The Acoustic Positioning System of the KM3NeT detector

ARENA 2024 • 10TH INTERNATIONAL WORKSHOP
on Acoustic and Radio EeV Neutrino Detection Activities

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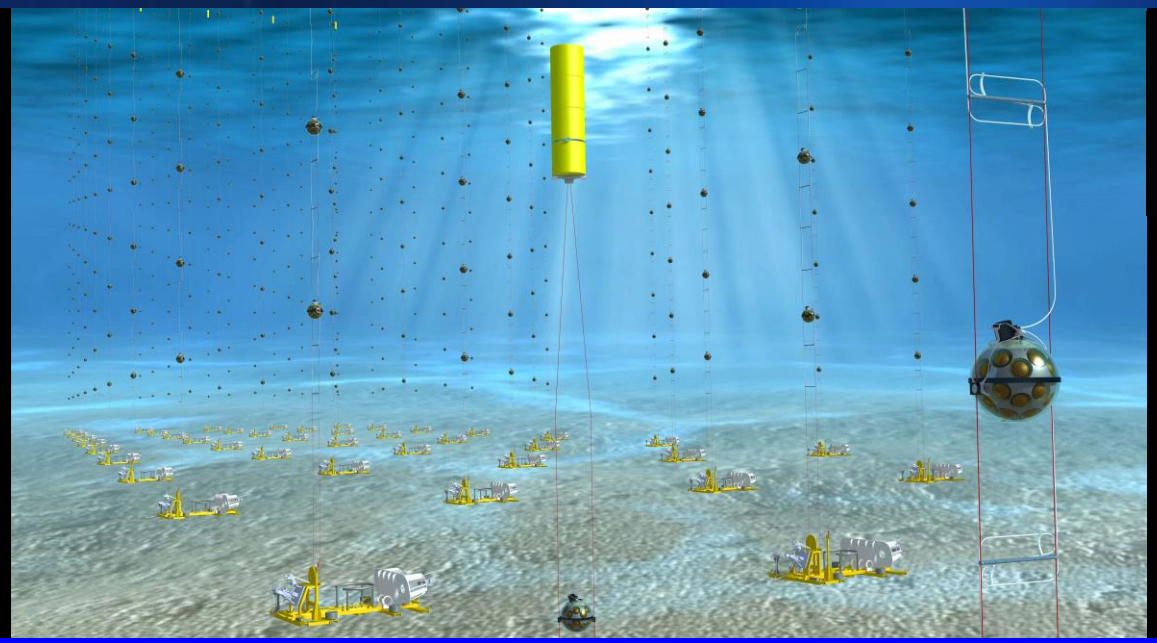
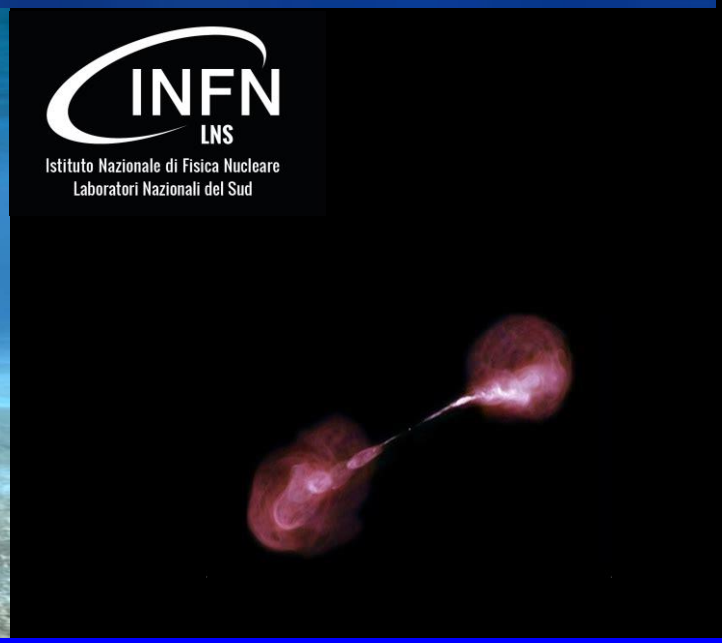
(on behalf of the KM3NeT Collaboration)

CHICAGO • JUNE 11-14, 2024

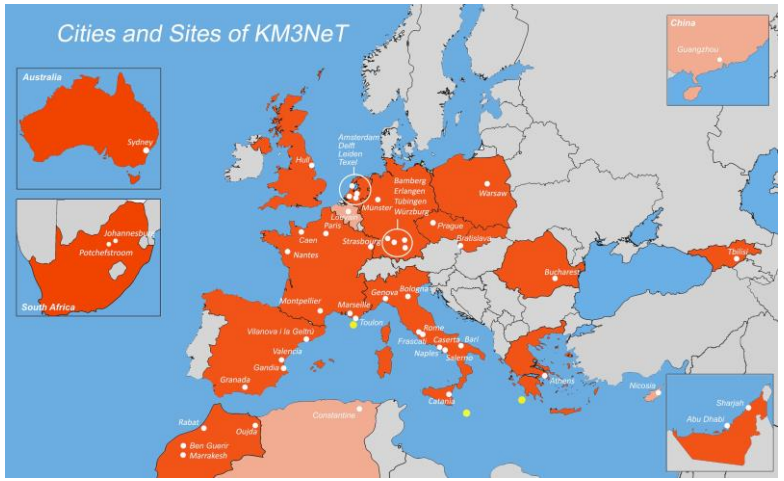


INFN
LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

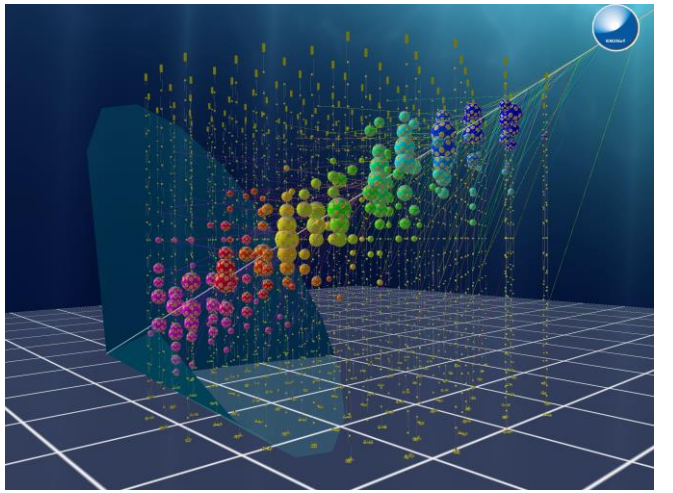


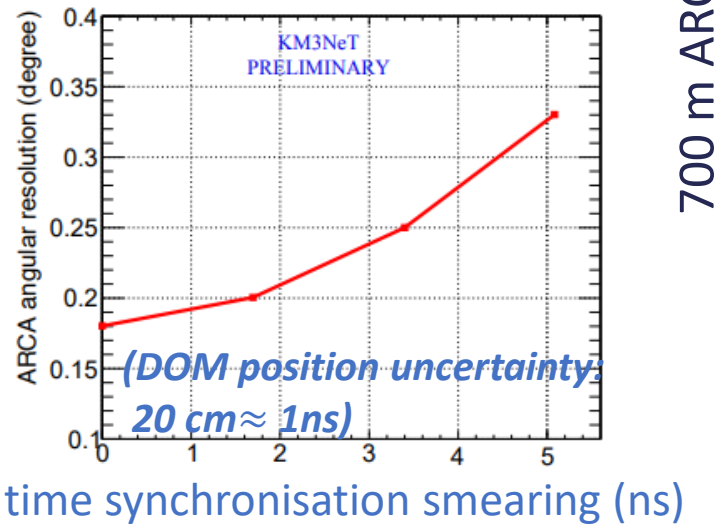
KM3NeT: the giant underwater HE ν telescope

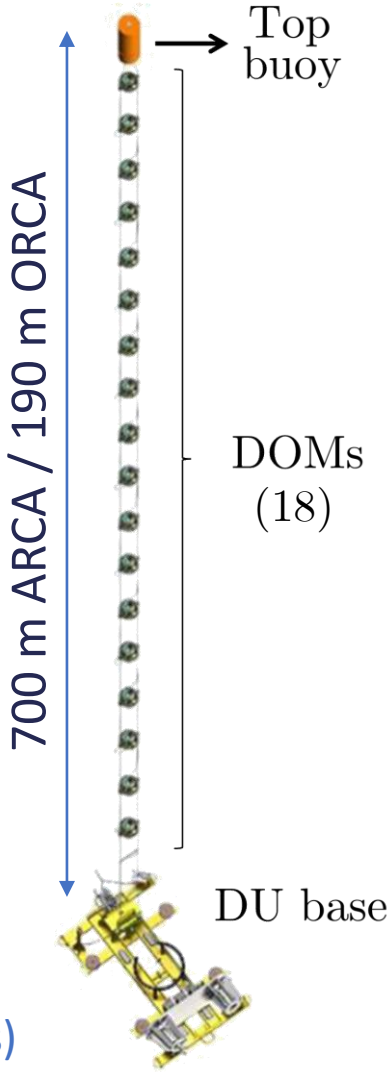
- **ARCA** (**A**stronomy **R**esearch with **C**osmics in the **A**byss)
  - 2 building blocks (few km among the blocks)
  - 115 Detection Units (DUs) / block
  - 18 DOMs (36 m inter-DOM), 90 m inter-DU distance
  - 1 km3 volume
- **ORCA** (**O**scillations **R**esearch with **C**osmics in the **A**byss)
  - 1 building block
  - 115 detection Units
  - 18 DOMs (9 m inter-DOM), 23 m inter-DU distance
  - 8 Mton volume



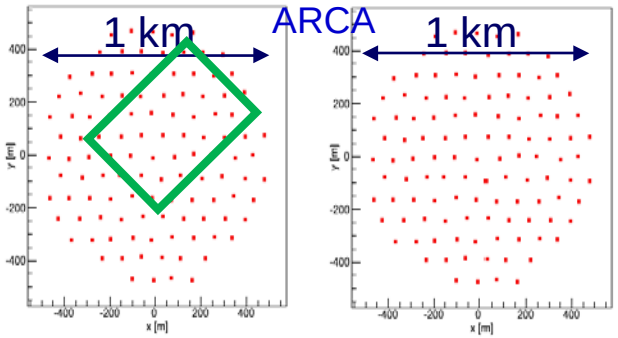
Time Synchronisation and DOM position calibration is the key parameter to optimise angular resolution





