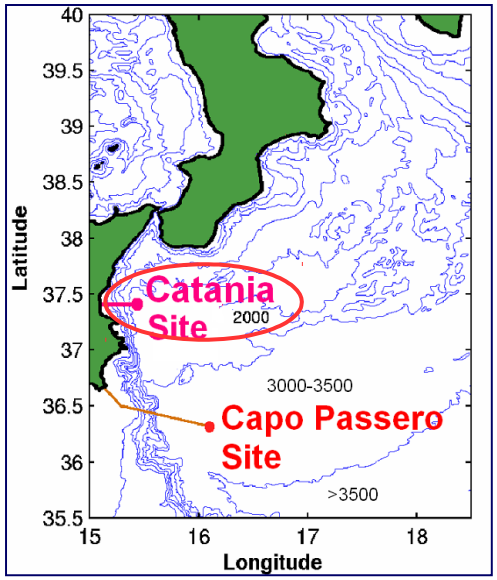
Scenario in the early 2000's:

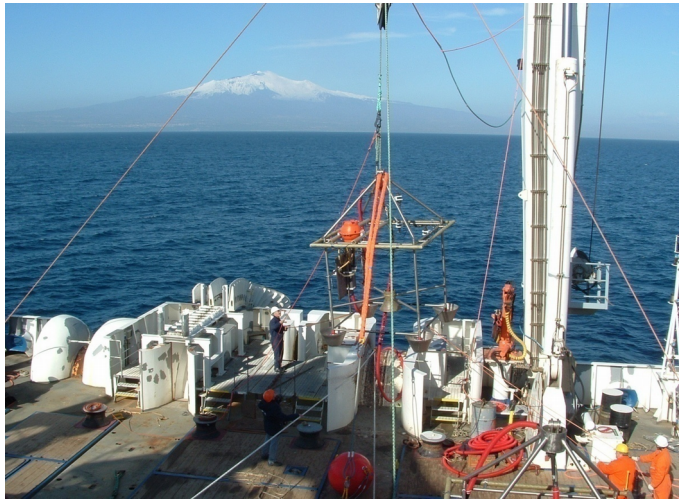
- Noise well characterized at surface by military studies

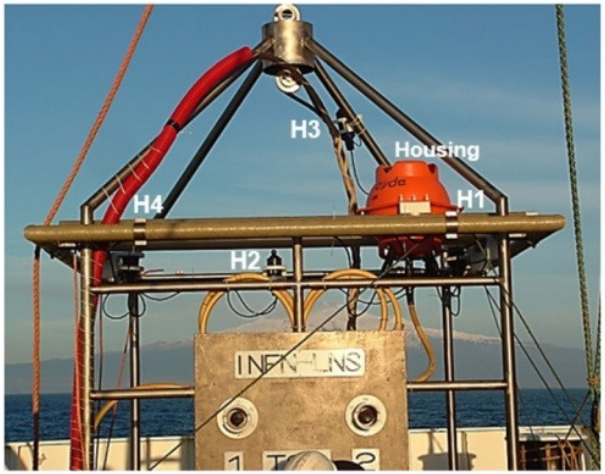
- Very few data in deep sea

NEMO-OνDE: Ocean Noise Detection Experiment

NEMO- OνDE was the first experiment to perform long-term measurement and monitoring of the acoustic background @2100 m depth







- Tetrahedral acoustic antenna (1m size):
  - 4 large bandwidth hydrophones
  - Low cost professional audio electronics
- Located 25 km off Catania (2100 m)
- All data to shore through a 25km long electro-optical cable
- In operation from January 2005 to November 2006

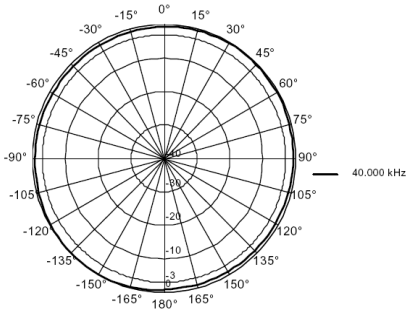
Istituto Nazionale di Fisica Nucleare

NEMO-OνDE: acoustic sensors

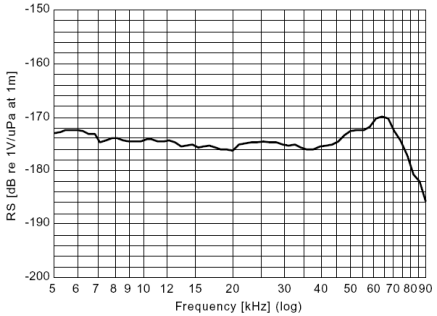
- 4 Reson TC4042 hydrophones (special production for 2500 m depth)
- Individually calibrated (receiving sensitivity from 5 kHz to 90 kHz, directivity)
- Low electronic noise
- Hydrophone pre-amplifier hosted in a pressure resistant aluminum vessel

Reson TC4042 hydrophone

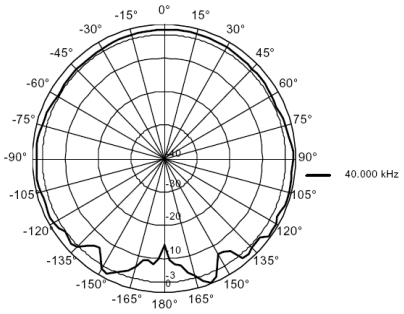
Horizontal directivity pattern



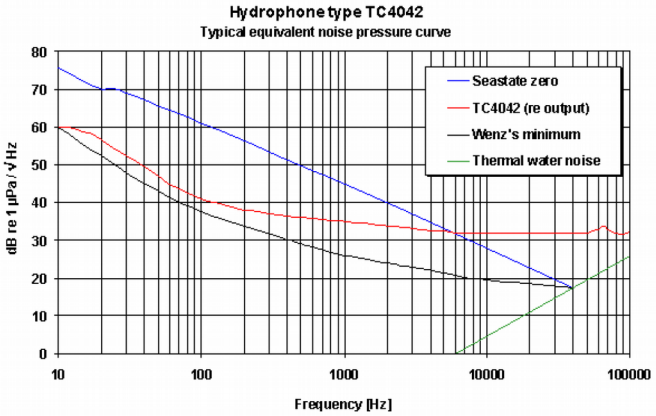
Receiving sensitivity



Vertical directivity pattern



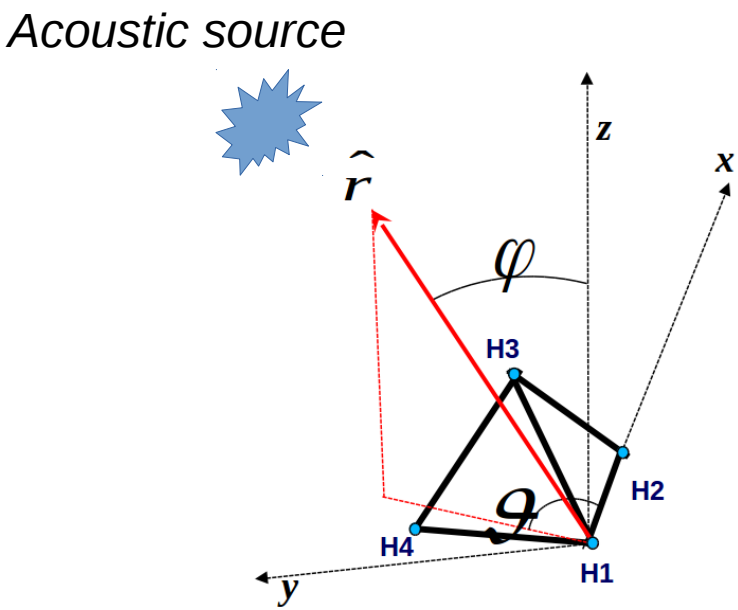
Impedance



Documentation:
Individually calibration curves:
Sensitivity at ref.: frequency: 250 Hz

NEMO-OνDE data acquisition system

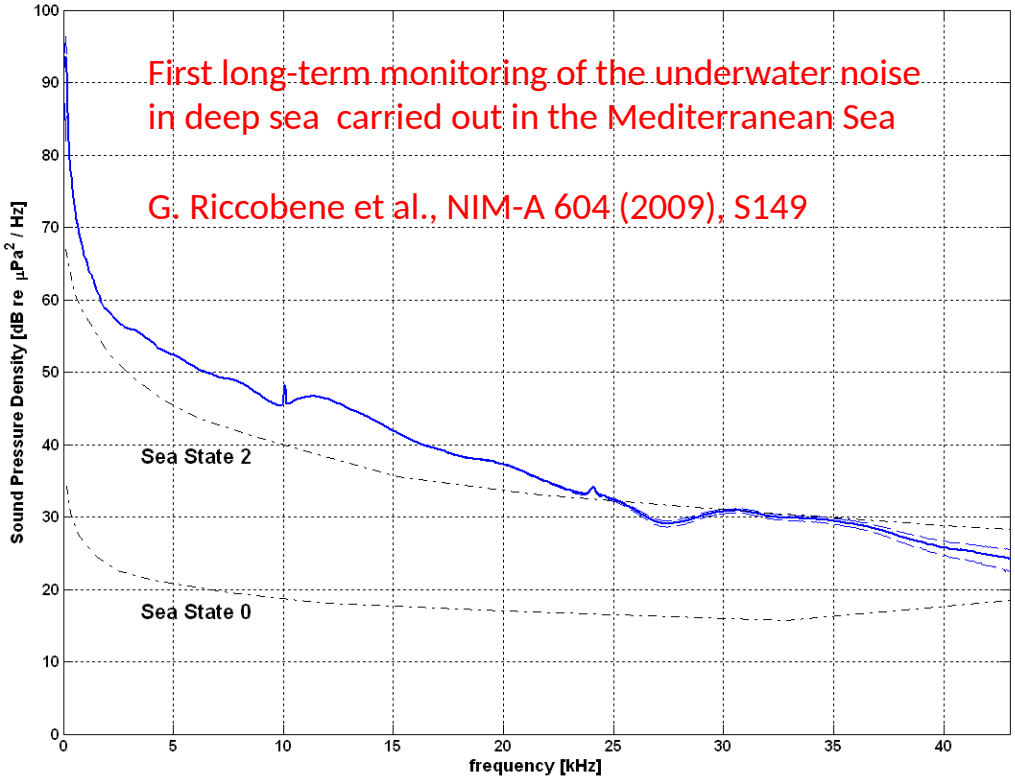
- Analog acoustic signal digitized off-shore. Low cost professional audio electronics
- 4 channel audio ADC system (96 kHz, 24 bit sampling, ΔΣ). Low noise electronics.
- Synchronous acoustic array → tracking of high frequency acoustic sources (Difference Time of Arrival technique)



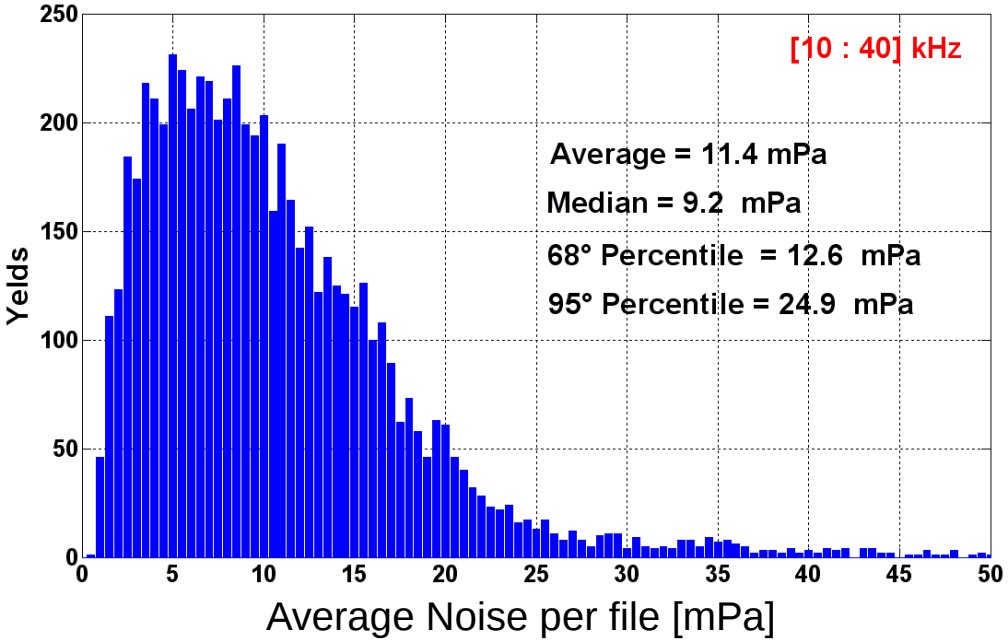
- All acquired data continuously transmitted to shore on optical fibers
- Duty cycle recording : 5 min/per hours from all hydrophones

NEMO-OνDE: background noise monitoring

Study of acoustic background levels and their variation as a function of time (due to weather, seismic, biological and anthropogenic sources)

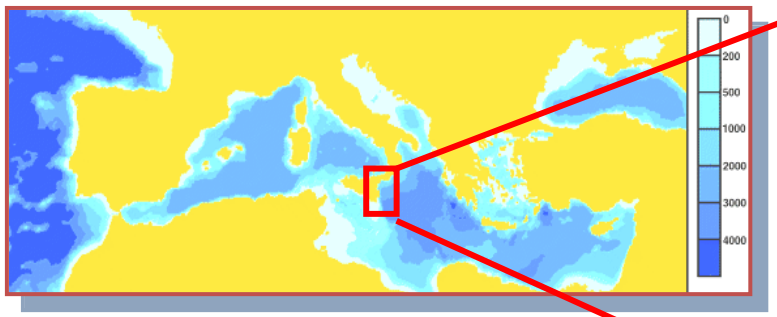


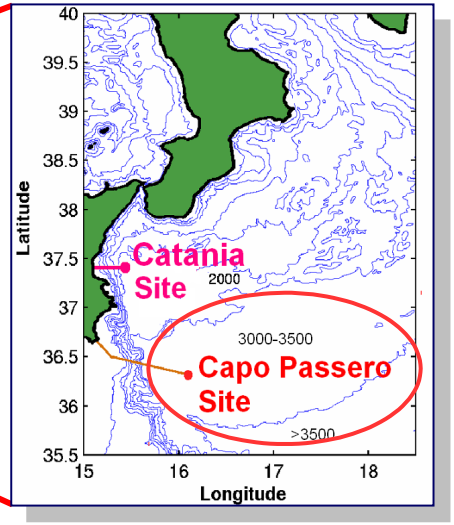
The average SPD is close to SS2, with increase at low frequency due to diffuse anthropogenic noise.
Peaks are due to pingers and shipping instrumentation continuously present in the area.



