VLVNT 2018

The Positioning System for KM3NeT

Giorgio Riccobene INFN-LNS

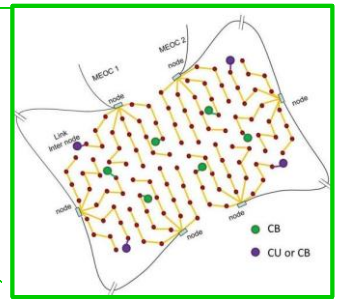
Dubna 2-4/10/2018

The KM3NeT detector

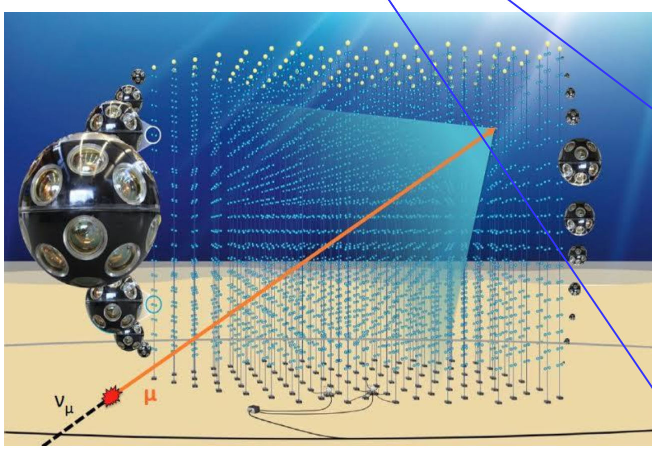
KM3NeT is a distributed research infrastructure composed of a network of cabled observatories located in deep waters of the Mediterranean Sea. Centrally managed: common hardware, software, data handling and control.

KM3NeT – ORCA (Phase 2)

Oscillation Research with Cosmics in the Abyss



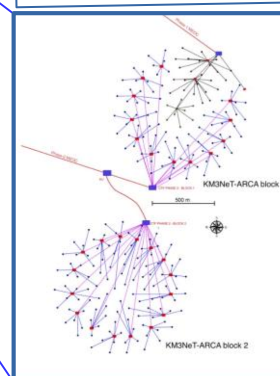
- 1 building block
- 115 Detection Units (DU)
- 18 Digital Optical Modules (DOMs) equipped with 31 3''- PMTs
- 9 m inter DOM distance
- 8 Mton



Letter of Intent for KM3NeT 2.0
2016 J. Phys. G: Nucl. Part. Phys. 43 084001

KM3NeT -ARCA (Phase2)

Astroparticle Research with Cosmics in the Abyss



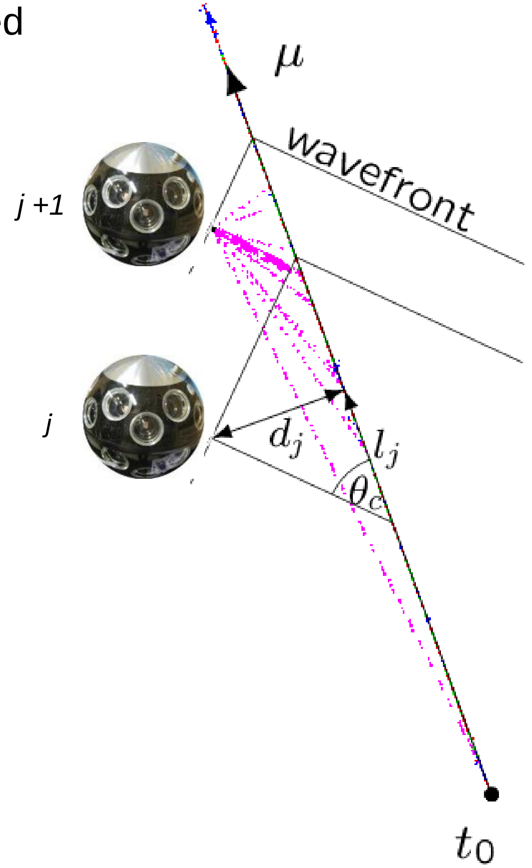
- 2 building blocks (few km apart)
- 115 Detection Units (DUs)
- 18 Digital Optical Modules (DOMs) equipped with 31 3''- PMTs
- 36 m inter DOM distance
- 1 km^3 volume

KM3NeT Calibration needs

The **arrival times of the Cherenkov photons** emitted along the charged particle track are related through a causality relation

$$c(t_j - t_0) = l_j + d_j \, tg(\vartheta_c)$$

Particle direction is determined by the **analysis of space-time correlated PMT signals**



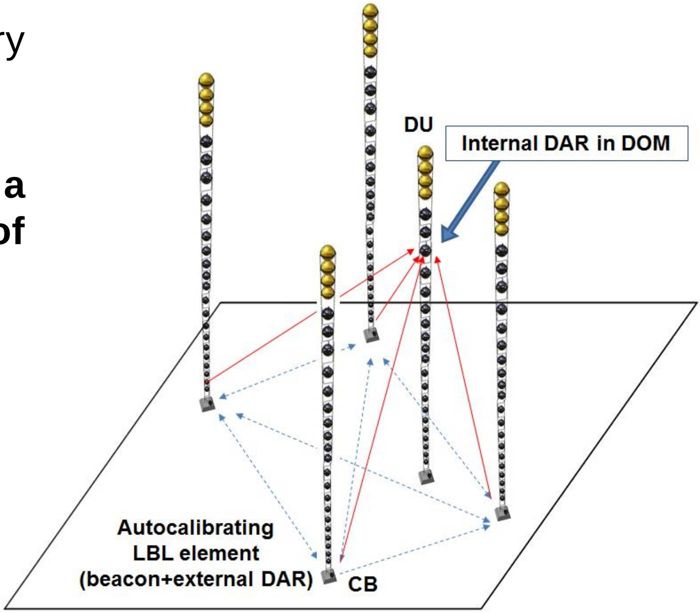
KM3NeT -ARCA project goals:

For E_ν >10 TeV track events (muons) → Median angular resolution <0.2°
For E_ν >10 TeV shower events → Median angular resolution < 2°

- Relative hit times accuracy ~ 1 ns (synchronization based on White Rabbit time distribution protocol)
- PMT orientation accuracy < 3°
- DOM position accuracy < 20 cm (corresponding to the distance traveled by Cherenkov photons in 1 ns)

Acoustic Positioning

Continuous monitoring of the DOMs positions is a mandatory requirement for an accurate direction reconstruction

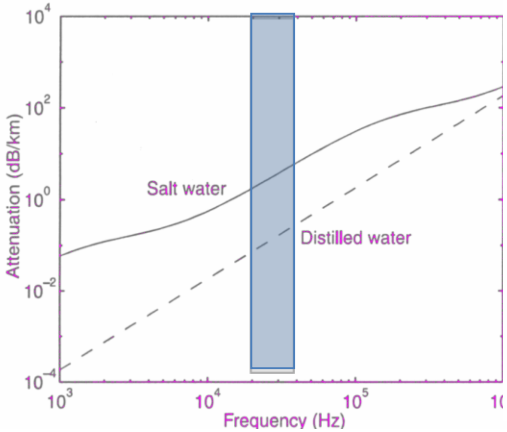


In KM3NeT the positions of the DOMs are recovered through a relative acoustic positioning system (RAPS) composed of three main sub-systems:

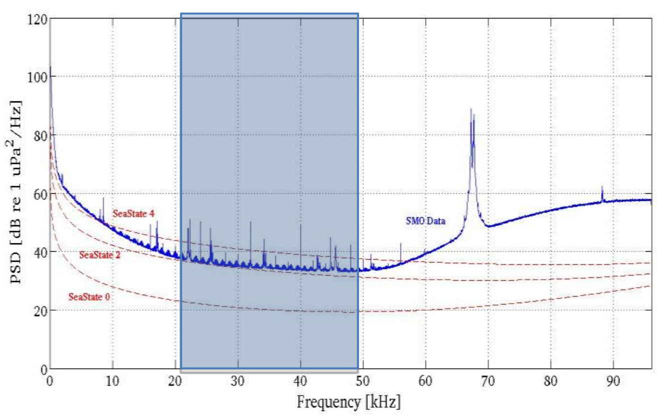
1. A Long Base-Line (LBL) of acoustic transmitters (beacons) and receivers, located at known positions
2. An array of digital acoustic receivers (DARs) installed along the detection units (DUs) of the telescope
3. A farm of PCs for the analysis of acoustic data

Acoustic emitter signals must be detected up to distances of 1 km

20 kHz – 50 kHz



20 kHz – 50 kHz



- **Suitable frequency range: 20 kHz-50 kHz**
- **Lowest level of PSD: ~40 dB re 1 uPa^2/Hz**
- **Attenuation: 1-10 dB/km**

Acoustic data acquisition system

In KM3NeT all underwater sensors and calibration devices (including acoustic emitters and receivers of the APS) are **time-synchronized through a custom system based on the White Rabbit protocol**. This system distributes synchronization signals (sub-nanosecond precision) from shore station to the underwater nodes of the White Rabbit net, represented by Central Logic Boards (CLBs) installed inside each DOM and DU base.

The acoustic data acquisition chain is based on "all data to shore" philosophy

- underwater sounds continuously digitized offshore (195 kHz, 24 bit)

- acoustic data stream labeled by Central Logic Boards with the absolute GPS time transmitted from shore

The Long Base-Line acoustic emission is driven by triggers at known times

↓

Synchronized array of acoustic emitters and receivers

↓

Errors in relative LBL-element location: main source of uncertainty for APS

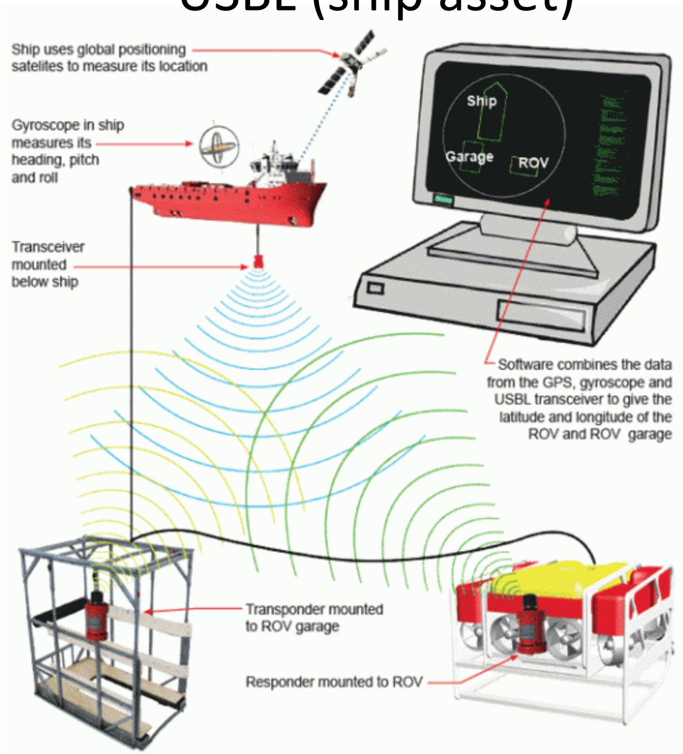
Navigation and Absolute positioning

Absolute position of the LBL elements is provided by NAAPS (Navigation and Absolute Acoustic Positioning System):

