A moving detector

Dynamical position and orientation calibration of the KM3NeT telescope

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KM3NeT

Nikhef

The KM3NeT telescope

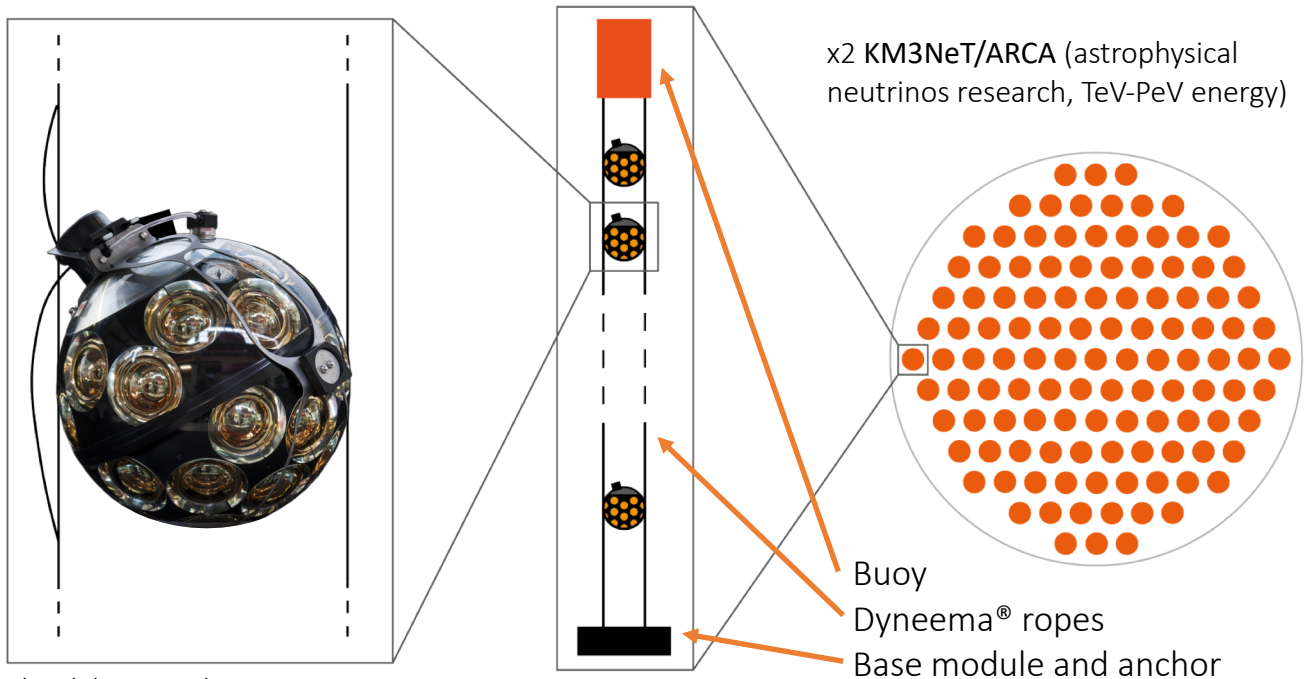
Digital Optical Module (DOM)
31 PMTs, electronics, acoustic sensor, magnetometer and accelerometer

Detection Unit
18 DOMs

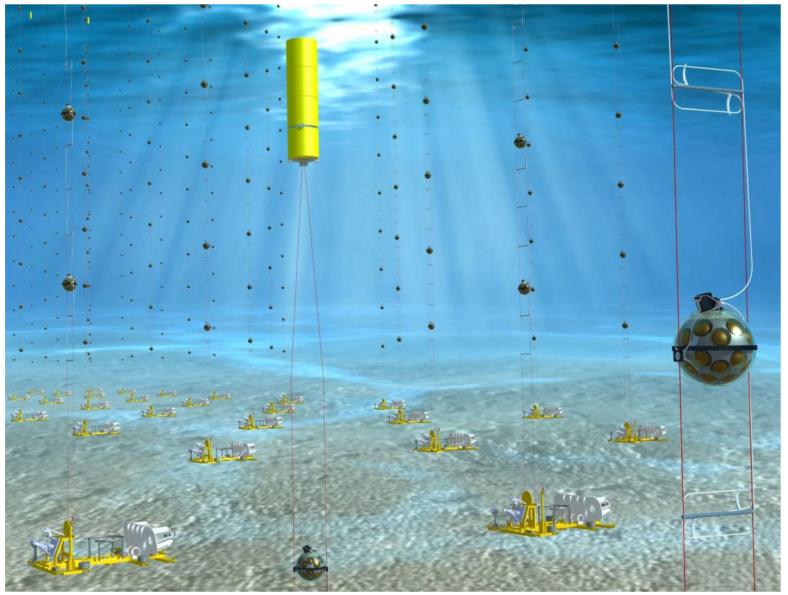
Building block
115 Detection Units

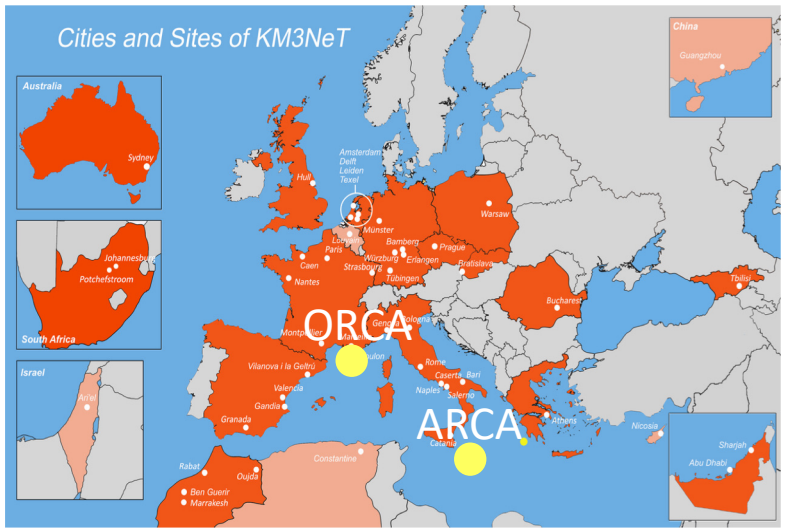
x1 **KM3NeT/ORCA** (atmospheric neutrino oscillations research, GeV-TeV energy)

x2 **KM3NeT/ARCA** (astrophysical neutrinos research, TeV-PeV energy)



