Recent Results from the ANTARES Deep-Sea Neutrino Telescope

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The ANTARES collaboration is currently constructing a large area neutrino telescope for deployment in the Mediterranean Sea. The ANTARES detector will be located 30 km off the southern French coast. After introducing the detection principle, the details of the detector design are considered. In describing the ANTARES site, emphasis is placed on results from more than 25 deployments of autonomous mooring lines instrumented with various measuring devices. These deployments have led to an understanding of the water and environmental parameters at the site. A neutrino telescope can address a wide-ranging scientific programme which covers topics in particle physics and astrophysics, a brief summary of this programme is made, following which, aspects of the expected detector performance, specifically the angular and energy resolutions, are discussed. Finally, the results from a "demonstrator string" are presented. This is a full-scale, part-instrumented string which was deployed in the Mediterranean Sea in late 1999. The string has provided the first recorded down-going muons which have been subsequently reconstructed and analysed, examples of these events and their properties are given. The demonstrator was also equipped with the instrumentation required for determining the position, inclination and orientation of the string as a function of time. The performance of these systems is also discussed.

1. THE DESIGN OF THE ANTARES DETECTOR

Muon neutrinos interact in rock or sea water to give a charged muon via the charged-current interaction. In the case of a high energy neutrino, the corresponding muon is highly relativistic and so gives a cone of Cherenkov light when passing through a suitable medium such as ice or water. The light yielded is blue (typically 350-550 nm) and is suitable for detection by photomultiplier tubes. Thus, instrumenting a large area of sea water with photomultiplier tubes enables a neutrino detector of large effective area to be constructed.

The basic design of the ANTARES detector follows this approach and is schematically illustrated in figure 1. It shows a detector which is an array of "strings" which are attached to the sea bed via an anchoring weight and which are held taut by their own buoyancy. On each string there are 30 "storeys" where 3 large-area hemispherical photomultiplier tubes (PMTs) are located. The PMTs are housed inside pressure-resistant glass spheres with silicon gel at the PMT-sphere inter-

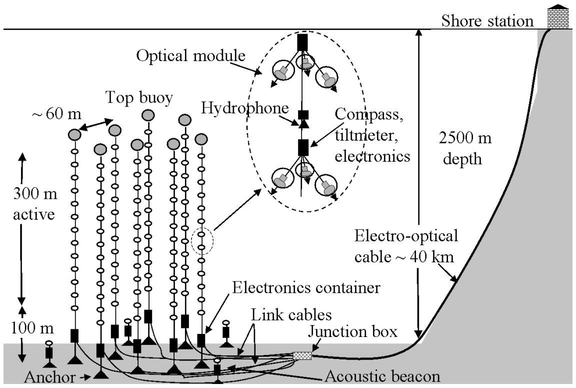

Figure 1. A schematic of the ANTARES 0.1 km^2 detector.

face to ensure good optical coupling. The PMT, glass housing and in-sphere electronics together form an "optical module". Storeys are spaced at 12 m intervals on a string and each string is 60 m from its neighbours, the first 100 m of water above the sea floor is uninstrumented. The PMTs are oriented at 45° to the downward vertical and look down in order to detect the Cherenkov light from upward-going muons created by neutrinos which have passed through the Earth. In this way, background (down-going) muons created by cosmic rays are suppressed.

Other instrumentation on the detector strings includes acoustic positioning devices, tiltmeters and compasses to accurately determine the position, orientation and heading of various points on the detector string which enable the 3-dimensional spatial profile of the string to be determined.

The first phase of the ANTARES detector will consist of 13 strings which will have an effective area of 0.1 km^2 for high energy neutrinos. Each string is connected via an electro-optical cable to a central "junction box" which, in turn, is connected via a 40 km long electro-optical link cable to an on-shore station where triggering hardware and data acquisition is located. This 13-string device is the first phase of a programme to build a 1 km^2 scale ANTARES detector in the Mediterranean.

