Calibration of the KM3Net Detector

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INFN – Laboratorari Nazionali del Sud

INTERNATIONAL WORKSHOP ON NEXT GENERATION NUCLEON DECAY AND NEUTRINO DETECTORS (NNN16)

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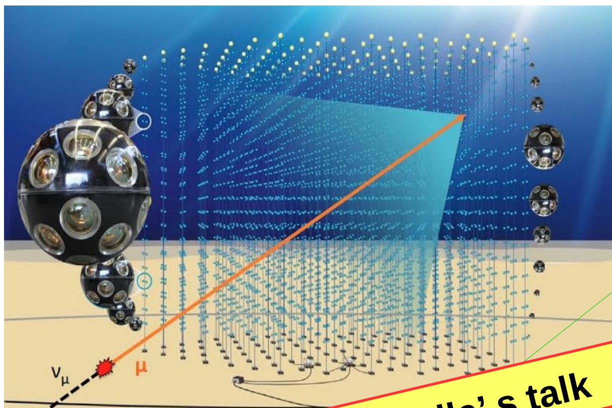
The KM3NeT detector

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

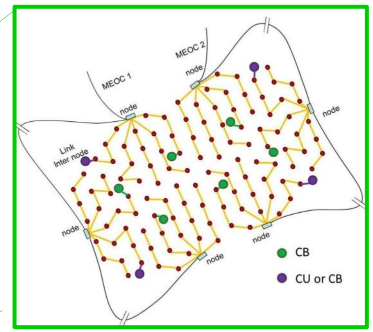


See Marco Circella' s talk

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

KM3NeT – ORCA (Phase 2)

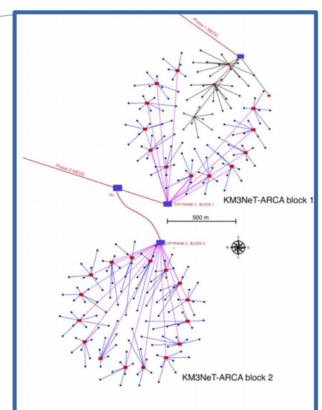
Oscillation Research with Cosmics in the Abyss



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

KM3NeT -ARCA (Phase2)

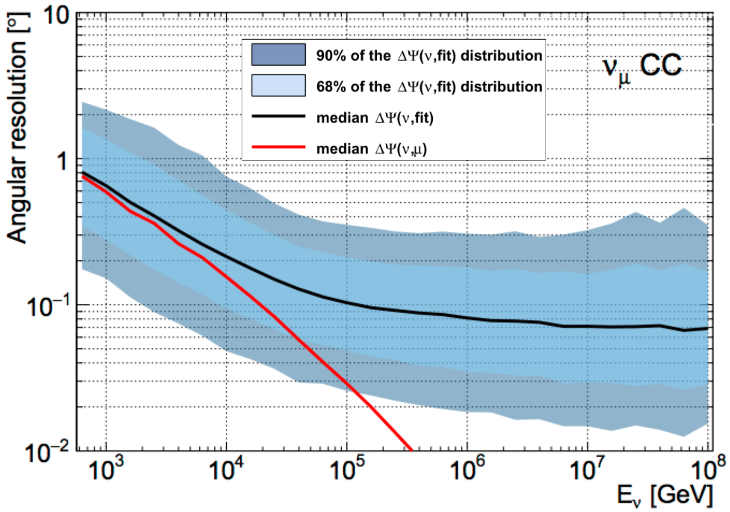
Astroparticle Research with Cosmics in the Abyss



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

KM3NeT ARCA (Phase 2) performance

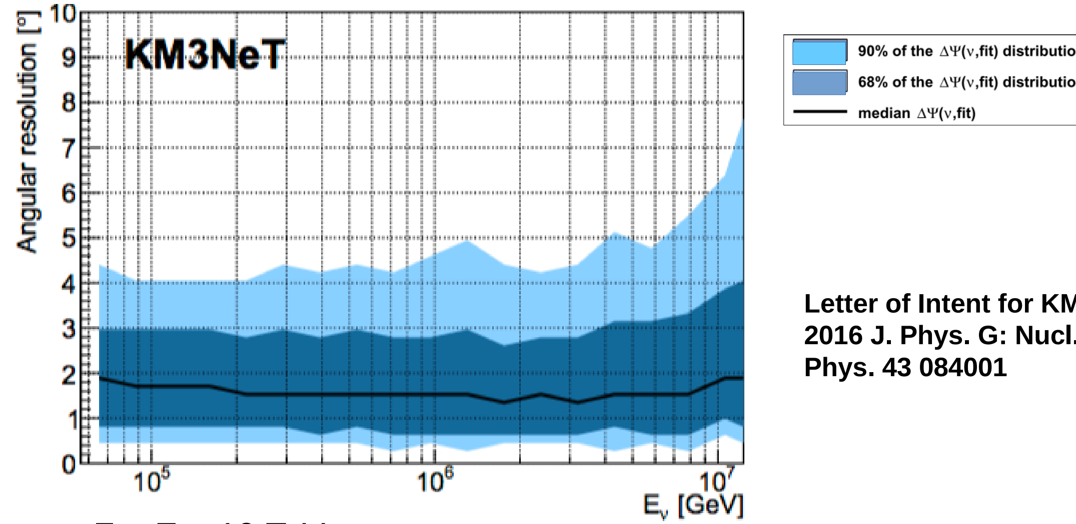
Tracks (muons)



