Results and simulation of the prototype detection unit of KM3NeT-ARCA

Hugon Christophe
INFN sezione di Genova
On behalf of the KM3NeT collaboration
The Neutrino telescope principle

- Main target: cosmic neutrinos going through the Earth
- Main background
  - Atmospheric muons
  - Atmospheric neutrinos

- Tcherenkov cone reconstruction thanks an array of photomultiplicator (PMT)
- Reconstitution of
  - The origin (typically 0.5 deg of resolution)
  - The energy of the event
**Multi-site option**

Astrophysics research with cosmics in the abyss
Oscillation research with cosmics in the abyss

<table>
<thead>
<tr>
<th></th>
<th>ARCA</th>
<th>ORCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Italy</td>
<td>France</td>
</tr>
<tr>
<td>String dist. [m]</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>DOM spacing [m]</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Volume [$10^6$ m$^3$]</td>
<td>$\sim$500</td>
<td>$\sim$3.8</td>
</tr>
</tbody>
</table>

**Multipurpose physics**

ORCA
100 MeV $\rightarrow$ 100 GeV
- Low energy physics
- Neutrino oscillation

ARCA
> 100 GeV
- High energy physics
- Extra-galactic physics

Neutrino telescope $> 1$ km$^3$

Goal: extends our knowledge of the Universe
- Study of neutrino point sources
- Measurement of cosmic neutrino diffuse fluxes
- Multi-messenger approach and 'exotics'
- Synergy with Earth and Sea sciences

Goal: extends our knowledge of the Universe

Neutrino telescope $> 1$ km$^3$
KM3NeT phase 1

- String-type with 18 optical modules
- 36 m between the optical modules

First phase
- Started in January 2014 with the first strings
- 2 strings working
- Funded with 31 million Euro
- 31 detection units will be deployed in 2015-2016
- Sites: KM3NeT-It off shore Capo Passero with 24 DUs, KM3NeT-Fr off shore Toulon with 7 DUs
- 3 times improvement in sensitivity w.r.t. Antares
Significance for cascade and upgoing muon diffuse flux ARCA

- Contained high energy cascade events
- Up-going TRACK analysis

Flux of high energy cosmic neutrino reported by IceCube will be measured after less than one year of data taking for cascade and muons respectively with KM3NeT 2.0
Discovery potential for point sources $\propto E^{-2}$ spectrum

KM3NeT discovery potential comparable or better than IceCube over almost whole sky
Detection Unit prototype

- 2 DOMs with 31 ETEL D783FLA PMTs
- 1 DOM with 31 Hamamatsu R12199-02 PMTs
- LED nanobeacon and piezo
- Deployed at the KM3NeT-It site at 3500m depth, 100 km off shore
- Operational since May 2014 until July 2015
The Digital Optical Module

Segmented cathode area: 31 x 3” PMTs
Light concentrator ring
Cathode area: ~3 x 10-inch PMT
Custom low-power HV bases

LED & piezo inside
Compass and tiltmeter inside

PMT ToT measurements
FPGA readout, optical line terminator

~14000 PMTs (phase-I)

↑ 12 PMTs
down 19 PMTs
DU prototype integration and deployment

Integrated at Nikhef (Amsterdam) and CPPM (Marseille)

Deployed at 3500 m depth at the site of Capo Passero (KM3NeT-It) in May 2014, removed in July 2015.
A full ray tracing simulation would be far too slow. A physics tables based simulation is used:

1) The charged lepton directionality and energy are simulated a priori, in function of the model
2) The density of the Tcherenkov photons production is calculated along the lepton (~100/cm)
3) The photon “presence” probability density in function on time is calculated along the Tcherenkov front
4) At the position of each Optical module the probability to be detected is calculated in function of
   1) The photon wavelength
   2) The photon incident point
   3) The photon incident angle

Tabulation of the angular efficiency in function of these parameters: need a ray tracing simulation (base on GEANT4)
A word about the KM3NeT GEANT4 ray tracing simulation

• Based on GEANT4
  - Generates the particles one by one and follows them in each processes (scatterings, decays, absorption…)
  - Works with high energy particles, but also optics (particle approach)
• Extended for Telescopes neutrino purposes
  - Not limited to KM3NeT, but also used for ANTARES, NEMO and can be used for any Tcherenkov detectors
    • First implementation in Kamland (Motta et al.)
    • Implemented for Auger (A. Creusot)
    • Implemented for ANTARES then KM3NeT
  - Added precise Smoluchowsky-Einstein scattering (based on literature and site direct measurements)
  - Added photocathode physics: Thin layer and complex index
The geometries

The PMT
The simulation uses the main parameters given by the constructor. Can reproduce any “bulb-like” PMT. The dynods are also taken into account, having an effect on the total efficiency.