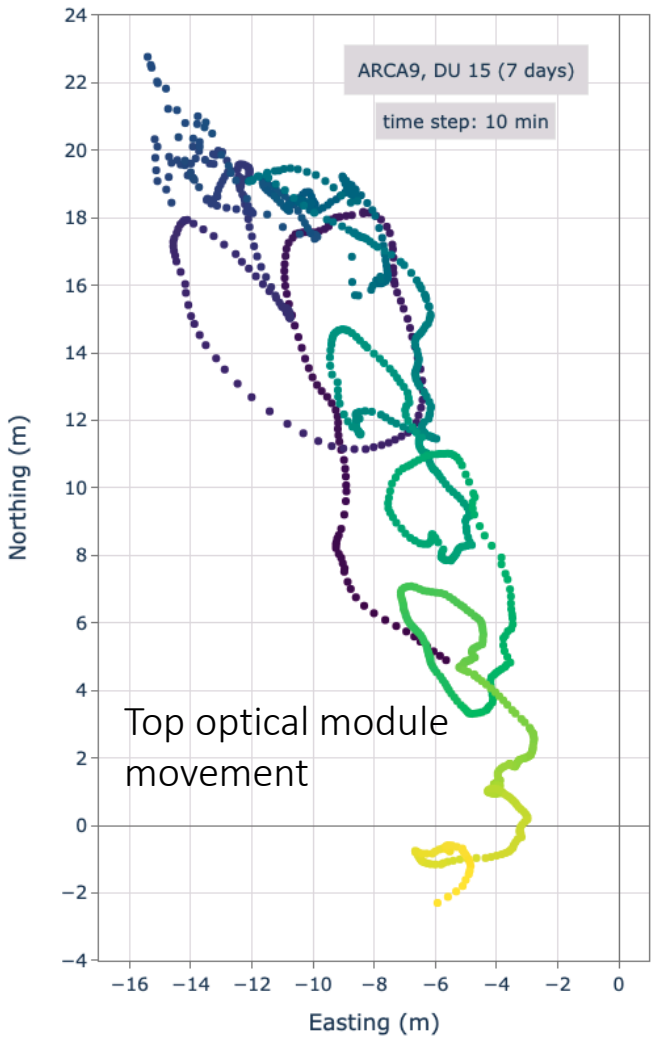
Sketch by Isis Hobus

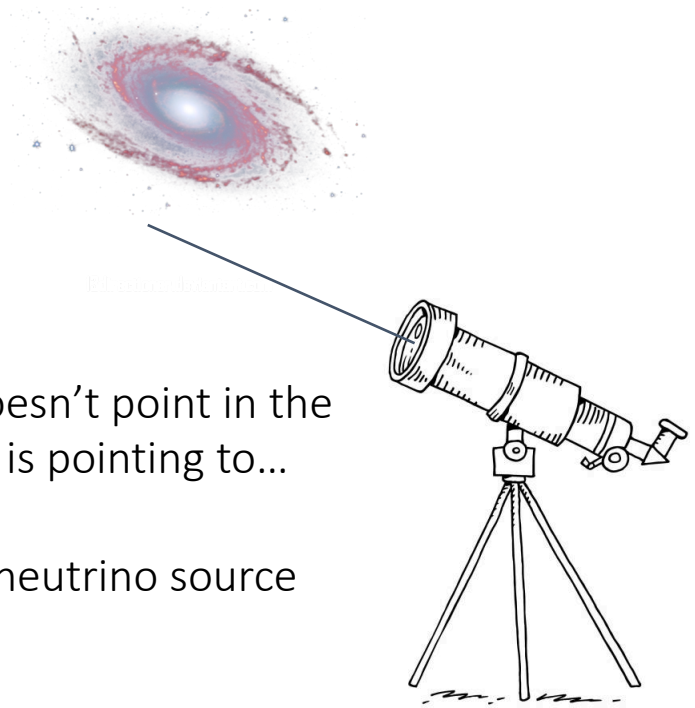




A moving detector…

Detection units sway with the deep sea currents





If the telescope doesn't point in the direction we think is pointing to…

… we mistake the neutrino source

continuous tracking of optical module positions and orientations required

- To not compromise envisaged angular resolution → KM3NeT/ARCA 0.05 deg (highest energy events)
- To not compromise the event reconstruction quality

Acoustic position calibration

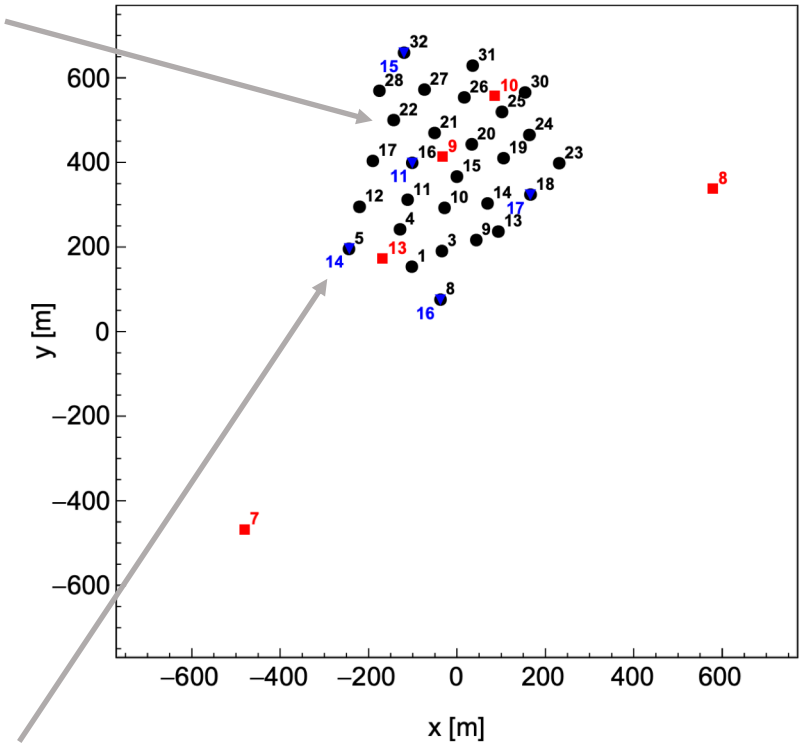
Autonomous acoustic emitters (~ 10 emissions / 10 min)

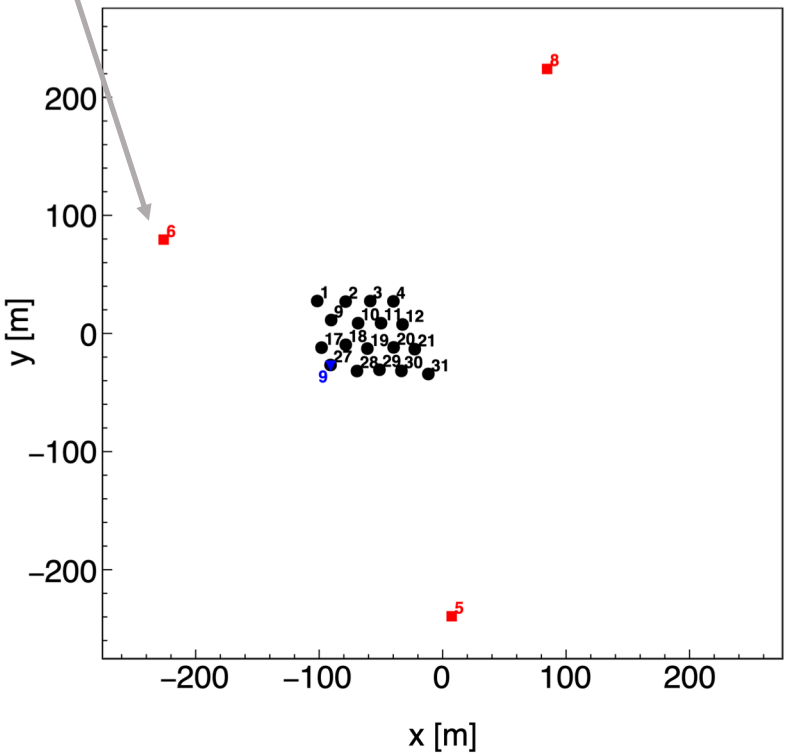
KM3NeT/ARCA (28 detection units)

KM3NeT/ORCA (18 detection units)

Detection units

Acoustic sensor in each optical module and base module





(current detector footprints)

Emitters on base modules or junction boxes

(~ 1 emission / 30 sec)