For E_ν >10 TeV

Median angular resolution <0.2°

Cascades



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

For E_ν >10 TeV

Median angular resolution < 2°

Project requests

DOMs position accuracy < 20 cm

DOMs orientation accuracy < 3°

Calibrated PMT amplitude response

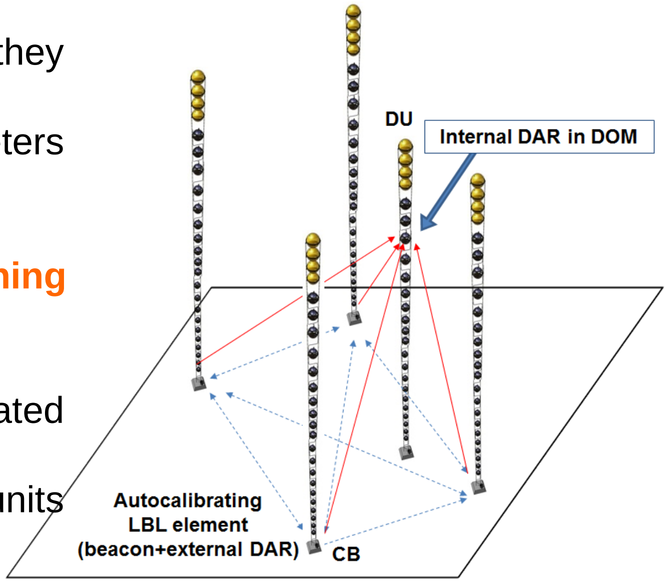
Relative hit times accuracy ~ 1 ns

KM3NeT positioning system 1/3

The KM3NeT DUs are kept vertical under the pull of a buoy but nevertheless they move a bit under the action of currents.
Continuous monitoring of the DOMs positions with an accuracy of tens of centimeters is an essential requirement for accuracy direction reconstruction

The positions of the DOMs are recovered through an acoustic positioning system that is composed of three main sub-systems:

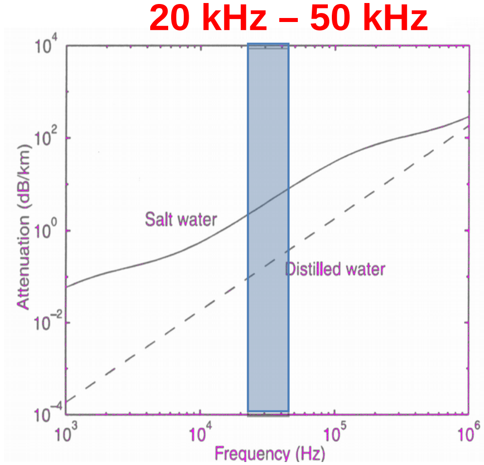
- a Long Base-Line (LBL) of acoustic transmitters (beacons) and receivers, located at known positions
- an array of digital acoustic receivers (DARs) installed along the detection units (DUs) of the telescope
- a farm of PCs for the analysis of acoustic data

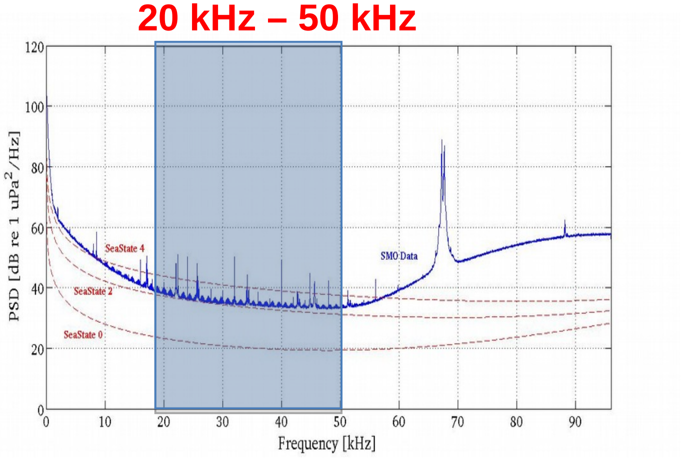


- **Beacon signals must be detected at distances of 1 km**
-
- **Suitable frequency range 20 kHz-50 kHz**

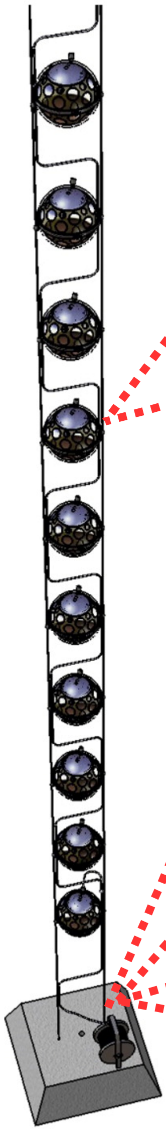
✓ **lowest level of PSD (~40 dB re 1 uPa²/Hz)**