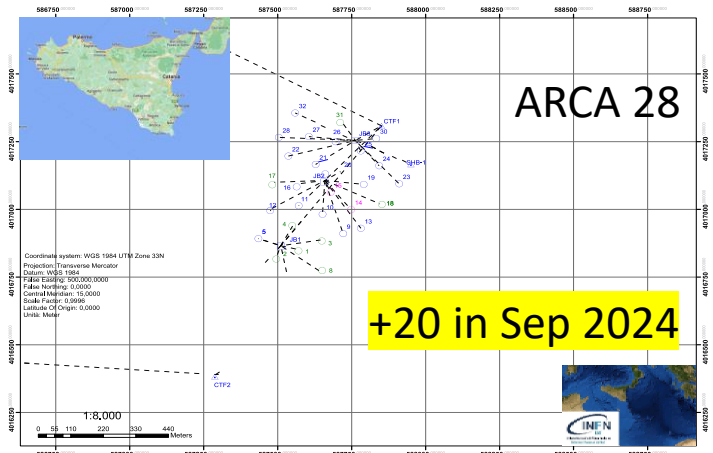


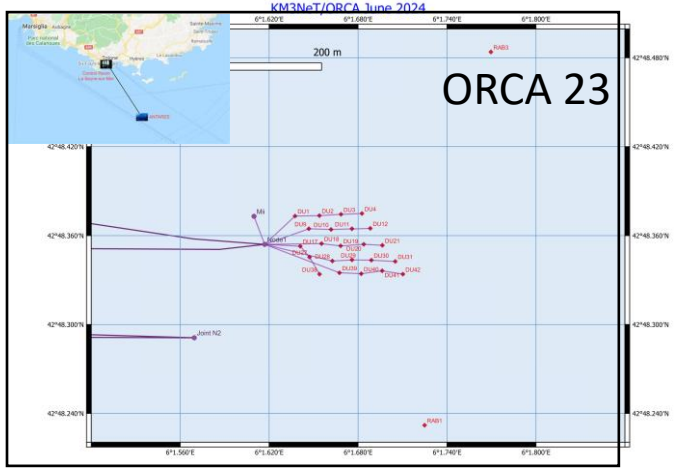
KM3NeT: the giant underwater HE ν telescope

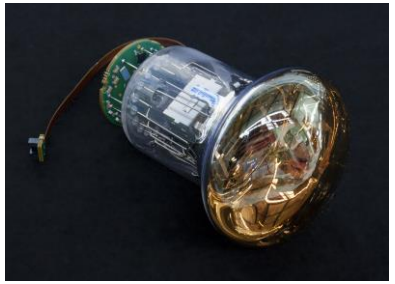


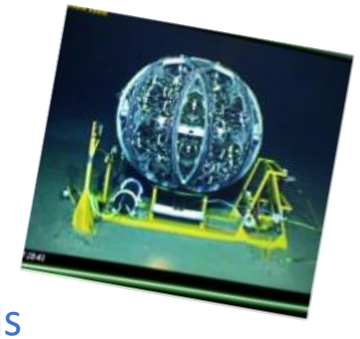
Phase 1: COMPLETE !

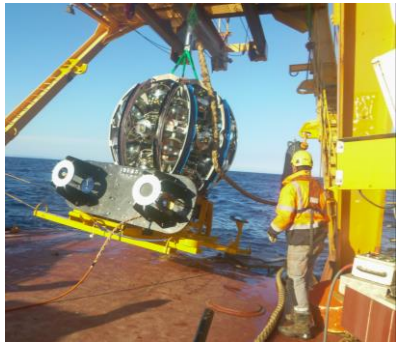
KM3NeT 2.0: TBD

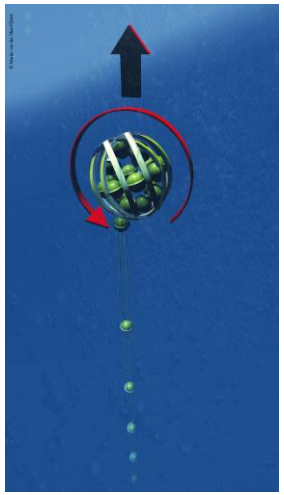












Digital Optical Module (DOM): 31 PMT channels
A fly's eye light detector Inside a 17'' glass sphere
Plus:
compass, acoustic sensor, front-end and data transmission electronics
1 hydrophone at each DU-base

KM3NeT time calibration: White Rabbit network

ARCA example

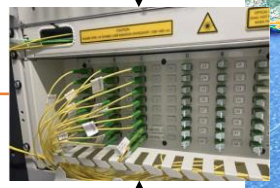
WR Master-Slave time synchronisation through signal “round-trip time” measurement

Phase 1: “hybrid” fabric

GPS

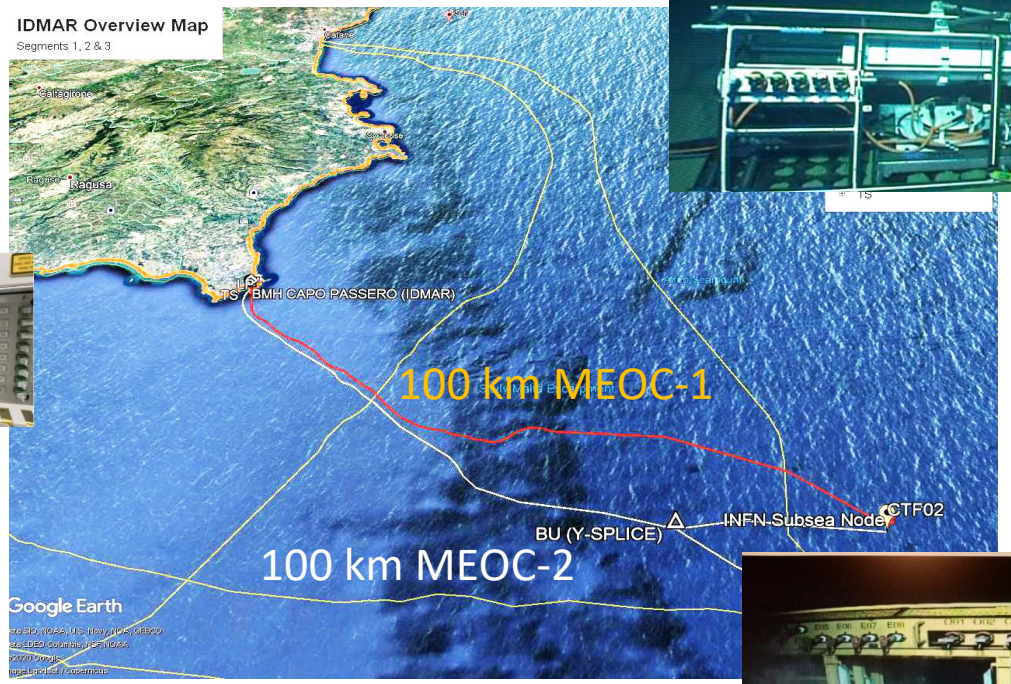
WR Grand Master

PMT data

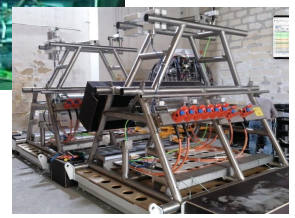


Phase 2: WR fabric

Phase 1: WR Broadcast
3 JBs, 28 DUs



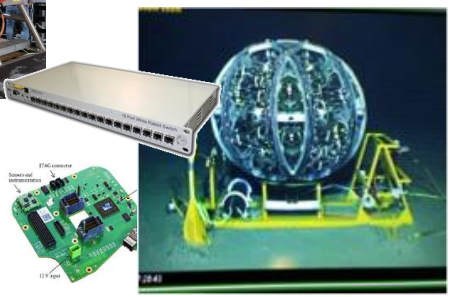
Phase 2: WR Point2Point
6 JBs, 85 DUs (x 2→block 2)



Junction Box

Detection Unit

DU Base: CLB WR slave
DOMs: CLB broadcast slave



DU Base: switch WR slave
DOMs: CLB WR slaves

KM3NeT time calibration: White Rabbit network

WR Master-Slave time synchronisation through signal "round-trip time" measurement

ARCA example

Phase 1: "hybrid" fabric

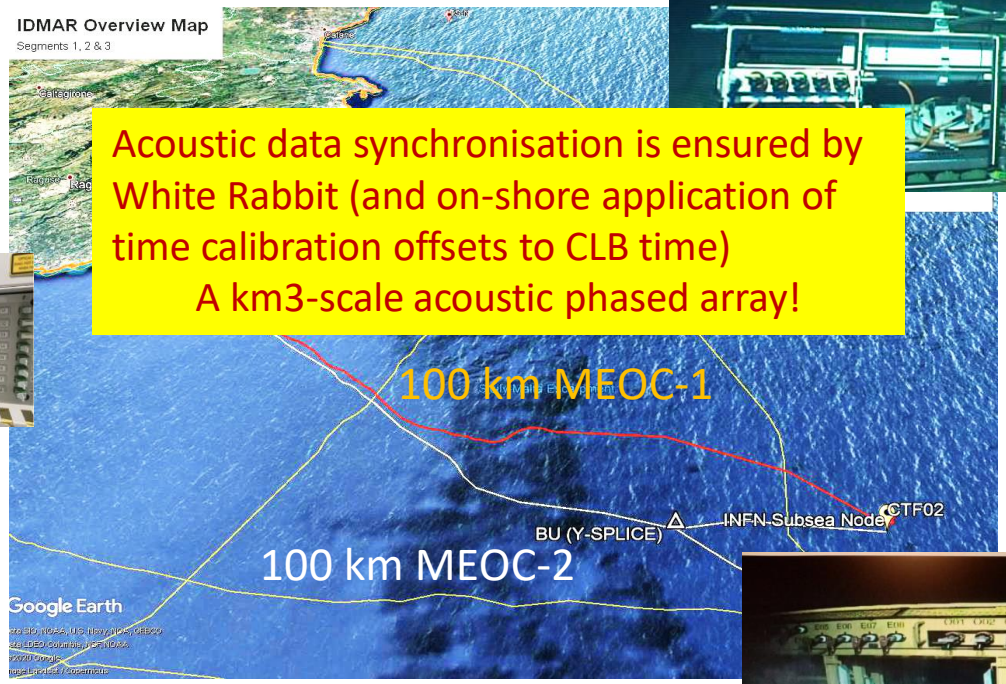
GPS

WR Grand Master

PMT data

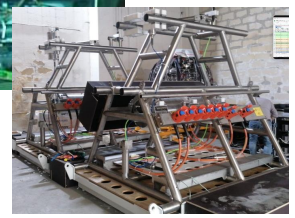
Phase 2: WR fabric

Phase 1: WR Broadcast
3 JBs, 28 DUs



Acoustic data synchronisation is ensured by White Rabbit (and on-shore application of time calibration offsets to CLB time)
A km3-scale acoustic phased array!