2. THE ANTARES SITE

In order to build a large-scale neutrino telescope, a suitable deep-sea site must be identified and tested in order to assess its suitability in terms of environmental parameters and water quality. Such a site has been found, 2400 m deep and 30 km off the coast of Toulon in Southern France. Situated, as it is, at a latitude of 42.8°N, 3.5π sr. of the sky is observable at the ANTARES site, furthermore, there is a 0.6π sr. effective overlap in solid angle with AMANDA [1], which will prove useful for studies of different systematic errors in the two experiments. The site has certain strong logistical advantages due to its close proximity to CPPM (Marseille) and to IFREMER (La Seyne) where the ships and submarines used in the deployment and recovery operations are based. To date, more than 25 deployments and recoveries of autonomous instrumented strings have taken place at and around the ANTARES site. These devices have measured the following water and environmental parameters.

2.1. Biofouling and sedimentation

There are two possible sources of degradation of the light transmission of optical surfaces, namely sedimentation, where particulate debris suspended in sea water descends and accumulates on the surfaces and a second type of fouling, where bacteria and other living organisms adhere to the glass surfaces.

These effects have been measured using instruments deployed at the ANTARES site. Combined biofouling effects have been assessed using pairs of optical modules, one containing light sources, the other pin diode detectors. The optical transmission is seen to reduce by less than 2% over a one year period for a light source and receiver in the horizontal plane, this is an acceptable level.

The sedimentation rate has been measured independently using sedimentation traps where the accumulation of falling particulate matter is measured over a period of time. The level is low, typically 200 $\mathrm{mg.(m^2 day)^{-1}}$, which poses no problems for transmission losses in the detector.

2.2. Optical backgrounds

Optical backgrounds arise from light sources at the ANTARES site which emit light at a wavelength which falls in the detector's window of sensitivity (350-550nm). In ANTARES there are two such sources which have been identified and measured. Potassium-40 (^{40}K) is a trace element in sea water. It is naturally radioactive and decays via β-decay. The electron emitted in the decay is relativistic and gives rise to blue Cherenkov photons. Furthermore, biological organisms exist at these depths capable of communicating via the emission of bursts of blue light.

The levels of background light have been measured using autonomous test strings comprising two or three PMTs which have been deployed at the ANTARES site and elsewhere. Figure 2

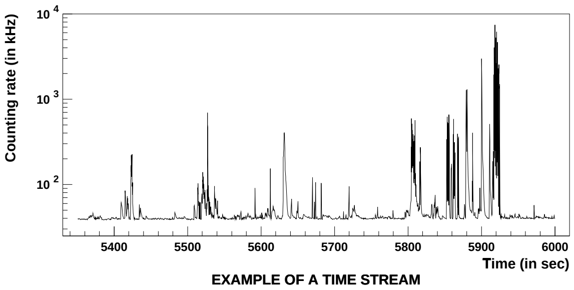

Figure 2. Background light rate at 0.3 p.e. threshold as a function of time at the ANTARES site.

shows a typical counting rate profile at 0.3 photoelectron (p.e.) threshold [2]. Two distinct components are observed, a continuous component which fluctuates over timescales of a few hours and distinct, short period bursts.

The continuous (non-fluctuating) component is identified with the ^{40}K and is seen to contribute up to 37 kHz (singles rate, 0.3 p.e. threshold) for an 8$''$ Hamamatsu PMT. The variable part of the continuous component and the short bursts are believed to be both due to different types of bioluminescent activity.

The effect of this background light on the detector has been assessed and has been seen to have a negligible effect on efficiency given the existing trigger and read out designs [2].

2.3. Water absorption and scattering

Two important properties of the sea water at the site, the absorption and the scattering, also need to be measured. The amount of absorption is an important parameter in determining how closely successive storeys on a string need to be spaced whilst, importantly, the amount of scattering limits the angular resolution of the detector as a whole and hence impacts directly on the physics potential of the device.