SMO – Submarine Multidisciplinary Observatory

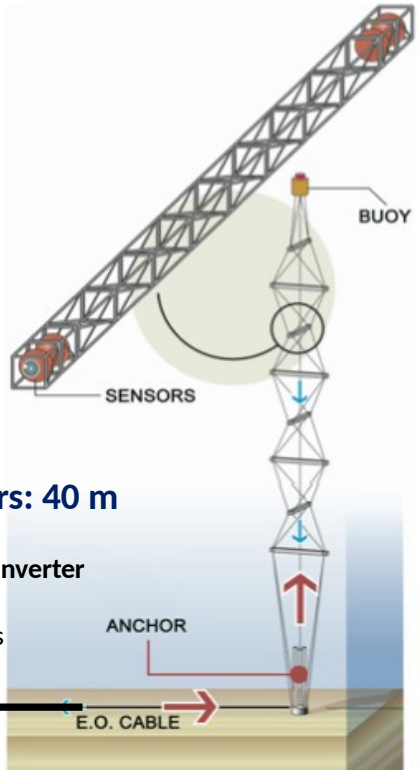
In 2013 in the framework of SMO (Submarine Multidisciplinary Observatory) project a 3D array of 14 large bandwidth acoustic sensors has been installed on board the Cherenkov neutrino detector prototype NEMO – Phase II,
SMO antenna was deployed at depth of 3500 m, about 100 km off-shore South-East Sicily.





NEMO-Phase II instrumentation:

- **32 optical modules (4 OMs/floor)**
- **14 acoustic sensors (SMO)**
- **environmental sensors (compasses, 2 CTDs , Current-meter, C-Star)**
- **3 acoustic beacon (at tower-base & at a distance of 400 m from the tower) for positioning**



Floor length: 8 m
Distance between floors: 40 m

DC/DC Medium Voltage Converter
max 10 kVDC /375 VDC
3 ROV mateable connectors

MVC

Electro-optical cable (100 km)
(20 fibres, 1 conductor 100 kW , sea return)

SMO goals

- **Deep-sea test of a novel acoustic positioning system for a km^3-scale underwater neutrino telescope**

- **Long term and real-time monitoring of high frequency acoustic background at different depths**

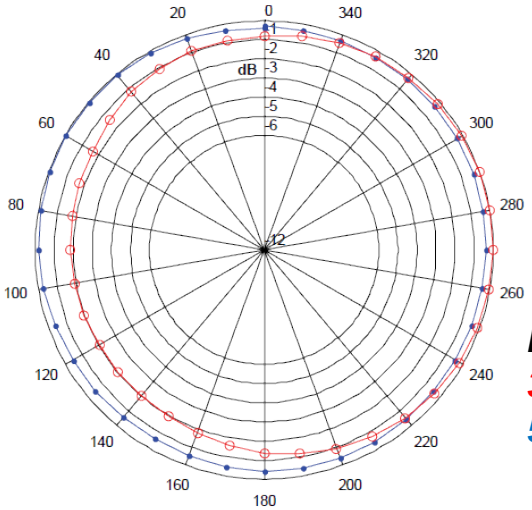
- **Development of new technologies for the detection of high energy particle interactions in water**

SMO: hydrophones

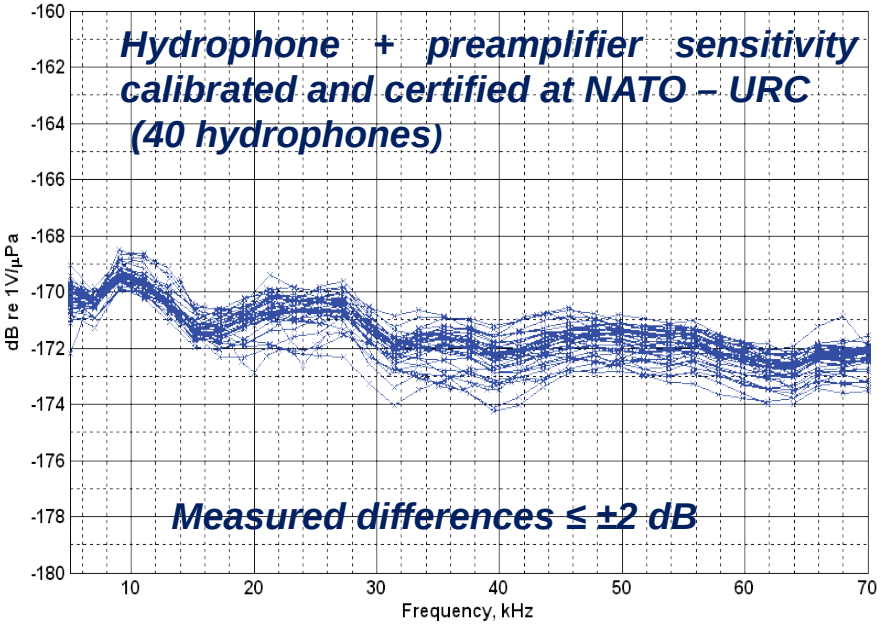
INFN and the italian company SMID have developed for SMO project a low cost hydrophone for 4000 m depth, with no change of sensitivity as a function of depth.

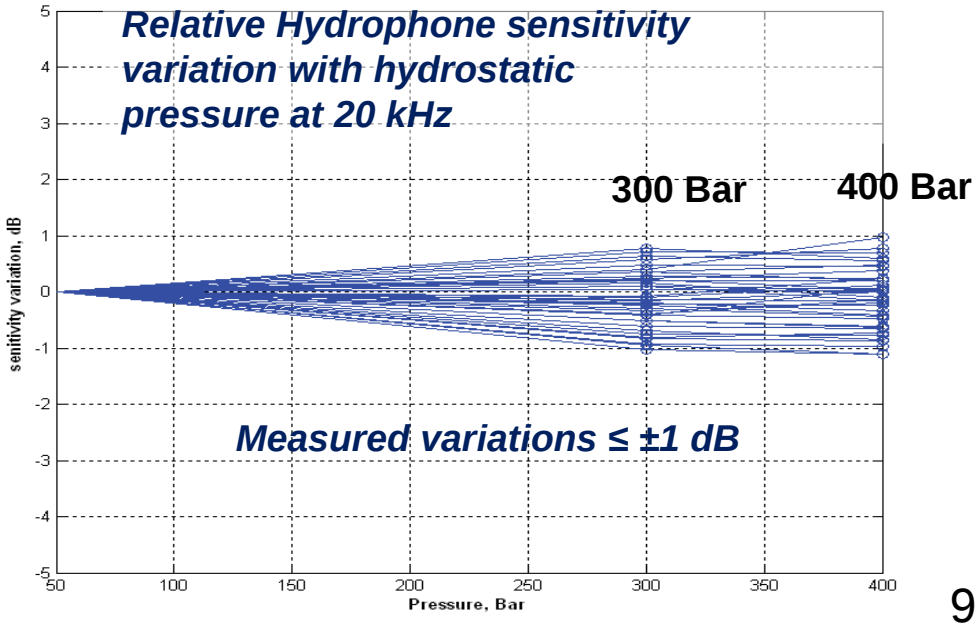
NATO has developed for/with INFN a standard procedure for calibration under pressure

Hydrophone + preamplifier moulded in deep sea cable 7.5 m length



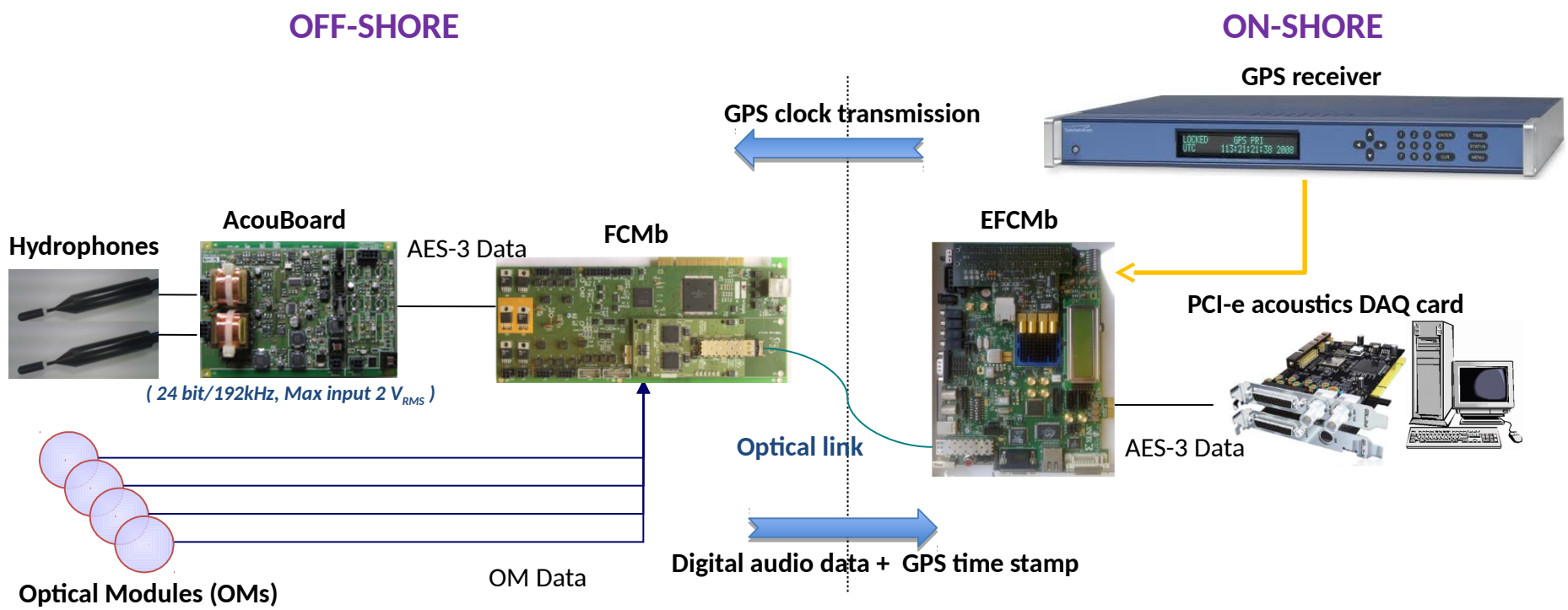
Radiation lobe
30 kHz
50 kHz





SMO: data acquisition system

The hydrophones data acquisition chain is based on "all data to shore" philosophy, raw data are continuously transmitted to shore on a local internet network.