The OMs
The simulation takes the number and position of PMT, the OM sizes (diameter and glass thickness). This simulation can also reproduce OM composed of one big PMT (e.g., ANTARES).
Integration of the photocathode in the GEANT4 simulation

Two crucial points in the photon propagation in the photocathode:
- The wave: multi-reflexion, auto-interferences
- The particle: ultimately absorbed in the thin layer, depends on the path length

The absorption length of the photocathode and the photon path are described by its complex index \( n \pm ik \)

New extension of the GEANT4 simulation:

![Graphs showing expected, classical GEANT4 simulation, and extended GEANT4 simulation results](image)
Simulation calibration

- PMT QE and efficiency taken from collaboration direct measurements of PMT (Erlangen's/APC):
- A system using a precisely calibrated LED can scan the PMTs to measure its QE and efficiency.
- Tens of PMTs were scanned. The mean values are used in the simulation.

- The exact QE can be estimated thanks to a measurement of the photocathode tension
- The excess of QE on the border is due to the thin photocathode projected also on the back of the PMT
- The central lower efficiency is due to the dynods (the photons are not reflected back to the photocathode)
$^{40}$K data and simulation

The very constant sea salinity at these deep implies a very constant $^{40}$K decay rate. This decay produce Tcherenkov photons ($e^-$ of 1 MeV). It permits on-site calibration of the detector and cross-check with the simulation.

PPM-DU DOM3 rates in fonction of aperture between PMTs

![Graph showing very good accordance of expected rates from the simulation and the data.](image-url)
Angular efficiency function of energy

The angular acceptance corresponds to the probability that a beam of photons is detected by the optical module.

The thin layer photocathode simulation allowed to take in account all the effects, to provide a precise table of angular acceptance.

Tabulated for all the PMTs, angles and energy:
- Used for the global simulation
- Used in the atmospheric muon simulation
PPM-DU: Searching for muons

- L1 trigger = coincidence between two PMTs in 25ns; unique PMTs are selected inside the DOMs in a 130 ns time window
- The change of shape shows the region in which muons become to be dominant over the optical background
- Directionality of the DOM 3 peculiar up/down shape
### Inter-DOM time calibration

- K-40 decay in sea water to calibrate Intra-DOM time offsets using local coincidences
- LED nanobeacons to calibrate Inter-DOM
- Atmospheric muons can be used to calibrate in time DOMs: very good agreement with MC simulations
Zenith angle reconstruction

- Reconstruction of zenith angle of atmospheric muons
- Inputs: position of the three DOMs and time of the local coincidences
- FWHM = 7.6 degree zenith angular resolution achieved
Summary and Conclusion

- The ANTARES detector proved the feasibility of undersea telescopes.
- KM3NeT represents the next generation of undersea telescope for:
  - HE neutrinos with ARCA
  - Low energy neutrinos and oscillations with ORCA
- The prototype of the detection units of KM3NeT showed promising results with a good reconstruction of muon an calibration.
- The current status of the simulation allows to obtain very accurate results. It reproduces the $^{40}\text{K}$ decay and the muon reconstruction.
- This simulation has been developed with the idea to be used with any neutrino telescopes. It’s used with success with KM3NeT, ANTARES and NEMO.
KM3NeT ARCA

- Objectives similar of ANTARES, but at bigger statistic, higher energy
- Measurements of neutrino signals reported by IceCube

1 building block

\[\sim 1 \text{ km}\]
Reminder – the IC signal

HESE with 3 years of IceCube data.
'hot spot' at \( l = +18^\circ, b = -9^\circ \)

\[
d\Phi/dE \sim E^{-2.46}
\]


+ flavour ratio measurement (arXiv:1502.03376, accepted PRL)
also provides a fit of signal flux \( d\Phi/dE \sim E^{-2.6\pm0.15} \)

ANTARES Constrains a Blazar Origin of Two IceCube PeV Neutrino Events (highlighted in *Nature* vol 520, April 2015)

- Introduces method to infer events rates in ANTARES given IceCube observed events
- Main result:
  - 2 of 6 blazars associate with one event each in ANTARES
  - Consistent with blazar-source hypothesis (and background)
Measurement of neutrino mass hierarchy

1 building block

ORCA
The neutrino mass hierarchy

- Prime discriminator for theory models
- Origin of neutrino mass and flavour
- Help measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Core-Collapse Supernovae Physics

![Neutrino mass hierarchy diagram]