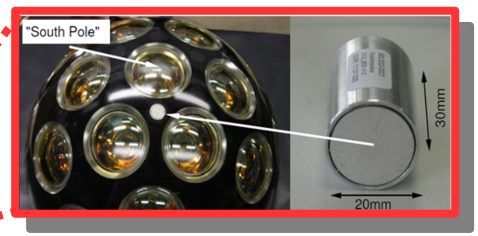
✓ **attenuation (0-10 dB/km)**





KM3NeT positioning system 2/3



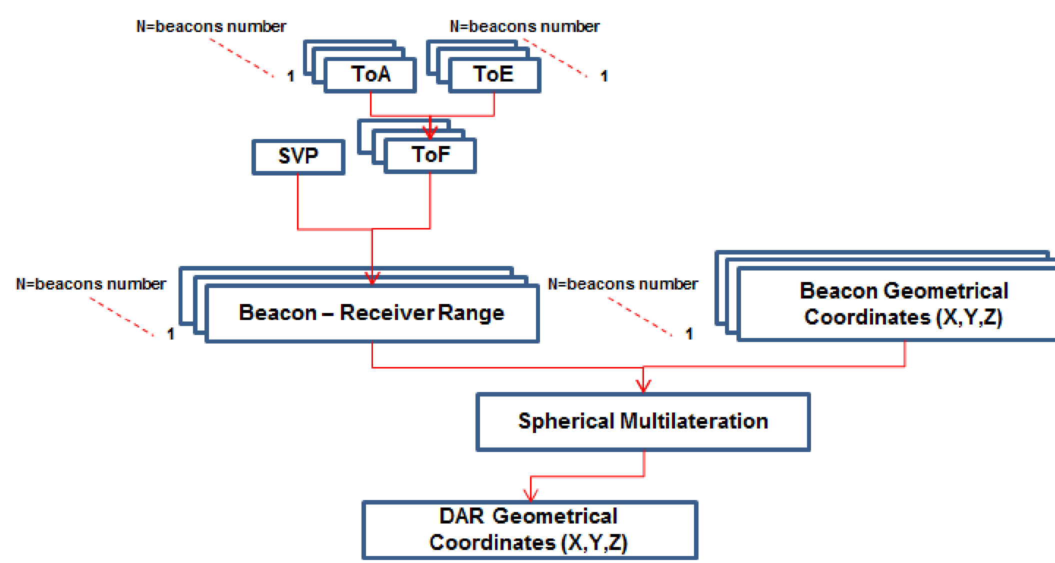


Internal digital acoustic receiver

External digital acoustic receiver

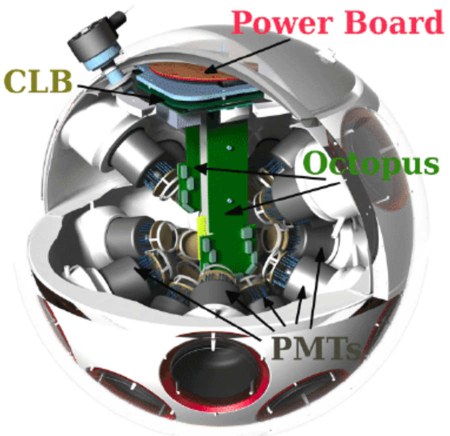
Acoustic Beacon

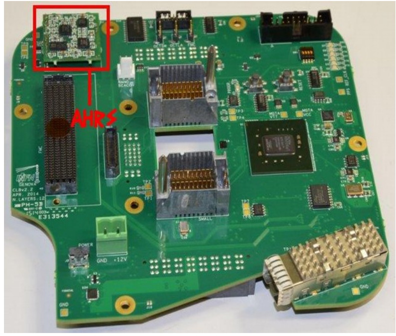
- The time of emission (ToE) is synchronized with the detector master clock with calibrated time delay of 7±1 μs.
- Acoustic data filters analyze the acoustic data stream in real time searching for active beacons' signals. Proper matched filter algorithms, based on cross-correlation functions, will recover the time of arrival (ToA) of the signals in the acoustic sensor



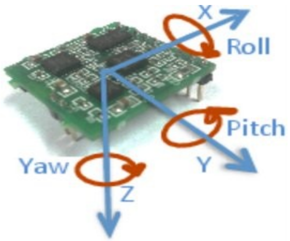
KM3NeT positioning system 3/3

Monitoring of the absolute orientation and acceleration of each DOM through an Attitude & Heading Reference System



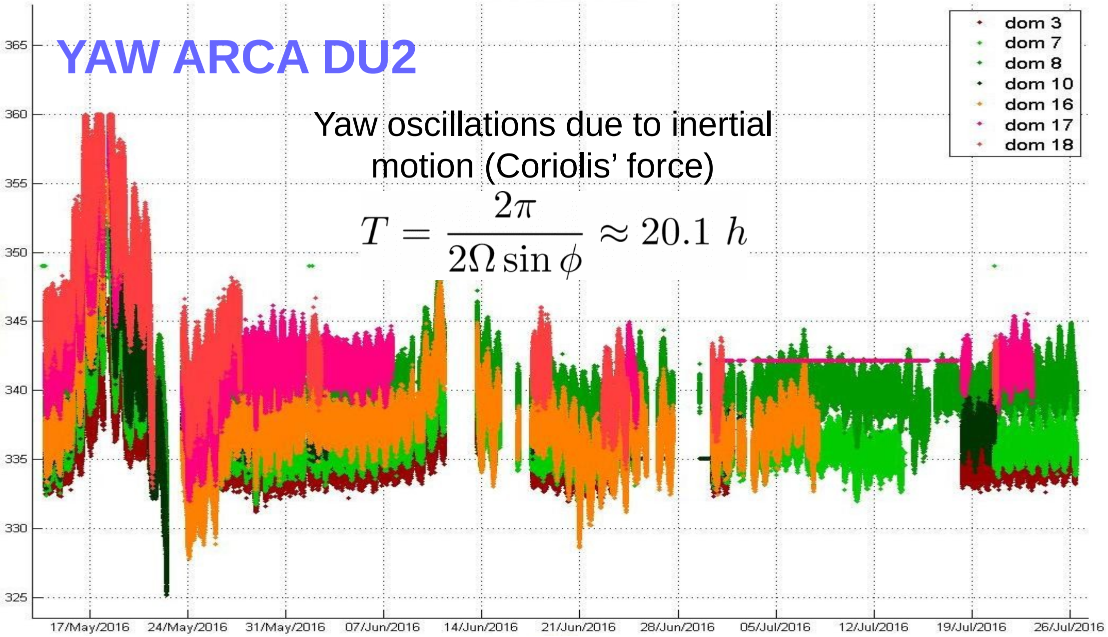


Control Logic Board (CLB)



AHRS
Attitude & Heading Reference System

- **Triaxial accelerometer** LIS3LV02DL
- **Triaxal magnetometer**
- HMC5843
-

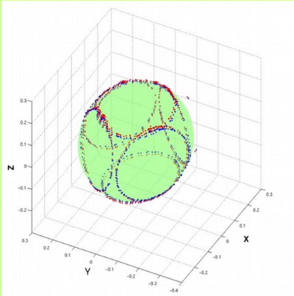


Yaw oscillations due to inertial motion (Coriolis' force)

$$T = \frac{2\pi}{2\Omega \sin\phi} \approx 20.1\ h$$

Each AHRS must be calibrated before the CLB integration in the DOM to take into account Hard Iron and Soft Iron effects.

Rotation of the magnetometer in the uniform magnetic field produces an ellipsoid in Hx,Hy,Hz space.



Calibration matrix

New single chip solution for KM3NeT 2.0

3 axial magnetometer and accelerometer in one chip

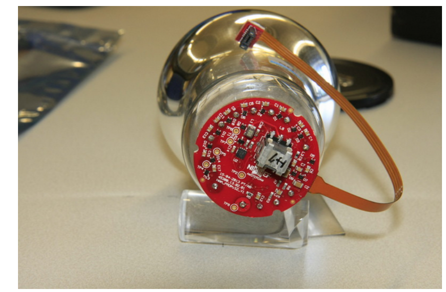
PMTs signal amplitude calibration

Massive test and calibration of PMTs in a special “Dark Box”, designed by the KM3NeT Collaboration to calibrate 62 PMTs simultaneously. **The Dark Box system allows to test up to 124 PMTs per day.**

The Dark Box automatically performs the following tests on each PMT:

- Determination of the optimal operating voltage;
- Dark count rate measurements;
- Measurements of spurious pulses (prepulses, afterpulses, delayed pulses)
- Transit Time (TT) measurements;
- Transit Time Spread (TTS) measurements;

After the test a data-sheet for each PMT is generated.
Calibration results are stored in a database



PMT operating voltage is tuned in order to have a gain of $3*10^6$, which corresponds to a Time over Threshold (ToT) of 26.4 ns for a single photo-electron

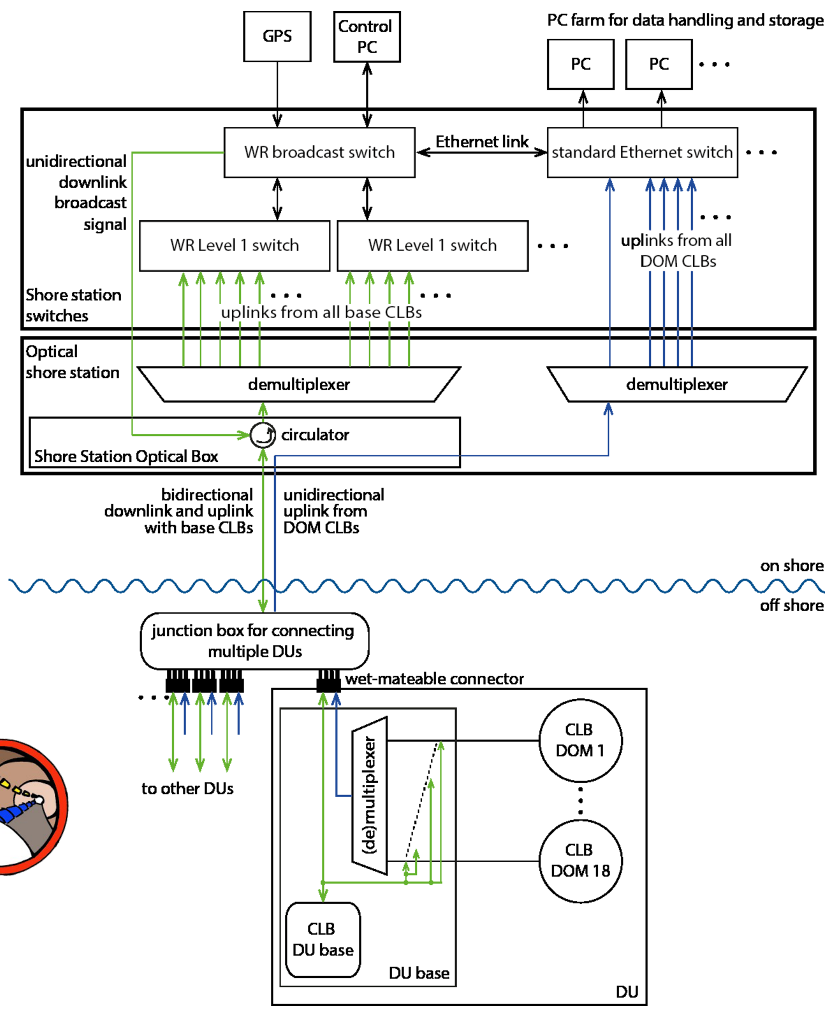
Different Transit Time for each PMT

Time Calibration

The signals from the PMTs are timestamped by the offshore nodes. The timestamping is performed by an FPGA, that is mounted on the Central Logic Board (CLB) inside the Digital Optical Module (DOM) that also contains the PMTs. Time synchronization of the nodes is based on a hybrid White Rabbit protocol.

- **Base CLBs:**
  Synchronization of all Base CLBs is achieved by establishing a WR link and subsequently by the Precision Time Protocol (PTP). **Time offset for each Base CLB is recovered from the Round Trip Time taking into account the time asymmetry of the transmission system**

- **DOM CLBs:**
  For all DOM CLBs the KM3NeT detector makes use of a clock distribution based on a fiber-optic **broadcast** (1 Gb/s)



Time calibration steps

The time calibration of each PMT of the telescope is obtained by the combination of:

- Calibration of the shore station and seabed infrastructures (asymmetry measurements)
- Intra-DOM calibration
- Inter-DOM calibration
- Inter-DU calibration

Time calibration of the shore station and seabed infrastructures

WR continuously performs round trip time (RTT) measurements to maintain the time synchronization between master and slave (base CLBs). The precise knowledge of the link delay is obtained by accurate hardware timestamps and calculation of the link asymmetry.

Time asymmetry calculation

Based on RTT measurements by using a reference CLB and time-calibrated optical patchs

- Measurement of the fixed delays, including circuit, electronic components, and FPGA internal latencies
- Measurement of the time asymmetry due to to the different paths of the signals in the shore station rack and junction boxes

Chromatic dispersion in the fibers

Due to the difference between the wavelength that is used for the downlink clock signal (λ_c) and the wavelength that is used for the uplink signal (λ_i) from the CLB in the base containers.

$$\Delta T_{dispersion}(\lambda_i) = T_{down}(\lambda_c) - T_{up}(\lambda_i)$$

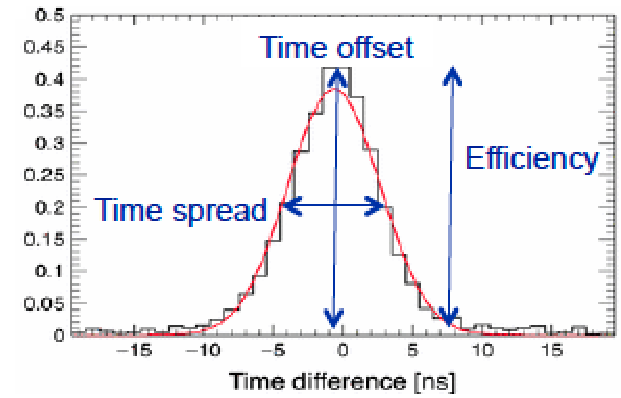
$$= L\left(\frac{1}{v(\lambda_c)} - \frac{1}{v(\lambda_i)}\right)$$