The acoustic signals are sampled by AcouBoard and "labeled" with GPS time by Floor Control Module board (FCMb) off -shore

Optical and Acoustic array synchronous and phased with the GPS time distributed from shore

SMO data acquisition architecture applied for the KM3NeT acoustic positioning system

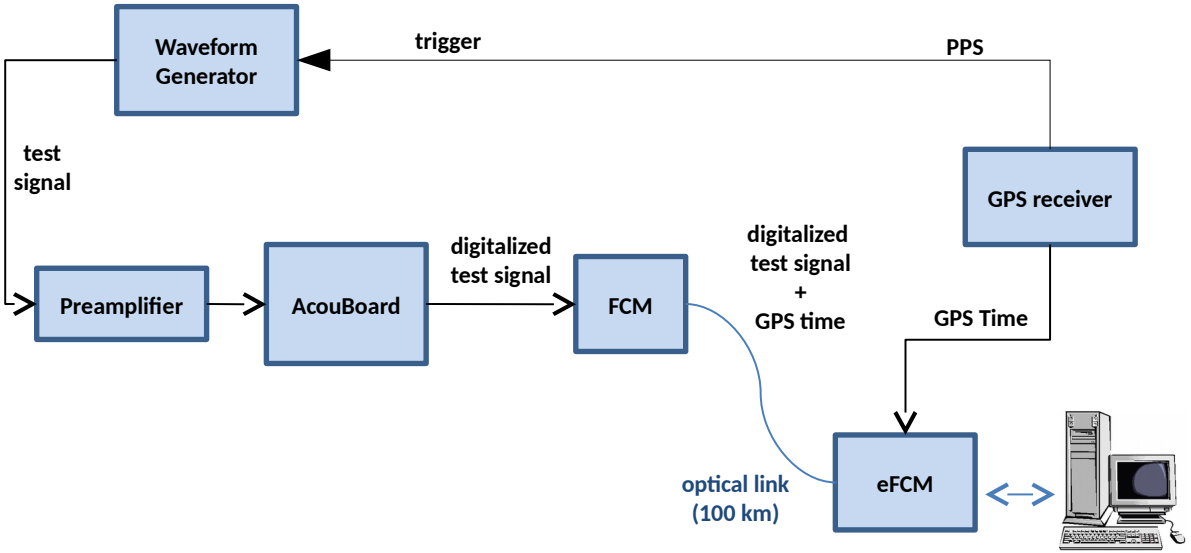
SMO: time calibration

The accuracy on the time stamping of acoustic signals depends on the accuracy of the latency time measurements of the whole data acquisition system

- **Electronics latency**

  PPS-triggered test signals as input of hydrophone preamplifiers.

- Test signal emission and acoustic DAQ driven by the same Master Clock → **Measurement error ~200 ns**



- **Data transmission delay**
  Different optical link length for each acquistion channel.
  Based on the measurement of the travel time of a data frame sent by the eFCMB (on-shore) to go forth and back over the optical link to the corresponding FCMB off-shore → **Measurement error: ~ns**

- **Hydrophone's ceramics latency**

  Measurements in water pool by using a calibrated projector triggered by the PPS signal of the GPS receiver

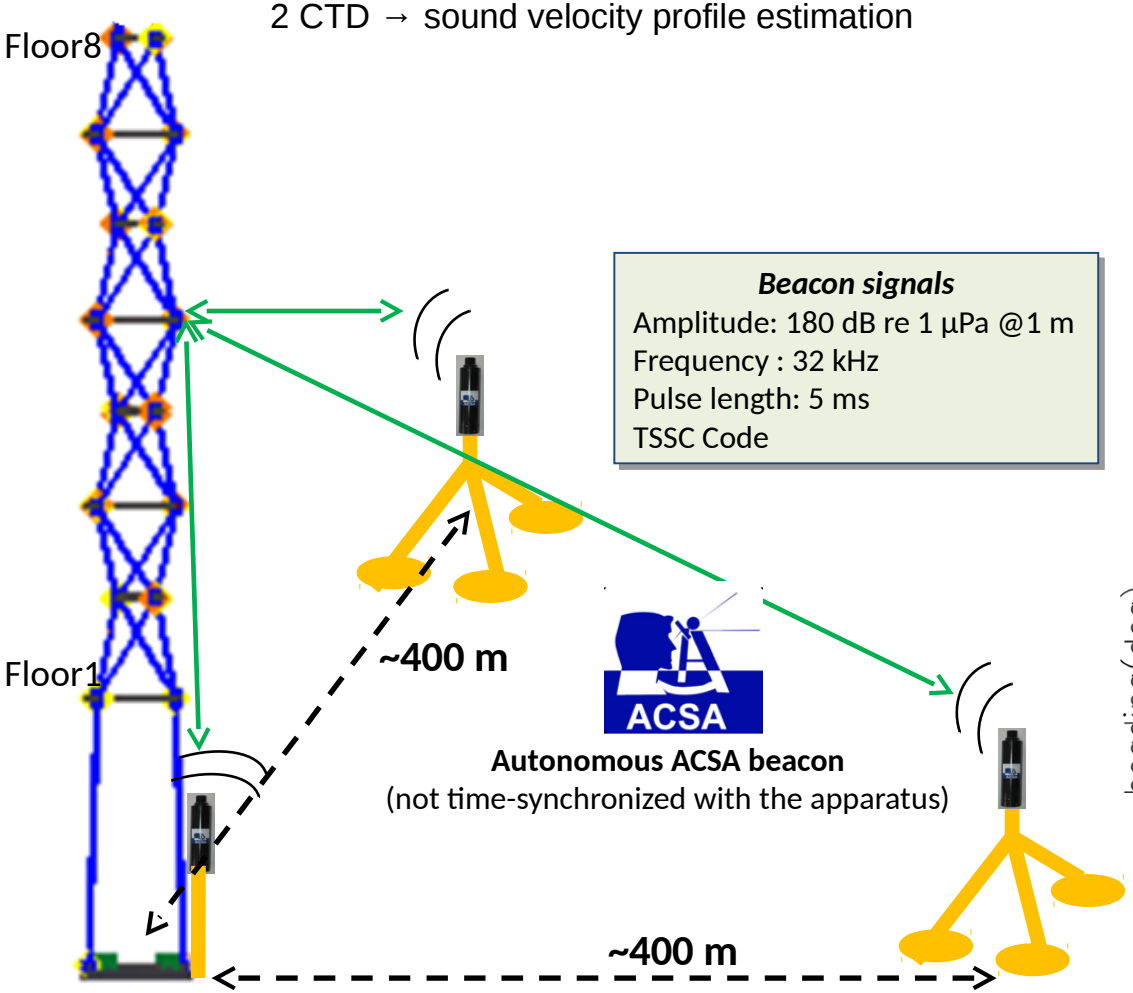
  Evaluation of the cumulative ceramics response time (emitter + receiver) as a function of the amplitude and the frequency of the acoustic signal → **upper limit 25 μs**

SMO results: positioning system

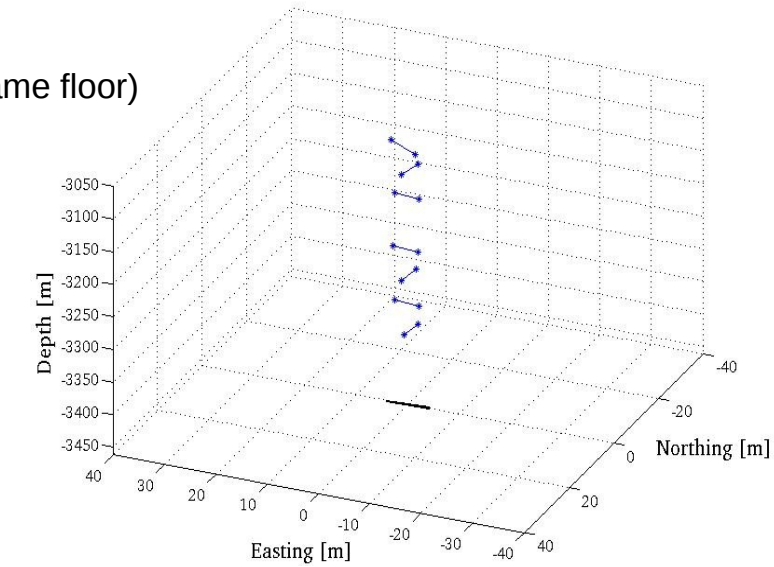
One of the main tasks of the SMO antenna was to provide a positioning system for NEMO Phase-II detector

NEMO Phase-II acoustic positioning system

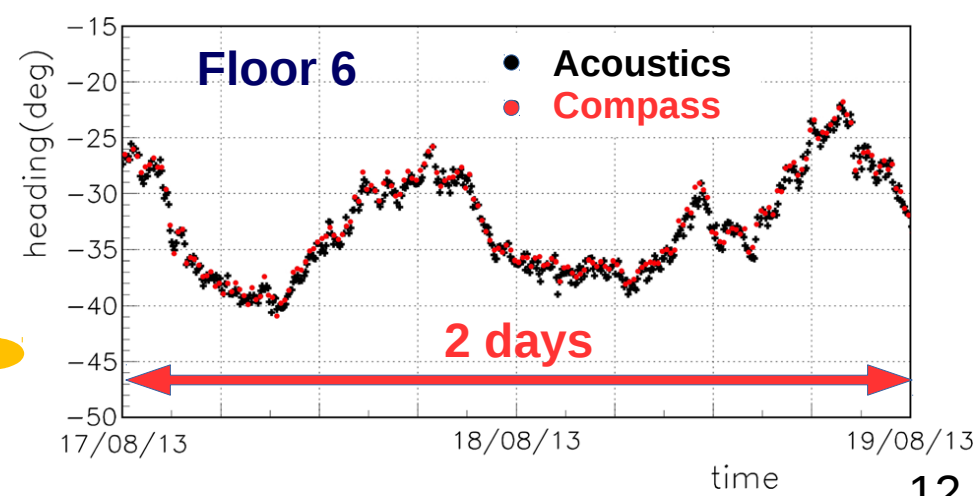
14 acoustic sensors (fixed distance between sensors on the same floor)
3 autonomous acoustic emitters
2 CTD → sound velocity profile estimation



Beacon signals
Amplitude: 180 dB re 1 µPa @1 m
Frequency : 32 kHz
Pulse length: 5 ms
TSSC Code



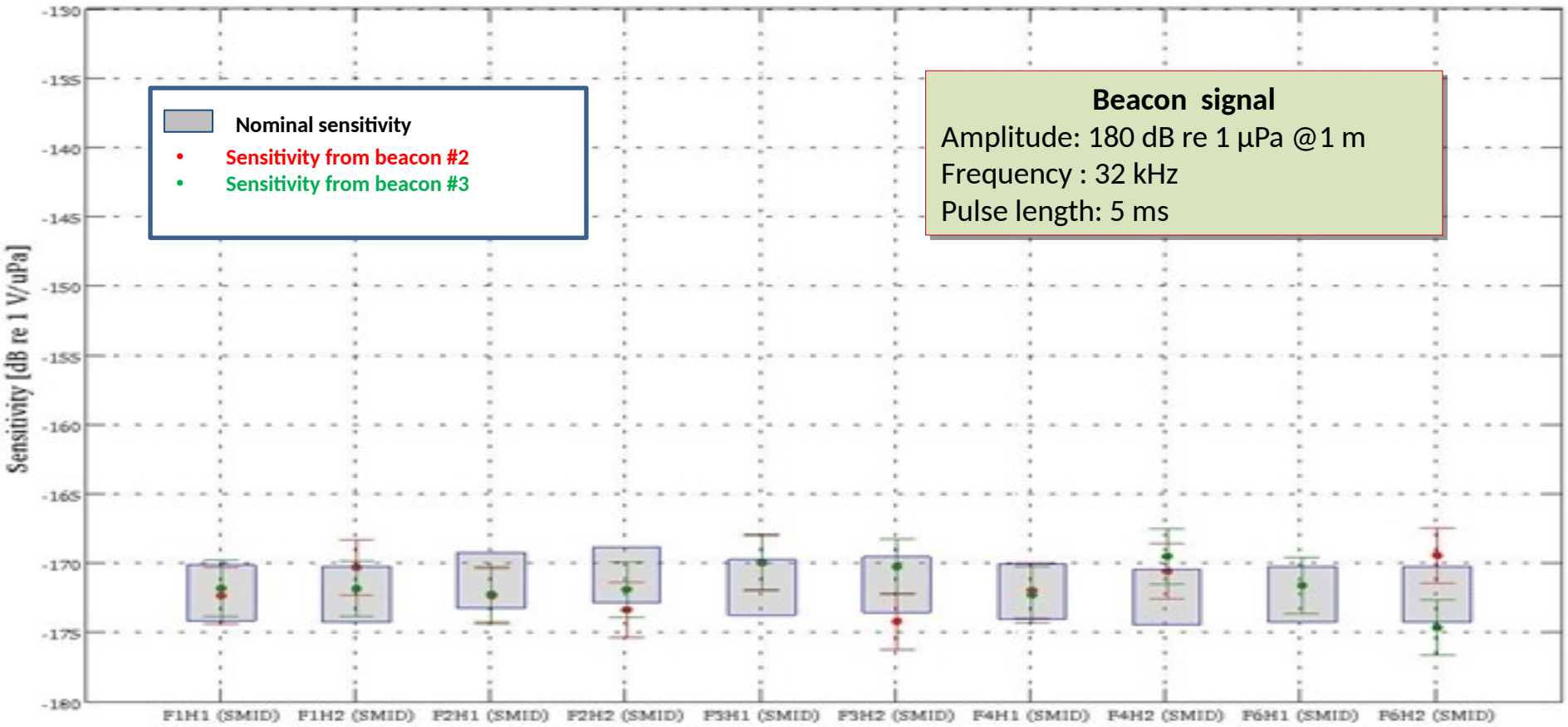
Good agreement with compass measurements



SMO results: sensitivity at high pressure

Acoustic signals at 32 kHz from external beacons (about 400 m far from tower base) confirmed the nominal sensitivity of SMO hydrophones at 3500m .