Phase 2: WR Point2Point
6 JBs, 85 DUs (x 2→block 2)



Junction Box

Detection Unit

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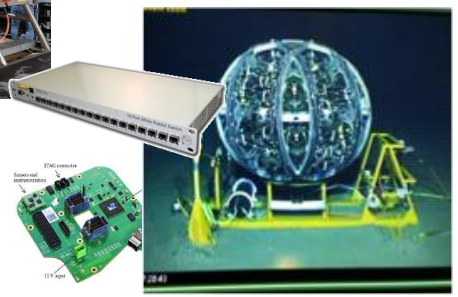


DU Base: switch WR slave
DOMs: CLB WR slaves

KM3NeT: Acoustic Positioning System

Navigation and absolute acoustic positioning system (NAAPS) - *commercial*

Used during sea operations to geo-reference the field asset

- Long Base-Line (LBL) of acoustic transducers (commercial).
- Ship (GPS reference) with main transducer

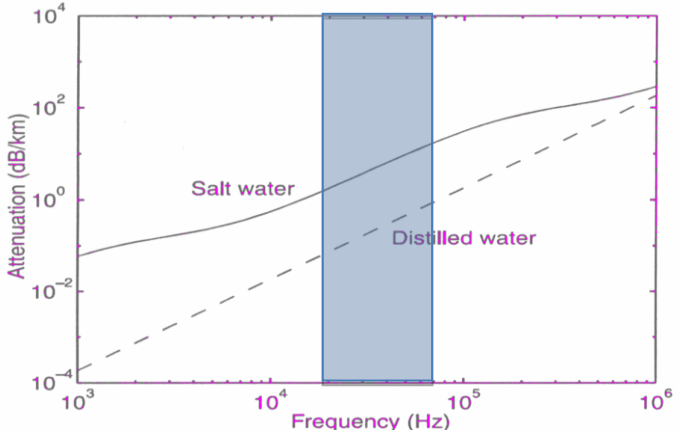
Relative acoustic positioning system (RAPS) - *custom KM3NeT*

Continuous monitoring of the DOMs positions

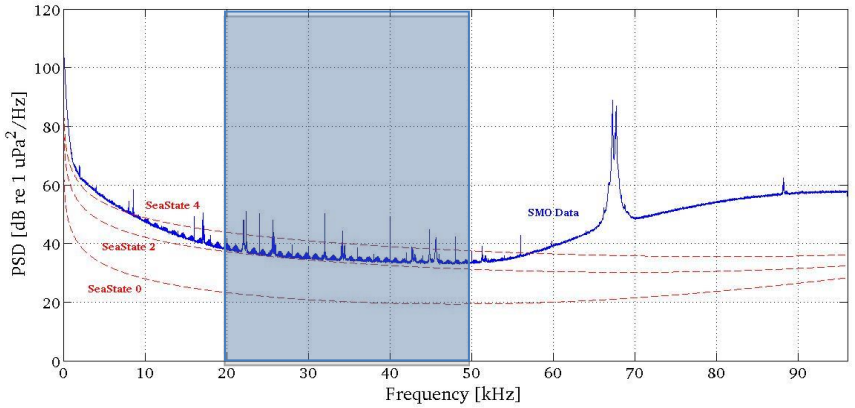
Acoustic Beacons (ABs) and Hydrophones, located at known positions on seabed

- Phased array of digital acoustic receivers (piezo) in each DOM

20 kHz – 50 kHz



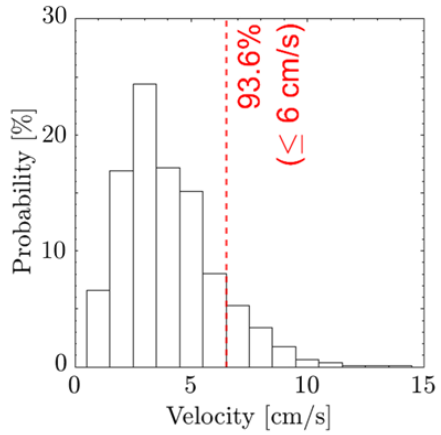
20 kHz – 50 kHz



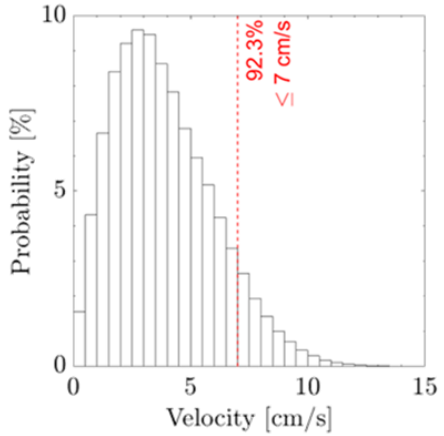
Suitable frequency range:
20 - 50 kHz
Lowest level of PSD:
~40 dB re 1 uPa²/Hz
Attenuation:
1-10 dB/km

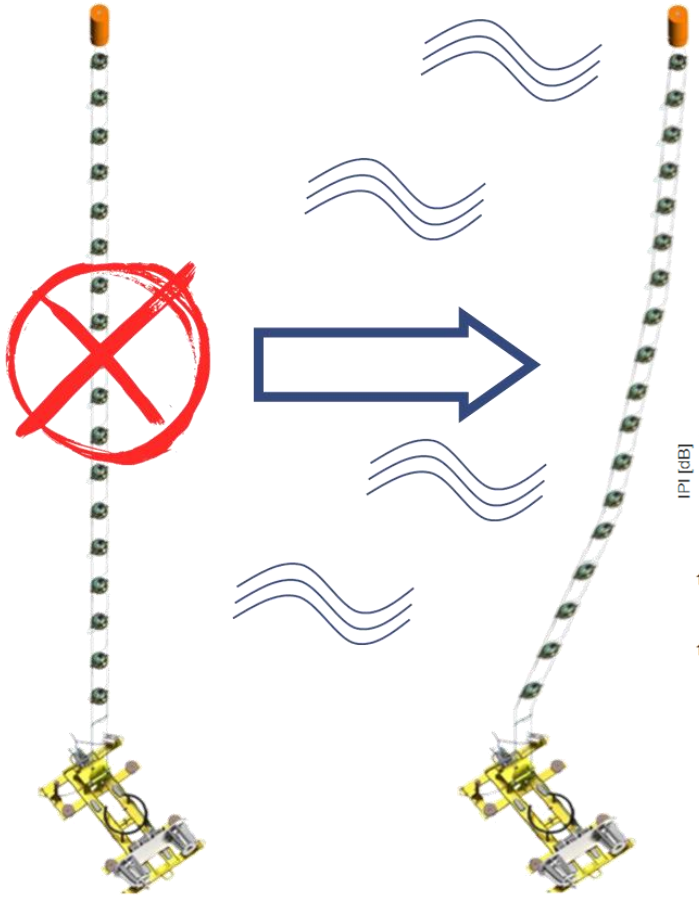
KM3NeT: acoustic positioning system

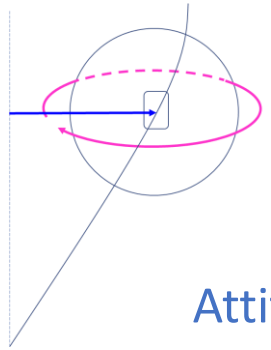
ARCA:
2001–2004 y 2007–2009



ORCA:
15/11/2020 – 15/11/2021

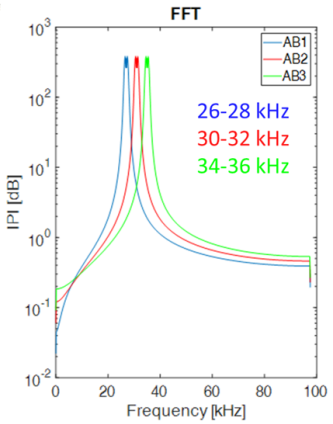


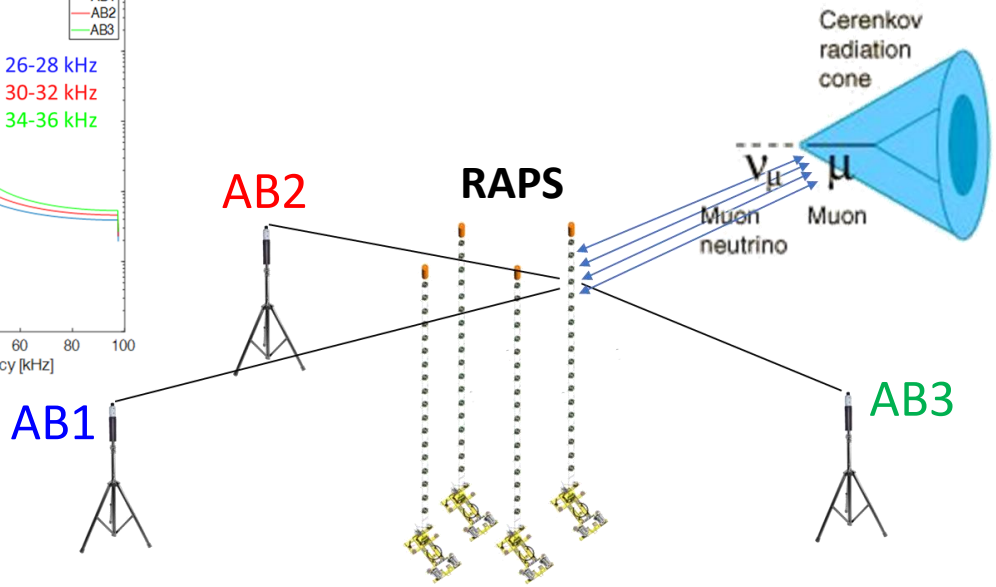




APS (DOM Position)
Acoustic Positioning System

AHRS (DOM Orientation)
Attitude and Heading Reference System

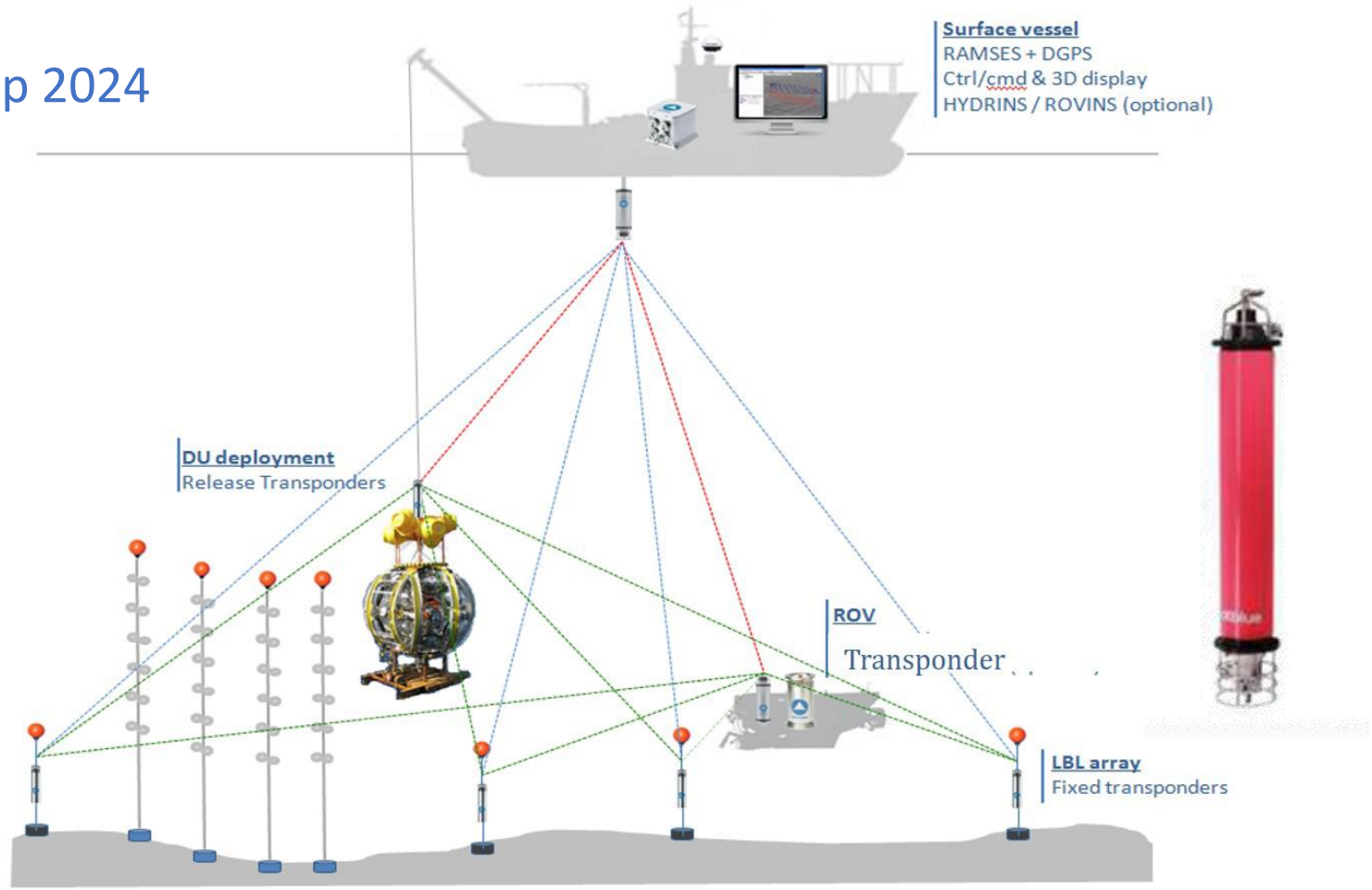




KM3NeT: NAAPS (commercial)