- Provides Geo-referenced positions of DUs
- Provides absolute position of LBL elements of RAPS
- Accuracy: ~ 2 meters

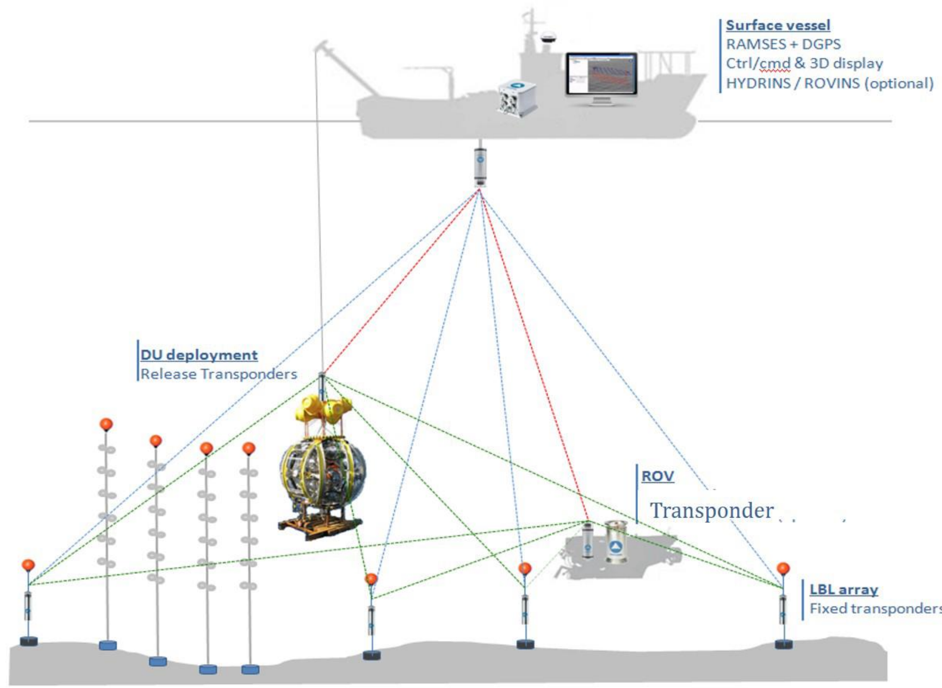
ARCA

USBL (ship asset)



ORCA

LBL (Ramses iXBlue)

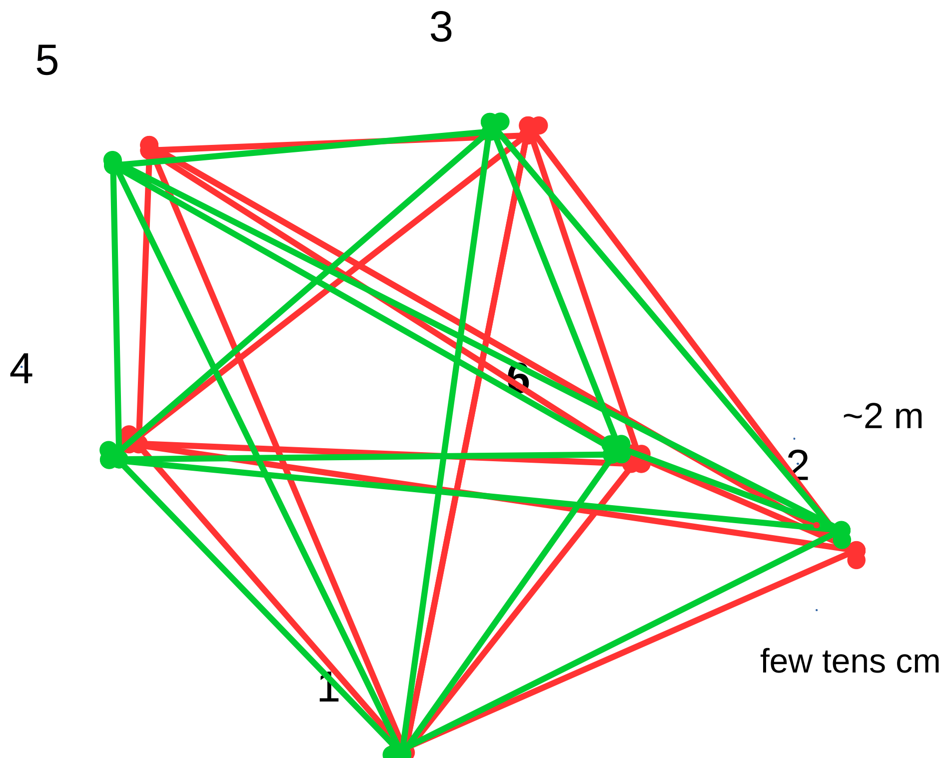


Acoustic data acquisition system

To provide relative DOM positioning with an accuracy of about 20 cm, the relative position of the LBL elements must be known with an accuracy of the same order.