These properties have been investigated using a system employing a pulsed light source and a fast TDC so that both absorption and scattering information can be determined simulataneously. The system uses light of two different wavelengths, namely blue light (466 nm) and UV light (370 nm).

Measurements indicate that for blue light, the absorption length is typically 60 m whilst for UV light it is of the order of 20 m. In both cases, the effective scattering length is greater than 100 m, this promises much improved angular resolution compared with ice-based neutrino telescopes.

3. SCIENTIFIC PROGRAMME

A detailed description of the science aims of the ANTARES project are beyond the scope of this manuscript, the interested reader can refer to [3] and references therein for a more complete description. The principle scientific goals of the experiment are summarised here.

3.1. Neutrino Astronomy

The ultimate goal of a large area (order 1 km^2) neutrino telescope is to detect high energy neutrinos from extragalactic sources. Potential candidate sources include a wealth of astrophysical objects, amongst which are gamma ray bursts (GRBs), active galactic nuclei (AGN) and supernovae remnants [4]. The observation of fluxes of high energy neutrinos from any of these or other sources will answer important questions on the extent and nature of hadronic processes in these bodies.

3.2. Searches for Dark Matter

One of the most promising candidates for cold baryonic dark matter is the supersymmetric particle known as the neutralino. The neutralino is a Majorana particle and can accumulate at the cores of celestial bodies such as the Earth and Sun via gravitational capture. In such cases, the increased number density leads to neutralino self-annihilations which produce high energy neutrinos as a decay product. Furthermore, there is strong evidence for a massive black hole at the centre of our own galaxy [5], this would lead to similar areas of high dark matter density close to the black hole. There is therefore a strong possibility that centre of our galaxy is a source of high energy neutrinos from neutralino annihilation [6].

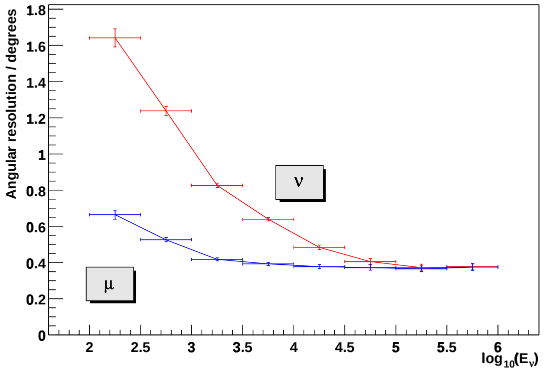

Figure 3. Predicted pointing accuracy as a function of energy.

3.3. Neutrino Oscillations

Recent results from SuperKamiokande [7] and other experiments can be interpreted as evidence for neutrino oscillations between muon neutrinos and either a tau or sterile neutrino ($\nu_\mu \rightarrow \nu_\tau, \nu_s$). ANTARES has the capability of exploring baseline lengths up to the Earth's diameter. The effective mass of the active volume of ANTARES is several orders of magnitude larger than that of earlier underground experiments (1000× the volume of Superkamiokande). By fitting oscillation hypotheses to the observed L/E distribution it should be possible to obtain values of $\sin^2 2\theta$ and Δm^2 simultaneously.

4. PREDICTED PERFORMANCE

The performance of the ANTARES detector has been assessed using simulation software which generates neutrino events in the ANTARES detector. The effects of scattering of photons in water are included in the results below for the first time, an optical model of water based on two Henyey-Greenstein phase functions [8] is used, the parameters of the model are chosen to agree with the observed water properties at the ANTARES site. Figure 3 illustrates the angular resolution of the detector. The plot gives the median angle between the reconstructed muon and simulated muon and neutrino. The difference between these two curves is due to the angle, $\theta_{\mu\nu}$, between the neutrino and muon at the point of creation of the muon. Figure 3 shows, that for neutrino energies of 10 TeV and above, the pointing accuracy is 0.5° or better and is dominated by errors in reconstructing the muon trajectory. At low neutrino energies the pointing accuracy is poorer and is dominated by $\theta_{\mu\nu}$.

