The Status of the ANTARES experiment

E. V. Korolkova[a] * for the ANTARES Collaboration

[a]Department of Physics and Astronomy, The University of Sheffield, Sheffield S3 7RH, UK

ANTARES is a neutrino telescope designed to search for high-energy neutrinos from astrophysical sources such as quasars, gamma-ray bursters, microquasars, supernova remnants and AGN. The objectives also include the indirect search for WIMPs, primary candidates for non-baryonic dark matter, by looking for neutrinos from neutralino annihilations in the centres of the Sun, Earth and Galaxy. The array of 12 lines with 900 photomultiplier tubes will be deployed by 2007 at a depth of about 2500 m in the Mediterranean sea near Toulon (France), 40 km off the coast. It will detect the Cherenkov light emitted in sea water by muons produced via charged-current interactions of neutrinos with surrounding matter. A prototype line and an instrumentation line for monitoring environmental parameters have been successfully deployed and connected to the electro-optical cable, which transmitted the data to the shore station. The current status of the project is presented.

1. INTRODUCTION

The acceleration of cosmic rays up to very high energies is one of unsolved problems of modern physics. The observed cosmic-ray particles with energies up to 10^{20} eV demonstrate the existence of sources capable of accelerating protons to such energies. Active galactic nuclei, supernova remnants, microquasars and gamma ray bursts are considered as candidate sources. High-energy particles can be produced in hadronic and electromagnetic processes. High-energy gamma rays from many point-like sources have been observed by ground-based telescopes. However, observation of gammas cannot reveal the hadronic nature of the acceleration process inside the source. Moreover, high-energy gammas interact with microwave and infrared cosmic background and cannot reach the Earth from large distances.

Neutrinos can be produced in pp or $p\gamma$ interactions of accelerated protons (or heavier nuclei) with matter or photon field via the decay of charged pions (and possibly kaons). As neutrinos are electrically neutral and weakly interacting particles, they can escape from the dense cores of potential sources and travel enormous distances without being absorbed, scattered or deflected by magnetic fields, delivering information on the processes of particle acceleration directly from the sources.

However, due to the extremely low neutrino cross sections with respect to the fluxes from potential sources, predicted by various models, neutrino detection requires the instrumentation of large target masses, suggesting the use of naturally abundant detection materials, such as water or ice. A high-energy neutrino interacts in rock, ice or water and produces a muon, which emits Cherenkov light while propagating in water or ice. The Cherenkov light can be detected by an array of optical sensors, called neutrino telescopes. Two Cherenkov neutrino telescopes AMANDA and Baikal [1] are already taking data and producing interesting results, others, such as NESTOR, NEMO and ANTARES are at the construction or evaluation stage. IceCube and KM3NET are cubic kilometre scale projects.

2. DETECTOR DESIGN

The ANTARES project (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) [2] has been started in 1996. The ANTARES Collaboration aims to build a deep underwater neutrino telescope in the Mediterranean Sea. The selected site is located at $42°50'N, 6°10'E$, about 40 km off the French coast, at a depth of about 2500 m. The site com-

*e-mail: e.korolkova@sheffield.ac.uk

bines the advantage of large depth with the proximity to the coast and infrastructure (harbours of Toulon and La Seyne). The detector location provides a 3.5 π sr coverage of the sky and allows the observation of the Galactic Centre for 67% of the time.

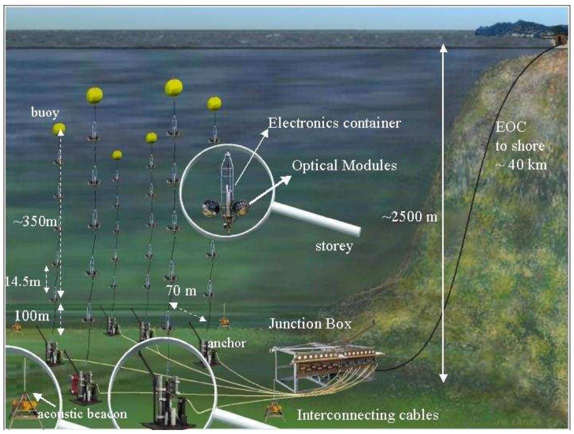

Figure 1. Schematic view of the ANTARES detector.