- Normal
- Inverted

- Atm. $\sim 2 \times 10^{-3} \text{eV}^2$
- Solar $\sim 7 \times 10^{-5} \text{eV}^2$

- $\sin^2 2\theta_{13} = 0.10$
- $\Delta m_{31}^2 < 0$
- $\Delta m_{31}^2 > 0$
Measuring the neutrino mass hierarchy with atmospheric neutrinos

- a « free beam » of known composition ($\nu_e, \nu_\mu$)
- wide range of baselines (50 → 12800 km) and energies (GeV → PeV)
- oscillation pattern distorted by Earth matter effects (hierarchy-dependent):
  - maximum difference IH → NH at $\theta=130^\circ$ (7645 km) and $E_\nu = 7$ GeV
- opposite effect on anti-neutrinos: IH($\nu$)≈NH(anti-$\nu$)
  - BUT differences in flux and cross-section:
    - $\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-$\nu$})$
    - $\sigma(\nu) \approx 2\sigma(\text{anti-$\nu$})$ at low energies
- measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos precisely, identify and count muon and electron channel events
- improve precision on measurement of $\Delta M^2$ and $\theta_{atms}$
- feasible now that $\theta_{13}$ is measured to be large

Feasible now that $\theta_{13}$ is measured to be large

Akmedov, Razzaque & Smirnov, JHEP 02 (2013) 082
Experimental signature

Muon channel (~10 M.yr)
Perfect detector

$\frac{(N^{\text{IH}} - N^{\text{NH}})}{(N^{\text{NH}})^{1/2}}$

(κinematics + detector resolution)

E, $\theta$ smearing

Electron channel (~10 M.yr)
Perfect detector

$\frac{(N^{\text{IH}} - N^{\text{NH}})}{(N^{\text{NH}})^{1/2}}$

Muon channel (~10 M.yr)
25% $E_\nu$, $\theta : 0.5 \sqrt{\text{m}/E_\nu}$

Electron channel (~10 M.yr)
25% $E_\nu$, $\theta : 0.5 \sqrt{\text{m}/E_\nu}$
Important Ingredients

- Direction resolution (track/cascade)
- Energy resolution (track/cascade)
- Cascade versus track separation
- Atmospheric muon background rejection
- Neutral current backgrounds
- Effective volume
- Geometry optimisation
- Trigger efficiency and rates (atms mu@36Hz, K40@19Hz)
- Systematic uncertainties
Expected NMH Sensitivity

Latest results include:
- Track vs shower event classification
- Full MC detector response matrices
- Atmospheric muon contamination
- Neutral current event contamination

Caveat: here $\delta_{CP} = 0$ fixed to zero and fit constrained to first quadrant

Interplay between parameters under investigation

Room for improvement:
- Combined track+shower reco,
- Bjorken-y,
- Detector optimisation...

3 sigma in 3 years
Latest results include:
Track vs shower event classification
Full MC detector response matrices
Atmospheric muon contamination
Neutral current event contamination
Caveat: here $\delta_{CP} = 0$ fixed to zero and fit constrained to first quadrant
Interplay between parameters under investigation
room for improvement:
combined track+shower reco, Bjorken-$y$, detector optimisation...

3 sigma in 3 years
Why is it important for neutrino telescopes

- Due to the refraction, the effect is negligible in air but strong in water

![Diagram showing the refraction in glass and water](image)
But what's about the QE in this model?

- The quantum efficiency is directly derived from the complex index
  - The absorption emit an electron of a considered quasi constant energy of about 1 eV
  - The electron has a mean free path of few tens of nm
  - When the electron reach the vacuum, its immediately accelerated by the electric field
  - Then the detection probability will depend to the dinods efficiency

- Those process are taken in account, but is the complex index well defined?
Scan fit for data and simulation

Simulation and data of OM efficiency

Very good fit between the simulation and data measurement done in laboratory on the different Optical modules.
Results on $^{40}$K measurements

The $^{40}$K natural rate is extremely stable.
The coincidences rates permits to:
- Calibrate the simulation and check the PMT trigger efficiency.
- Evaluate the efficiency PMT per PMT/OM per OM.
Results on $^{40}K$ measurements

<table>
<thead>
<tr>
<th></th>
<th>Antares</th>
<th>NEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{40}K$ coincidences rate</td>
<td>15.5 Hz</td>
<td>21.0 Hz</td>
</tr>
<tr>
<td><strong>Simulated $^{40}K$ coincidence rate</strong></td>
<td>15.3 Hz</td>
<td>21.6 Hz</td>
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</table>