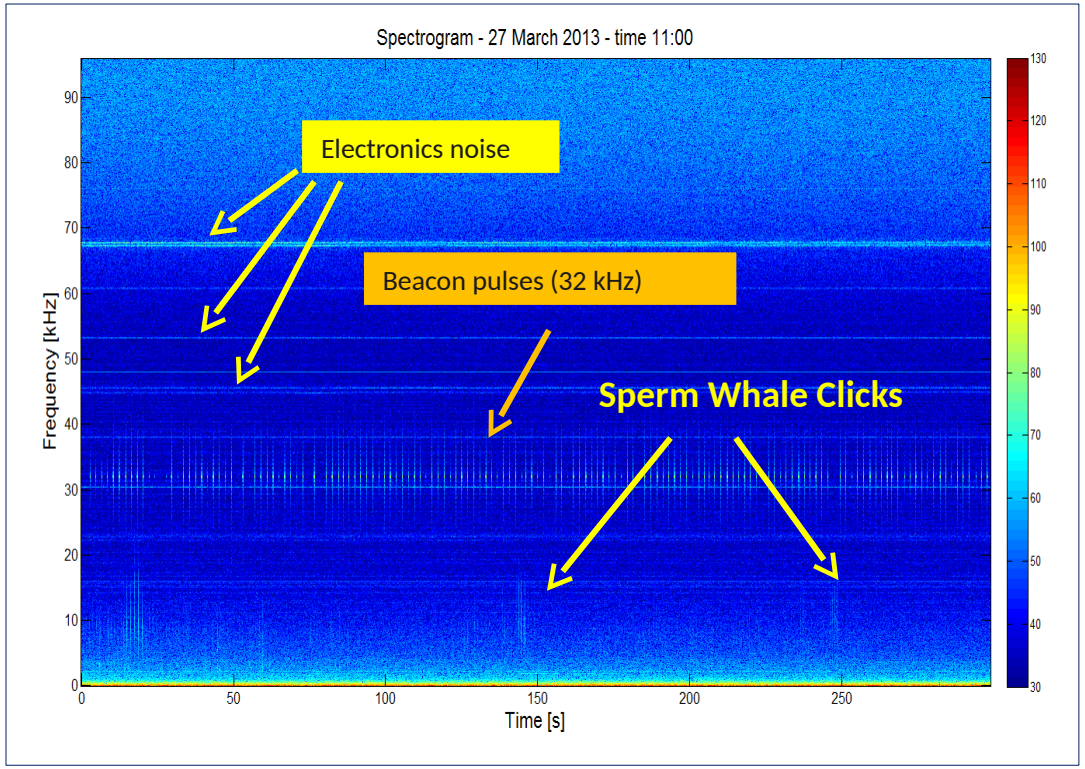
Sensitivity has been calculated taking into account the geometrical attenuation and absorption related to the ionic relaxation of $MgSO_4$ and $B(OH)_3$.



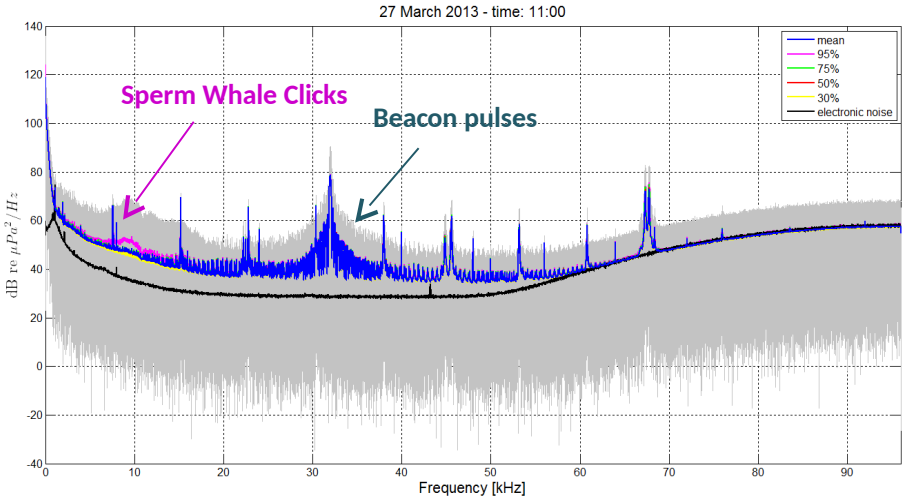
SMO: acoustic monitoring in deep sea

5 minutes of unbiased raw data from each sensor have been stored on a digital library

Monitoring of impulsive and continuous acoustic signals in a very large frequency bandwidth (up to 96 kHz) in the KM3NET - ARCA site (3500 m depth)

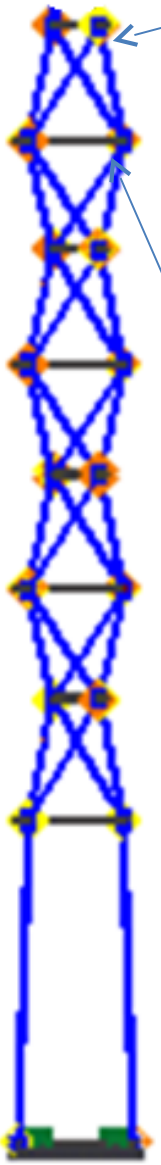


Power Spectral Density (NFFT= 65536) is calculated every 34 ms time-slice for each 5 minutes recording (grey area). The average value and percentiles are stored.

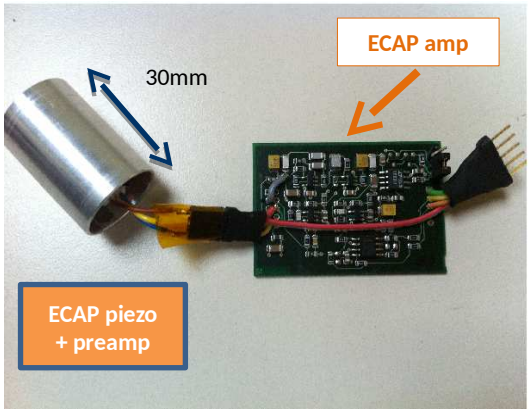


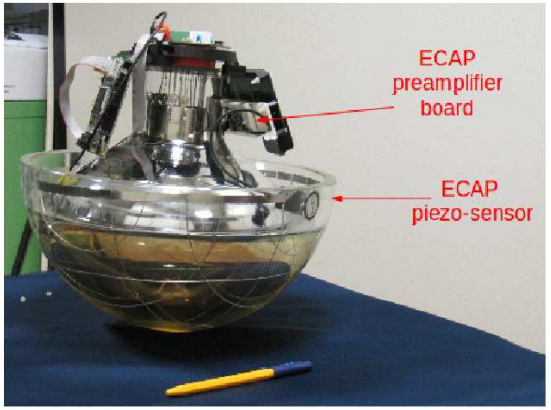
Acoustic background monitoring from February 2013 to July 2015

SMO: test bench for KM3NeT sensors



Floor #8
Piezo sensor + preamplifier developed by ECAP for KM3NeT positioning system



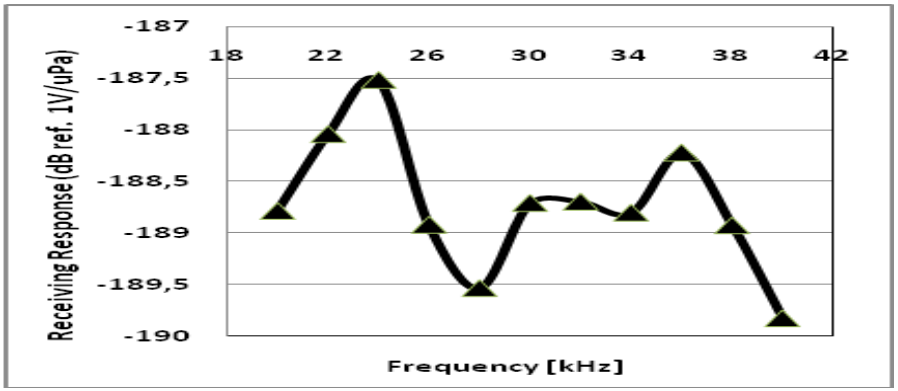


ECAP ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Technology applied for KM3NeT acoustic positioning system

Floor #7
FFR (Free Flooded Rings) transducer used in KM3NeT LBL emitter

Sensor Technology STD
FFR - SX30



UNIVERSITAT POLITÈCNICA DE VALÈNCIA

IGIC Instituto de investigación para la gestión integrada de zonas costeras

SMO-OνDE2

The same technology developed for the acoustic antenna installed on NEMO Phase-II detector has been applied for the SMO-ONDE2 antenna, installed in 2012 at the ONDE location.

Deployed in 2012

Fully operational since February 2017

4 calibrated large bandwidth hydrophones

2 synchronized stereo ADCs (192 kHz/24 bits)

Power supply: 320 VDC

Power consumption: < 17 W

SMO-OνDE2: Background noise analysis

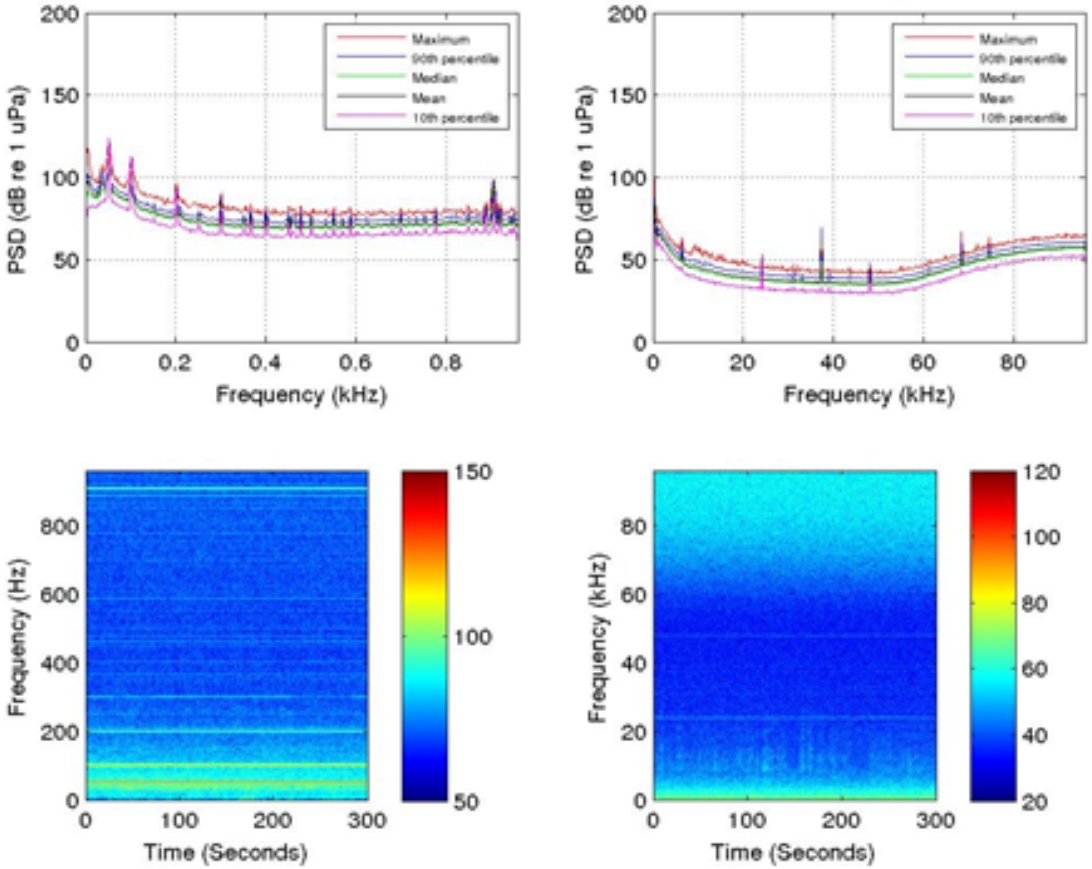
- **UNBIASED RAW DATA SAVED AND STORED @ INFN SERVERS**
  Duty cycle 5 min/hour
  Sampling frequency 192 kHz