LBL (Ramses & Canopous iXBlue/EXAIL)
ORCA
ARCA starting from Sep 2024

Geo-referencing accuracy ≈2m

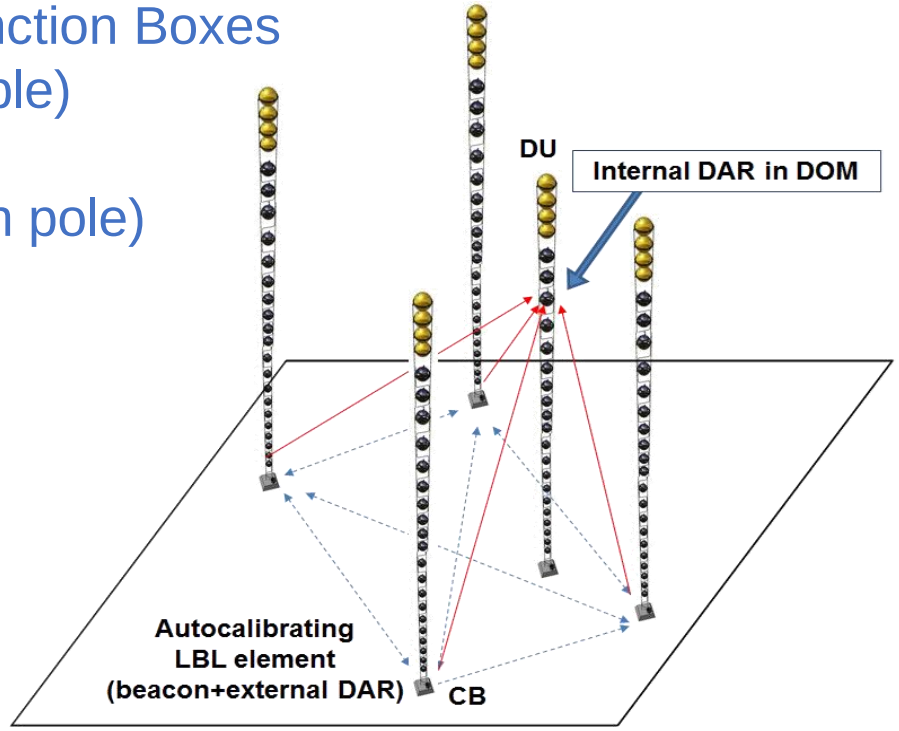


KM3NeT: RAPS proprietary

Digital acoustic receivers (192 kHz/24 bits) synchronized with detector master clock (<1 μs)
All data to shore in real time
→ the largest (scientific) phased array of acoustic receivers subsea

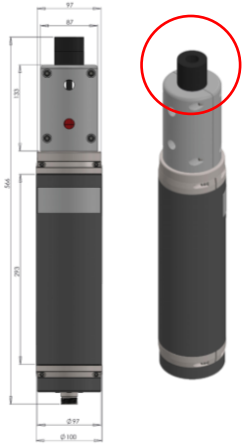
Long baseline of acoustic emitters and receivers

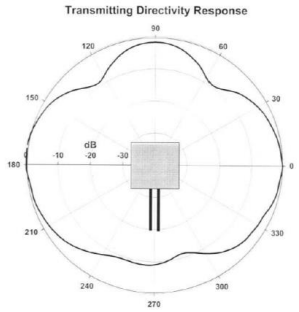
- reconfigurable beacons on selected DU bases and on ARCA Junction Boxes
- autonomous beacons on tripods at the subsea field rim (retrievable)
- hydrophones on each DU base and on ARCA Junction boxes
- acoustic sensors glued to the inside of each DOM (close to south pole)



KM3NeT RAPS: LBL Beacons

ARCA location of Acoustic Beacons (ABs):
- Selected DUs bases (ratio 1 DU Beacon/8 DU Standard)
- Junction Boxes (JBs): 6
- Calibration Base (CB): 1
- Tripod with Autonomous Beacons (TAB): 6 Available

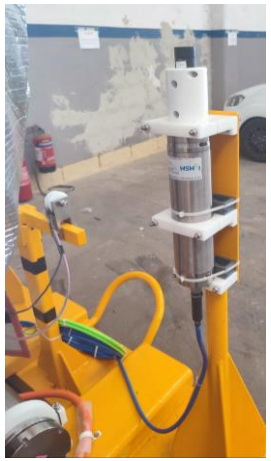




Sound Pressure Level (SPL)	170 dB (re 1 µPa at 1 m) in 30 kHz at 30 V
Frequency range	20 kHz to 60 kHz
Maximum variation of the TVR per frequency	±6 dB in the frequency range interval
Beam pattern (Radial; Horizontal plane)	Omnidirectional (±2dB) for each work frequency
Test Pressure	400 bars

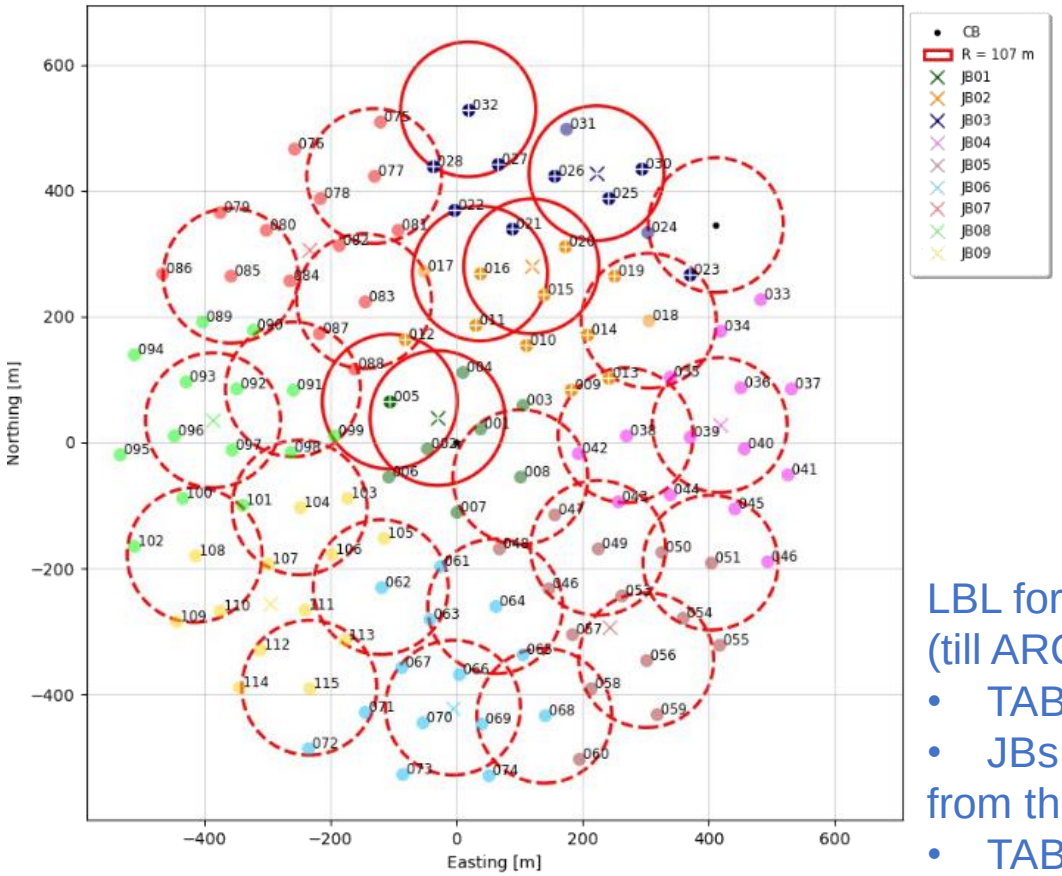
Supply Voltage	12 V
Current consumption	250 mA
Communications	Serial Port RS-232 Baud rate 9600, 8 bits No parity 1 stop bit
Trigger Signal	Differential 1Vpp galvanic isolated Accuracy > ±1µs
Emission Latency	<10 µs
Synchronization accuracy	<1 µs

AB in aluminium (TAB)



AB in titanium (DU,JB,CB)

KM3NeT RAPS: LBL Beacons in ARCA

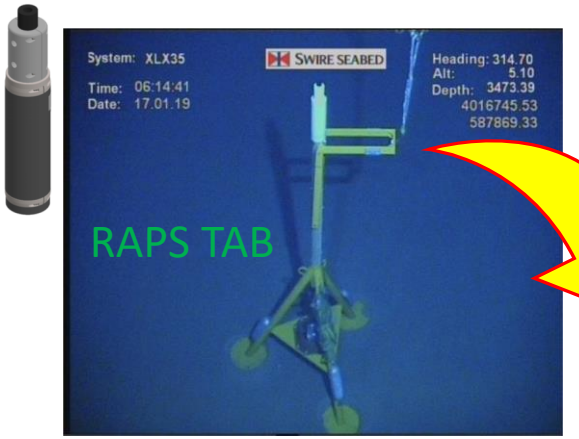


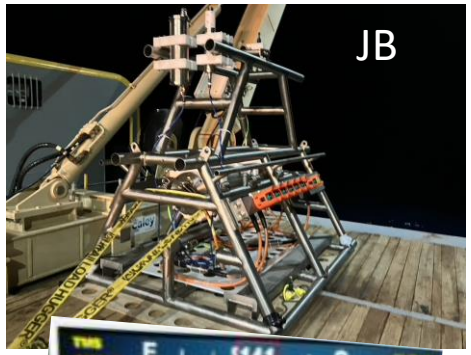
LBL for the NAAPS (till ARCA 28):

- TABs x3
- JBs x3

from the next sea op

- TABs x4 (+ Canopus)
- JBs >5 (+ 1 Ramses)