<table>
<thead>
<tr>
<th>KM3NeT coincidences folds</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment $^{40}K$ coincidences rate</strong></td>
<td>1.2 kHz</td>
<td>45 Hz</td>
<td>4.5 Hz</td>
</tr>
<tr>
<td><strong>Simulated $^{40}K$ coincidence rate</strong></td>
<td>1.2 kHz</td>
<td>50 Hz</td>
<td>6 Hz</td>
</tr>
</tbody>
</table>
Shower reconstruction Performance (similar for nu mu)
Background Rejection

Main background: atmospheric muons misreconstructed as upgoing

Muon contamination efficiently suppressed by cuts on
- track fit quality parameter $\Lambda$
- reconstructed position of vertex: $R_\nu$
- $R_\nu$ inside instrumented volume

Optimisation procedure based on boosted decision tree
$\sim 1\%$ contamination rate achievable, with small signal loss

$R_\nu < 107$ m
Flavour (mis)identification

- Discrimination between 2 classes of events: track-like ($\nu_\mu^{CC}$) and shower-like ($\nu^{NC}$, $\nu_e^{CC}$)
- Classification using “Random Decision Forest” machine-learning algorithm
- Discrimination mainly due to event reconstruction observables

![Graph showing probability to classify as track-like vs energy](image)

80 to 90% correct event topology identification
Sensitivity to PMNS parameters

Red dotted line: current world-average uncertainty

Caveat: here $\delta_{CP} = 0$ fixed to zero and fit constrained to first quadrant
Studies of systematics

Capozzi et al. arXiv1503.01999
PINGU resolutions and effective masses

\[ \sin^2 \theta_{23} \text{ in } [0.4; 0.6] \]
Studies of Systematics (WIP)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nuisance Parameter</th>
<th>Default</th>
<th>Constraint</th>
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<tbody>
<tr>
<td>Normalisation</td>
<td>$R_{Norm}$</td>
<td>1</td>
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<tr>
<td>Mass difference</td>
<td>$\Delta M^2$</td>
<td>$2.43 \cdot 10^{-3}$ eV</td>
<td>none</td>
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<tr>
<td>Mixing angle</td>
<td>$\theta_{13}$</td>
<td>9°</td>
<td>1°</td>
</tr>
<tr>
<td>Mixing angle</td>
<td>$\theta_{23}$</td>
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<tr>
<td>CP phase</td>
<td>$\delta_{CP}$</td>
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</tr>
<tr>
<td>Energy slope</td>
<td>$\epsilon_E$</td>
<td>0</td>
<td>3%</td>
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<tr>
<td>Energy scale</td>
<td>$\Delta E$</td>
<td>0</td>
<td>0.3 GeV</td>
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<tr>
<td>Angular slope</td>
<td>$\epsilon_{\cos \theta}$</td>
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<td>1%</td>
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<tr>
<td>Angular scale</td>
<td>$\Delta_{\cos \theta}$</td>
<td>0</td>
<td>0.01</td>
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<tr>
<td>Asymmetry $\nu/\bar{\nu}$</td>
<td>$\epsilon(\nu/\bar{\nu})$</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Asymmetry $\mu/e$ track/shower</td>
<td>$\epsilon(\mu/e)_{tr/sh}$</td>
<td>0</td>
<td>0.05</td>
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<tr>
<td>NC scale</td>
<td>$\epsilon_{NC}$</td>
<td>0</td>
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<tr>
<td>$\nu_\tau$ scale</td>
<td>$\epsilon_{\nu_\tau}$</td>
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<td>$\sigma(E)$ scale</td>
<td>$\epsilon_{\sigma(E)}$</td>
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<td>0.05</td>
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<tr>
<td>$\sigma(\cos \theta)$ scale</td>
<td>$\epsilon_{\sigma(\cos \theta)}$</td>
<td>0</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 6: Summary of systematic effects

Coming soon: simultaneous minimisation with up to 7 degrees of freedom
dec

Reasonable computing time
Minimisation converges without problems
first indications-effect of new systematics small

53° resolution on CP phase
Angular efficiency with comparison with the old simulation

477nm km3sim document
470nm Lew; 0.9 x qe=0.2
470nm Lew; 0.9 x qe=0.173
477nm Christophe
Angular efficiency, why it wasn't seen before

Simply believed that the cone angle was 30 degree from its technical design.
Angular efficiency, why it wasn't see before

The preliminary results sounded correct
Effect in air strongly reduced

It cannot be seen in air, so experimentally hard to find out (needs measurements in water)
The angle of impact of a big part of events are at very big angle for small AA angle. Then it shift to higher efficiency zone.
Still under investigation, the effect might be due to the 40-60 zone.