- **ON-LINE NOISE ANALYSIS**

1. Power Spectral Density is calculated every second.

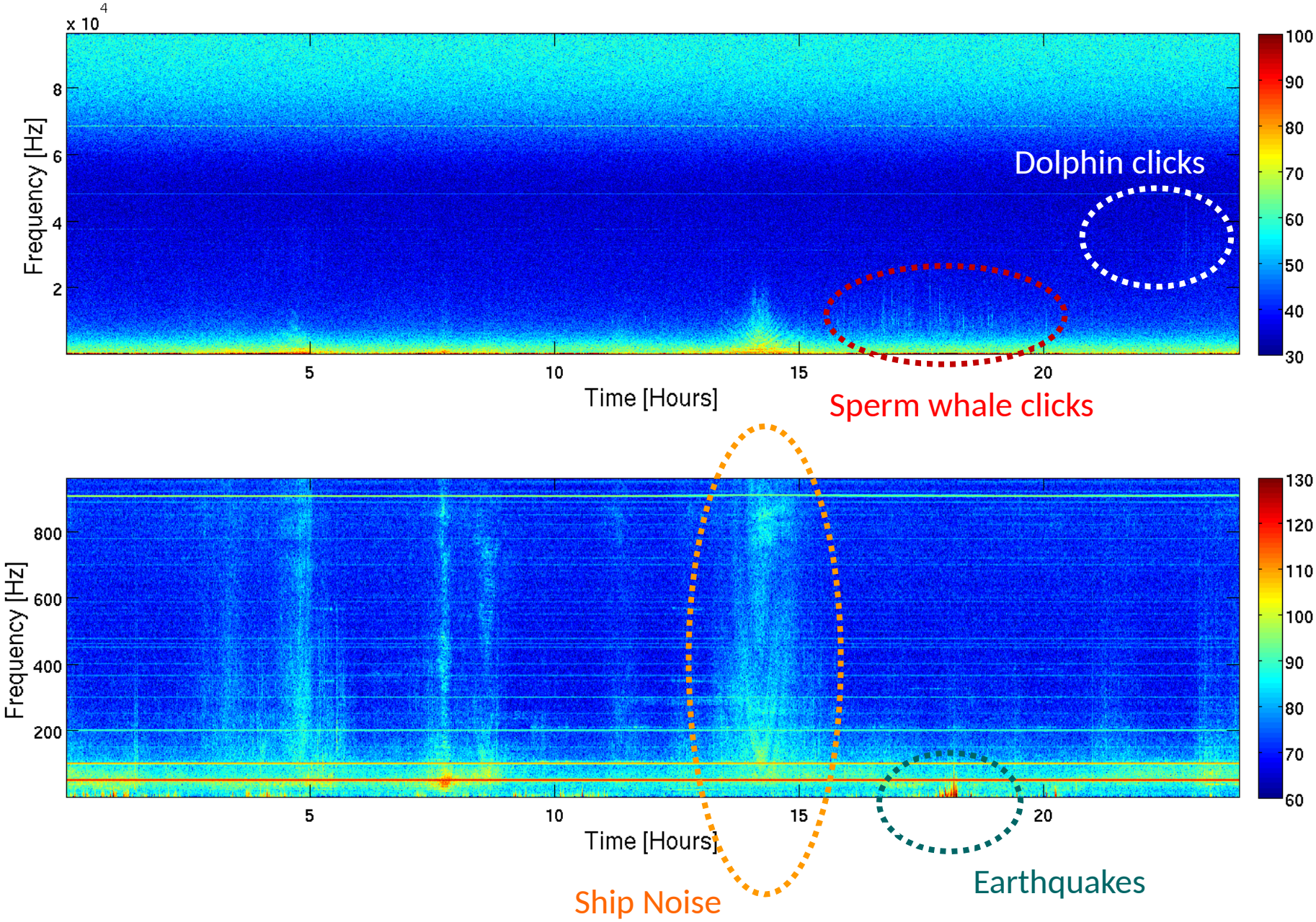
2. Maximum, 90th percentile, 50th percentile, mean values , 10th percentile are computed for each frequency bin in 5 min long windows.

3. Spectrogram, percentiles values and jpeg images related to 5 minutes long acquisitions are continuously stored in a digital library



SMO-OνDE2: on-line noise analisys

Daily spectrograms are computed every day for a fast visualization of the underwater soundscape



Monitoring of underwater transient signals

Biological sounds (dolphin and sperm whale echolocation clicks) and anthropogenic noises (ship cavitation,sonars, pingers, …) represent a background for acoustic neutrino signals.

Lack of information on transient signals in deep sea.

Collaboration with different scientific communities (biology, geology, ocenography,…) for a systematic study of the underwater transient noises

These multidisciplinary studies have been conducted in collaboration with prestigious National and International Research Institutes

Consiglio Nazionale delle Ricerche

OGS

Università degli Studi di Messina

CIBRA

UNIVERSITÀ degli STUDI di CATANIA

ENEA
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

CoNISMa
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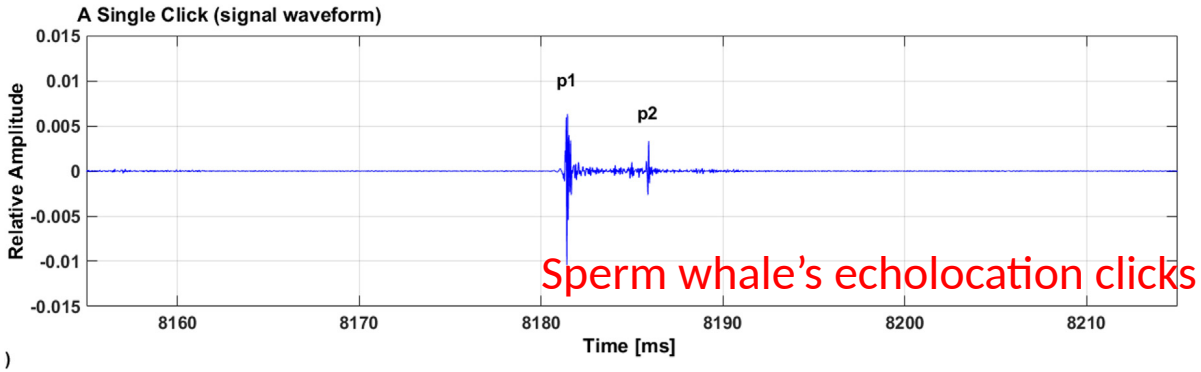
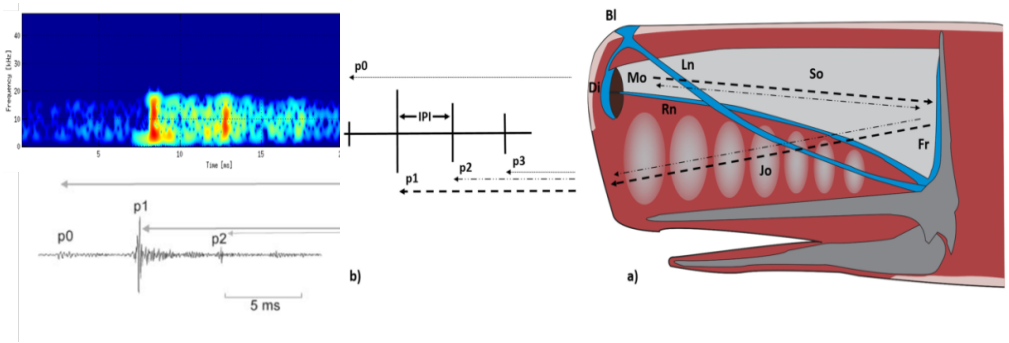
Sperm whale clicks

One of the most frequent transient signals found in INFN recordings is the sperm whale echolocation click





p0 – p1 = Varies according to the recording geometry

p1 – p2; p2 – p3 = Stable → **"Nominal IPI (Inter Pulse Interval)"** [from 2 to 10 ms]

Analysis of sperm clicks in ONDE data → Paper on size distribution of sperm whale population in the Ionian Sea

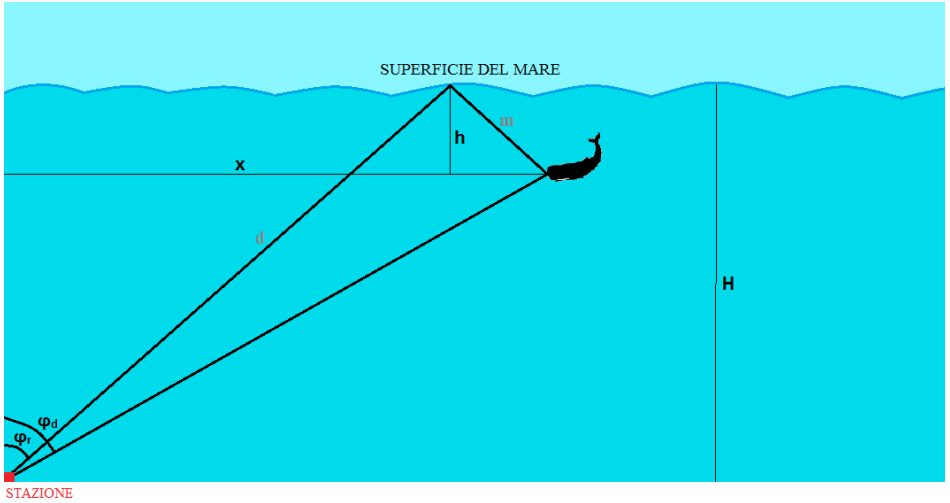
F. Caruso, V. Sciacca et al. (2015) **Size Distribution of Sperm Whales Acoustically Identified During Long Term Deep-Sea Monitoring in the Ionian Sea**. PLoS ONE 10(12): e0144503. doi:10.1371/journal.pone.0144503

Acoustic tracking of sperm whales

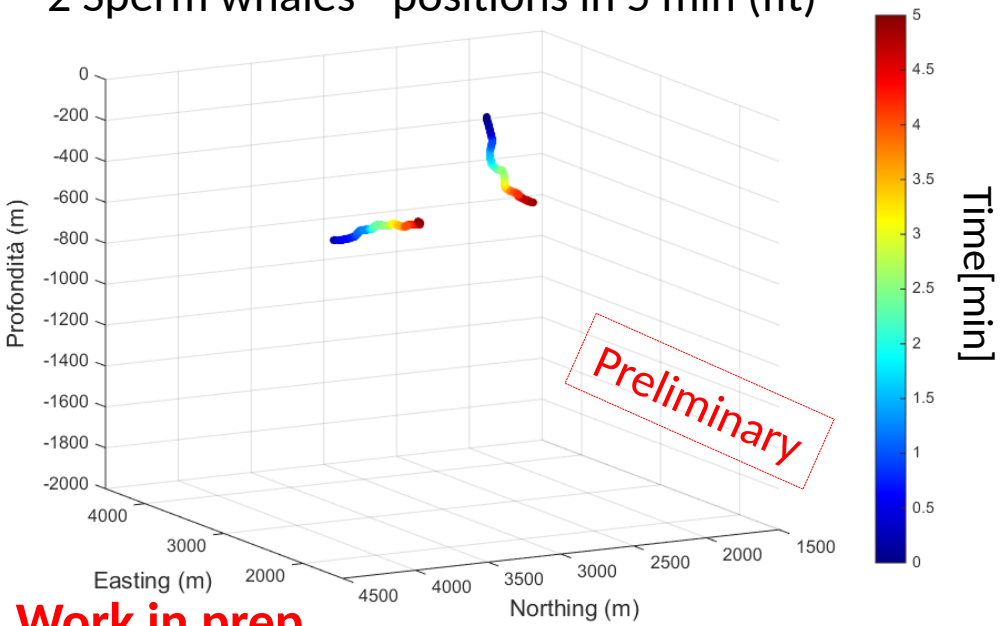
The study of sperm whales clicks allowed us to improve acoustic localization techniques

A tracking algorithm has been developed on purpose. It consists of three main steps:

1. Recognition of the sperm whale clicks (and their reflections on the sea surface);
2. Calculation of the arrival directions though methods based on DTOA (Time Difference of Arrival)
3. Use of the arrival directions of the direct and reflected waves to estimate the depth and *3-D localization of the animal.*



2 Sperm whales - positions in 5 min (fit)



Work in prep.