This pointing accuracy is significantly better than that achieved by experiments in ice, due to the improved scattering length of blue light in water. The observable sky is divided into pixels, the area of each being proportional to the square of the pointing accuracy, therefore an improved angular resolution promises an important increase in the detected signal to noise ratio in each pixel.

The energy resolution of the device has also been studied. At high energies, catastrophic energy losses dominate and the energy of the incident muon and hence neutrino can be estimated from a parametrization of the energy loss. At low energies however, the range of the muon must be used to estimate the energy loss, this is done by using contained or partially-contained events. Figure 4 plots the relationship between generated and reconstructed energy for high energy muons. Above 1 TeV the agreement is good, at such energies the muon energy is reconstructed to a factor of 3 or better.

5. A DEMONSTRATOR STRING

In November 1999, a "demonstrator string" was deployed at a site 40 km off the coast of Marseille at a depth of 1100 m. The choice of site was dictated by the availability of a suitable electro-optical cable. The string structure is depicted schematically in figure 5. Whilst it is not mechanically identical to its 0.1 km^2 detector counterparts it contains many components that are common to both designs. The demonstrator string was equipped with seven PMTs, six 8$''$ and one 10$''$ and was also instrumented with assorted measuring devices such as tiltmeters, compasses and an acoustic positioning system. The string was controlled and read out via a 37 km long optical cable which was connected to a shore sta-

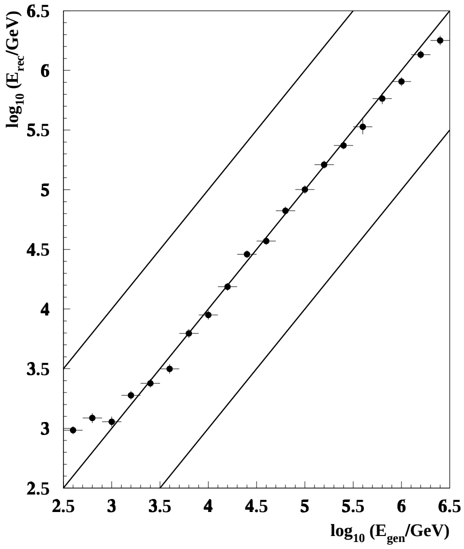

Figure 4. Reconstructed versus generated muon energy for high energy muons.

tion in Marseille. During the operation of the string, which was retrieved in July 2000, more than 50000 down-going seven-fold co-incidences were recorded.

The aims of the deployment and operation of a demonstrator string were numerous and included: acquiring experience of deploying a full-scale device; tests of undersea connection and disconnection of a string to an electro-optical cable; tests of the positioning systems; recording of down-going muon and multi-muon events.

5.1. Performance of the positioning systems

Accurate knowledge of the three-dimensional shape of each string is important in order to successfully reconstruct the muon trajectories in the detector. To facilitate this a number of different devices are foreseen, each providing information on different aspects of the position, tilt or orientation of string elements.

The demonstrator string was equipped with 11 tiltmeters and compasses, data from these instruments indicate that over one week of operation