Acoustic position calibration

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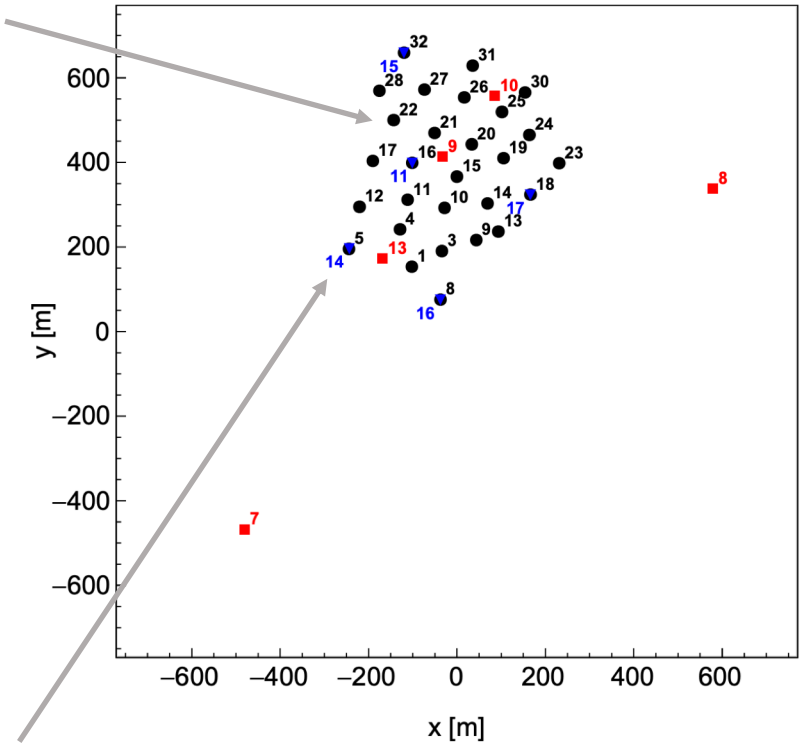
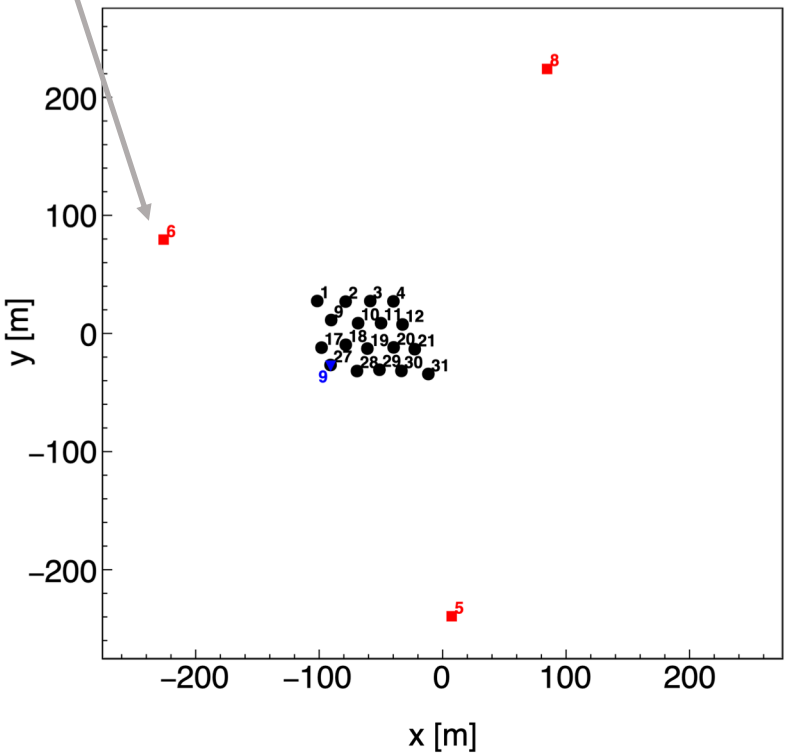




(current detector footprints)

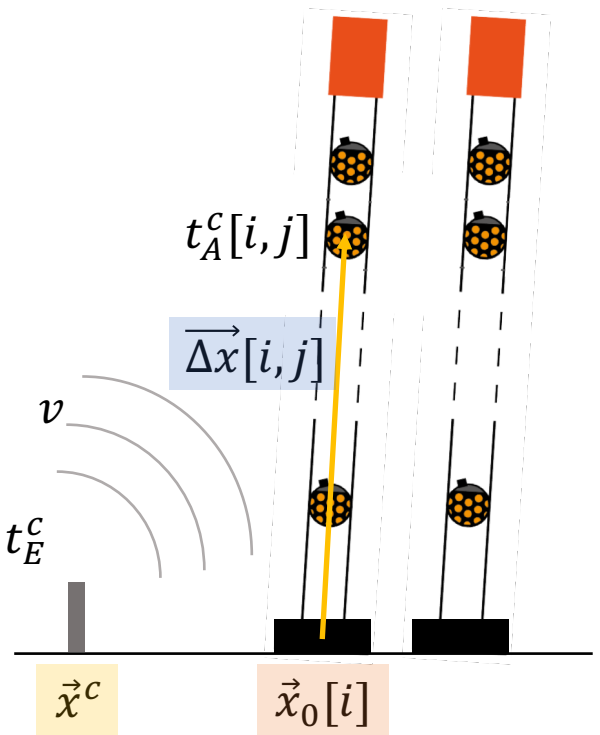
Emitters on base modules or junction boxes

(~ 1 emission / 30 sec)

- Different signal frequency for each emitter
- Correlate acoustic raw data with signal template

→ ID emitter, time-of-arrival signal

Acoustic fit

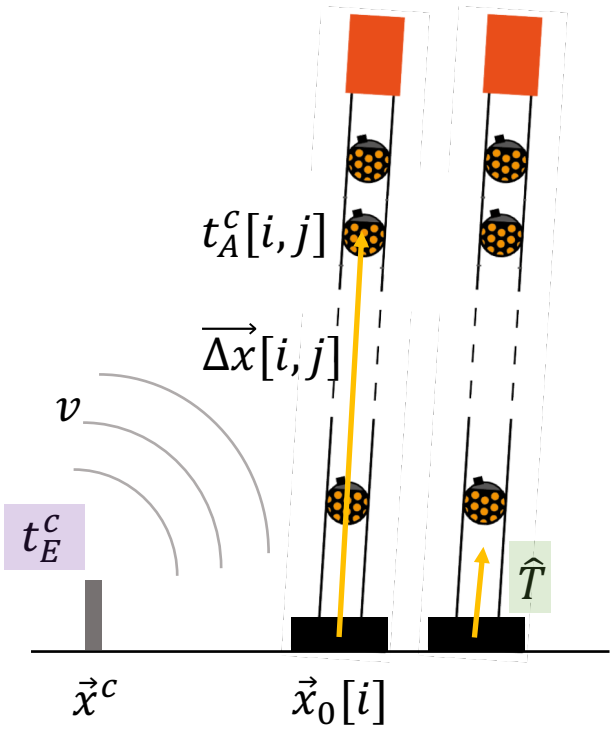


Model of the detector geometry fitted to the acoustic data every 10 min

$$t_A^c[i,j] = t_E^c + \underbrace{|\,\vec{x}_0[i] + \Delta\vec{x}[i,j] - \vec{x}^c\,|}_{\text{distance}}\, v^{-1}$$

time-of-arrival time-of-emission distance speed of sound

Acoustic fit



Model of the detector geometry fitted to the acoustic data

$$t_A^c[i,j] = t_E^c + \mid \vec{x}_0[i] + \Delta\vec{x}[i,j] - \vec{x}^c \mid v^{-1}$$

$$\Delta x[i,j] = T_x[i]z'[i,j] + T_x^{(2)}[i](z_0[i,j])^2$$

$$\Delta y[i,j] = T_y[i]z'[i,j] + T_y^{(2)}[i](z_0[i,j])^2$$

$$\Delta z[i,j] = f^{-1}(\,(1+\alpha[i])z_0[i,j]\,)$$

Tilt vector:

$$\hat{T} = (T_x, T_y, (1 - T_x^2 - T_y^2)^{1/2})$$

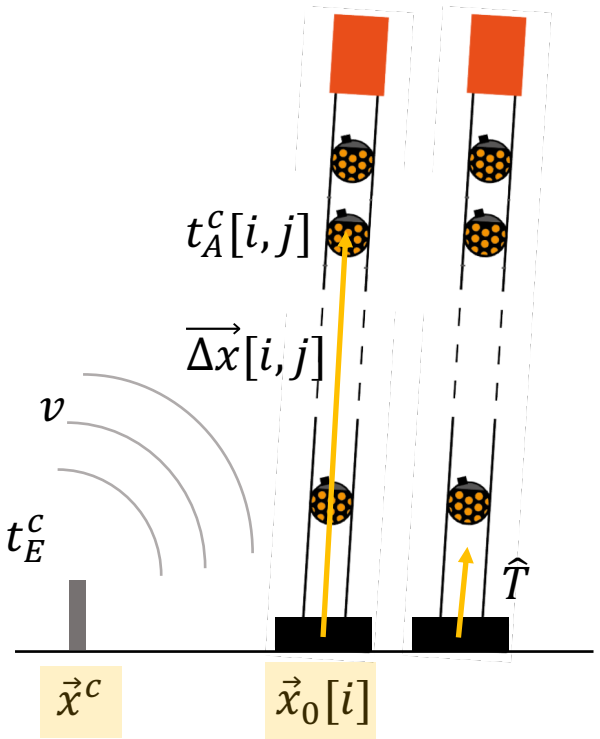
Mechanical model:

$$z' = (1+\alpha)\ z_0 + b\log(1 - a\ (1+\alpha)\ z_0)$$

What do we fit? → **Dynamic parameters** (fit every 10 min)

t_E^c	Time-of-emission
T_x, T_y	**Tilt** of the DU
$T_x^{(2)}, T_y^{(2)}$	Second order corrections to the tilt
$1+\alpha$	**Stretching** of the DU

Acoustic fit



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Mechanical model:

$$z' = (1+\alpha)\, z_0 + b\log(1 - a\,(1+\alpha)\, z_0)$$

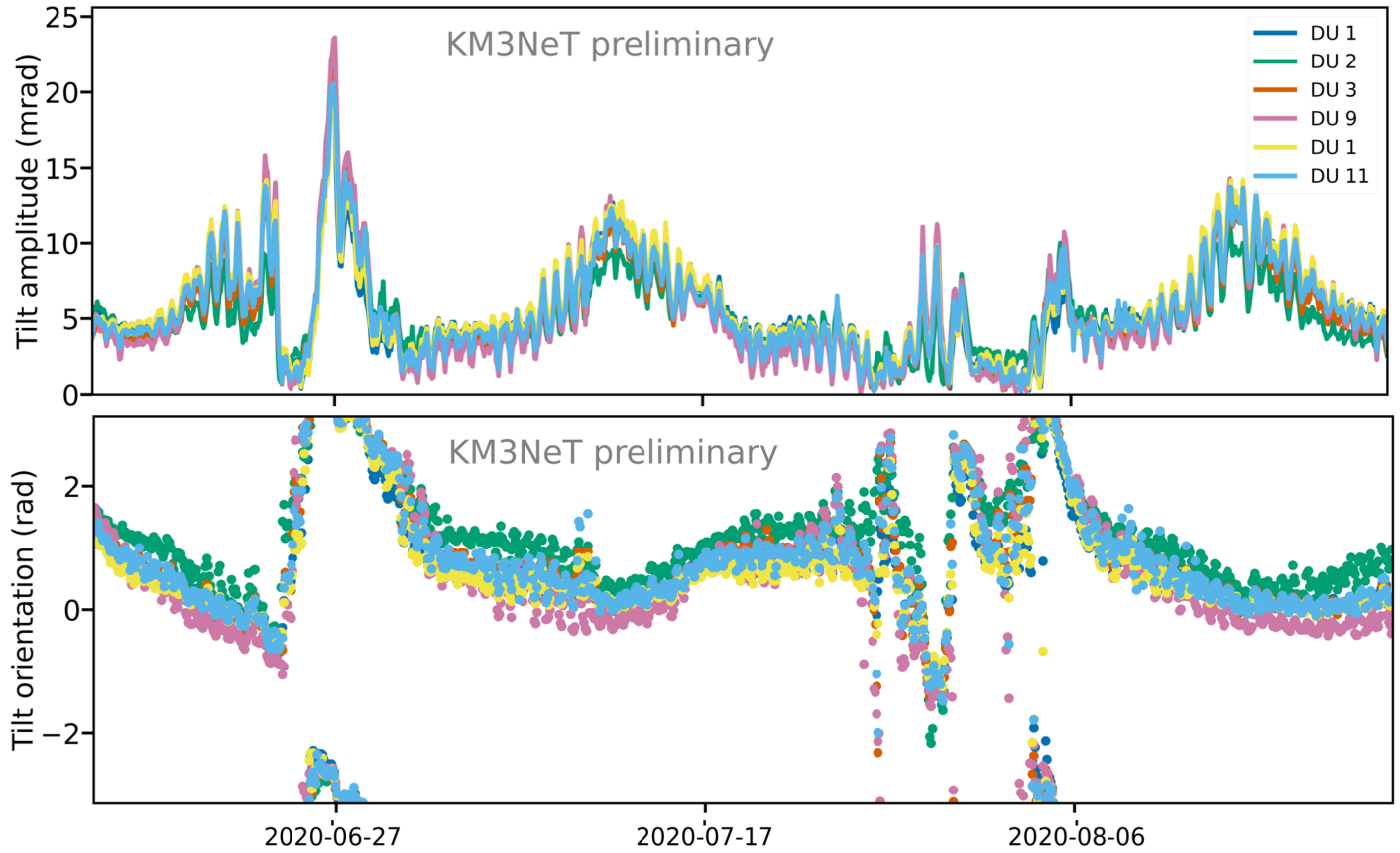
What do we fit? → **Static parameters** (fitted once)

- $\vec{x}_0$ DU position on the sea bed
- z_0 Nominal height of each DOM in the DU
- $\vec{x}^c$ Emitter position on the sea bed

Dynamic position calibration

KM3NeT/ORCA (6 detection units)

From acoustic data



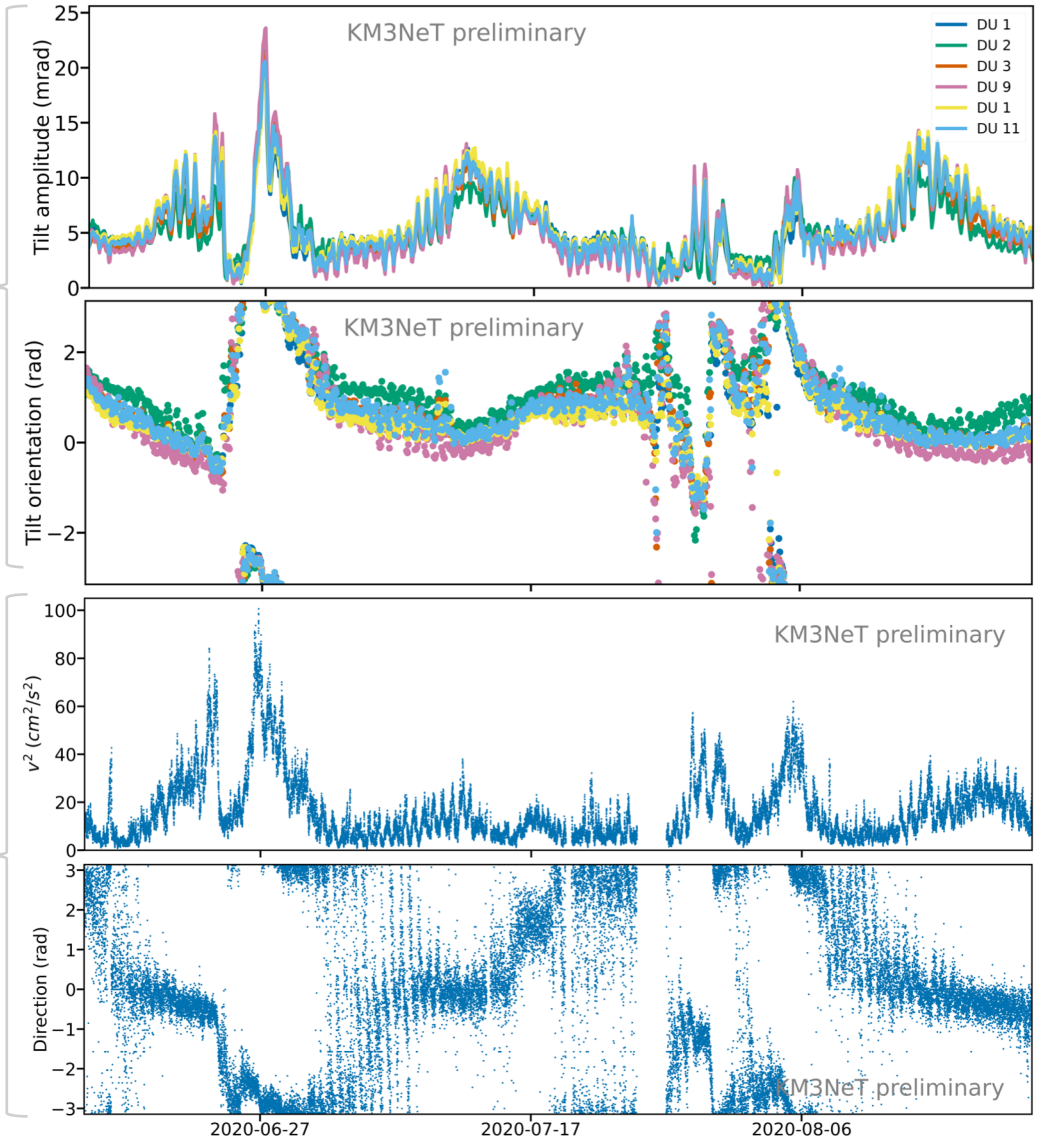
- 4 months of data
- Coherent movement between detection units
- Highest tilts measured so far ~ 5.7 deg (see additional slides)