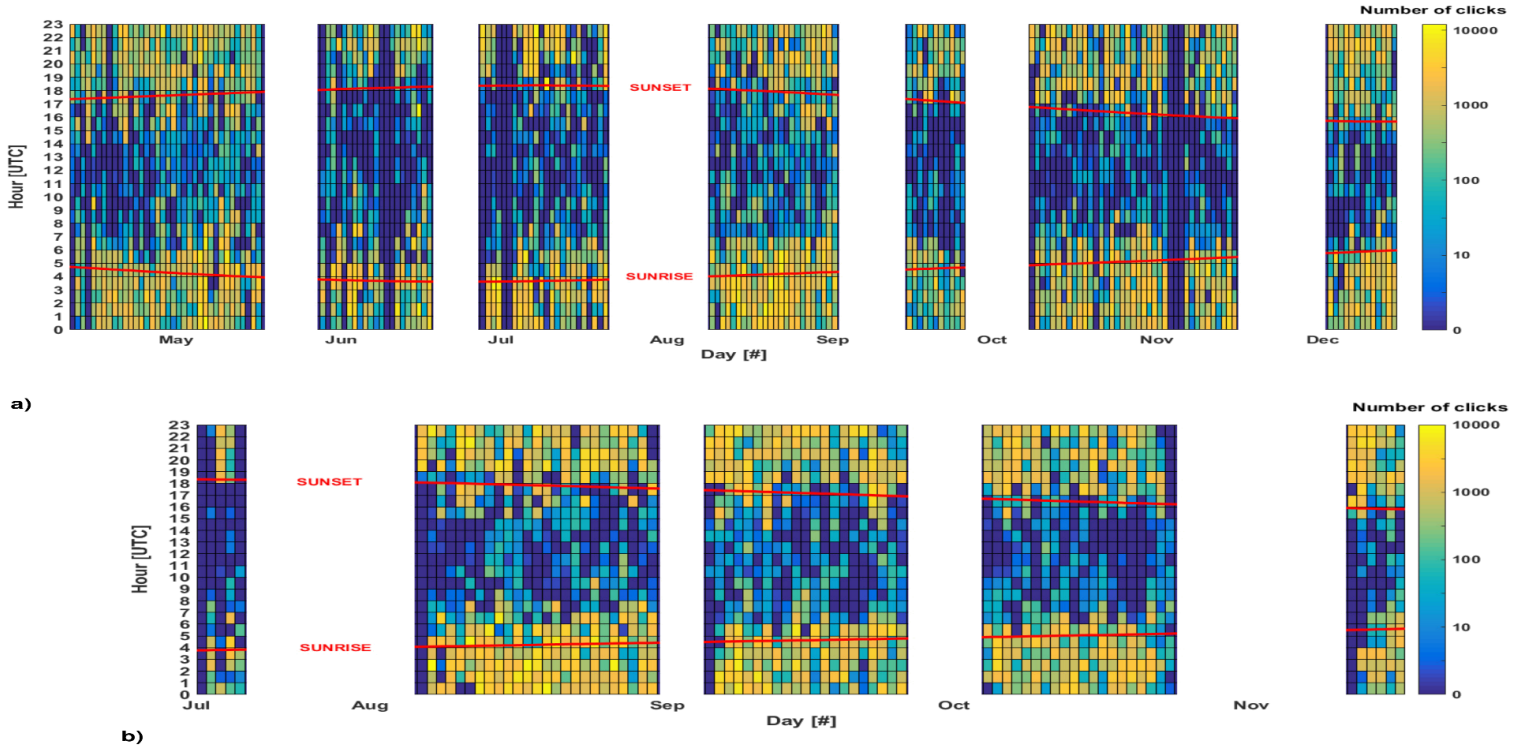
Dolphins echolocation clicks

Dolphins clicks represent an almost continuous background for the neutrino acoustic detection (f> 25 kHz).

Different species of dolphins are present in the Ionian Sea.

Dolphins clicks have been detected in 79% of the recordings acquired in 2005 and 87% in 2006.

Long term monitoring of the echolocation activity allowed the discovery of diel patterns.

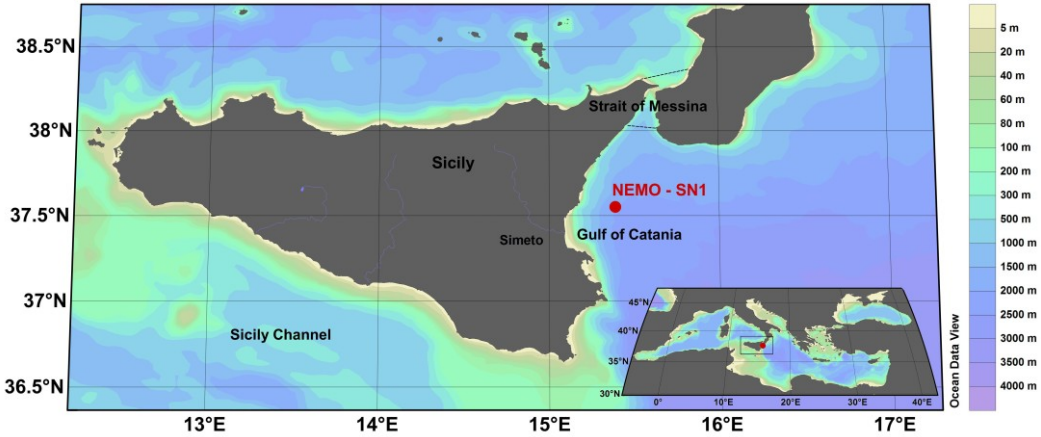


Caruso et al. 2017. **Long-Term Monitoring of Dolphin Biosonar Activity in Deep Pelagic Waters of the Mediterranean Sea**. Scientific reports.

2012-2013: NEMO – SN1

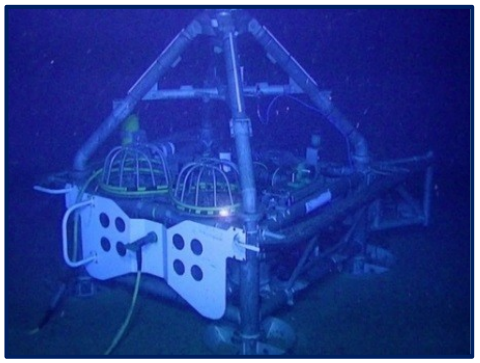
INFN has been also involved in the construction and operation of the multidisciplinary observatory NEMO SN1

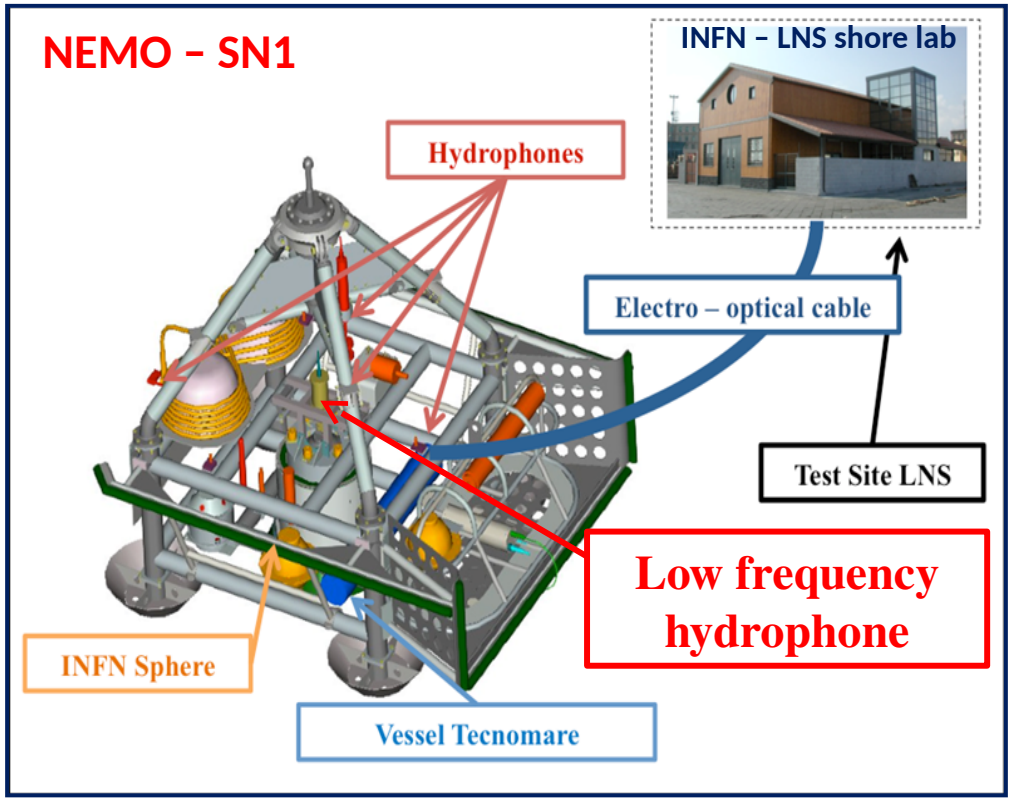
NEMO - SN1 is the first-established node of EMSO (European Multidisciplinary Seafloor Observatory).
http://www.emso-eu.org/



Up: *geographic location of the NEMO – SN1 multidisciplinary observatory*

Right: *NEMO – SN1 operative underwater*





Operated from June 2012 to May 2013

NEMO-SN1: acoustic data acquisition

- **High frequency acoustic array**

  - 4 SMID large bandwidth calibrated hydrophones (same model used in SMO and SMO-OνDE2 acoustic arrays)
  - Commercial four-channel audio analog-to-digital (A/D) converter off-shore
  - Acoustic data-stream (4 synchronized channels) time-stamped on shore

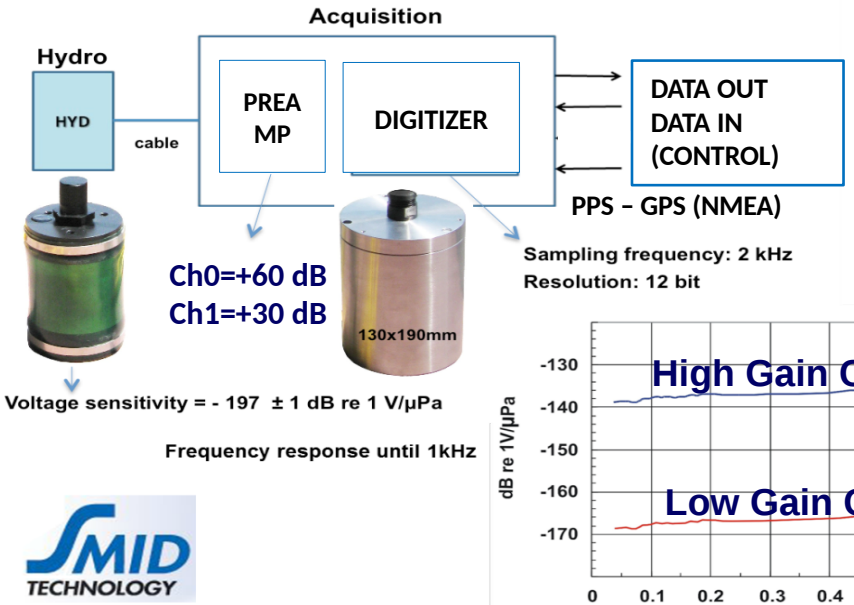
NEMO-SN1 large bandwidth hydrophones

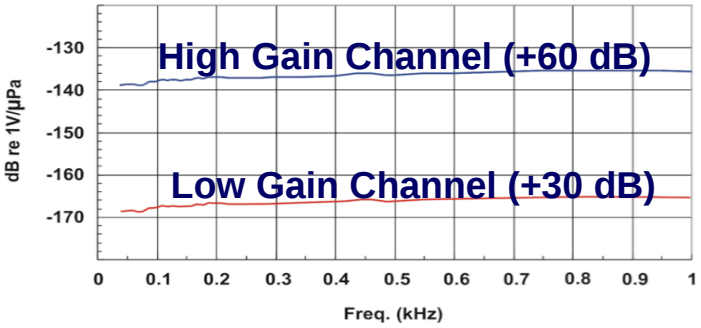
13" Glass Housing for high frequency hydrophones DAQ system

- **Low frequency hydrophone**

Low frequency hydrophone model SMID DT405D (1 Hz< f< 1 kHz)

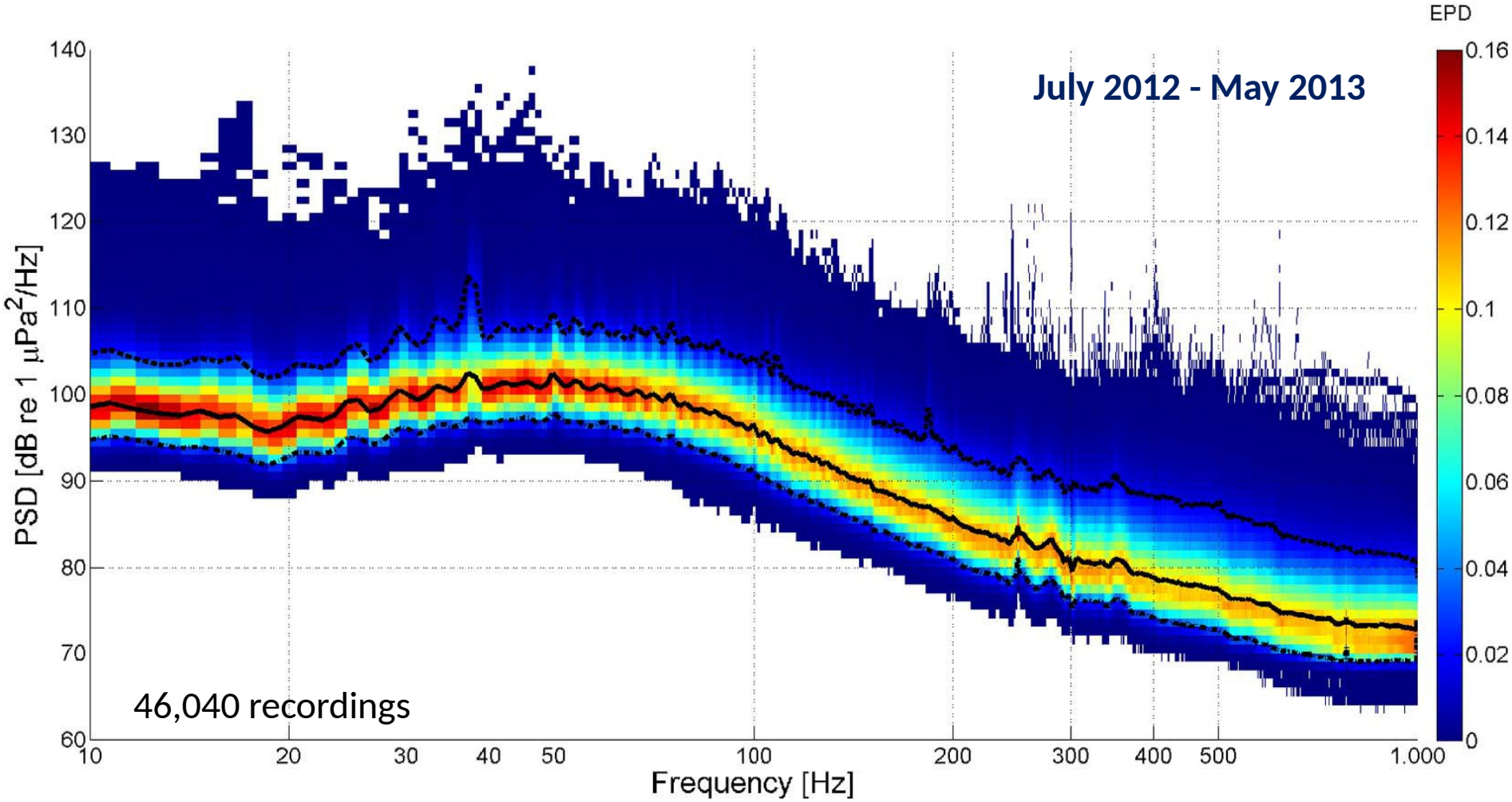
Acoustic data were collected from **June 2012 to May 2013**, 24 hours per day, at a sampling frequency of 2 kHz, saved in 10 min long files and stored at the INFN – LNS.