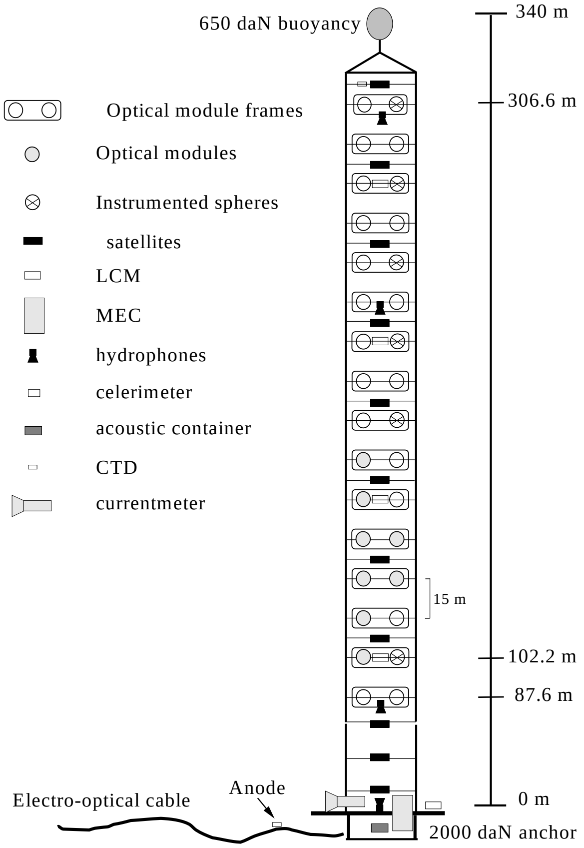

Figure 5. Schematic representation of the ANTARES demonstrator string.

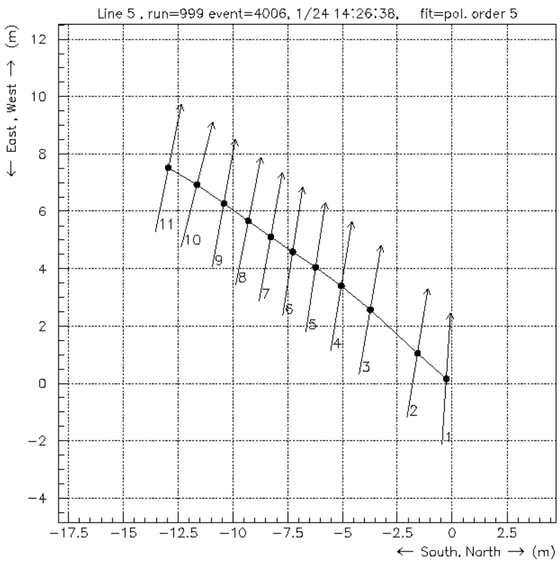

Figure 6. Reconstructed 3D profile of the demonstrator string.

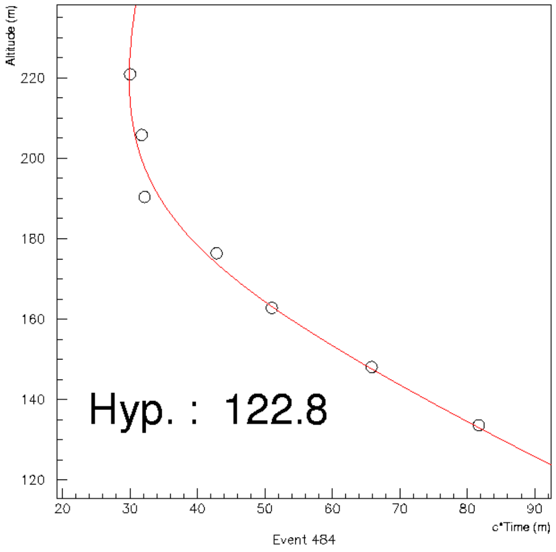

Figure 7. Reconstructed down-going muon event.

virtually no twist is observed (headings were stable to within 2° over the week) and tilt stability, as measured by tiltmeters at the top and bottom of the string, was stable to 0.2° over the same period.

The tiltmeter and compass data were combined to allow the overall 3-dimensional line shape to be reconstructed as a straight string inclined at 2.5° to the vertical, this is illustrated in figure 6.

Additional positioning information was available via an acoustic system of 3 rangemeters located on the string and 4 acoustic transponders situated on the sea floor approximately 200 m from the string base.

This system allowed 12 different transponder to rangemeter distances to be simultaneously determined via a global fit, the residual on each of these distances is typically 5 cm, in expectation with the instrumental specifications. In addition, inter-rangemeter and inter-transponder distances could be established, in both cases a residual of the order of 1 cm was observed. Overall, the performance of the positioning system exceeded the design requirements.

