ANTARES and Beyond: Neutrino Telescopy in the Mediterranean

Physics with $\nu$ Telescopes

ANTARES: Design and Status

Towards the KM3NeT Detector

Acoustic Detection

Summary

MPI Colloquium
Munich, 16. December 2003
The Neutrino Telescope World Map

Lake Baikal

DUMAND

ANTARES

NESTOR

NEMO

AMANDA

IceCube

South Pole

km³ projects

ANTARES and Beyond...
The principle of neutrino telescopes

Čerenkov light:
- \( \cos \theta_C \approx \frac{1}{n} \); in water: \( \theta_C = 42^\circ \).
- Spectral range used: \( \sim 350 - 500 \text{ nm} \).

Role of the Earth:
- Screening against all known particles except \( \nu \)'s.
- Atmosphere = target for production of secondary \( \nu \)'s (atmospheric \( \nu \)'s).

Neutrino reactions:
- Reaction mechanism studied in detail at accelerators (in particular HERA).
- Extrapolation to highest energies \( \gtrsim 100 \text{ TeV} \) uncertain.
- Key reaction: \( \nu_\mu N \rightarrow \mu X \) (\( \nu_\mu \) CC).
**Particle and Astrophysics with Neutrino Telescopes**

**Neutrino Oscillations:**
Direction, Energy, Flavor

**Low-energy limit:**
- short muon range;
- only few photo sensors give signal;
- in sea water: $^{40}\text{K}$ background prohibitive.

**Dark matter search (WIMPs):**
Direction, Energy

**Cosmic point sources:**
Direction, (Energy)

**Diffuse cosmic neutrino flux:**
(Direction), Energy

... and also:
- GZK–neutrinos
- Z bursts
- magnetic monopoles
- topological defects
- top–down scenarios
- supernova detection

**High-energy limit:**
- fluxes decrease as $E^{-2} \ldots E^{-3}$;
- large detection volume needed.

Ultimate volume (at least) one cubic kilometer.
Neutrino Fluxes and Event Numbers

Observed event numbers for diffuse fluxes:

\[
\frac{dN_{\text{evt}}}{dE_{\nu} \, dt} = \int_{\Omega} \frac{dN_{\nu}}{dE_{\nu} \, dt \, dA \, d\Omega} \cdot \sigma(\nu_{\mu} N \rightarrow \mu X) \cdot (\rho \, V_{\text{eff}}) \cdot T \, d\Omega + \frac{dN_{\text{evt}}(\nu_e, \nu_{\tau})}{dE_{\nu} \, dt} + \frac{dN_{\text{evt}}(\text{NC})}{dE_{\nu} \, dt}
\]

- **Incoming cosmic flux** \( \Phi \propto E_{\nu}^{-2} \)?
- \( \nu_{\mu} \) CC cross section \( \sigma \propto E_{\nu} \) (weaker rise at \( E \gtrsim 10 \text{ TeV} \))
- eff. volume, increases with range(\( \mu \)). But: bad \( E_{\nu} \) measurement
- contributions from other neutrino flavors and NC reactions

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**Graphs**

- Neutrino Survival Probability
- Log-log plot of \( E_{\nu} \) vs. \( dE_{\nu} \)
  - **Baikal**, **MACRO**, **AMANDA B10**, **AMANDA B10 UHE**
  - **SDSS91**, **M95 loud A**, **Submitted to Physical Review Letters**
  - **MPR98**, **WB98 [6]**

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**References**

- AMANDA B10, astro-ph/0303218
  - Submitted to Physical Review Letters
- WB98 [6]
Neutrinos from Astrophysical Point Sources

- **Sky coverage:**
  Complementary to AMANDA/IceCube,
  Galactic Center seen
  $\sim 70\%$ of the time.

- **High sensitivity**
  due to good angular resolution
  ($0.2-0.3^\circ$ at high $\nu$ energy);
  energies $\gtrsim \mathcal{O}(100\ \text{GeV})$.

- **Expectation after 1 year:**
  Improve existing limits
  for Southern hemisphere
  or discover something!

- **Associate neutrino flux to specific ** **astrophysical objects**;
- **Study physics processes** inside source;
- **Relate to “events”** by time correlation.
Indirect WIMP detection

- **Gravitational trapping:**
  WIMPs may be trapped in the gravitational field of Earth, Sun or Galactic Center.