Underwater background noise at low frequency

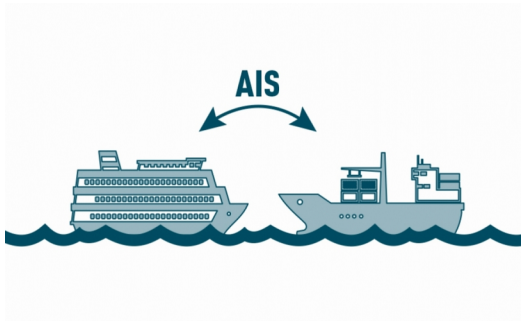
Empirical probability density (EPD) of the mean values of the PSD within each 10 min long recording (binning: 1 dB re 1 µPa2/Hz). 2048 FFT points, Hamming window: 2048 samples, overlap 50%). 50th (solid line), 5th (dash-dotted line) and 95th percentiles (dashed line) of the mean values of the PSD for the whole acoustic dataset.

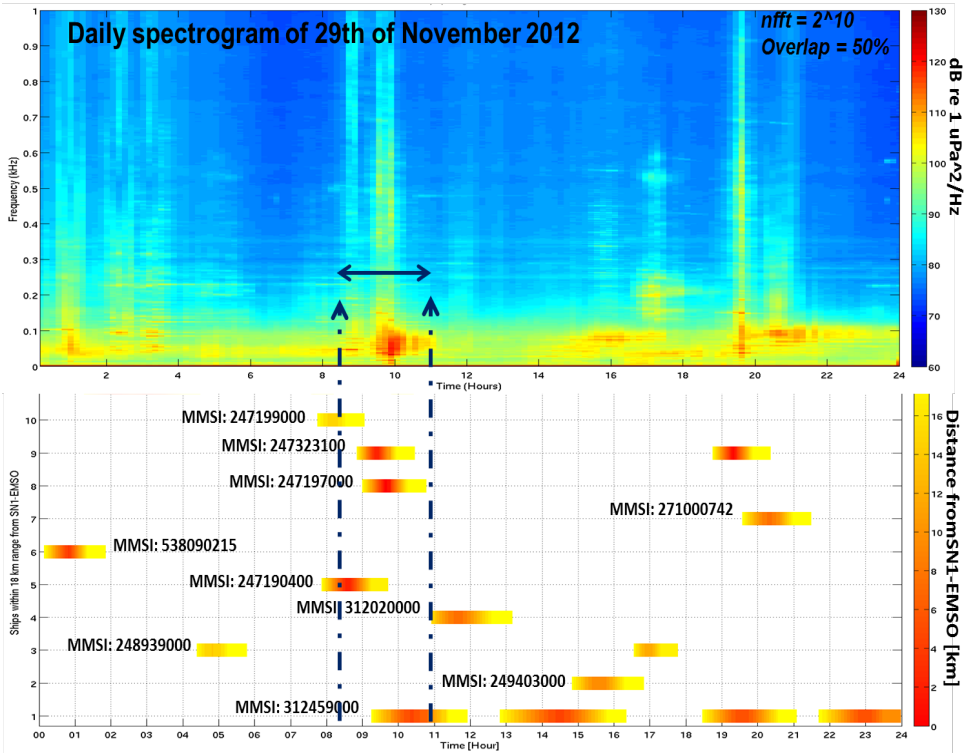


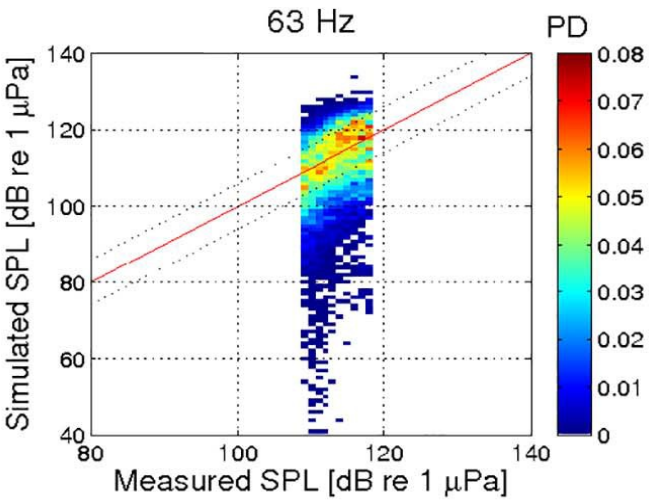
Viola et al. **Continuous monitoring of noise levels in the Gulf of Catania (Ionian Sea). Study of correlation with ship traffic.** Marine Pollution Bulletin (2017), http://dx.doi.org/10.1016/j.marpolbul.2017.05.040.

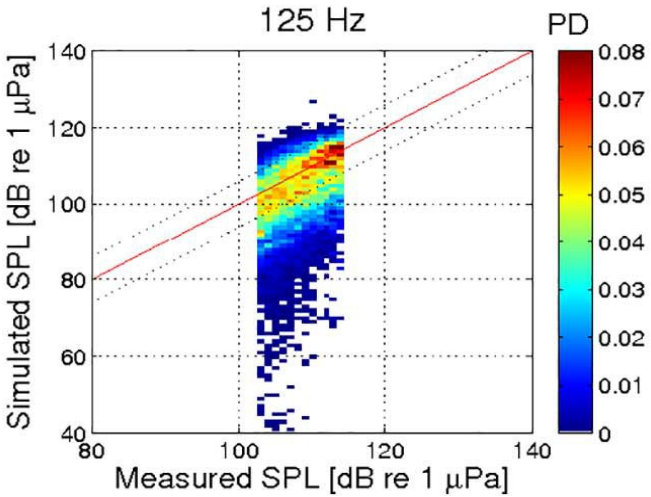
Noise levels and correlation with ship traffic

Noise level were correlated with the ship traffic in the area. Ship traffic information is provided by an **AIS (Automatic Identification System)** antenna installed at the INFN LNS. This system is used by ships for identify and locate vessels. It gives information such as position, mmsi, speed and length.







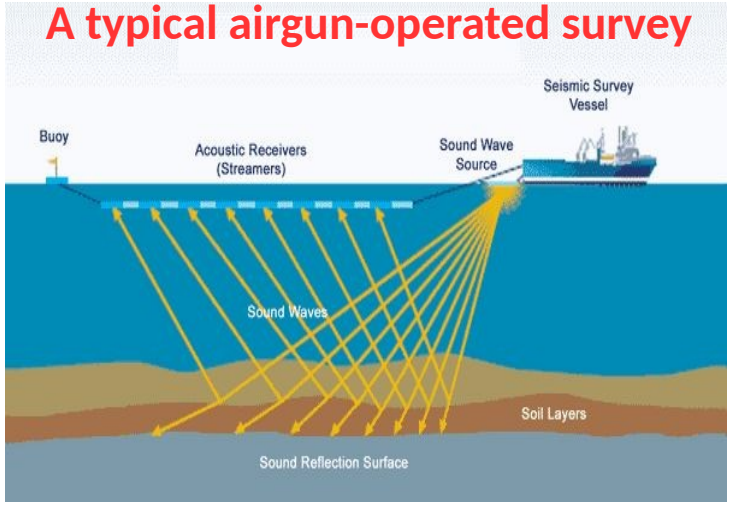


Probability density (PD) of the simulated SPLs (RANDI 3.1 model) as a function of the measured SPLs for the 1/3 octave bands considered by MSFD. Binning is 1 dB re 1 µPa for both axes.

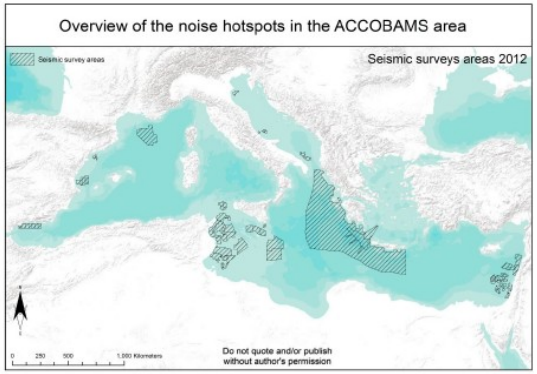
Viola et al. Continuous monitoring of noise levels in the Gulf of Catania (Ionian Sea). Study of correlation with ship traffic. Marine Pollution Bulletin (2017), http://dx.doi.org/10.1016/j.marpolbul.2017.05.040.

Acoustic noise induced by seismic airgun surveys

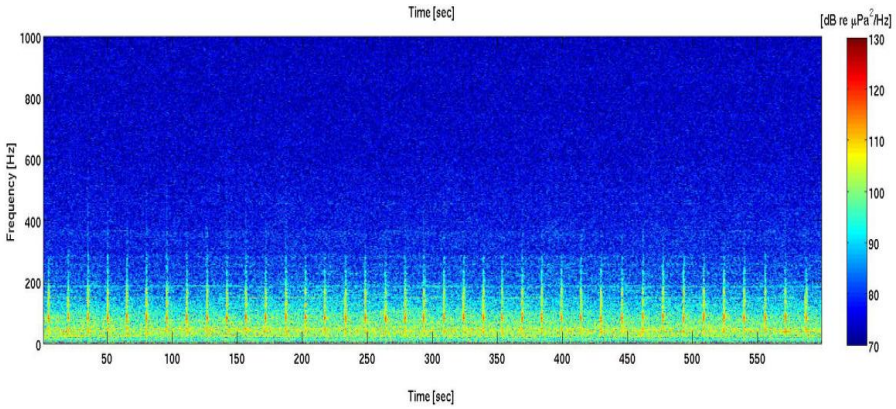
Seismic prospecting with airguns introduce a considerable amount of energy underwater. Broad band (2–200 Hz at the source), high amplitude impulsive sounds.

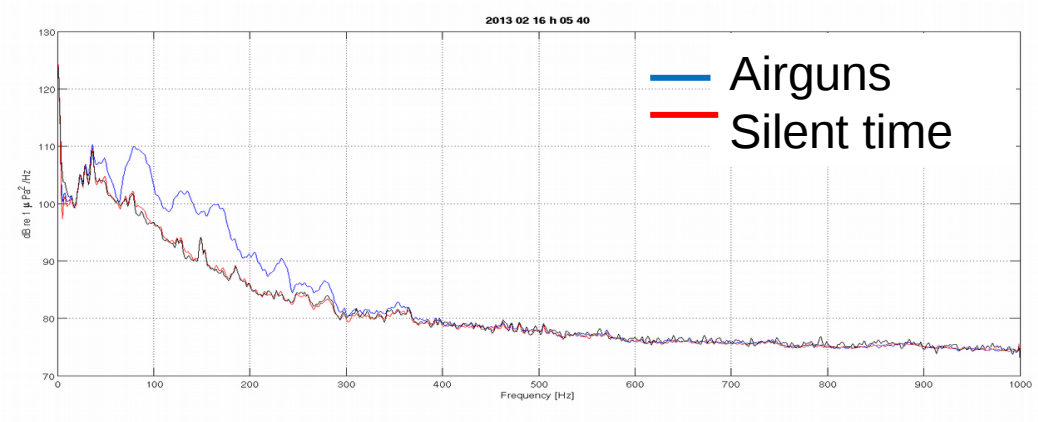


Seismic airgun signals were recorded by NEMO-SN1 from November 2012 to February 2013, compatible with seismic operation offshore Greece



Maglio A. et al., (2016). Overview of the noise hotspots in the ACCOBAMS area. Part I - The Mediterranean Sea. Report to ACCOBAMS



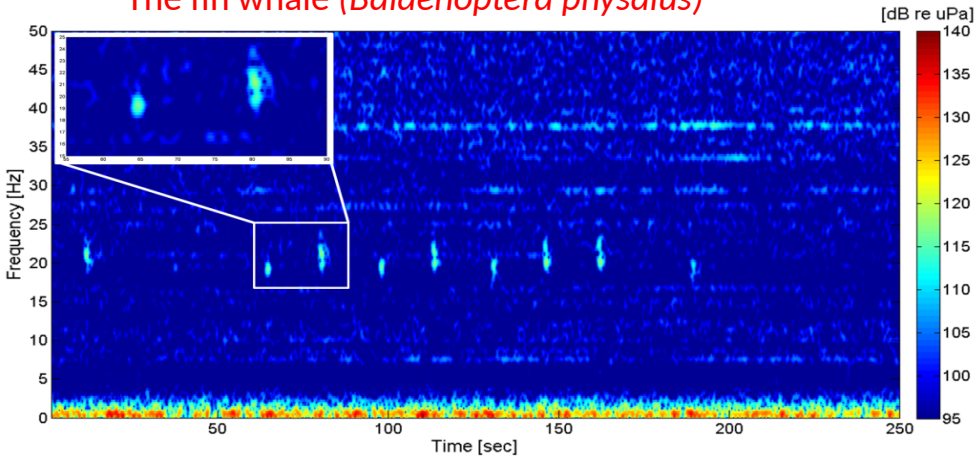


Source of acoustic pollution and threat for marine life.