The choices of the geometrical parameters of the instrumented lines have been guided by the results of measurements performed on water transparency, sedimentation, water current and optical background. The absorption length is about 60 m at 470 nm and mainly limits the size of the instrumented region and the photomultiplier tube (PMT) spacing. The effective scattering length is more than 200 m. The optical background is due to β decays of ^{40}K and a continuous bioluminescence rate of about 60 kHz per PMT which is sporadically increased by short bioluminescence bursts up to MHz. The dead-time due to these processes is a few percent per PMT randomly distributed over the detector, however the requirement for coincidences significantly decreases the dead-time for the whole detector. The average loss in the light collection at the optical module due to bio-fouling and sedimentation is less than 2% in the horizontal direction after one year of deployment and it tends to saturate with time [3].

The ANTARES detector will consist of 12 vertical lines arranged in an octagonal geometry (see Figure 1). Neighbouring lines are separated by about 70 m. The lines are anchored to the sea bed and kept vertical by buoys attached to the upper ends. They float in the sea current and the positions of active detector elements are permanently monitored by an acoustic calibration system. All lines are connected to the junction box, which links the detector to the shore station via a 40 km electro-optical cable, distributes the electric power and control signals, and sends data to the shore station.

Each line is equipped with 75 optical modules (OMs) [4] arranged in triplets (storeys); there are 25 storeys per line. The distance between two adjacent storeys is 14.5 m. The storeys are interconnected with an electro-optical mechanical cable supplying the electric power and the control signals, and transferring the data to the bottom of the line. The anchor is placed 100 m below the lower storey. The total height of such a line is about 450 m. The detector will be complemented by a special instrumentation line equipped with devices for monitoring the environmental parameters and tools used for studies in oceanography, marine biology and seismology.

The ANTARES OM is a pressure resistant glass sphere which contains a hemi-spherical PMT with a photocathode of 10-inch diameter, its base and a pulsed LED for timing monitoring. The PMT looks downwards at 45° to the vertical to avoid sedimentation. The PMT is surrounded by a μ-metal cage which acts as a shield against the Earth's magnetic field. A cylindrical titanium container houses the local electronics. Some storeys contain supplementary calibration equipment like acoustic and optical beacons.

The PMTs detect photons with a quantum efficiency above 20% for the relevant wavelengths between 330 nm and 460 nm. The signals of each PMT are read out by two ASICs (two chips allow reduction of the overall dead time). For simple pulses the charge and arrival time are digitised and stored for transfer to the shore station. For more complex pulses the pulse shape is digitised with a 1 GHz frequency. The time stamps are synchronised by a clock signal which is sent in regular intervals from the shore to all electronics cards. All signals above the threshold (corresponding to about 0.3 photoelectrons) are sent to the shore station where a PC farm performs data filtering (the data volume is reduced by a factor of 100), selection of event candidates, event building etc. These shore computers also facilitate the remote control and the monitoring of the junction box and of the lines.

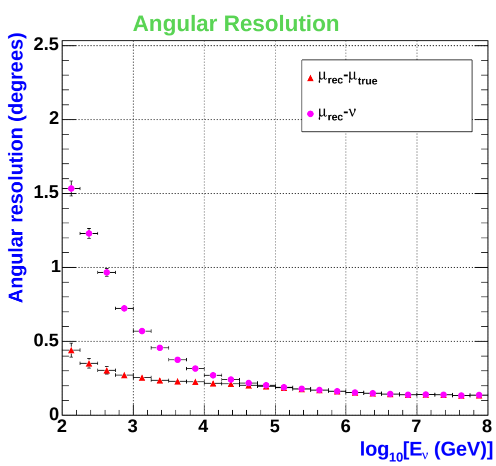

Figure 2. Median angle between the reconstructed muon and the simulated muon (triangles) or the simulated neutrino (circles) versus neutrino energy.

For a good track reconstruction two main calibrations must be performed accurately. The time calibration is critical for the ANTARES experiment. The time resolution of the signal pulses will be limited by the transition time spread of the PMTs (σ is about 1.3 nsec). Each line is equipped with optical beacons (OB) for timing calibration: a laser beacon located at the bottom of the line and LED beacons placed along each detector line. The time calibration system aims to achieve a relative precision better than 0.5 ns which allows the reconstruction of muon tracks with angular resolution better than 0.3° for energies higher than 1 TeV and absolute time precision of about 1 msec.