Dynamic position calibration

KM3NeT/ORCA (6 detection units)

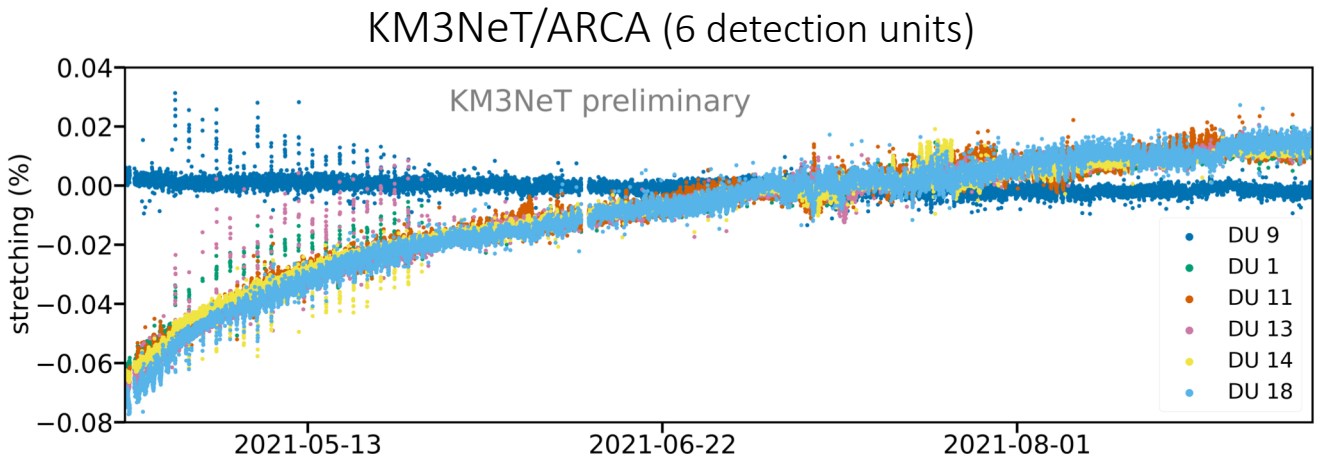
From acoustic data

Independent sea current measurement



- coherent movement between the detection units and sea current speed and direction

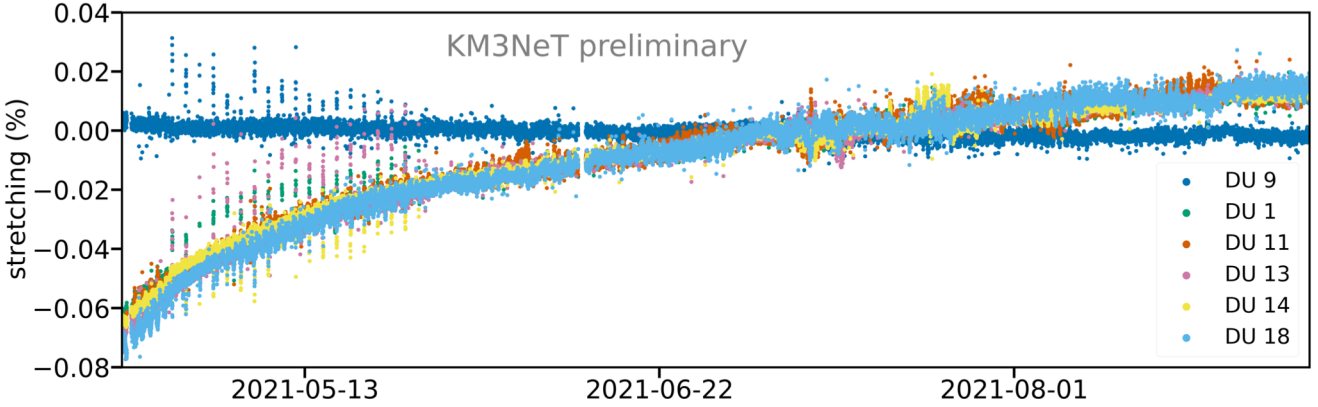
Dynamic position calibration



- Stretching over time for ~ 3 months of data
- Creep of the Dyneema® ropes of the newly deployed detection units, up to ~ 60 cm

Dynamic position calibration

KM3NeT/ARCA (6 detection units)



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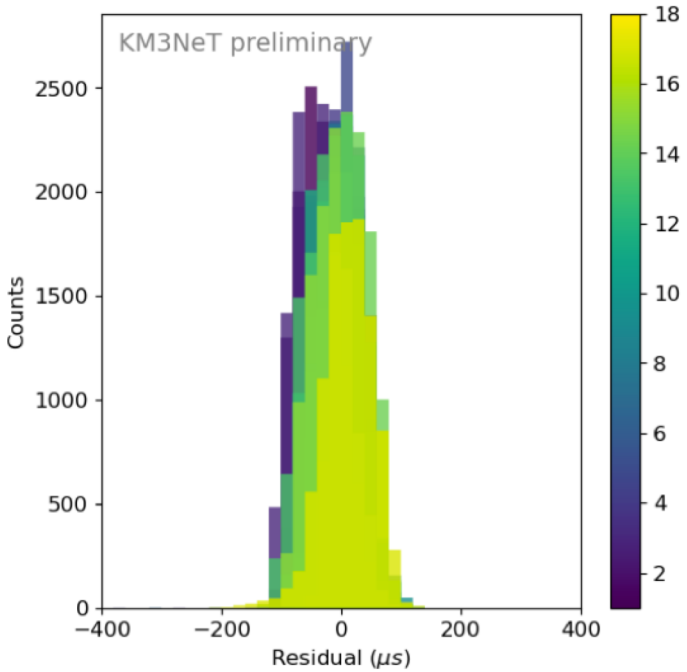
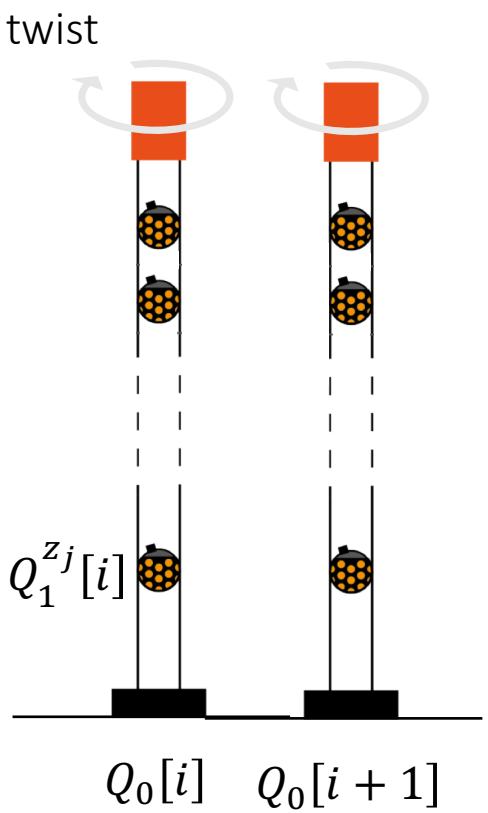
KM3NeT/ARCA (21 detection units)