Sciacca et al. - *Shipping noise and seismic airgun surveys in theIonian Sea: Potential impact on Mediterranean fin whale*.Proceedings of Meetings on Acoustics, Vol. 27, 040010 (2017)

Fin whale acoustic presence

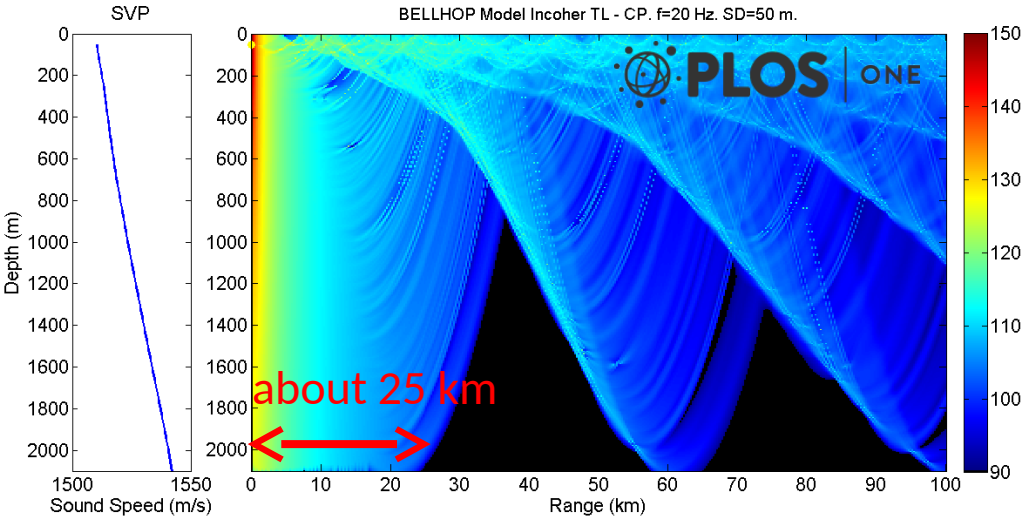
The fin whale *(Balaenoptera physalus)*



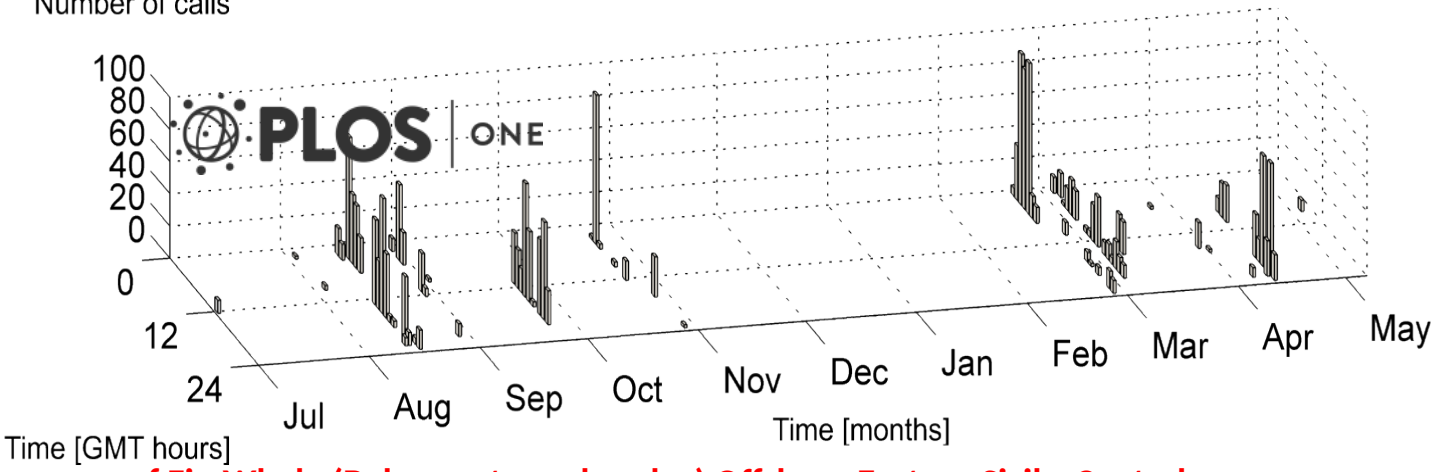
Analyzed time [hours]	7215,67
Detection time [hours]	43
Days with fin whales detection	27

Sound propagation model → typical detection range for fin whale calls by NEMO-SN1

Sound source depth: 50 meters (typical fin whale calling depth).
Source Level 190 dB re 1µPa at 1m.
NEMO – SN1 hydrophone depth: 2100 m.



Peaks in acoustic activity observed during Spring and Summer months



Sciacca et al. (2015) **Annual Acoustic Presence of Fin Whale (Balaenoptera physalus) Offshore Eastern Sicily, Central Mediterranean Sea.** PLoS ONE 10(11): e0141838. doi:10.1371/journal.pone.0141838

Development of automatic detection algorithms

On-shore data acquisition architecture developed for INFN cabled arrays allowed the development of independent automatic detection scripts

Triggers implemented in SMO-ONDE2:

- *FIN WHALE TRIGGER*
- *SEISMIC AIRGUN TRIGGER*
- *DOLPHIN TRIGGER*
- *SPERM WHALE TRIGGER*

- Extraction of the signal from the acoustic data stream (40 ms around detection)

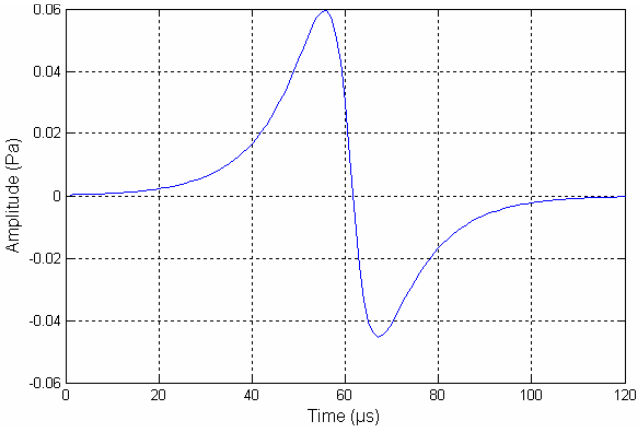
- Signals labeled with the GPS time of acquisition and made available for **off-line tracking**

Search for neutrino signals

Preliminary studies for the development of a neutrino signal trigger are on going.

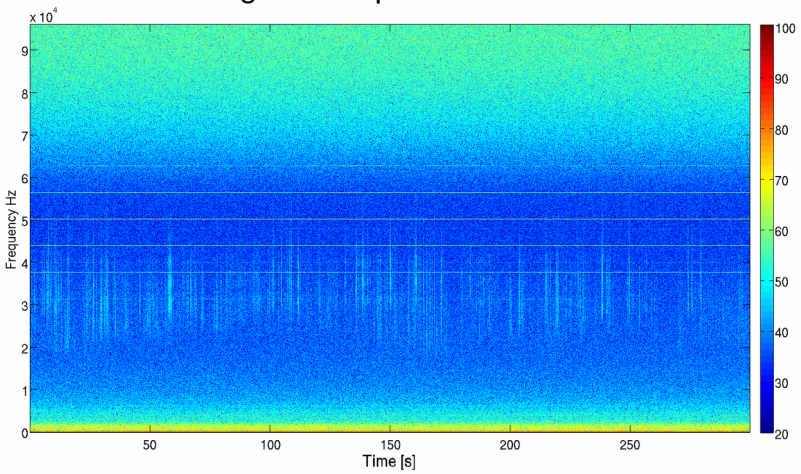
INFN is working on methods to discard possible sources of false detection.

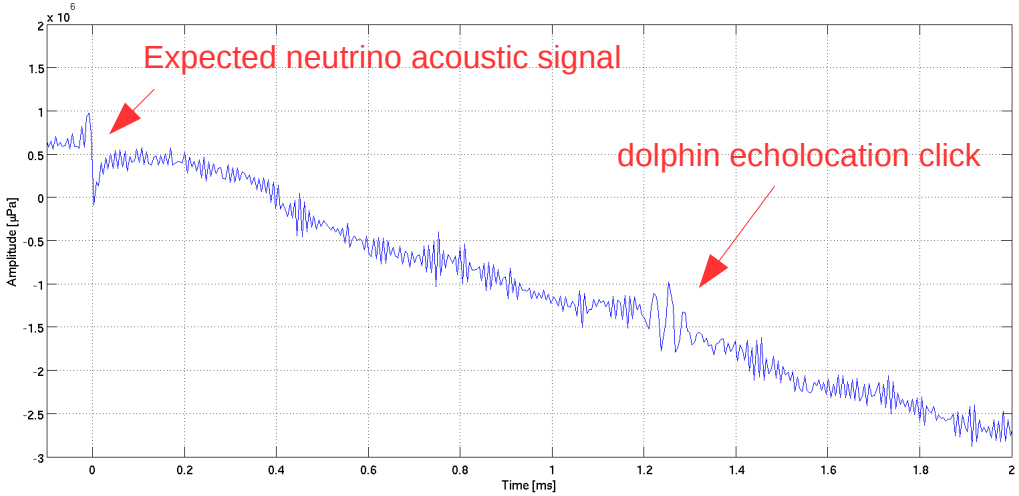
Expected neutrino acoustic signal
(E=10^{21} eV, distance: 1.05 Km, Angle 0°)



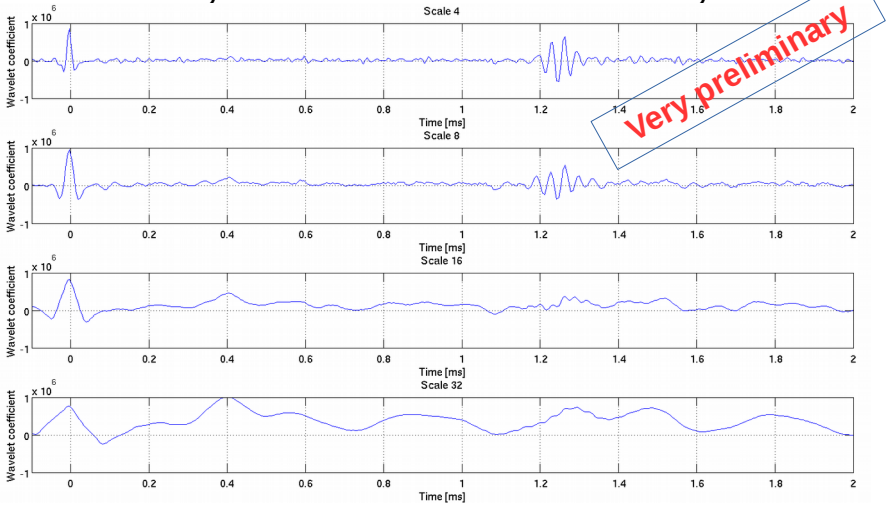
From Vandenbroucke et al .Astrophysical Journal 621:301-312

5 min recording with dolphin echolocation clicks





Preliminary studies based on wavelet analysis



Conclusions

- 15 years of activities on underwater acoustics allowed INFN to develop new technology for acoustic neutrino detection.

- An innovative data acquisition architecture, based on "all data to shore" philosophy, has been developed in the framework of SMO project. Signal processing entirely performed on shore. The SMO data acquisition architecture has been applied to KM3NeT acoustic positioning system.

- INFN acoustic data represent the largest data-set of underwater sounds in the Mediterranean Sea → Acquired data can be used as background in simulations of acoustic neutrino signals or to test the performance of the acoustic neutrino signal detection algorithms

- First studies on acoustic neutrino detection techniques are on going.

- Passive acoustic monitoring at deep sea → Opportunity for multidisciplinary studies on biology, geology, oceanography, ecology, ...

Thank you