The positional calibration is achieved using a system of acoustic beacons placed on and around ANTARES and acoustic detectors (hydrophones) located on each storey to measure the position of each OM along the line. This system gives a relative measurement of position of each element of the detector with an accuracy of a few centimetres. The absolute calibration comes from the GPS measurements of the line positions during the deployment and is about 1 metre.

3. THE DETECTOR PERFORMANCE

Most studies in the ANTARES programme are concentrated on the charged current interactions of muon neutrinos. The detector will operate by detecting the intensity and the arrival time of the Cherenkov light emitted by relativistic charged particles produced by neutrino interactions. The PMT signals are used to reconstruct the muon track. In ANTARES, several muon reconstruction algorithms have been developed. They use the direct Cherenkov hits but take also into account secondary effects like diffusion, dispersion and electromagnetic showers which accompany high energy muons. The muon trajectory can be determined from the knowledge of the arrival times of photons recorded by the PMTs and of their positions. The pointing accuracy will be better than 0.3° for energies above 1 TeV. Figure 2 shows the median angle between the reconstructed muon and the simulated muon (triangles) or neutrino (circles) versus the neutrino energy. Below 1 TeV the median angle between the muon and the parent neutrino is dominated by the kinematics of the interaction, while at larger energies it is limited by the intrinsic angular resolution (PMT transit time spread and light scattering in water). The limiting values are about 0.15°.

Different energy reconstruction algorithms have been developed for the ANTARES experiment [5]. The muon energy can be estimated using the methods based on the knowledge of the features of muon energy losses: the increase of the amount of emitted light due to muon catastrophic energy losses above 1 TeV. However, the measurement is compromised by the fact that these radiative processes are stochastic, the neutrino interaction point is invisible in most cases and only a short fraction of the muon track is seen in the detector. Since the energy loss of muons at high energies has large fluctuations, a parameter used is the logarithmic energy resolution, $log(\sigma_E/E)$. The simulations show that this resolution is 0.2–0.4 for muons with energy above 1 TeV. At lower energies, below 100 GeV, the muon energy can be measured from the muon range in sea water.

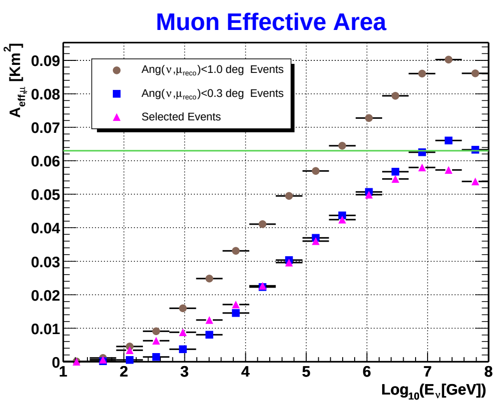

Figure 3. Muon effective area versus neutrino energy for selected events (triangles) and for reconstructed events with the requirement that the angle between the simulated neutrino and the reconstructed muons is less than 1° (circles) and 0.3° (squares).

The effective area is one of the important parameters which characterise the performance of the detector. The muon effective area is the ratio of the rate of the selected events to the flux of incident muons and depends on selection criteria used for any specific analysis. The effective surface area of ANTARES depends on the muon (neutrino) energy, the efficiency of reconstruction and selection cuts. Figure 3 shows the muon effective area as a function of neutrino energy for isotropically simulated events after a selection based on reconstruction quality cuts (triangles) and just requiring an angle between the reconstructed muon and the simulated neutrino direction lower than 1° (circles) and 0.3° (squares).

For point-like source searches, when a signal should be found in the whole sky and not necessarily associated with any known object, strict selection criteria are needed to keep only well reconstructed events. This ensures a good pointing accuracy and a good rejection of the background of atmospheric muons. Other searches, for instance for bursting known sources, such as gamma-ray bursts, which are almost background free on time scales of hundreds of seconds, can be done by replacing stringent cuts on the quality of the reconstruction by an angular cut around the supposed known source. In this case the effective area calculation is performed by requiring that the angle between the direction of the reconstructed muon and the neutrino direction is less than a defined angular cut. For well reconstructed muon tracks (accuracy better than 1°) the effective surface area increases from about 10^{-3} km^2 at neutrino energy 0.1 TeV to more than 0.06-0.07 km^2 at neutrino energy higher than 100 TeV. The angular distribution is averaged over the upward going hemisphere. The increase of effective area with energy is explained by the increasing muon range and increasing light output of muons due to radiative processes.