- Residuals of the acoustic fit for 1 detection unit (lower module = 1, top module = 18)
- Residuals contained within ±100 μs (~ 15 cm)

Orientation calibration



Magnetometer and accelerometer in each optical module (a.k.a. "compass") → Continuous data taking every 10 sec

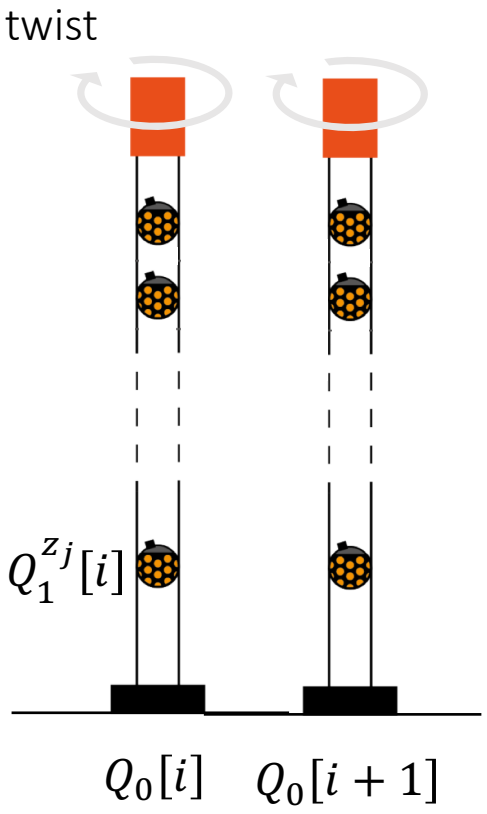
After some corrections

(Correction for magnetic declination and meridian convergence angle + in-lab calibration)

Conversion to **quaternions**

$$Q \equiv (\cos(\theta/2), \sin(\theta/2)\hat{u})$$

Orientation calibration



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Conversion to **quaternions**

$$Q \equiv (\cos(\theta/2), \sin(\theta/2)\hat{u})$$

Static calibration: alignment of the optical modules of each detection unit during a period in which the sea current is low

Model of the DU twist fitted to the compass data
for each DU (every 5 min)

$$Q = Q_0\, Q_1^{z_j} \ ,$$

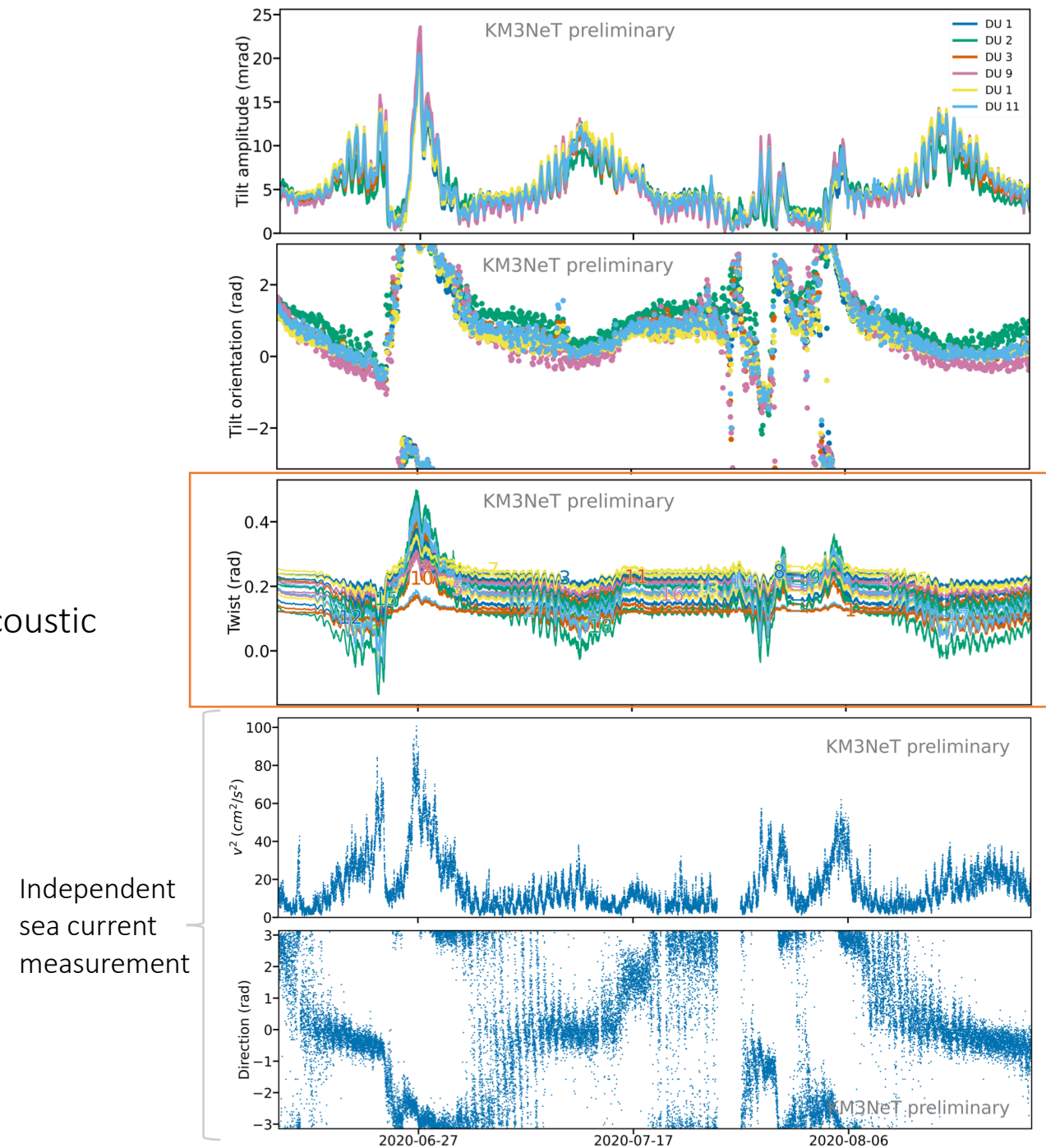
Q_0 : Tilt DU

$Q_1^{z_j}$: Twist DOM J

Dynamic orientation calibration

Orientation updated very 5 min

- Optical modules move coherently among themselves
- as well as with the tilt derived from the acoustic data and the sea current measurements