- **Candidate particle:**
  SUSY Neutralino ($\chi$).

- **WIMP annihilation**
  \[
  \chi + \chi \rightarrow \text{hadrons} \rightarrow \nu + X \\
  \chi + \chi \rightarrow Z^0Z^0 \rightarrow \nu\bar{\nu} + X
  \]
  \(\nu\) energy spectrum depends on neutralino mass and on annihilation products
  \(\rightarrow\) estimated sensitivity extremely model-dependent.

- **The ANTARES sensitivity**
  covers part of the SUSY parameter phase space.
  High sensitivity for low \(\Omega_\chi\) (high annihilation cross section).
The diffuse cosmogenic neutrino flux

- Search limited to $\sim 10^5 - 10^8$ GeV;
- Constraints on acceleration mechanism and energy budget at cosmological scales.
The ANTARES Project

The ANTARES Collaboration
- European Collaboration: France, Germany, Italy, NL, Spain, Russia, UK
- Particle physics, astronomy and sea science institutes.

The mission
Design, construct and operate a neutrino telescope in the Mediterranean Sea.

The objectives
- Physics: Detect neutrinos, astrophysical sources, WIMP annihilation, neutrino oscillations, ...
- Technology: Prove feasibility and long-term stability of a deep-sea neutrino telescope.

The challenge
Build a high-tech particle detector in a hostile, poorly known and uncontrollable deep-sea environment.
Detector strings

Electro-optical-mechanical cable (EMC):
- Lines for data transfer, voltage supplies, ...;
- “Mechanical backbone”.

Per storey:
- 3 optical modules (OMs);
- Read-out electronics (signal digitization, data transfer, slow control, ...);
- Calibration instruments (compass, tiltmeter, optical beacons, acoustic transponders).

On the sea floor:
- Electronics;
- Measurement devices for sound velocity and pressure;
- Release mechanism for string (acoustically activated);
- Connection to Junction Box.

1 sector = 5 storeys

14.5m
60m
5 sectors in total

100m cable
**Optical Modules**

- **Photo multiplier tubes:**
  Hamamatsu 10” (550 cm² cathode area); transfer time spread (TTS) ~ 2.7 ns; quantum efficiency > 20% @ 1760 V for 330 nm ≤ λ ≤ 460 nm.

- **Glass spheres:**
  outer diameter 43 cm; qualified for 600 bar; light transmission ≥ 95%.
Environmental conditions

Control measurements

Continuous survey of:
- light absorption;
- current velocity;
- velocity of sound;
- salinity;
- temperature and pressure.

Optical background:

- Continuous rate from $^{40}$K decays and noise:
  $\sim 70\,\text{kHz/PM}$
- Short-term (?) MHz-rates caused by bioluminescence (bacteria, jellyfish, shrimp, fish, ...)
  $\rightarrow$ dead-time/PM $\sim 5\%$. 
The background from above

- Dominant background:
  Muons from atmospheric showers.
- Can penetrate to 2 km water depth if their energy exceeds \( \sim 1 \) TeV.
- Neutrino telescopes need the Earth as screen, except
  - if the vertex of the \( \nu \) reaction is detected (hadronic shower);
  - possibly at highest energies.

Muons at sea level

\[ \Phi \sim 3 \times 10^4 E^{-3.7} \]
The ANTARES field of view

- $3.5\pi$ field of view, of these $0.5\pi$ 24h/day.
- Complementary to AMANDA/IceCube, $1.5\pi$ overlap.
- Galactic center and many potential point sources are accessible.
- $E_\nu \gtrsim 100$ TeV . . . 10 PeV: Earth is opaque for neutrinos ⇒ restricted field of view (only horizontal $\nu$'s).

**EGRET catalogue**
- Active Galactic Nuclei
- Unidentified sources
- Pulsars
- LMC

**Galactic center**

Visibility time

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
**Angular resolution**

- Average angle $\theta_{\nu\mu}$ depends on $E_\nu$:
  $$\langle \theta_{\nu\mu} \rangle \approx 0.7^\circ / E_\nu [\text{TeV}]$$
- Uncertainty of muon angle:
  - detector calibration (position, time);
  - multiple scattering.
- Search for point sources: $S/B \propto 1/\Delta \theta^2$
  $$\Rightarrow$$ large advantage of ANTARES over ice experiments ($\Delta \theta_{\text{IceCube}} \sim 1^\circ$).