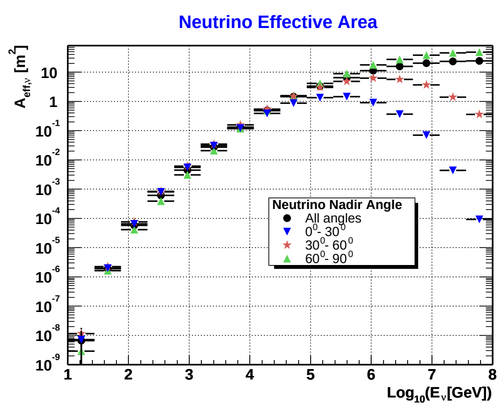

Figure 4. Neutrino effective area as a function of the neutrino energy in ranges of neutrino nadir angle.

Figure 4 gives the effective area for neutrinos as a function of the neutrino energy for three different nadir angles and for the averaged over nadir angle area. The neutrino effective area is calculated taking into account the detection efficiency, the probability of interaction, the probability that neutrino survives its journey through the Earth and the energy loss of muons. Small neutrino cross sections change the scale of the effective area from squared kilometres to squared metres; the opacity of the Earth limits the effective area to values below 30 m^2. The effect of neutrino absorption is visible since the area for vertical directions is smaller than for horizontal ones.

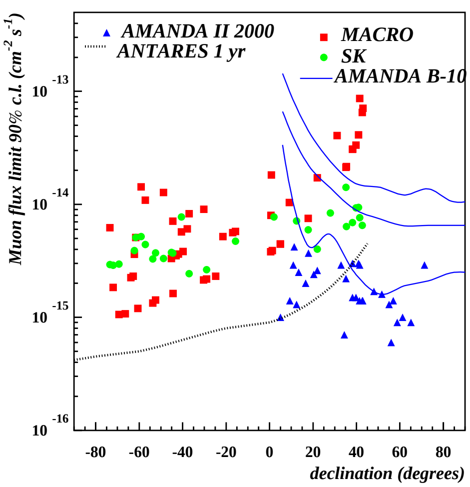

Figure 5. ANTARES sensitivity (after 1 year of operation) to the neutrino-induced flux from astrophysical point sources, compared to the upper limits from other experiments (see [7] for references).

Atmospheric down-going muons and up-going neutrinos constitute the physical background for the ANTARES astrophysical programme. Atmospheric muons, in particular muon bundles, can be misreconstructed as up-going neutrino-induced muons. This background is currently under study. Preliminary results show that the large depth and sophisticated reconstruction algorithms can help to suppress this background sufficiently to be sensitive to astrophysical neutrinos. The signal from atmospheric neutrinos is indistinguishable from astrophysical neutrinos. Using the above performance parameters one can estimate that ANTARES will detect about 2500 upward going muon tracks from atmospheric neutrinos per year. The only difference is the energy spectrum, which is known to be soft for atmospheric neutrinos (power index of about -3.6), but is harder for cosmic neutrinos (power index of about -2). This background, however, is negligible in a search for point sources of high-energy neutrinos, provided the angular resolution of better than 1° can be achieved in practice.

4. SENSITIVITY TO POINT-LIKE SOURCES, DIFFUSE FLUX AND DARK MATTER

Detailed simulations have been carried out to assess the physical sensitivity of ANTARES. Neutrino telescopes may detect astrophysical point-like sources of high energy neutrinos as an excess of events above the atmospheric neutrino background. The sensitivity therefore depends on the pointing accuracy of the detector. Methods based on binning or clustering algorithms have been developed, together with a method which does not require any binning. The latter is based on a likelihood ratio test and uses the information on the neutrino angular resolution as a function of energy [6].

The effective area and angular resolution of the detector determines its sensitivity for point-like sources, since the signal–to–noise ratio depends on these quantities. The bin size has been optimised in order to obtain the discovery potential and exclusion limits for a source with a spectrum proportional to E^{-2}. It is varied with declination in order to keep constant the average number of background events per bin (which is equal to 0.3). The optimal cluster size for sources with E^{-2} spectrum has been estimated to be 1.0°. In these methods the significance of a possible excess can be calculated analytically from the data itself. These methods do not rely on the predicted spectrum or on the energy reconstruction for further rejection of atmospheric neutrinos.