5.2. Reconstructed Events

As mentioned previously, a large number of 7-fold co-incidences were recorded with the demonstrator string. A typical event is illustrated in figure 7 where the result of a hyperbolic fit to the PMT hits is superimposed.

A second example of a reconstructed down-going event can be seen in figure 8, here the boxes correspond to hits that have been identified as potential potassium-40 hits and subsequently excluded by the reconstruction algorithm.

Those data studied to date have been analysed in terms of the observation of a combined flux of down-going single and multiple-muon events. These events exhibit different characteristics, for example, the timing residuals are different for the two event classes due to the fact that multi-muon events have a greater multiplicity. The timing residuals for all reconstructed events is depicted in figure 9, it clearly consists of two distinct components, both of which are fitted to a gaussian function. The parameters of these two gaus-

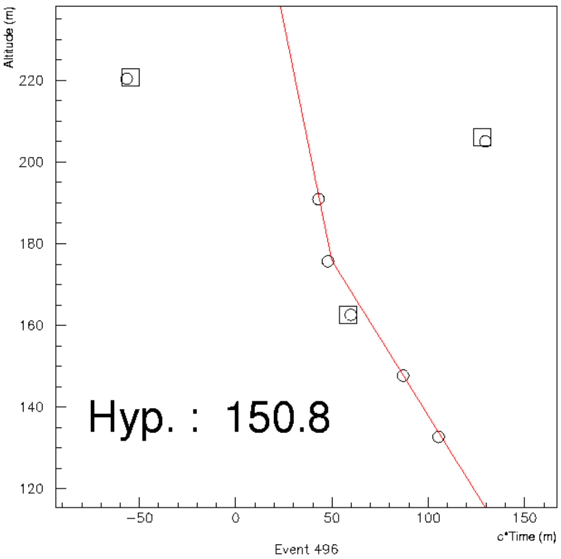

Figure 8. Reconstructed muon event with ^{40}K hit rejection.

sians agree well with Monte Carlo expectations for these two event classes.

6. CONCLUSIONS AND OUTLOOK

The ANTARES project has made significant progress in the two years since the last Neutrino conference. A site has been identified with excellent water quality and which satifies all other criteria. More than 25 successful deployments and recoveries have been made. Recently a full-scale partly-instrumented demonstrator detector string has been successfully deployed, operated and recovered in 1100 m of water in the Mediterranean Sea. More than 50000 events have been recorded and analysis of these events is underway.

The future programme for ANTARES aims to have all 13 strings for a 0.1 km^2 scale detector deployed by the end of 2003. This is the first step towards a 1 km^2 detector in the Mediterranean Sea.

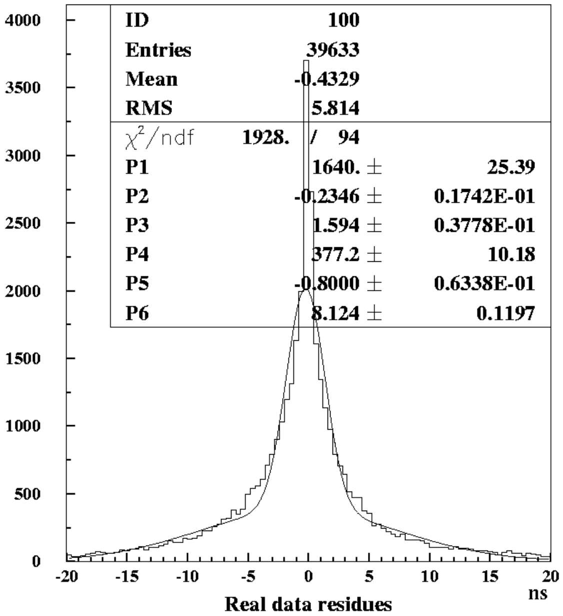

Figure 9. Timing residuals for reconstructed events.

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