**Energy determination**

- $E_\mu \lesssim 200 \text{ GeV}$: $\mu$ range.
- $E_\mu \gtrsim 1 \text{ TeV}$ (cosmic sources):
  $$dE/dx$$ (signal amplitude).
- Resolution:
  factor of $2 - 2.5$ in $E_\mu$
  for $E_\mu \gtrsim 1 \text{ TeV}$.
- Neutrino energy $E_\nu$:
  - $E_\nu > E_\mu$;
  - $\text{RMS}(E_\mu/E_\nu) < 1/\sqrt{12}$.
ANTARES: The preparatory phase

Environment assessment

- **Development of tools** for measuring environmental parameters.
- **Numerous measurement campaigns:**
  - optical parameters of water;
  - salinity, temperature, ...;
  - current velocity and direction;
  - sedimentation and biofouling;
  - bioluminescence;
  - bathymetric profile.
- **Sea floor survey** with deep-sea submarine.

Prototype string

- **Design:**
  16 storeys à 2 PMs, 350 m long, equipped with full readout electronics and slow control devices.
- **Operation:**

**Determination of $\Lambda_{\text{attenuation}}$**

![Graph showing the determination of $\Lambda_{\text{attenuation}}$.](image)

- $\Lambda_{\text{attenuation}}$: $41 \pm 1_{\text{stat}} \pm 1_{\text{syst}} \text{ m}$
- Measurement in water
- Calibration in air
- D: Distance between LED and PMT
- $\Phi_{\text{LED}}$: LED luminosity to obtain a constant current on PMT

storey with LCM (local control module)

12 m

storey with MLCM (master local control module)

100 m

string socket with acoustic release

Main Electro Optical Cable (deployed Oct. 2001)

Junction Box (JB) (deployed Dec. 2002)

both lines connected to JB in March 2003 by NAUTILE


Sound velocity, current profile

Optical beacon, transmissiometer, acoustic receiver

seismometer, acoustic transmitter/receiver

U. Katz

ANTARES and Beyond...
Sea operations

Junction Box deployment

Underwater connection by NAUTILE

Preproduction line deployment

Positioning accuracy

- **Surface position** monitored and stabilized by differential GPS.
- **Underwater position** monitored by acoustic triangulation.
- **Accuracy on sea bed:** a few meters!
The clock failure

- **The symptom:**
The clock signal did not arrive at the readout modules (both lines!)

- **The consequences:**
  → no data with ns time resolution;
  → no measurement of signal charges;
  → no acoustic positioning.
However, we still were able to
  → measure PM rates;
  → control HV settings, thresholds;
  → take slow control data (compasses, tiltmeters etc.).

- **The diagnose:**
One plastic tube around the optical fiber for the clock signal collapsed.
  ⇒ Plastic material changed by manufacturer without notification.
  ⇒ Even worse: material not qualified for high-pressure applications!

- **The remedy:**
Final cable design modified (use steel tubes now).

A water leak

- **The symptom:**
The mini instrumentation line stopped to work on April 11.

- **The consequence:**
Immediate recovery of the line.

- **The diagnose:**
An o-ring secured connector had developed a leak,
 Specifications of hole diameter and tolerances by manufacturer were wrong.
No problems seen in pressure tests!

- **The remedy:** different connectors.
Rate measurements and bioluminescence

- Strong variability of rates: bursts and slow changes.
- “Base line rate” (BR) and “burst fraction” (BF).
- Some correlation between BR and BF, but low-low, high-low, low-high, high-high all appear.
- Mostly bioluminescence ($^{40}$K: $\sim 50$ kHz/PM).
The storeys move "as a rigid body". Correlation with current!?

- Current measurement operational.
- Short-term movements correlated with PM rates (bioluminescence?).

Heading vs. date (data from compasses in preproduction line)

The detailed understanding of environmental conditions is vital and achievable.
Summary: ANTARES

• **ANTARES:** A first-generation water Čerenkov neutrino telescope in the Mediterranean

• First installation steps successfully completed, prototype detector modules deployed and operated.