A method not relying on any binning is based on likelihood ratio and operates by finding the position and the flux of the most likely source candidate using the information on the neutrino angular resolution as a function of energy. This method gives a 30% improvement in sensitivity compared to the method based on binning. The ANTARES sensitivity to high energy cosmic neutrinos is defined as the upper limit at 90% confidence level (CL) on the muon flux induced by neutrinos, with a typical E^{-2} energy spectrum, in the absence of a signal. For declination angles below 40° the sensitivity, after one year of exposure time, will be in the range $(4-50)\cdot 10^{-16}$ cm^{-2}s^{-1} (depending on declination) for point-like sources, as shown in Figure 5.

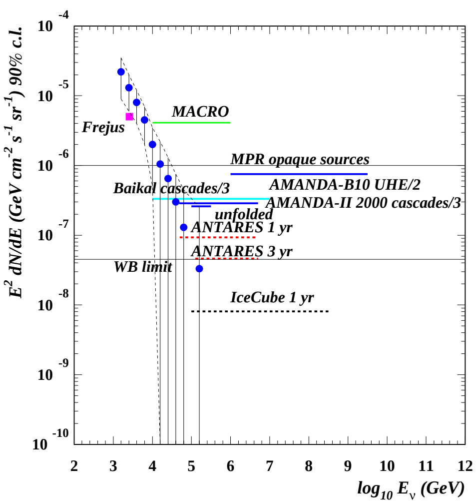

Figure 6. ANTARES sensitivity to diffuse fluxes as a function of the neutrino energy. The upper limit that can be set by ANTARES after one year and three years of data taking are shown together with theoretical predictions and results of other experiments. The circles show the atmospheric neutrino spectrum measured by AMANDA (see [8] for references of the theoretical models and experimental limits).

Diffuse fluxes from astrophysical models are expected to exceed the atmospheric neutrino background at energies above 50–100 TeV, so the search for diffuse neutrino fluxes is possible only at high energies using the information about the reconstructed muon energy. After one year of data taking the ANTARES sensitivity to E^{-2} diffuse neutrino flux is expected to be $E^2 d\Phi_\nu/dE_\nu$ $\leq 8\cdot 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1} and can be improved to the value of $3.9\cdot 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1} after 3 years of data taking that makes the experiment capable of probing the Waxman-Bahcall upper limit of $4.5\cdot 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1} [9].

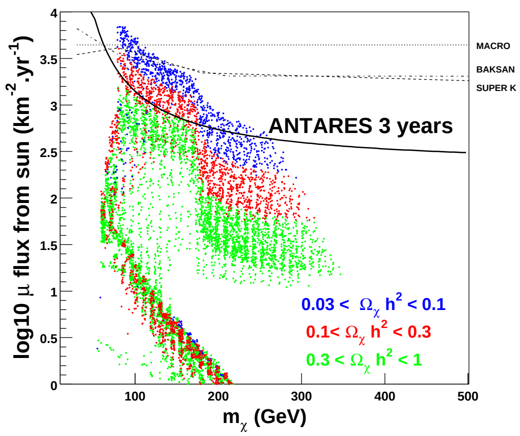

Figure 7. ANTARES sensitivity to the muon flux from neutralino annihilations in the centre of the Sun, compared to the upper limits from other experiments and mSUGRA models.

The search for cold non-baryonic dark matter is an important part of the ANTARES scientific program apart from astronomy. Neutralinos, the best candidates for cold dark matter, can be gravitationally captured in the massive astrophysical objects such as the Sun, the Earth or the Galactic Centre. The neutralinos can annihilate producing neutrinos in the decay chain. Expected ANTARES sensitivity to the muon flux from neutralino annihilation in the centre of the Sun for the case of a "hard" neutrino spectrum (assuming 100% annihilations to WW) is shown in Figure 7 [10].

5. THE CURRENT STATUS OF THE EXPERIMENT

In 2000 the ANTARES collaboration achieved an important milestone with the deployment and operation of a "demonstrator line" equipped with seven PMTs, slow-control devices and an acoustic positioning system at a depth of 1100 m. This exercise confirmed the accuracy of relative and absolute positioning to be about 5 cm and 1 metre, respectively, verified the validity of the data transfer to the shore station and allowed the measurements of the angular distribution of atmospheric muons.