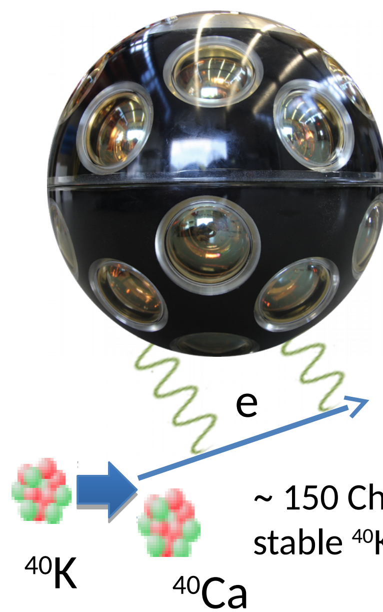
Measured on the main electro-optical cable (looped back)

Intra-DOM calibration based on ^{40}K

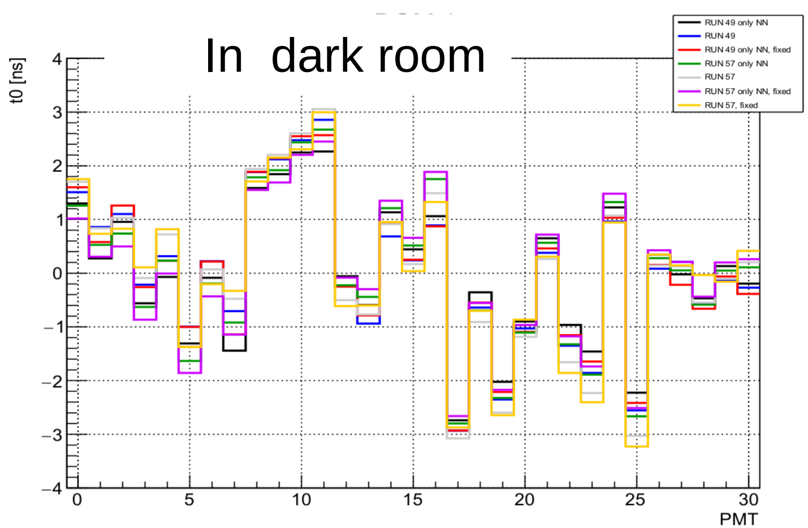
The relative time offset of the PMTs in each DOM can be obtained from the dark room data by analyzing the signal from ^{40}K in the glass sphere of the DOM. This can also be done after deployment of the DU, by analyzing the signal from ^{40}K in the sea.

2-fold PMT coincidence in a DOM

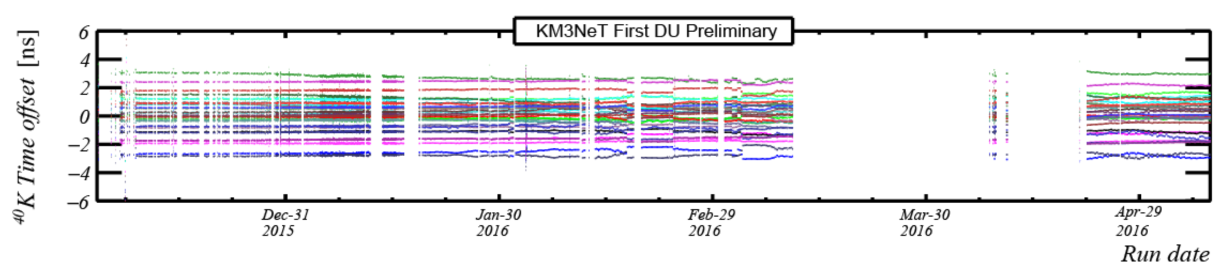




~ 150 Cherenkov photons per decay
stable ^{40}K concentration



In situ (3000m-3500m water depth)

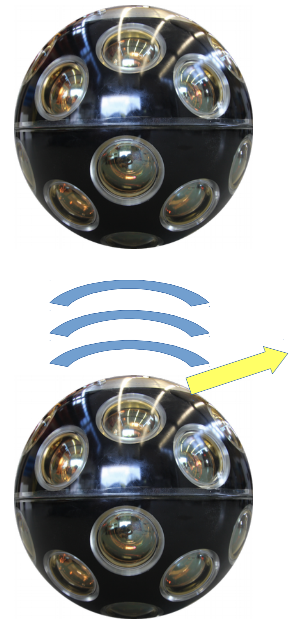


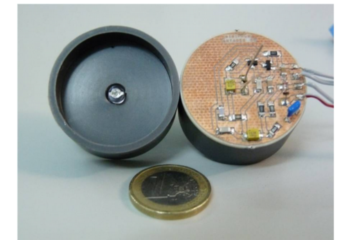
Inter-DOM calibration in situ

Nanobeacons

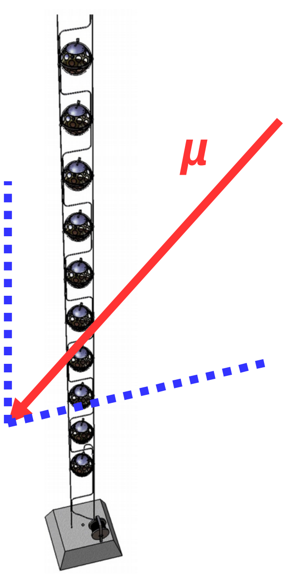
Each DOM is equipped with a remotely controlled flashable LED (nanobeacon), installed on the top of the DOM, pointing upward to DOMs higher in the DU.

The difference between the time of the detection of the LED light and the emission time of the light by the LED is monitored, by using the PMT time offsets obtained from the dark room and taking into account the travel time of the light in the medium.



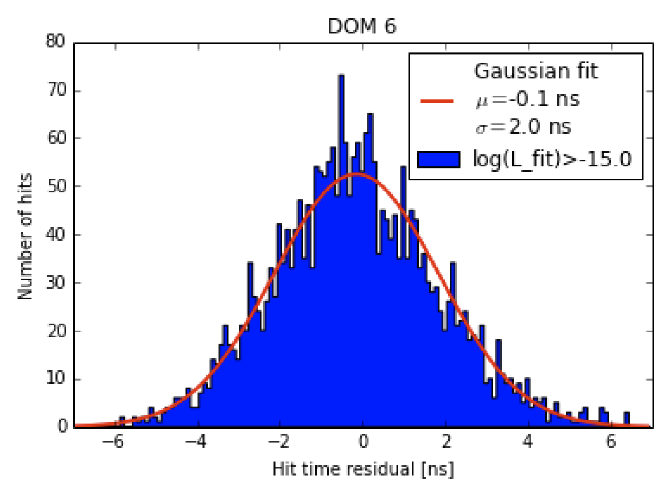


Rise time: ~2 - 3 ns
Wavelength: 470 nm
Repetition rate: 1 Hz - 20kHz
Intensity: 0-24 V