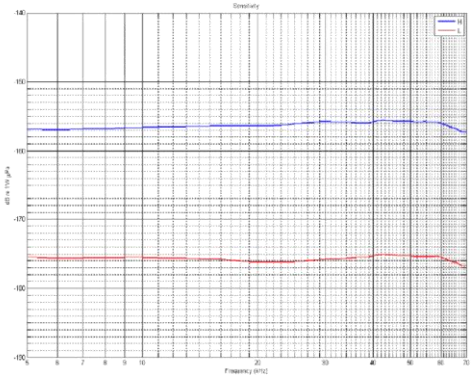


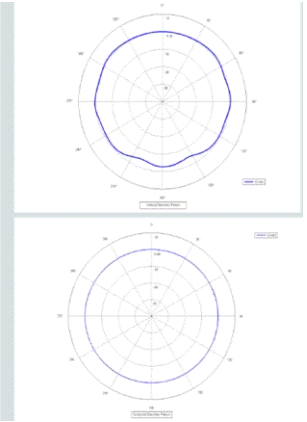


KM3NeT RAPS: LBL Hydrophones in KM3NeT

One hydrophone in each DU-Base, in CB and (in ARCA) in each JB

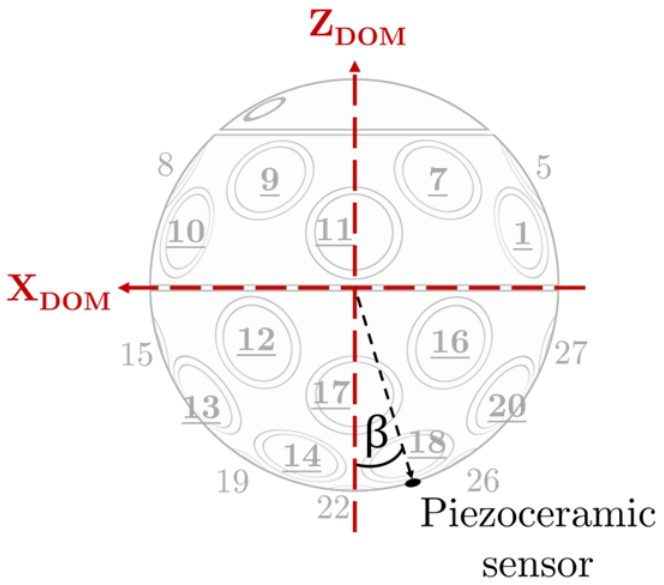
co.l.mar.





Working band: 5-90.000 Hz
High pass filter on preamplifier : 700 Hz (on demand)
CH1 output sensitivity: -156dB re 1V / uPa @ 5kHz
CH2 output sensitivity: -176 dB re 1V / uPa @ 5kHz
Directivity : Spherical - Omnidirectional
Max working depth : 3500 m
Gain @5kHz: 46 dB (CH1), 26dB (CH2
Equivalent input acoustic noise @5kHz: 34 dB re 1uPa / sqrtHz
Input impedance: 10 MOhm
Supply voltage range: 9 -18 Vdc
Current consumption: 100mA @ 12 Vdc
Output: AES3 protocol
Weight in air: 1600 gr with 4m cable
Body construction: POMC (stainless steel inner core)
Dimensions: 330 x 52 mm

KM3NeT RAPS: Piezo Sensors



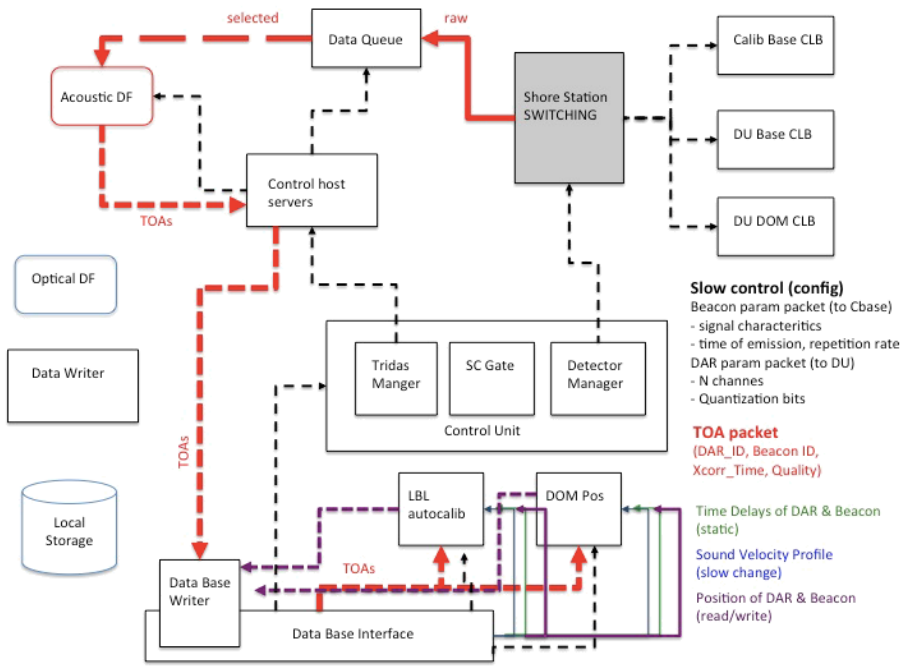
The movement of the DUs due to underwater currents is monitored thanks to "internal" piezo-electric Digital Acoustic Receivers (DAR) glued from the inside to the glass sphere of each KM3NeT Digital Optical Module (DOM)

The nominal sensitivity of the sensors is - 160 dB re 1V/μPa at 50 kHz with 3 dB variation (long time average) in the range 10:70 kHz.

10–70 kHz
-160 ± 6 dB (re 1 V/μPa at 1 m)

KM3NeT RAPS: Data Analysis

The acoustic positioning data analysis is entirely performed **on-shore**.
All acoustic receivers data are transmitted to shore.
A farm of PCs parse 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.



Time synchronised receivers
Hydrophone ID is encoded in the data-stream

Beacon ID is assigned by TOA Analyser (*x-corr* of the signal)

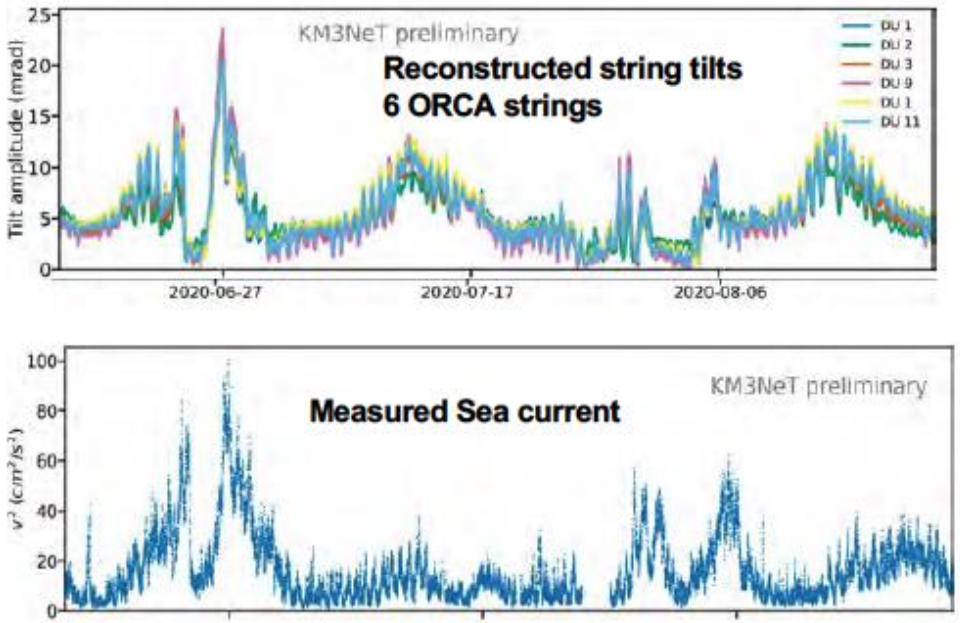
The system is flexible and modular:
Signal identification modules (signal, detection method) can be inserted in the ADF

The system can be adapted to search for biological or astronomy signals!

KM3NeT: RAPS

Goal 20 cm accuracy (1 ns / DOM radius)
Two reconstruction methods in action:
1) Global fit of ToAs (only DOM receivers) [used at present for data analysis for ARCA and ORCA]
2) Measurement of Time of Emission (ToE, beacon/hydro) and Time of Arrival (ToA, beacon/piezo) plus multi-lateration; independent measurement of DOM position

Method 1



ICRC 2023

C. Galtius at ICRC23 - PoS(ICRC2023)1033

Work in progress: DU mechanical fit, on-line monitoring of sound speed and sea current in situ

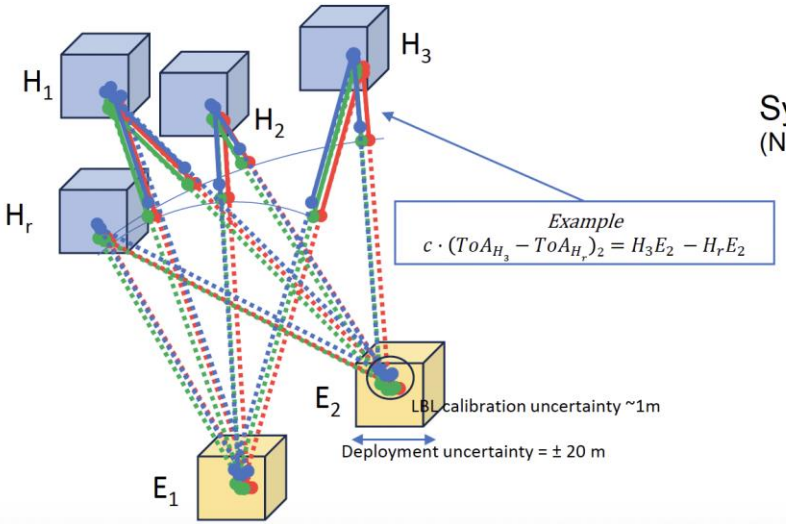
KM3NeT: LBL Autocalibration

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)

  - The accuracy on the relative positions of the fixed assets provided during deploymentsis too large to reach the accuracy on DOM relative positions requested by the project (~ 20 cm)

  - LBL calibration goal: reduce errors on relative positions of the fixed LBL elements



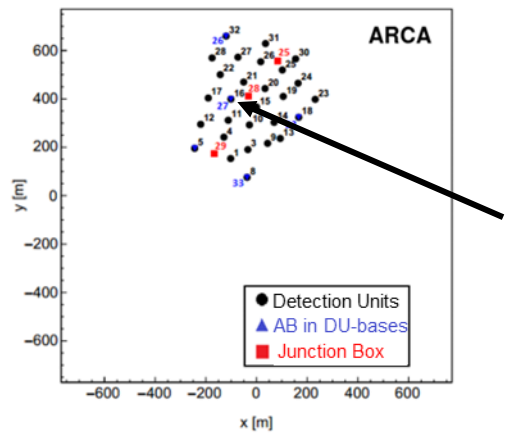
System of N*(M-1) equations in (N+(M-1))*3 variables
(N=number of emitters ; M=number of hydrophones)