Auto-calibrating Long Baseline of acoustic emitters and hydrophones

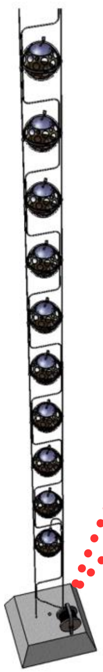
- Autocalibration procedure based on range measurements (knowing the sound velocity in situ)
- Iterative algorithm → starting point: nominal position provided by NAAPS
- Constraint: fixed hydro-emitter distance in Calibration bases
- Output: positions of each LBL element, quality factor (sum of squared residuals)



Acoustic emitters

- The **commercially available piezo-ceramic Free Flooded Rings (FFR) transducers SX30** from Sensor Tech Ltd have been chosen for LBL beacons. Each beacon can be reconfigured via a dedicated RS232 connection for "in situ" optimization of the signal detection. The signal emission trigger is synchronized with the detector master clock with calibrated time delay of 7±1 μs.

Mediterráneo Señales Marítimas



Signal Emitted length:
- from 0 to 50 ms

Maximum emission amplitude:
180 dB @ 34kHz re 1 μPa at 1 m

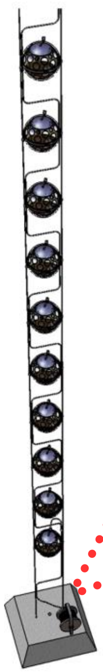
Type of acoustic signals:
- - Monochromatic signals configurable from 1 kHz to 80 kHz
- - Sine Sweep signals configurable from 1 kHz to 80 kHz
- - Maximum Length Sequence (MLS) signals with lengths from 5.12 ms to 40.96 ms (at 200 ksamples/s)

LBL emitters can be also operated as autonomous emitters.

In this case, the Time of Emission (ToEs) is recovered from the Time of Arrival (ToA) of the pulses to the hydrophones at DU bases (fixed positions), knowing the distance between emitter and receivers, and the sound velocity.

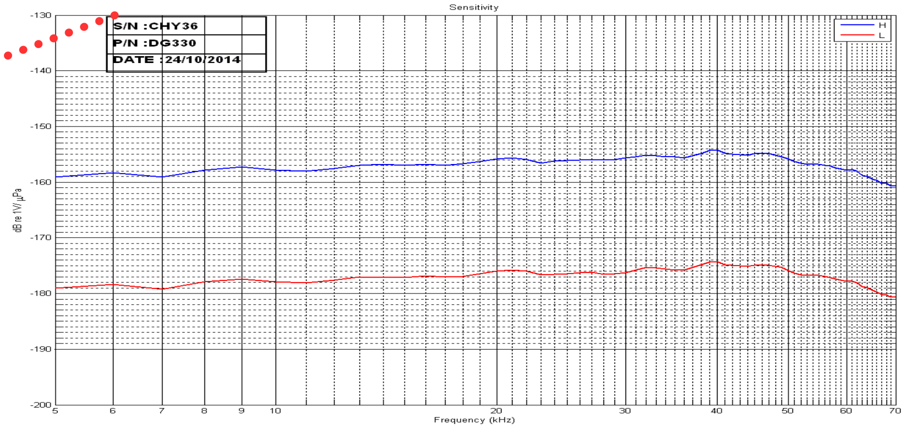
The hydrophone on DU Bases

Digital hydrophones are hosted on the base of the DUs. These ‘external’ hydrophones are used to calibrate the LBL by measuring the relative distance among LBL elements. The selected hydrophone is the DG0330 manufactured by Colmar s.r.l.. It consists of a **spherical piezo-ceramic element read-out by an analogue preamplifier followed by an ADC (sigma - delta).**



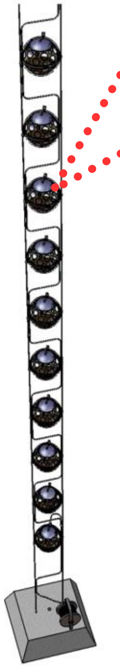
All hydrophones calibrated in pressure sensitivity and directionality

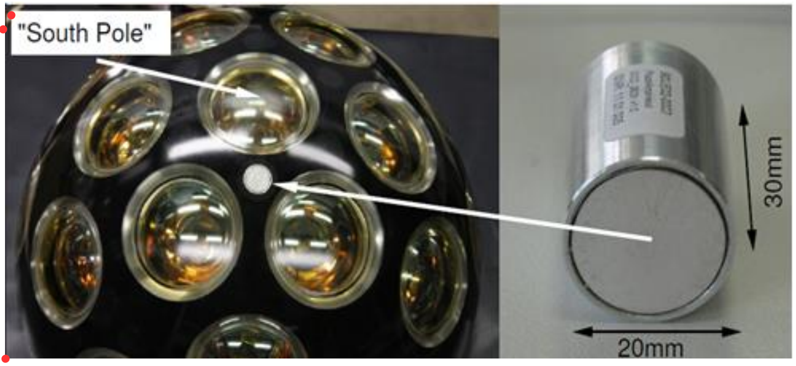
Sampling frequency : 195312.5 Hz
Resolution: 24 bits