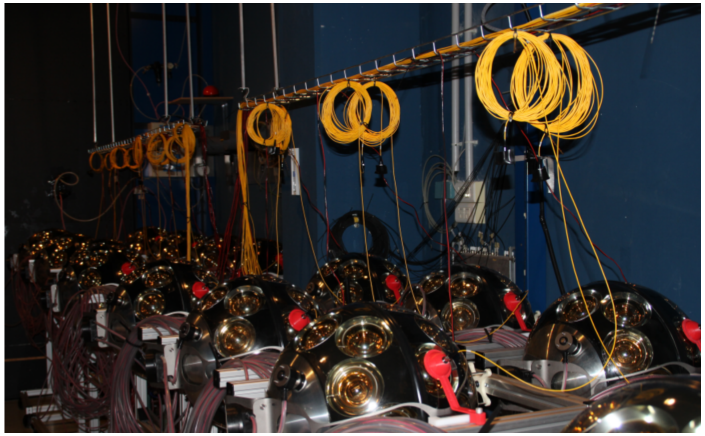
Atmospheric muons

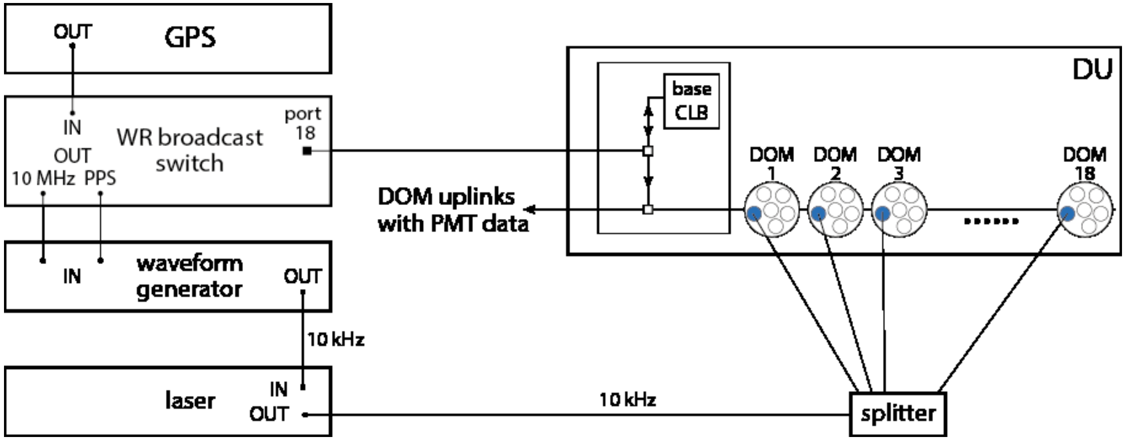
Eventually atmospheric muons are used to contribute to the ultimate time calibration of the KM3NeT detector. Well-reconstructed events can be used as the “true” track. Deviations from the expected hit times can be attributed to misalignment in the time offsets assumed.



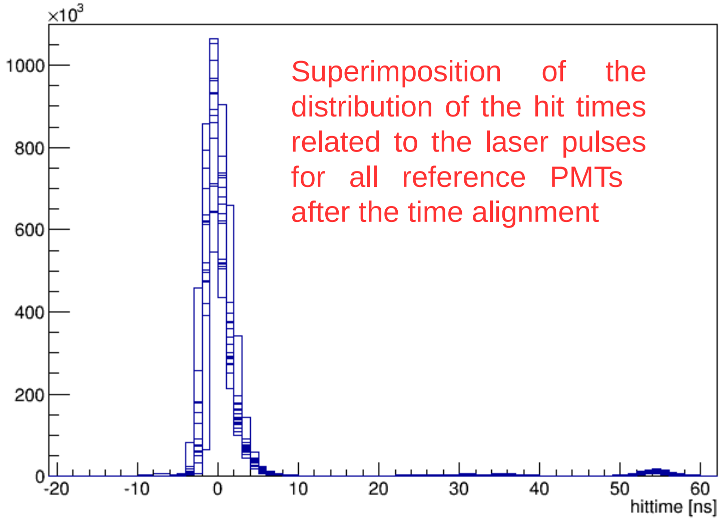
Inter-DOM calibration with laser

The employing of the White Rabbit protocol allows to perform the inter-DOM calibrations also in the dark room, before the deployment. The time offset of a reference PMT in each DOM in a DU is determined by using a laser calibration signal.