• Mass production starting after minor design modifications, detector expected ready by early 2007

• Discovery potential for cosmogenic neutrinos and dark matter

• Feasibility proof for neutrino telescope in sea water.
A northern-hemisphere km$^3$ $\nu$ telescope

The physics case:
- Complement sky coverage of IceCube.
- Observe galactic center.
- Increased point source sensitivity.

The requirements:
- Sufficient volume to measure cosmic neutrino fluxes: 1 km$^3$ or 10 km$^3$? Extendable!
- Sensitivity to $\nu_e$, $\nu_{\tau}$ and to $\nu$ from upper hemisphere.
- R&D and construction within 8–10 years.

Some links between physics requirements and design considerations:

![Graph showing E^2*Phi(E) vs. E(GeV) with threshold and sensitivity dependencies on detector design, noting important points for point sources.]

Deterioration due to screening by Earth. Sensitivity depends on:
- detector volume
- architecture
- observation of (parts of) upper hemisphere.
- detection of $\nu_e$, $\nu_{\tau}$

Important for point sources. Threshold and sensitivity depend on detector design (e.g. photo sensor spacing).

How large is the real diffuse flux?
**Past and present \( \nu \) telescopes**

<table>
<thead>
<tr>
<th>Fresh water</th>
</tr>
</thead>
<tbody>
<tr>
<td>• <strong>no potassium</strong>;</td>
</tr>
<tr>
<td>• <strong>surface ice</strong>: access, calibration;</td>
</tr>
<tr>
<td>• <strong>water transparency</strong>, bioluminescence;</td>
</tr>
<tr>
<td>• <strong>depth</strong> ( \lesssim 1400 ) m.</td>
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<tr>
<td>• <strong>Lake Baikal</strong></td>
</tr>
<tr>
<td>demonstrated feasibility of water</td>
</tr>
<tr>
<td>Čerenkov ( \nu ) telescope.</td>
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<tr>
<th>Salt water</th>
</tr>
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<tbody>
<tr>
<td>• <strong>optical water properties</strong>;</td>
</tr>
<tr>
<td>• <strong>sufficient depth</strong> (→ site choice);</td>
</tr>
<tr>
<td>• <strong>potassium</strong>, bioluminescence;</td>
</tr>
<tr>
<td>• <strong>chemically aggressive</strong>;</td>
</tr>
<tr>
<td>• <strong>no “surface”</strong>.</td>
</tr>
<tr>
<td>• <strong>DUMAND</strong>:</td>
</tr>
<tr>
<td>pioneering work, stopped 1995.</td>
</tr>
<tr>
<td>• <strong>ANTARES, NESTOR</strong>:</td>
</tr>
<tr>
<td>first data from prototype installations.</td>
</tr>
<tr>
<td>• <strong>NEMO</strong>:</td>
</tr>
<tr>
<td>R&amp;D towards a ( \text{km}^3 ) ( \nu ) telescope.</td>
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<table>
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<tr>
<th>Ice</th>
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<tr>
<td>• <strong>AMANDA</strong>:</td>
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<tr>
<td>data taking.</td>
</tr>
<tr>
<td>• <strong>IceCube</strong>:</td>
</tr>
<tr>
<td>( \text{km}^3 ) project, in preparation.</td>
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**The Mediterranean Sea offers optimal conditions** …

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<tr>
<td>• due to its <strong>properties</strong> (water quality, depth, temperature, ...);</td>
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<tr>
<td>• due to the existing <strong>infrastructure</strong>;</td>
</tr>
<tr>
<td>• since the world <strong>expertise</strong> for sea water ( \nu )T’s is concentrated in the European countries;</td>
</tr>
<tr>
<td>• since it is a perfect stage for a large <strong>European science project</strong>.</td>
</tr>
</tbody>
</table>

**Common European effort needed to realize a future \( \text{km}^3 \) \( \nu \) telescope in the Mediterranean Sea.**
The Neutrino Telescope in Lake Baikal

- Pioneers in under-water technology for $\nu$ telescopes.
- Atmospheric $\nu$'s observed, limits on diffuse $\nu$ fluxes.
- Further extension planned, but km$^3$ hardly reachable.