The acoustic receiver in the DOM

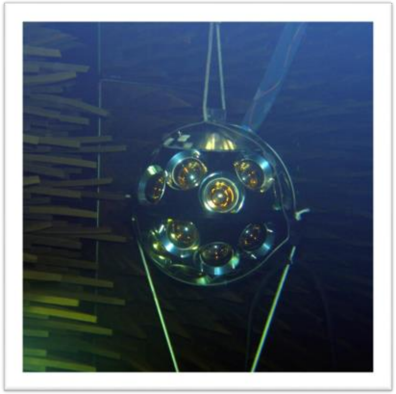
The movement of the DUs due to underwater currents is monitored thanks to “internal” piezo-electric Digital Acoustic Receivers (DAR) glued from the inside to the glass sphere of each KM3NeT Digital Optical Module (DOM)





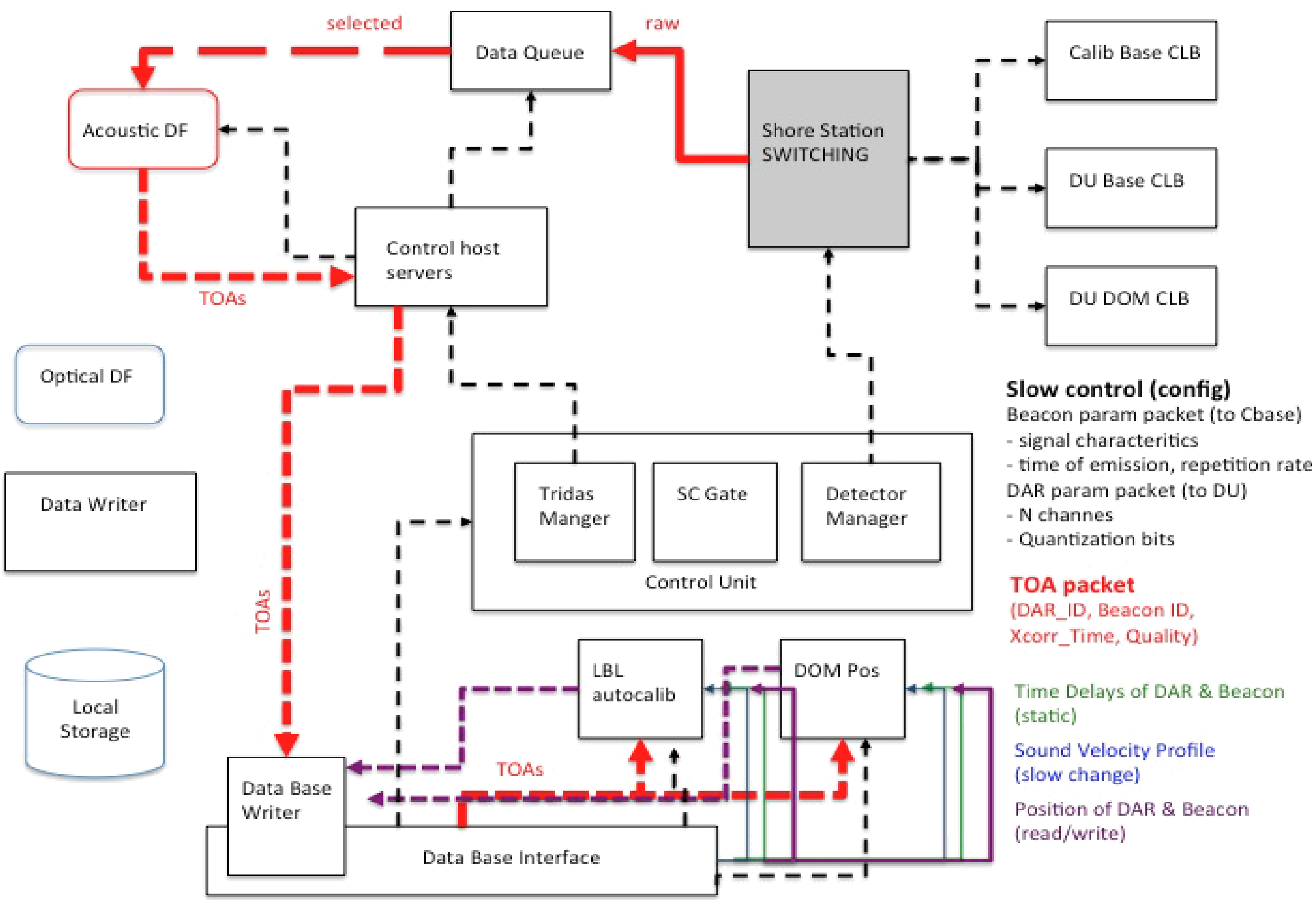
The nominal sensitivity of the sensors is - 160 ± 6 dB re 1V/μPa at 50 kHz with a ± 3 dB variation in the range 10 ÷ 70 kHz.

Tests are on going in anechoic acoustically insulated pool at TNO to characterize the acoustic behavior of the DOMs in water (internal echoing, sensitivity as a function of frequency and of angle of incidence, dependency on gluing quality).



Km3NeT DAQ scheme

The acoustic positioning data analysis is entirely performed on-shore. A farm of PCs on an intranet, parses acoustic data from the main detector data stream. LBL signal identification is performed on line by using software algorithms based on cross-correlation methods. Once a LBL-beacon pulse is identified, the software associates it with the absolute GPS time of the detection (ToA) and with a quality factor.