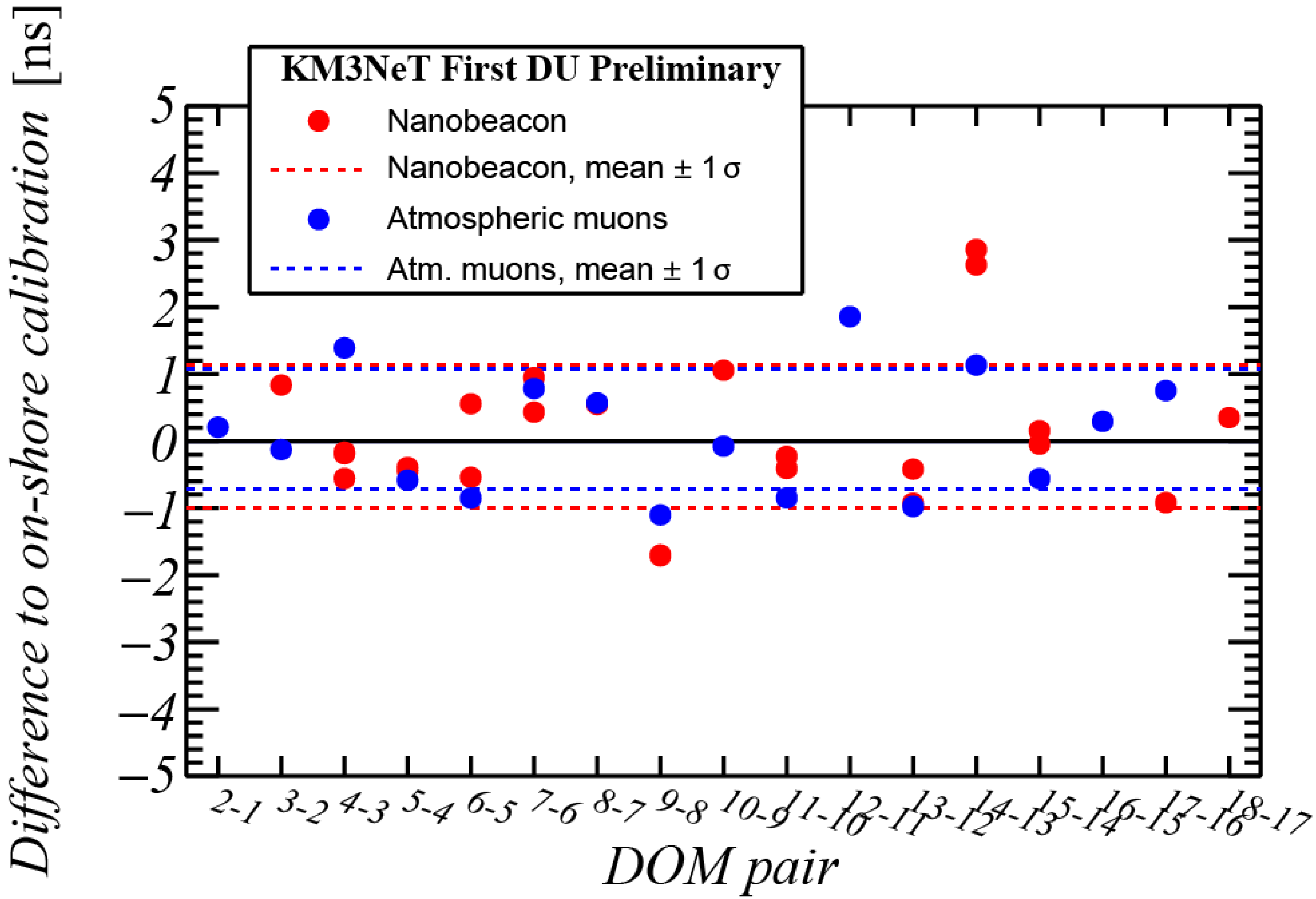


- The PPS signal from the WR broadcast switch is the trigger that is used to generate the laser trigger signals. Based on the PPS signal the waveform generator produces a pulse.
- The output signal is connected to the laser input.
- The laser head is connected to a fiber optical splitter (fiber of equal length).



Inter-DOM calibration results

Difference with respect to the on shore calibration for nanobeacon and atmospheric muons techniques



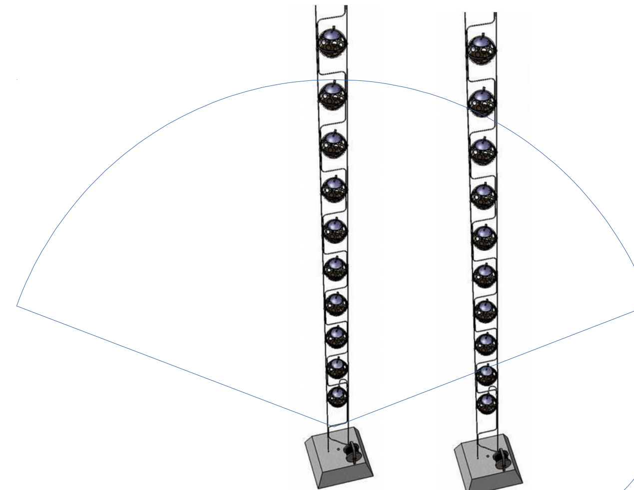
Inter-DU calibration in situ 1/2

Laser beacon

The laser beacon consists of a laser head and control electronics.
The laser beacon is capable of illuminating DOMs located at a horizontal distance of 200 m from the beacon, and at a vertical distance of 50 m above the seabed.

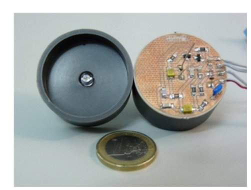
Laser Beacons @ 532 nm

- Titanium vessel
- High intensity (25 µJ) per pulse and shorter pulses < 1 ns
- Remotely controlled
- Tunable by Liquid Crystal Optical attenuator
- Collimated beam -> Diffusion device needed



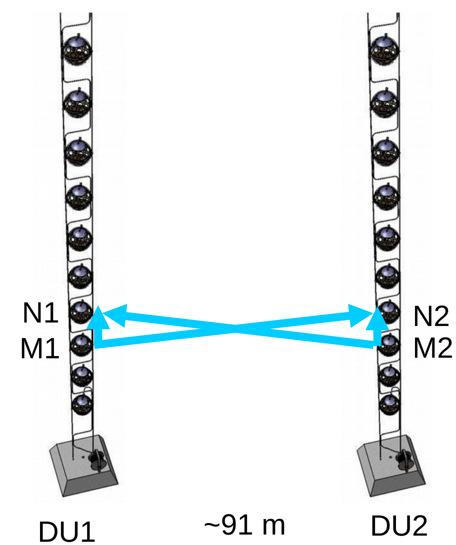
Nanobeacon

Comparison of nanobeacon pulse arrival times on some reference PMT, assuming that the strings are approximately symmetric.