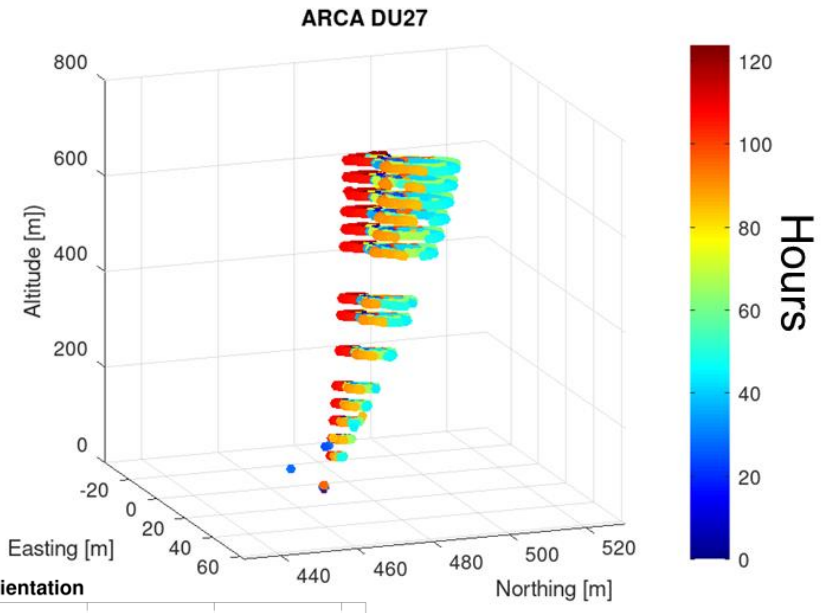
$$c \cdot (ToA_{H_i} - ToA_{H_r})_j = \overline{H_iE_j} - \overline{H_rE_j}$$

Sound velocity

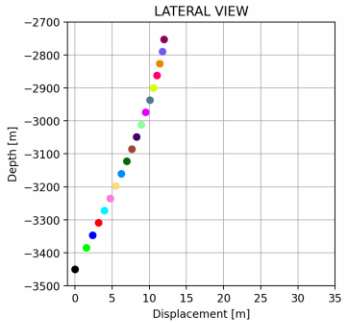
Method 2

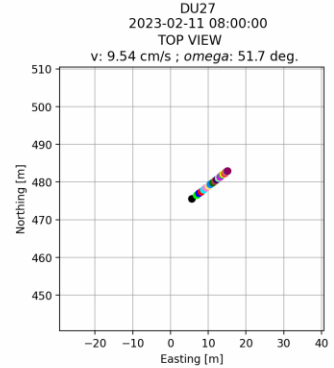
KM3NeT RAPS: DU reconstruction

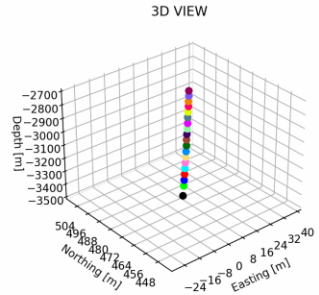


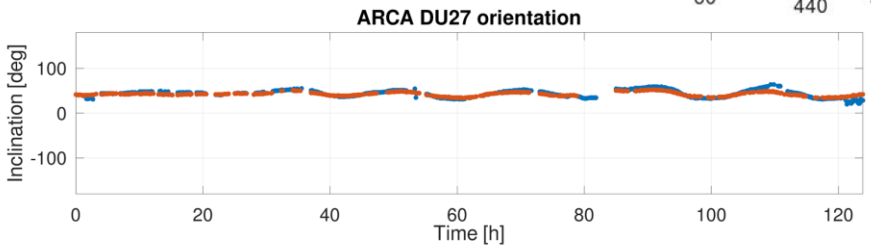


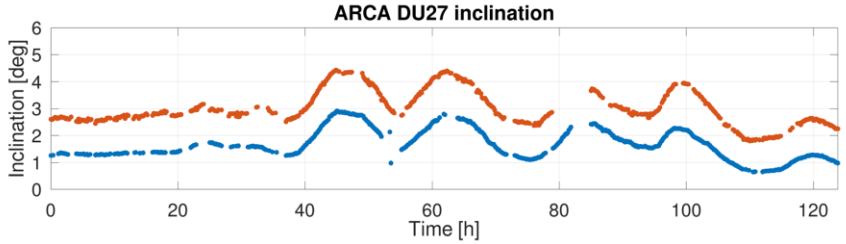
Method 2 Preliminary: WORK IN PROGRESS

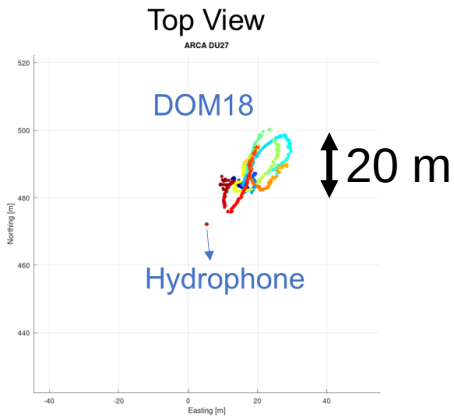


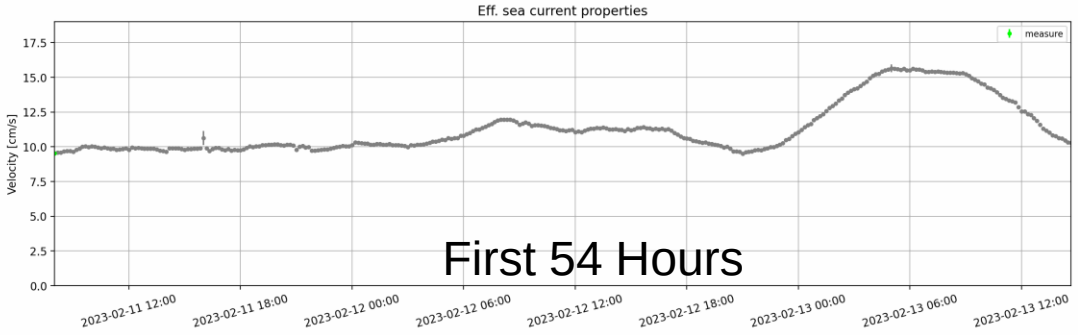












Summary and Outlook

Upon completion, the KM3NeT detector will be one of the largest tracker and calorimeter ever designed

Angular resolution (and overall sensitivity) is strongly dependent on DOM timing and position accuracy

Calibration of KM3NeT (Focal points)

- timing (ns accuracy required) – based on CERN White Rabbit paradigm (first time over multi 10km cables)

- Acoustic positioning (20 cm accuracy needed)
  - Innovative Acoustic Positioning System designed and operated. A km3 –scale acoustic phased array in sea !
  - actual accuracy dominated by absolute positioning uncertainties of emitters
  - Improved NAAPS, operation of more beacons and improved signal analysis should reduce soon the uncertainties

Cross fertilization with Earth and Sea Science well established

Opportunity for neutrino acoustic detection (studies)!

KM3NeT is a good candidate for detector due to the number of hydrophones (200 + 100) and peizoceramic sensors (4140 + 2160) that will be operational and synchronized with each other (directivity, trajectory, energy studies, etc...).

ARENA 2024 • 10TH INTERNATIONAL WORKSHOP
on Acoustic and Radio EeV Neutrino Detection Activities

Dídac Diego-Tortosa
(on behalf of Girogio Riccobene)
riccobene@lns.infn.it

CHICAGO • JUNE 11-14, 2024

INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

THANKS FOR YOUR ATENTION

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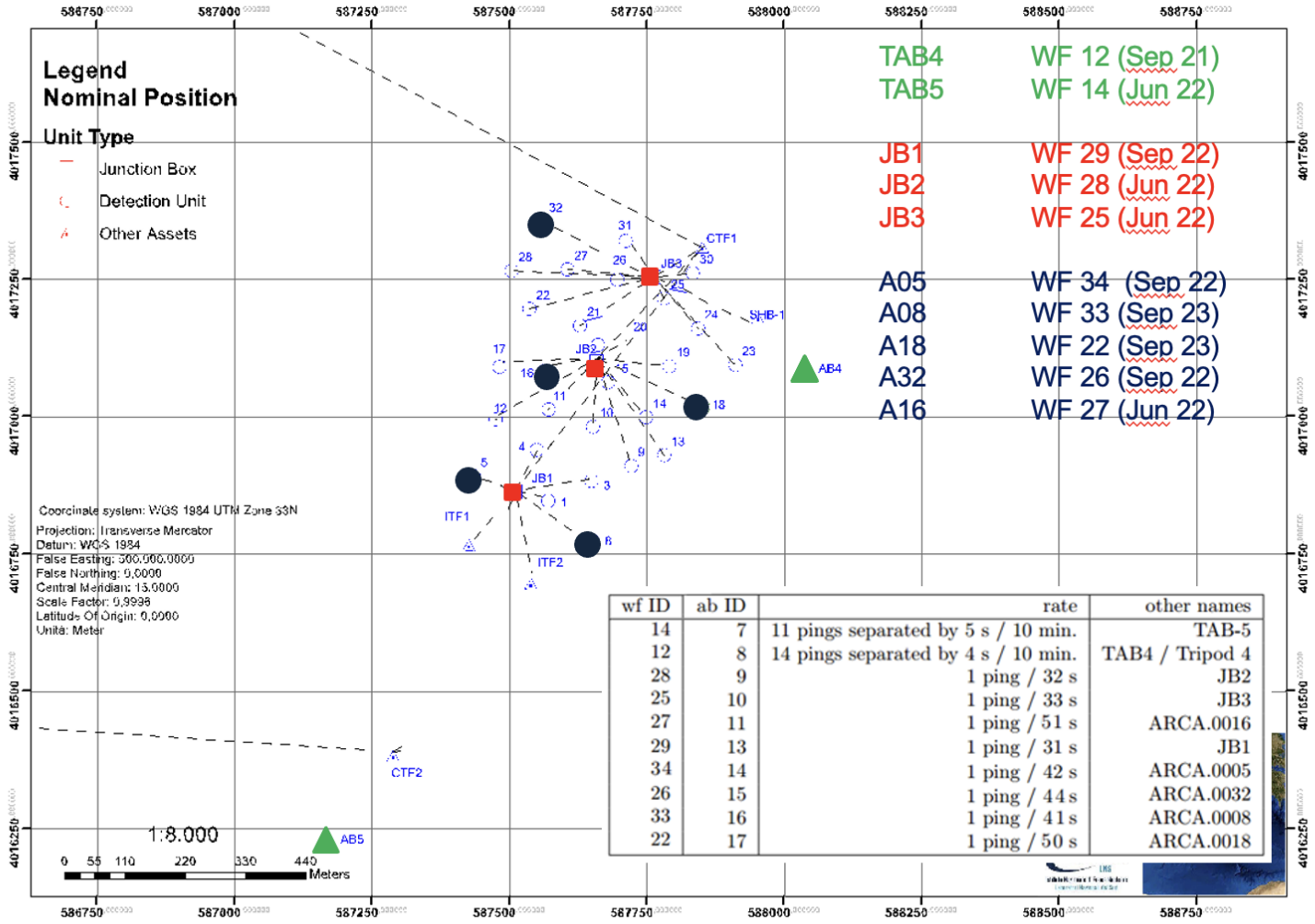
BACKUPS