First Results

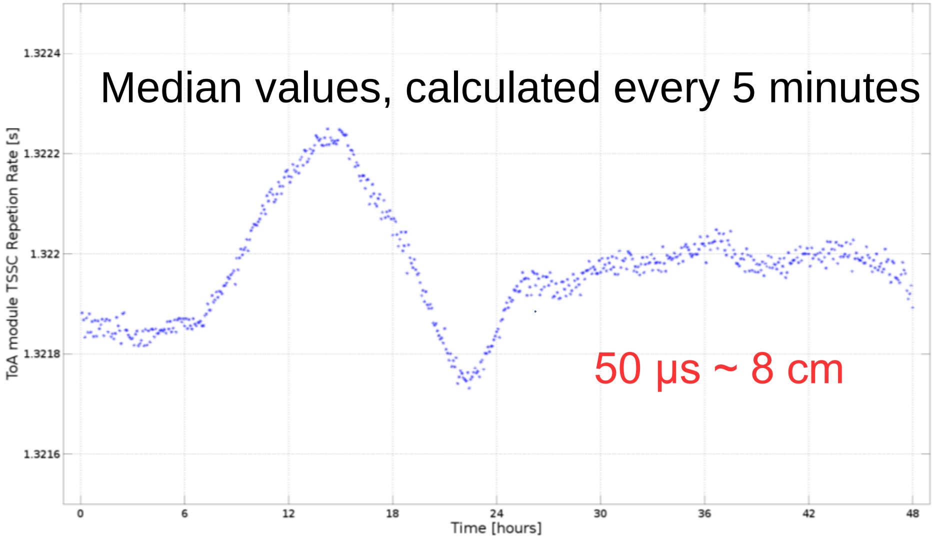
Up-to-date KM3NeT-ARCA acoustic positioning system:

- 1 autonomous emitter (emission of a pattern of 6 sinusoidal pulses at 32 kHz, 5 ms long with a repetition rate of about 12 s, amplitude 170 dB re 1 μPa @1 m)
- 2 Detection Units (about 200 m and 250 m far from the emitter) equipped with only internal DARs

Under-determined system

However, the accuracy of measurement of the emitter-receiver Time of Flight has been evaluated by calculating ToAs to the internal DARs *modulo* the emitter repetition rate.

Currently, the accuracy for each single ToF measurement is about 300 μs, corresponding to an uncertainty on range measurement of about 50 cm. The precision can be improved to about 50 μs, considering the median values calculated every 5 minutes.



First Results

Time Difference of Arrival (TDoA) measurements in situ are in agreement with the values expected considering the nominal positions of the internal DARs and the typical sound velocity profile.

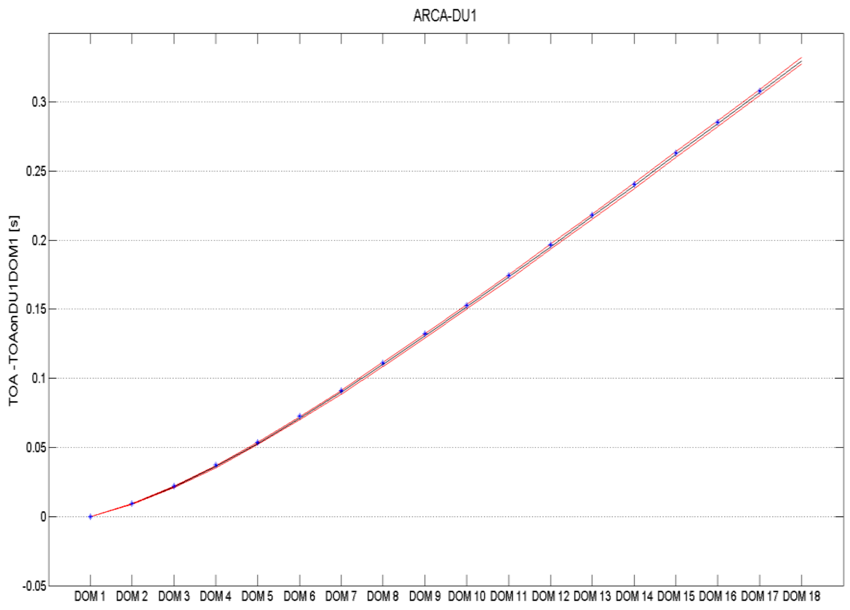
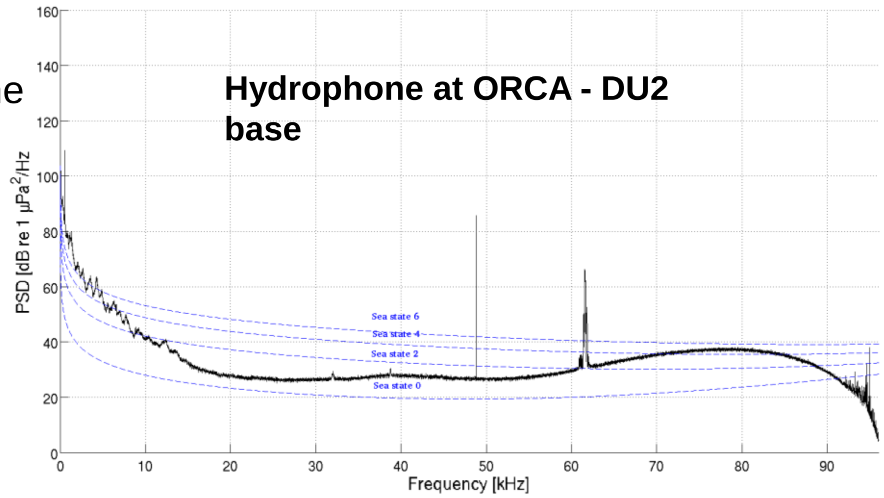


Figure shows the median values in six hours of the difference between ToAs to each DOM operating in ARCA-DU1 and ToAs to the lowest DOM of DU1. Blue dots represent experimental measurements, the band enclosed by the two red lines refers to the expected time difference, assuming the DU is perfectly vertical and considering the position accuracy of the autonomous acoustic beacon and of the DU base.