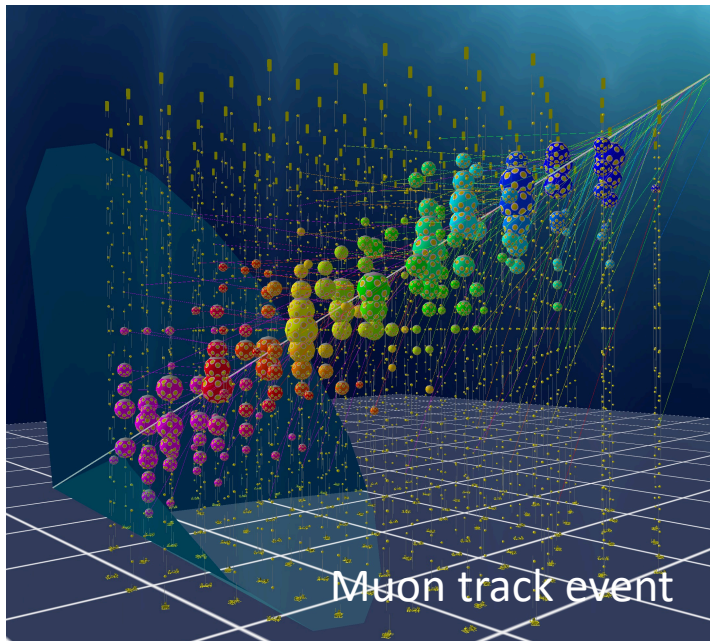


From acoustic data

Compass data

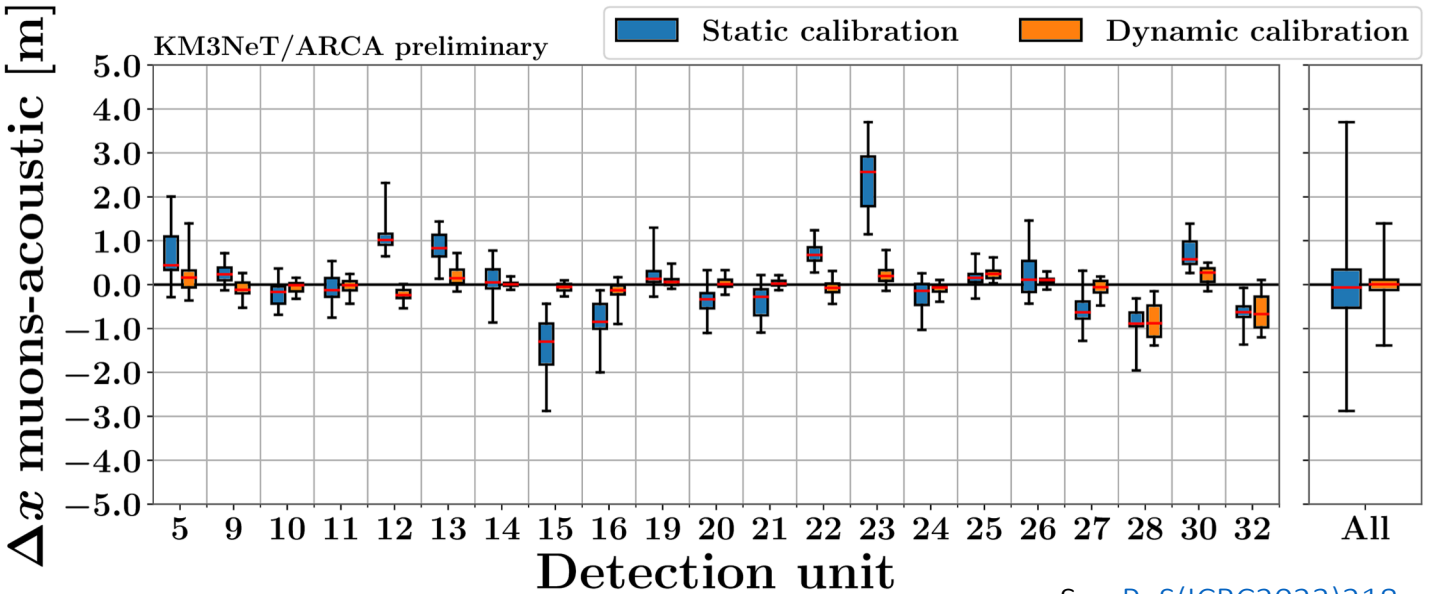
Independent sea current measurement

Final check of the calibration → muon calibration



Muon calibration → exploits muon track reconstruction to find optimal orientation and position of the optical modules.

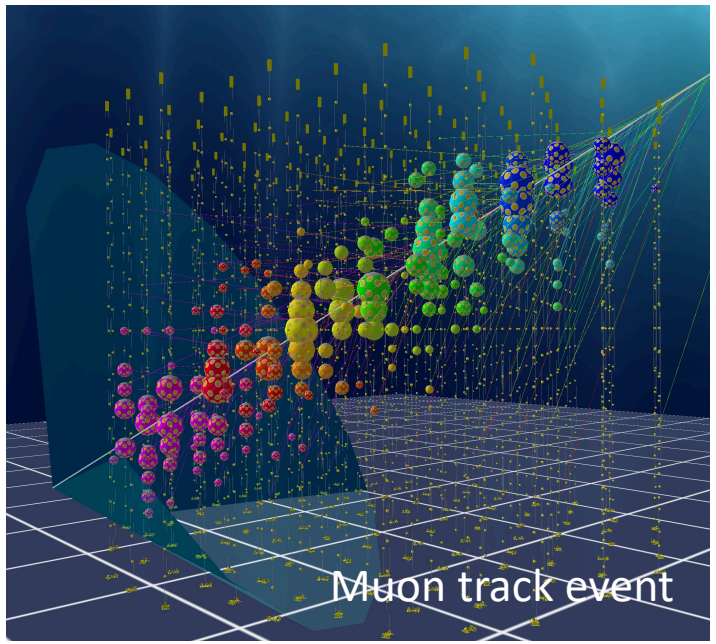
- **Positions** agree with the muon calibration within a range of ±10 cm



See PoS(ICRC2023)218.

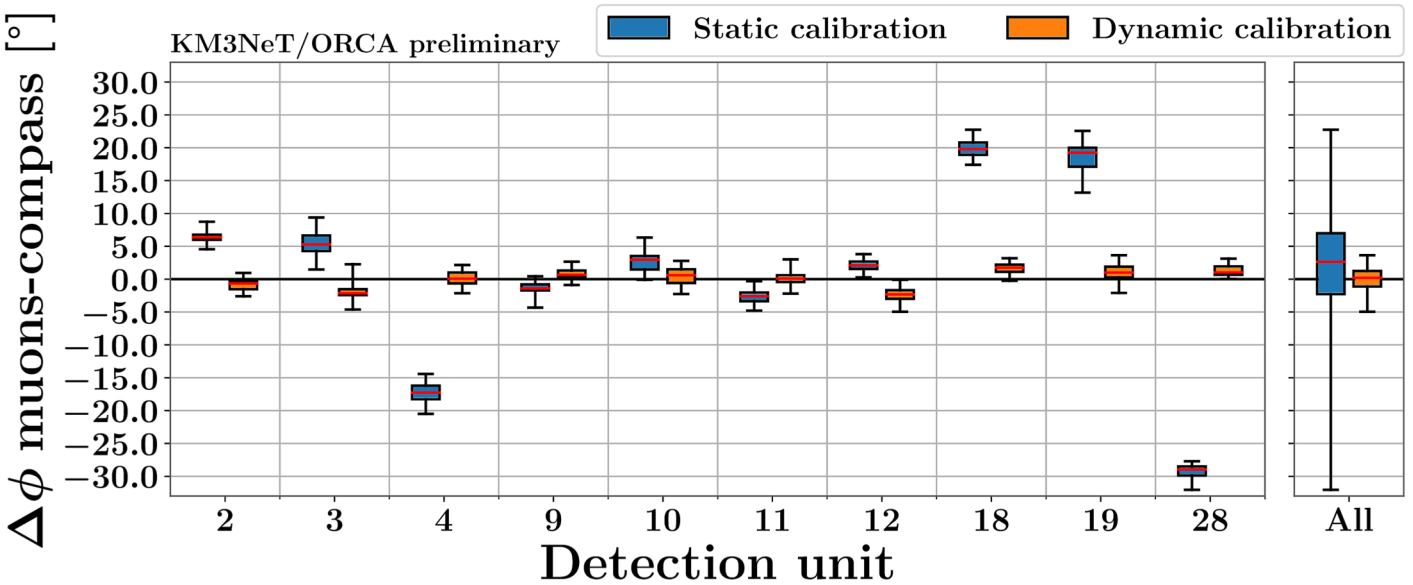
Plots for 5000 consecutive events
boxes ≡ 50% of entries (between 1st and 3rd quartiles)
whiskers ≡ minimum and maximum values

Final check of the calibration → muon calibration



Muon calibration → exploits muon track reconstruction to find optimal orientation and position of the optical modules.