KM3NeT: ARCA 28 snapshot

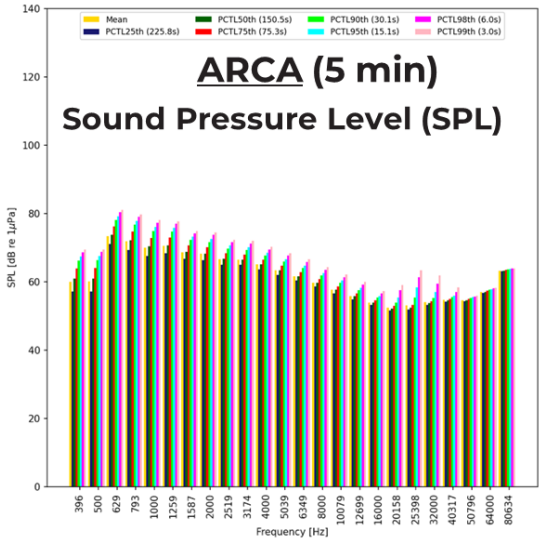


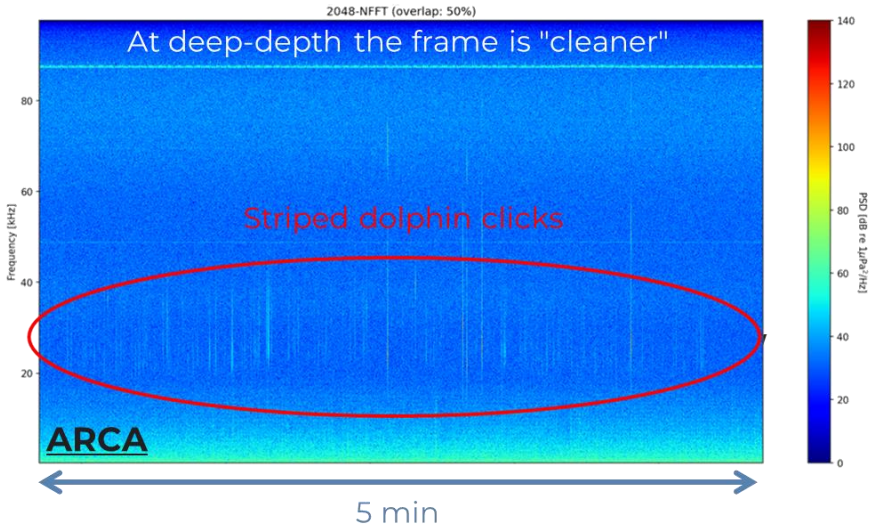
wf ID	ab ID	rate	other names
14	7	11 pings separated by 5 s / 10 min.	TAB-5
12	8	14 pings separated by 4 s / 10 min.	TAB4 / Tripod 4
28	9	1 ping / 32 s	JB2
25	10	1 ping / 33 s	JB3
27	11	1 ping / 51 s	ARCA.0016
29	13	1 ping / 31 s	JB1
34	14	1 ping / 42 s	ARCA.0005
26	15	1 ping / 44 s	ARCA.0032
33	16	1 ping / 41 s	ARCA.0008
22	17	1 ping / 50 s	ARCA.0018

Assets and waveforms

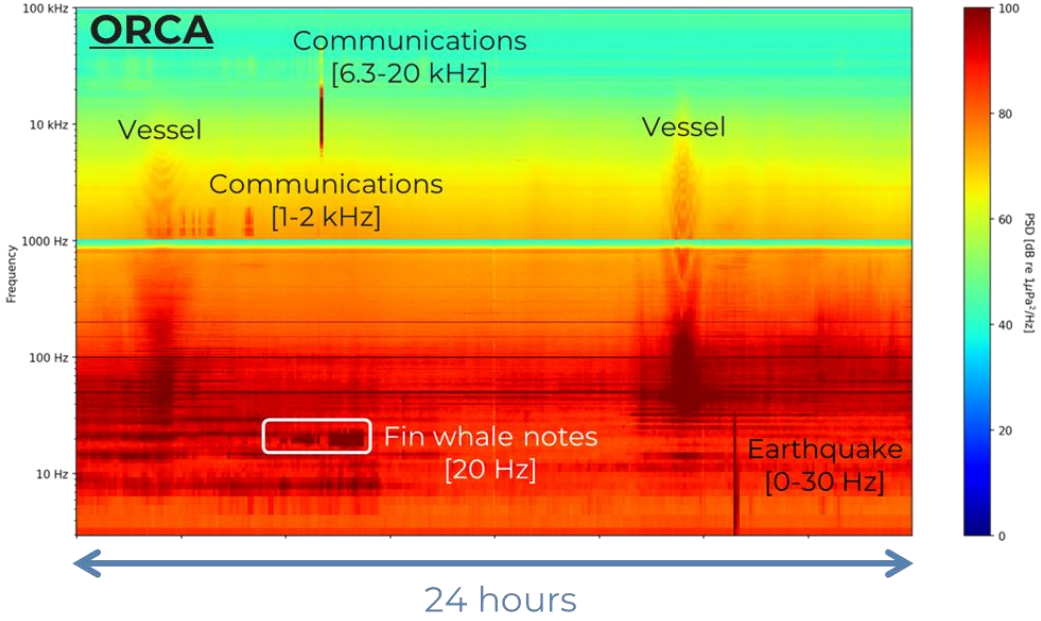
KM3NeT RAPS: Multidisciplinary science

KM3NeT is a huge acoustic sensors array connected onshore:
Possible marine science laboratory (monitoring noise levels, detection of bioacoustic events...)

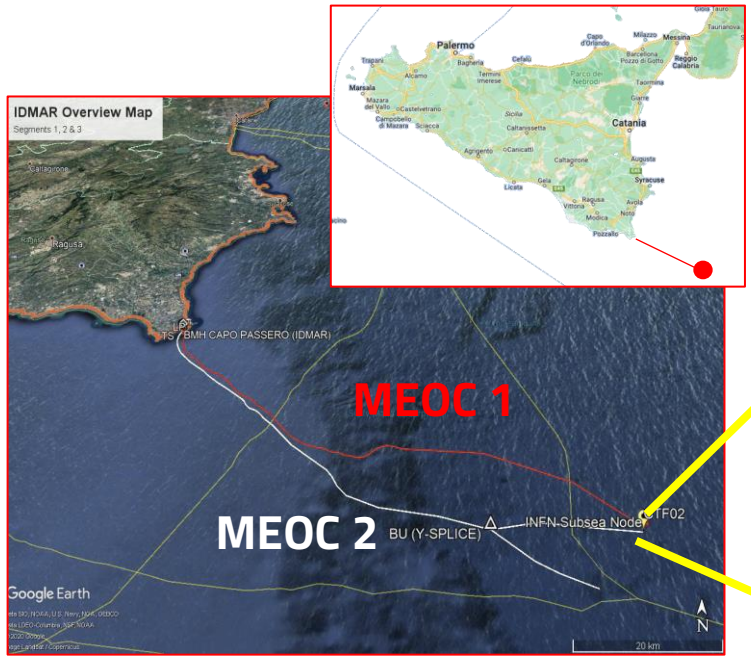


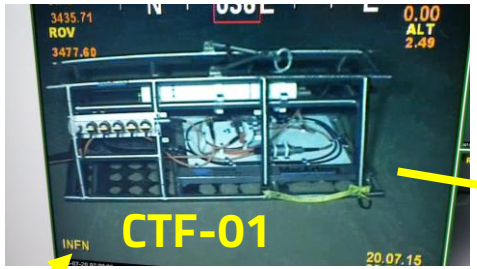


Percentile (PCTL) 99th of PSD in long-term to represent impulsive noises



INFN-LNS: Marine infrastructure East Sicily

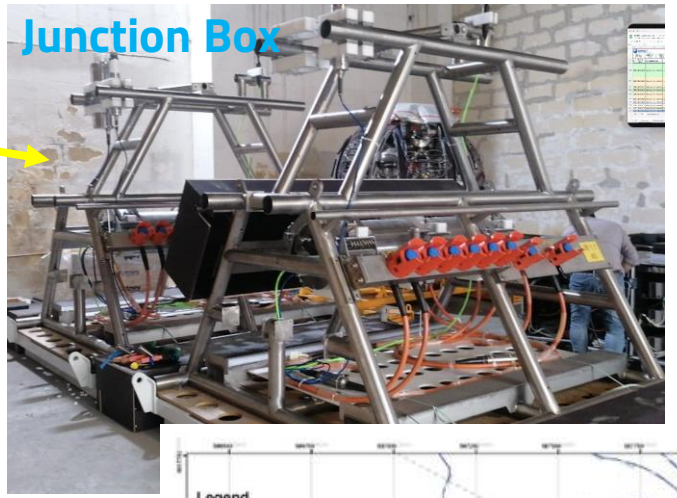


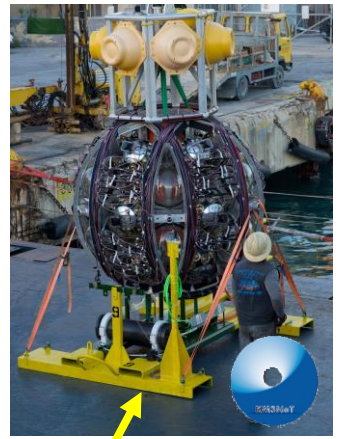


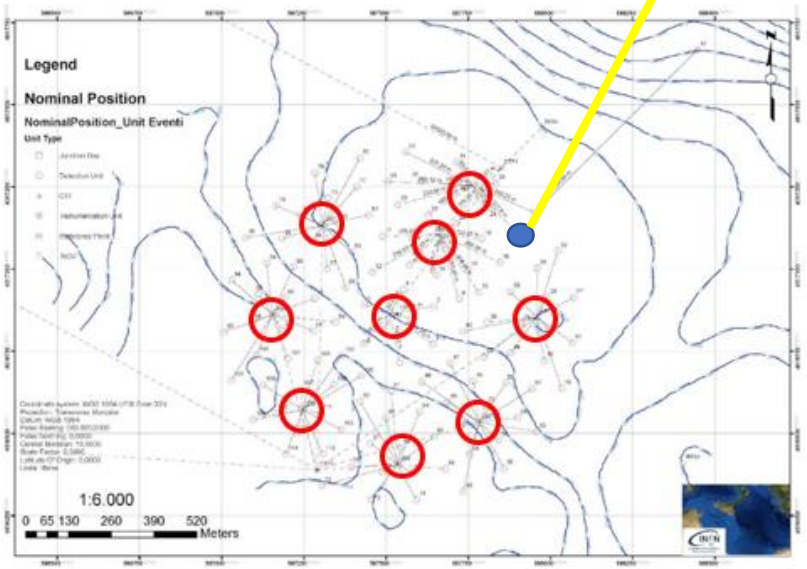
5 electro-optical ports in CTF 1

16 electro-optical ports in CTF 2

9 JBs: 12/14 electro-optical ports per JB







The Capo Passero site

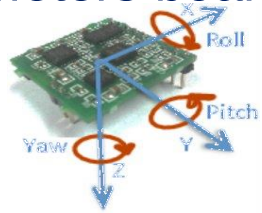
deep-sea infrastructures and observatories offer unprecedented tools to