M1 → N2 = M2 → N1
M1 → N1 = M2 → N2

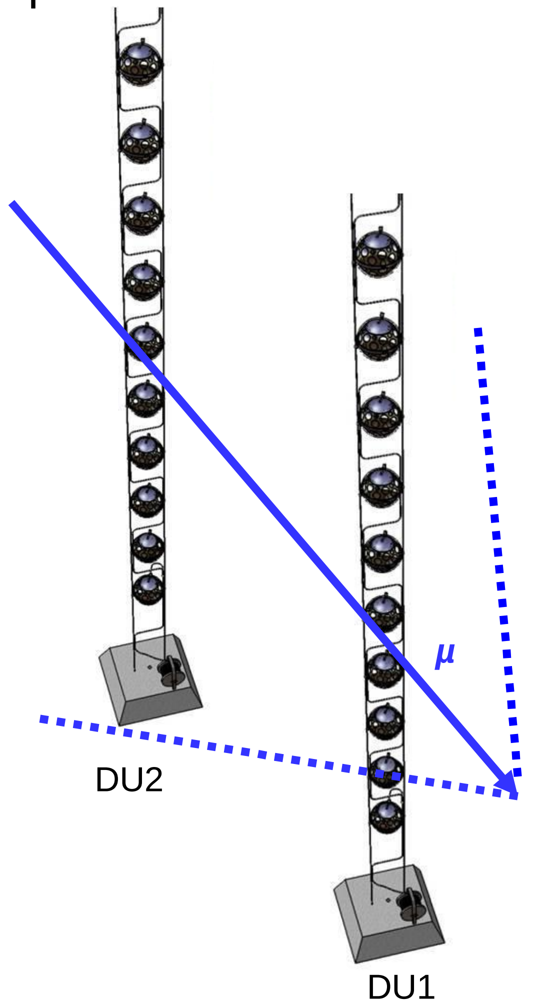
By appropriately adding/subtracting the measured offsets, we can get both the **difference in light travel** time and the relative **T0s**.

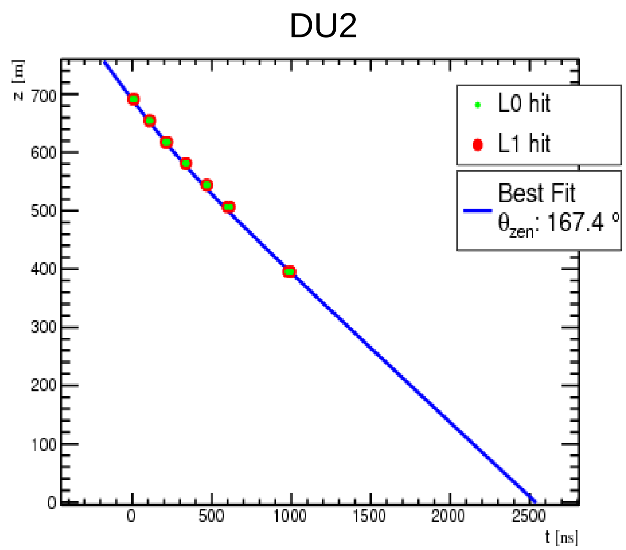


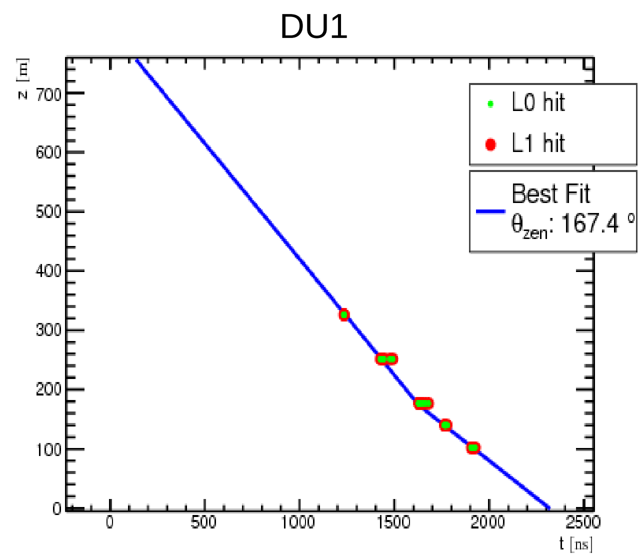
Inter-DU calibration in situ 2/2

Atmospheric muons

Eventually atmospheric muons are used to contribute to the ultimate inter-DU time calibration. This calibration is based on the measurement of the deviations from the expected hit times of atmospheric muon track considering the L0 and/or L1 hits







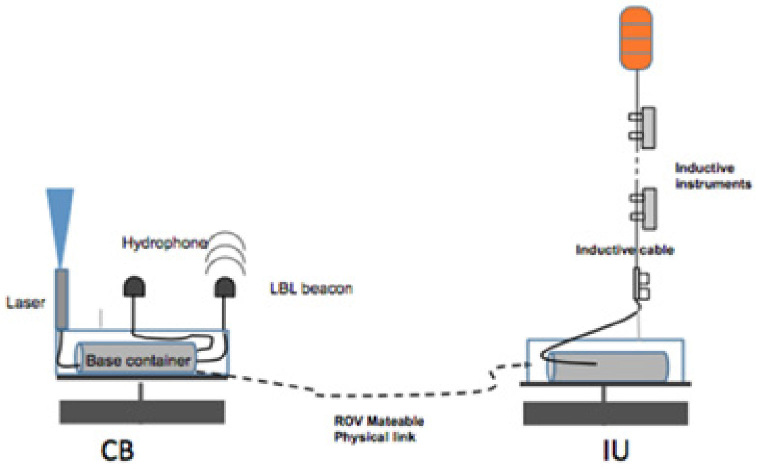
L0 filter: refers to the threshold for the analogue pulses which is applied offshore

L1 filter: refers to a coincidence of two (or more) L0 hits from different PMTs in the same optical module within 25 ns

Calibration Unit

In KM3NeT, the environmental conditions which may affect light and sound transmission will be continuously monitored through the Calibration Units.

The Calibration Unit (not yet installed) will comprise two sub-systems: a Calibration Base (CB) and an Instrumentation Unit (IU), powered through the CB.



- **CB instrumentation**
- Laser Beacon
- Hydrophone
- LBL Acoustic Beacon
-
- **IU instrumentation**
- CTD (Conductivity, Temperature, Depth) probe
- Sound velocimeter
- Acoustic Doppler Current Profiler (ADCP)

The IU is recoverable in order to allow the change of batteries and the periodical recalibration required by some of the instruments.

Conclusions

KM3NeT project goals require accurate calibration procedures.

- Position of each DOM must be known with an accuracy better than 20 cm → Acoustic positioning system

- Orientation of each DOM must be known with an accuracy better than 3° → AHRS

- PMTs amplitude response must be equalized → HV tuning in dark box

- Relative arrival times on PMTs should be known with an accuracy better than 1 ns → obtained by the combination of the calibrations of the shore station, the seabed infrastructure, and dark room.

- Time offsets before the deployment must be monitored for stability, and if necessary adapted in situ through dedicated calibration devices (laser beacon, nanobeacon) and the analysis of atmospheric muons tracks.

Thank you