- **Orientations** show an agreement within a range of less than ±3 deg



See PoS(ICRC2023)218.

Plots for 5000 consecutive events
boxes ≡ 50% of entries (between 1st and 3rd quartiles)
whiskers ≡ minimum and maximum values

Conclusion

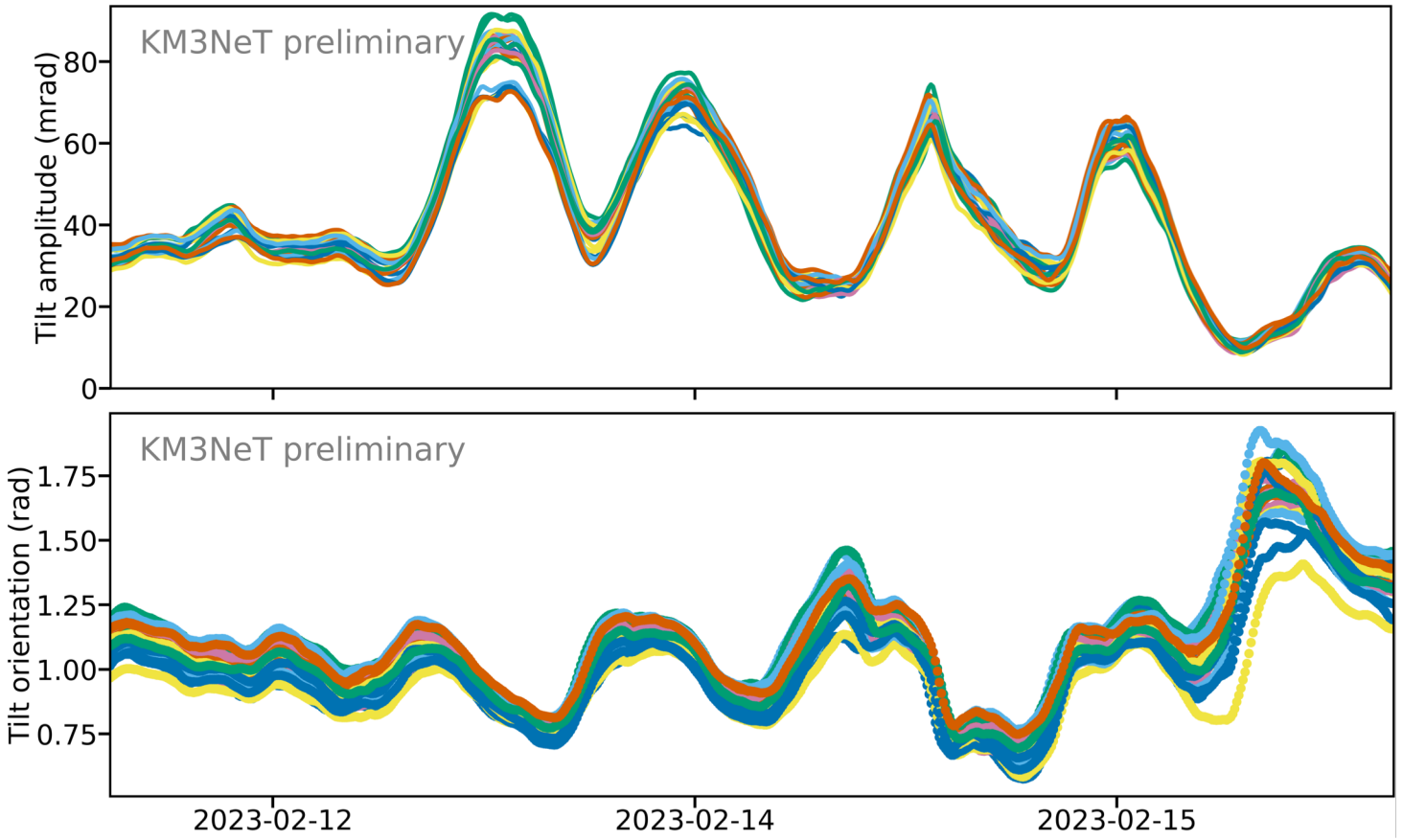
- Acoustic positioning method **in place** to determine optical module positions
- **Method to calibrate orientations of the optical modules** *in-situ* and determine their dynamic orientation
- **Methods agree with the muon calibration** technique:
  - Positions ± 10 cm
  - Orientations ± 3 deg
- **Agreement within required specifications** to achieve:
  - Envisaged angular resolution of the KM3NeT/ARCA telescope of 0.05 deg
  - Not compromise event reconstruction quality

KM3NeT calibration is ready to point back at neutrino sources!

For more details see PoS(ICRC2023)1033

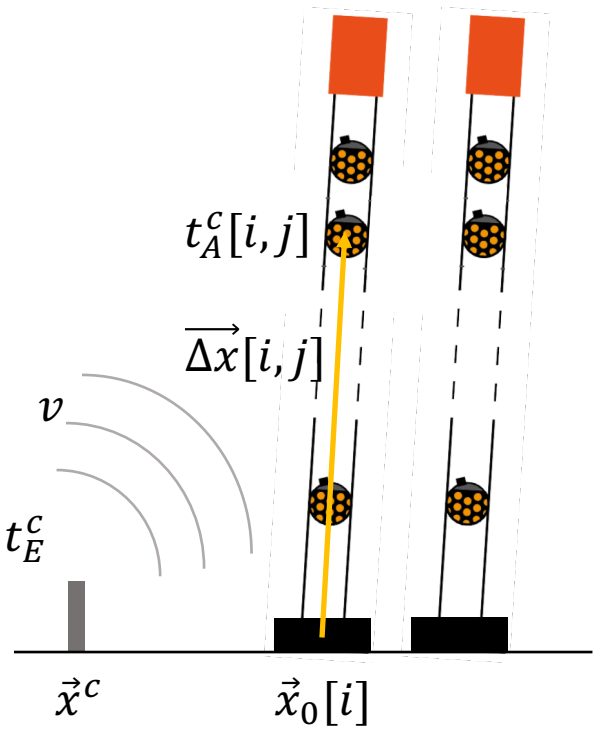
Additional slides: Dynamic position calibration

KM3NeT/ARCA (21 detection units)



- Highest tilts measured so far ~ 5.7 deg

Additional slides: acoustic fit



Model of the detector geometry fitted to the acoustic data
(every 10 min)

$$t_A^c[i,j] = t_E^c + \mid \vec{x}_0[i] + \Delta\vec{x}[i,j] - \vec{x}^c \mid v^{-1}$$

Number of data points: $n_p = \sum_{i=1}^{M} n_i \cdot N \cdot 18$

Number of free parameters: $n_f = \sum_{i=1}^{M} n_i + 5N$

M = # emitters
N = # DUs
n_i = # emissions in 10 min

$$\chi^2 = \frac{\sum_{n_p}(t_A^{measured} - t_A^{modelled})}{\sigma}, \quad \sigma = 50\ \mu s\ \ (\sim 8\ cm)$$