The BAIKAL NT-200 Neutrino Telescope
• **Tower-based** detector (titanium structures).
• **Dry connections** (recover – connect – deploy).
• **Up- and downward looking PMs**.
• **4000 meters** deep (5200 m available at Pylos site).
• **Instrumented volume:**
  \[ \sim 0.0003 \text{ km}^3 \text{ per tower}. \]
• January 2002:
  Deployment of LAERTIS at 4200 meters depth, successful taking of environmental data.
• March 2003:
  Deployment of first prototype floor (reduced size).
• PM signals read out, wave forms available, 5 million event triggers taken, background rates as expected.
• Muon tracks reconstructed.
How to Increase $\nu$ Telescopes to a km$^3$?

Existing $\nu$T’s times 100–1000?
- Too expensive:
  ANTARES $\times$ 100$=\mathcal{O}(2 \times 10^9)$ Euros.
- Too complicated:
  production/deployment take forever, maintenance impossible.
- Not scalable:
  e.g. readout bandwidth, online filter, power distribution, . . . .

Research and Development needed:
- Cost-effective solutions:
  Reduce price/volume by factor $\gtrsim 10$.
- Increased stability:
  Goal: maintenance-free detector.
- “Fast” installation:
  Time for construction & deployment less than detector life time.
- Photo sensors:
  High quantum efficiency, large area, low noise, directional sensitivity.
  . . .
The NEMO project

- Extensive site exploration (Capo Passero, depth 3340 m).
- R&D towards km³: architecture, mechanical structures, readout, electronics, cables, ...
- Measurements at Catania test site planned (depth 2000 m).

64 towers,
16 arms each,
20m arm length,
arms 40m apart.

64 PMs per tower,
4096 altogether.

Underwater
connections.

Up– and down–
looking PMs.

Instrumented
volume:
1.2 km³
A Common European Effort

End of 2002:
ANTARES, NEMO and NESTOR
decided to cooperate in
preparing a future km³ νT
in the Mediterranean Sea

KM3NeT Design Study:
• Instrument of the EU FP6
programme to fund preparatory
work and feasibility studies
for research infrastructure.
• Proposal in preparation,

Work Packages:
• Design Study Management
• Scientific assessment
simulation, design optimization, ...
• Cooperation with industry
to develop commercial products
• Information technology
read-out, data transport,
on-line processing
• Infrastructure & support
site, deployment & recovery,
shore station, maintenance
• Quality assurance
• Resource exploration
funding, legal aspects, management
• Associated sciences
interfaces for usage by biologists,
oceanographers, geologists,
environmental scientists, ...

success
rejcted

proceed, TDR in 2007
proceed with national funding ?!
Site Characterization and Selection

3 suitable sites explored in detail:

Site selection:
- **Delicate decision**
  Strong national interests and political arguments involved.
- **Major scientific criteria:**
  → water quality;
  → depth;
  → geological environment;
  → distance to shore;
  → infrastructure.
- **Decision path:**
  - Further input provided by running of prototypes.
  - Arguments reviewed by ApPEC.
  - Not clear who decides . . .
- **Meanwhile:**
  continue to organize common effort and start up activities.

Measurements and assessments:
- Optical properties of water (absorption, scattering);
- Current velocity and direction;
- Bathymetric surveys;
- Bioluminescent activity;
- Biofouling;
- Sedimentation;
- Geological stability;
- . . .
The Architecture

**Some questions:**

- **Strings or rigid towers or flexible towers or . . . ?**
  Determines mechanical stability, significant impact on overall cost, . . .

- **Wet or dry connections?**
  Cost and long-term availability of deep-sea submarines?
  Effort for underwater connections depends on detector depth.

- **Distance of photo sensors?**
  Depends on water transparency and on active area and efficiency of photo sensors.
  **Note:** Factor 2 in average distance gives factor 8 in detector size with same number of sensors.

- **Homogeneous detector or dense core?**
  $E_\nu$ dependence of effective volume.
Photo Sensors

Development goals:
- Increase area and efficiency.
- Retain or improve time resolution.
- Obtain directional sensitivity.
- Reduce costs.
- Ensure long-term stability in deep-sea environment.

Approaches:
- Hybrid photomultipliers (see below).
- Hybrid photo diodes (HPDs).
- Avalanche photo diodes (APDs).
- Photocathode improvements (spectral quantum efficiency).
- Gas electron multiplication (GEM)

The Baikal HPM:
Hybrid PM + scintillator photo sensor.
Large sensitive area with low-diameter PMs.