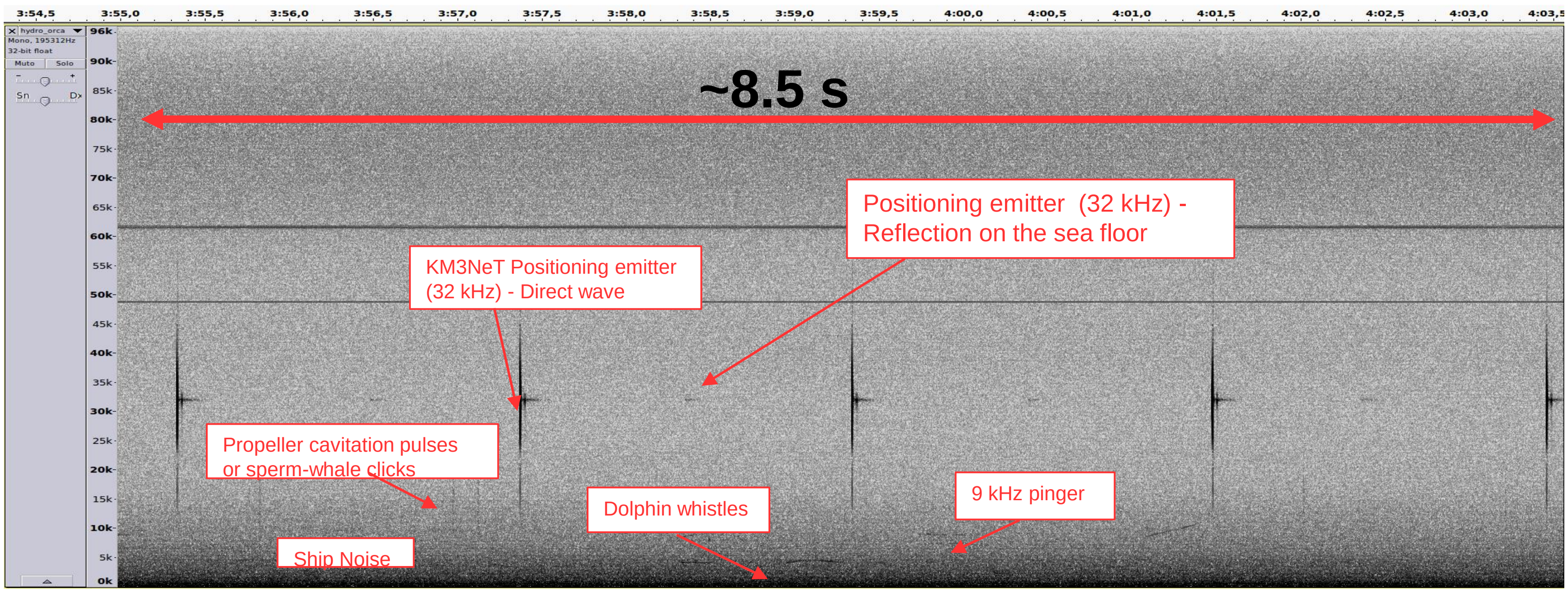
Multidisciplinarity with acoustic

In the KMNeT APS all data acquired by the acoustic receivers are transmitted to shore at 195 kHz/24 bit for the real-time identification of the acoustic beacon pulses.

Thanks to the KM3NeT data acquisition architecture the acoustic data stream can be also addressed to other software tools for other purposes (acoustic neutrino detection, bio-acoustics, geophysics,..).



Hydrophone at ORCA DU2 base

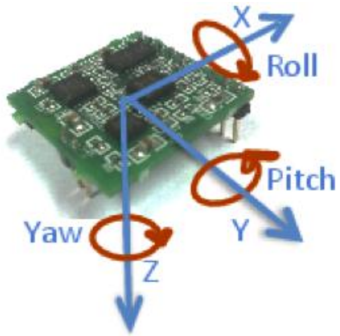


DOM Orientation: Compasses

DOM Orientation in KM3NeT is recovered using custom compass boards interfaced with the detector electronics (CLB)