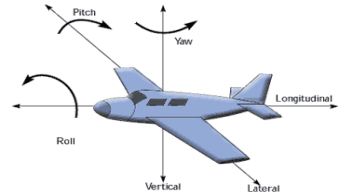
- develop and test novel marine technologies and detectors
- monitor geophysics and biological phenomena and anthropic footprint

KM3NeT DOM orientation: AHRS boards

DOM orientation/tilt constantly monitored by 3D compass + 3D accelerometers board

- 3D orientation reconstruction of the DOM: (yaw, pitch, roll)
- Continuous data flow

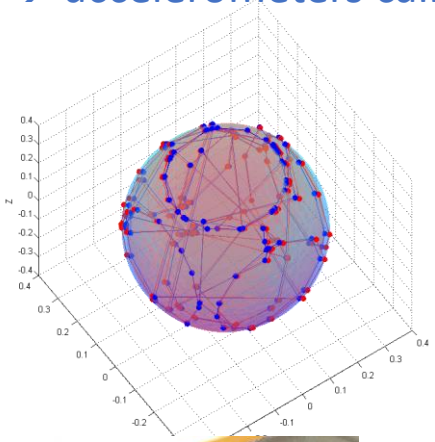


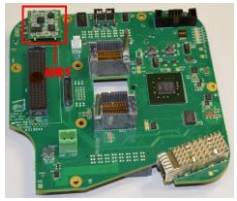


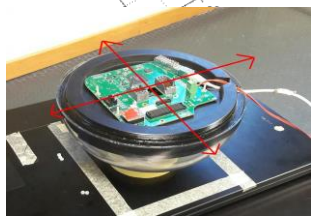
3D CLB "wobbling"

→calibration of "hard iron" effects of compass

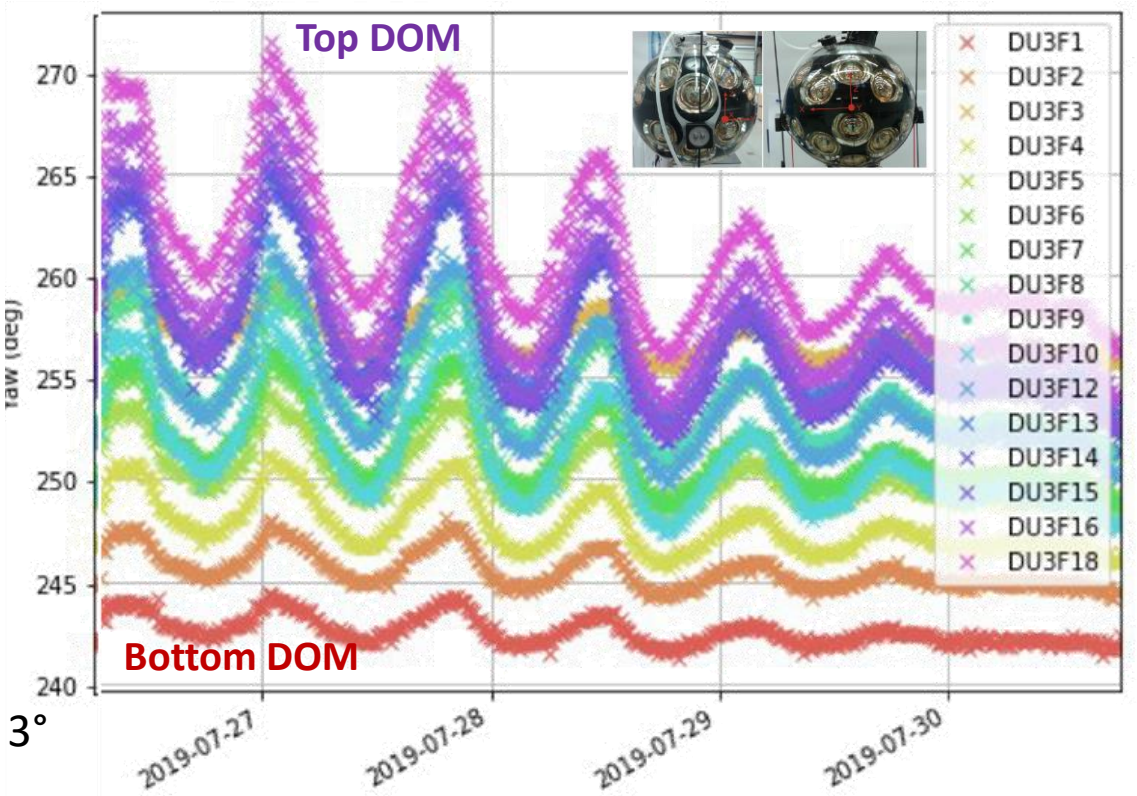
→ accelerometers calibration







target resolution 3°



KM3NeT: calibration unit

Allow streaming of water column oceanographic properties

- Sound Velocity
- Water Current (Doppler acoustic sensor)
- Conductivity, Temperature, Depth, Oxygen Probe (CTD)
- Absolute Pressure (bottom)

ARCA 700 m
ORCA 300 m

inductive cable technology
(no connectors, up to 100 instruments)

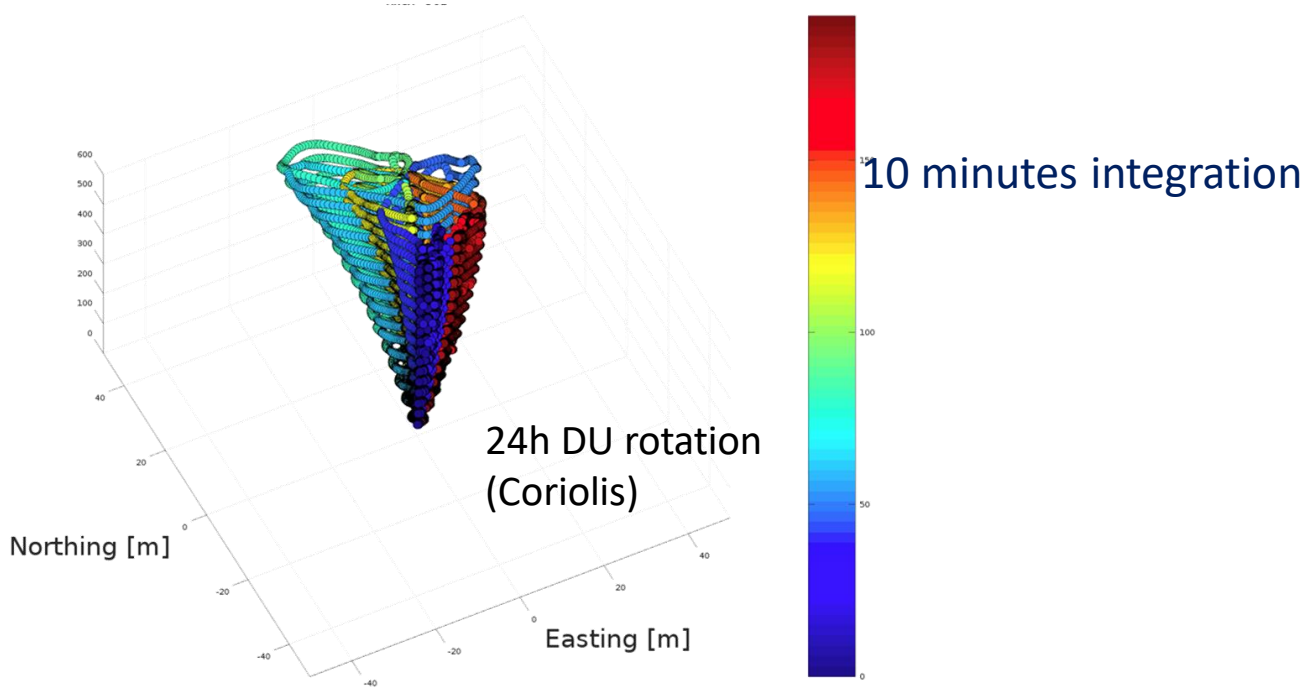
Retrievable unit: re-calibration/re-configuration of instruments

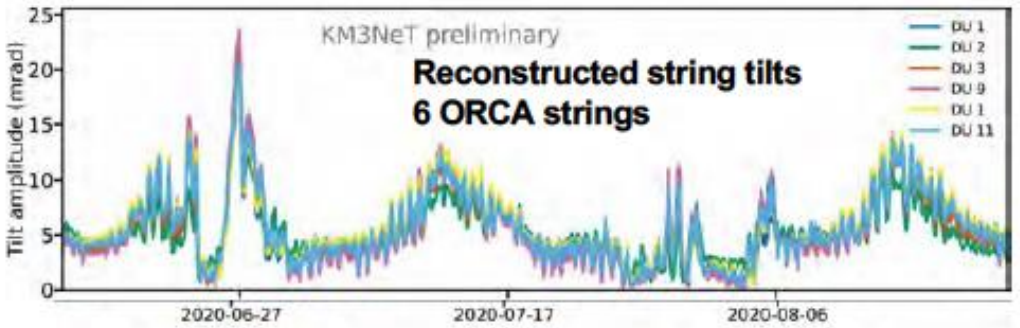
Installed far at the rim of the detector footprint
for safe multiple recovery/deployment

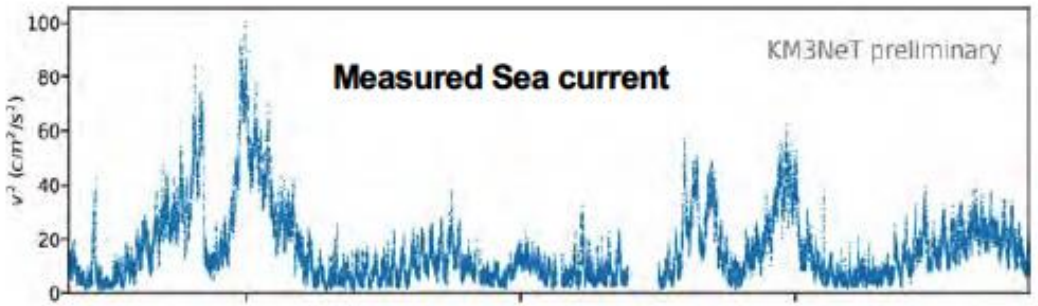
R. Le Breton JINST 16-C09004, 2021

KM3NeT: Positioning Analysis

Goal 20 cm accuracy (1ns / DOM radius)
Two reconstruction methods in action:
1) Measurement of time of emission (ToE, beacon/hydro) and Time of arrival (ToA, beacon/piezo) plus multi-lateration; LBL calibration and independent measurement of DOM position
2) Global fit of ToAs (only DOM receivers) [used at present for data analysis for ARCA and ORCA]







C. Galtius at ICRC23 - PoS(ICRC2023)1033

Work in progress: DU mechanical fit, on-line monitoring of sound speed and sea current in situ (IU)