Developments at INFN Genova:
- Optimize geometry:
  - transfer-time spread improved to $\mathcal{O}(1\,\text{ns})$;
  - correlation of $\gamma$ and $e$ impact positions.
- Use light guides to determine light direction.
Problems:

- **Enormous data stream to shore:**
  ANTARES × 100: $O(750 \text{ GByte/s})$.

- **Large Power consumption**
  of the off-shore electronic components poses problems to power distribution
  and to cooling.
  (ANTARES power × 100: $O(3 \text{ MWatt})$)

- **Operation stability:**
  Is rate of failures that stop the
  system proportional to the number of
  components?
  Is system operatable?

- **Maintenance:**
  How many deep-sea operations per year
  are needed to keep 90%, 80%, …
  of the functionality?

Ideas:

- **Fast optical data transmission:**
  Profit from developments
  in industry.
  DWDM technology:
  one color per photo sensor?

- **Realize readout with passive/optical elements:**
  – reduces power consumption;
  – avoids failures;
  – “maintenance-free”.

- **Trigger and filter on shore:**
  May be installed later to use
  latest technology.
  Allows for modifications to match
  the needs of data taking.
Material Considerations

Material must . . .

- withstand high pressure
  - steel;
  - titanium.
- withstand corrosion
  - titanium;
  - certain synthetics;
  - GRP (glass reinforced plastic).

Current installations almost exclusively use titanium (material and machining expensive).

Solutions:

- Composite structures
  Use separate material layers: outer layer against corrosion, inner layer against pressure.
  E.g. NEMO JB design.

- Mechanical structures
  (struttings, towers, etc.):
  Use of GRP seems possible.

NEMO design for a composite–structure Junction Box:

- To be filled with oil
- Steel vessel
- Synthetic material (e.g. GRP)
• Strong physics motivation for km$^3$-scale neutrino telescope in Northern hemisphere

• Mediterranean offers optimal conditions

• Large amount of R&D required (current detectors not scalable)

• Common European effort initiated to obtain funding for preparatory phase

• Time scale set by IceCube project and “community life time” – go for it either now or never!
Acoustic detection: Can you hear neutrinos?

Motivation:
- Large range of sound in water → large-volume detectors.
- Detection of the hadronic/elm. shower → $4\pi$ acceptance.
- Sensitivity to all neutrino flavors.
- Complementary to radio Čerenkov method in ice (RICE experiment @ AMANDA).

\[ p \propto \frac{E(dV/dT)}{d^2} \]

\[ \Delta T = \frac{E}{c_{H_2O}M_{H_2O}} \approx 60 \text{nK} \]

\[ T_{\text{Mediterranean}} \approx 14^\circ C > 4^\circ C \]

\[ \Rightarrow dV/dT > 0 \]
Background conditions

Rough estimate:
- Optimal conditions, 2 km depth: Background $\sim 5\mu Pa/\sqrt{Hz}$
  $\Rightarrow \sim 500\mu Pa$ in range $15-25\ kHz$.
- Signal $\leq$ background:
  - many hydrophones per signal;
  - efficient signal filtering;
  - spatial and time correlations $\rightarrow$ beam forming

G.M. Wenz,
Acoustic R&D in Erlangen

Activities:
(some in close collaboration with AMANDA/IceCube group at DESY-Zeuthen)

• Generation/acquisition of acoustic signals
• Characterization of commercial hydrophones (Piezo-based)
• Development of calibration sources
• Development of specialized hydrophones
• Development of simulation software
• Development of signal filters and triggers
• Beam tests at Uppsala (Feb. 2004)
• Equipment of 2 ANTARES strings with hydrophones (late 2005)
Some “acoustic pictures”

- Voltage pulse
- d=10cm ~ 70μs
- Signal first reflection
- Electromagnetic coupling
- Transducer signal

Resistor as calibration source

Piezo elements

Resistor signal
Summary: acoustics

- Acoustic detection may be a promising future method for investigation of cosmic neutrinos above \( \sim 10 \text{ PeV} \)
- Several acoustic R&D projects in Erlangen, in concert with world-wide activities
- First encouraging results
- Decisive milestone: long-term measurements in ANTARES environment