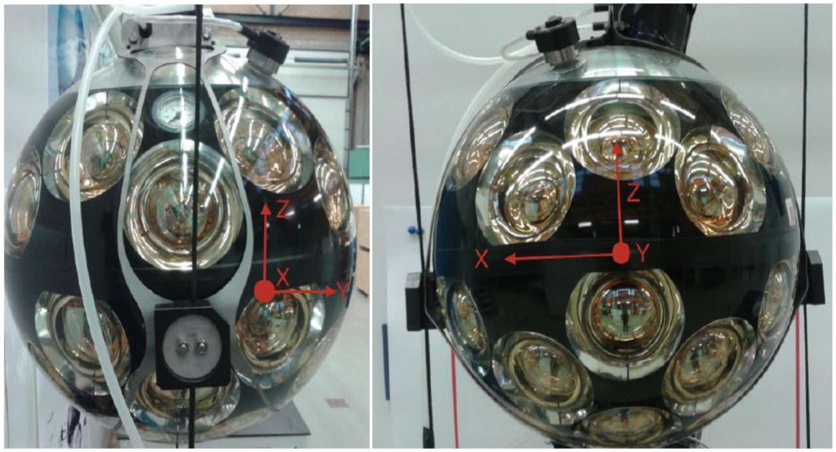
We use the AHRS (Attitude Heading Reference System) to recover DOM "yaw", "pitch" and "roll" from 3-D magnetometers and 3-D accelerometers data.

Raw data are sent to shore and analysed taking into account the calibration coefficients of each compass.
Compasses cannot be calibrated in situ (the DU cannot be rotated in water!)
Calibration of the compass before deployment plays a fundamental role



The LNS-AHRS board

The LSM303 board

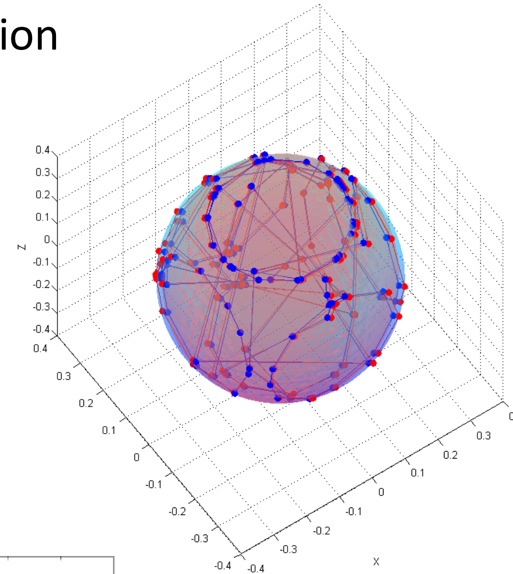


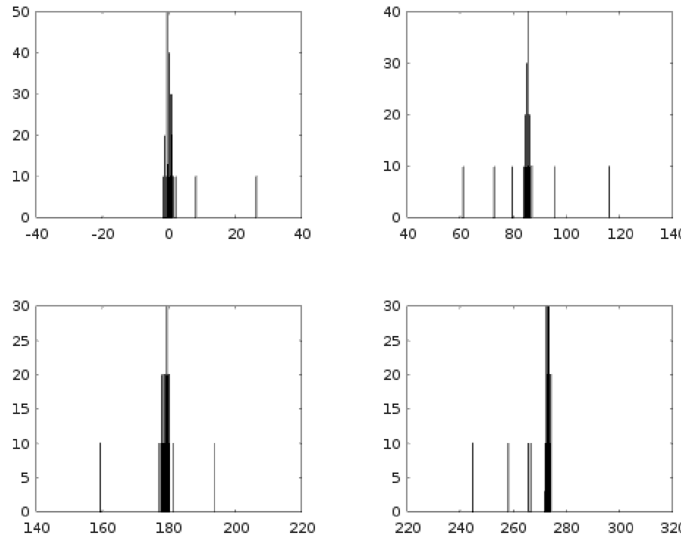
Compass calibration

Each compass mounted in the CLB board and calibrated.
After DOM integration the compass (inside the DOM) is tested
Acceptance criteria: error less than 3.5° wrt to each cardinal direction

Gyro-gimbal for
AHRS calibration

Compass calibration: wobbling

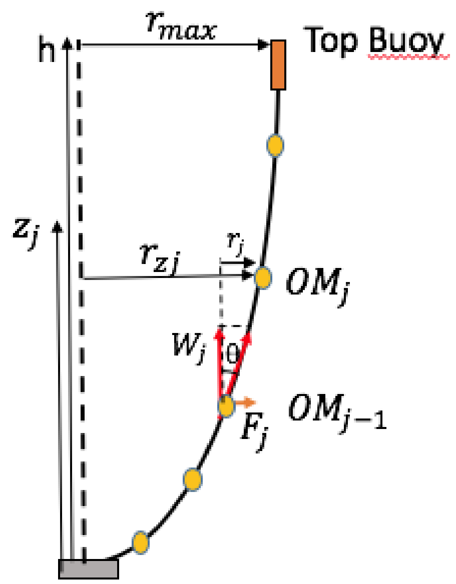




Compass check
after DOM
integration

Results

The orientation of each DOM in the DU is successfully recovered



Work in progress:

DU line fit with information from

- acoustic positioning
- compasses
- mechanical model of the string
- underwater currents

Summary and Outlook

Positioning system for KM3NeT is fully integrated with the detector electronics

Acoustic Positioning:
- Absolute and Navigation – commercial (accuracy 2m)
- Relative – developed by KM3NeT
  - Autocalibrating LBL
  - Underwater GPS thanks to White rabbit synchronisation
  - accuracy 10 cm
  - Data useful for Earth and sea science
  - Working on: acoustic neutrino detection

Compass:
- commercial chips embedded in custom boards
- calibration is mandatory!
- resolution 3.5° (OK with detector performance simulations)

Next Steps:
- DU line fit