Before launching the mass production of the detector elements, to prove the validity of the final design and to assess the reliability of complex marine operations for deployment, connection and recovery of the lines in realistic conditions, it was decided to build and deploy two lines: a prototype line consisting of five storeys with 15 OMs (which is a basic building block of the detector line) and a mini-instrumentation line (MIL) equipped with devices for time calibration, the positioning system and the instruments for measuring environmental parameters. The prototype line has been assembled in summer 2002. In order to verify the functioning of the PMTs and DAQ system the line has been tested in the laboratory before deployment. The OMs have been illuminated by a pulsed laser in the dark room. The most important result is the verification of the timing accuracy which can be reached by the system. After corrections for cable delays the time resolution of the pulses have been confirmed to be 1.3 nsec at the single photoelectron level.

In 2001-2003 a series of complex marine operations has been carried out. In October 2001 the 40 km long electro-optical cable which connects the ANTARES site with the shore station has been deployed. In December 2002 the junction box was connected to off-shore cable ending and deployed. Since then the slow control of the junction box has been maintained and shows its very stable behaviour. Then in December 2002 and February 2003 the prototype and the mini instrumentation lines have been deployed and positioned on sea bed within a few metres from their nominal positions. In March 2003 a manned submarine Nautile successfully connected both lines to the junction box. The data have been taken continuously until the recovery of the prototype line in July 2003 and analysed to study the optical background at the ANTARES site.

Two problems occurred in the prototype tests. A water leak developed in one of the MIL electronic containers due to a faulty supplier specification for a connector. This made further operation impossible and the line was recovered in May 2003. Also, a defect in the clock signal transmission caused by a broken optical fibre inside the line meant that data with timing information at nanosecond precision were unavailable.

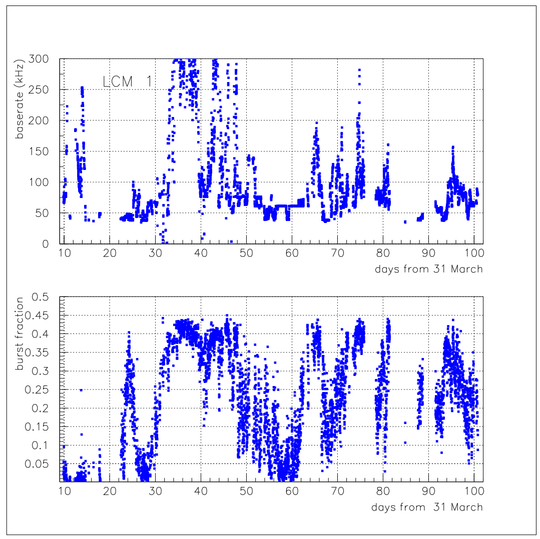

Figure 8. Baseline rate in kHz (top) and burst fraction (bottom) as a function of the date of measurements. See text for details.

Nevertheless, during about 100 days of the prototype line operation data were recorded, both on the functionality of the detector and on environmental conditions. In particular, the rate of signals above threshold was monitored continuously for each OM. It was found that the rates exhibit strong temporal variations that are attributed to bioluminescence organisms. A continuous rate, which is caused by ^{40}K decays and bioluminescence coming from bacteria, slowly varying between about 50 kHz and 250 kHz per OM, is accompanied by short light bursts of several hundred kHz lasting from seconds to minutes which are possibly caused by bio-luminescence coming from larger animals. The top plot of Figure 8 shows the baseline rate in kHz, which is defined as a median of the recorded count rate during a 15 minutes time interval. The bottom plot shows the burst fraction (defined as the fraction of time when the rate exceeds the baseline rate by more than 20%). A correlation between bioluminescence rate and water current velocity has been observed. The measured optical background is 50-70% of time below 100 kHz, a rate acceptable for data taking. The heading and tilt of the storeys in the prototype line have also been monitored. It was found that they move almost synchronously, i.e. the line behaves as a pseudo-rigid body in water current.

6. CONCLUSIONS

The construction of the ANTARES neutrino telescope has started with the deployment of the main electro-optical cable and the junction box at the detector site. The experience gained from the marine operations validate the detector concept, design and deployment techniques. The tests with the prototype and mini instrumentation lines have proven to be functional in real data taking conditions. The data acquisition system has demonstrated its capability to cope with high events rate, and the remote control of the lines was fully functional. The detected problems have been studied, corrected and will be avoided in future deployments. Detailed and extensive R&D studies have been performed.Mass production for the full scale detector have been started. The ANTARES neutrino telescope will be fully operational by 2007. Data from the first detector lines are expected in 2005.

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