Data from the ANTARES Neutrino Telescope

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Abstract. Since 29 May 2008 the ANTARES Neutrino Telescope is complete. Even before the completion, with a partial detector containing increasing numbers of operational lines as time progresses, data has been recorded since March 2006. Details of the detector design and construction are given together with results from the analysis of the first data which indicates the quality of the detector and its ability to cleanly recognise neutrino events.

1. Introduction

ANTARES is the first neutrino telescope constructed in the deep sea. Its location in the northern hemisphere makes it complementary in sky coverage with the South Pole neutrino telescope projects AMANDA and ICECUBE. It is now larger than the other northern hemisphere neutrino telescope: the BAIKAL detector in Siberia.

This article describes the detector and gives information on the stages of its construction. The calibration of the detector is an essential step which is now well advanced. Analysis of the data already recorded shows the observation of more than 400 upward going neutrino candidates.

2. Design of ANTARES Neutrino Telescope

The ANTARES detector consists of 12 mooring lines, each with a total height of 450 m: which are weighted to the sea bed and held nearly vertical by syntactic-foam buoys at the top. An artist's impression of the layout of the neutrino telescope is shown in figure 1, while figure 2 illustrates the components within a typical line. Each line has a total of 75 photomultipliers housed in glass spheres, referred to as optical modules (OM) [1], used to detect Cherenkov light from charged particle tracks in the sea water. The sea bed at the site is at a depth of 2475m and the OMs are positioned at depths between ~2400m and ~2000 m.

The buoy at the top of the line is floating free and so each line moves under the effect of the sea current, with movements being a few metres at the top for a typical sea current of 5 cm/s. The positions of the OMs are measured with a system of acoustic transponders and receivers at discrete positions on the line and on the sea bed, together with tilt meters and compasses on each storey of the line. The positioning system gives a real time measurement, typically once every few minutes, of the position of every OM with a precision better than 10 cm in space.

The default readout mode of ANTARES is the transmission of the time and amplitude of any photomultiplier (PMT) signal above a threshold corresponding to 1/3 of a photo-e1ectron for each optical module. Time measurements are referenced to a master reference clock signal distributed to each storey from shore. All signals are sent to shore and treated in a computer farm to find hit patterns corresponding to muon tracks or other physics events producing light in the water. The grouping of three optical modules in a storey allows local coincidences to be made for this pattern finding and also in certain circumstances local triggers to be formed to reduce the readout rate. In addition the front end

electronics allows a more detailed readout of the PMT signal than the standard time and amplitude mode. With this detailed readout it is possible to sample the full waveform of the signal with 128 samples separated by ~2 ns, enabling special calibration studies of the electronics.

The readout architecture of the detector has several levels of multiplexing of the photomultiplier signals. The first level is in the Local Control Module (LCM) in each storey of the detector where the analogue electrical outputs of the PMTs are digitised in a custom built ASIC chip, the Analogue Ring Sampler (ARS) before being treated by a data acquisition card, containing an FPGA and microprocessor, which outputs the multiplexed signals of the three local optical modules on an Ethernet optical link. The links from 5 storeys, forming a Sector, are combined in an Ethernet switch in the Master Local Control Module (MLCM) at every fifth storey and the combined link output is sent on a particular wavelength to a dense wavelength division multiplexing system in an electronics container, the String Control Module (SCM), at the bottom of each line. In the SCM the outputs from the five MLCMs along the line are multiplexed on to one pair of optical fibres. These fibres are then connected to a junction box (JB) on the seabed via interlink cables. In the junction box the outputs from up to 16 lines are gathered onto a 48 fibre electro-optical submarine cable, the Main Electro-Optical Cable (MEOC), and sent to the experiment shore station in the town of La Seyne-sur-Mer, in France. The optical links between each MLCM and the shore station are connected using only passive components.
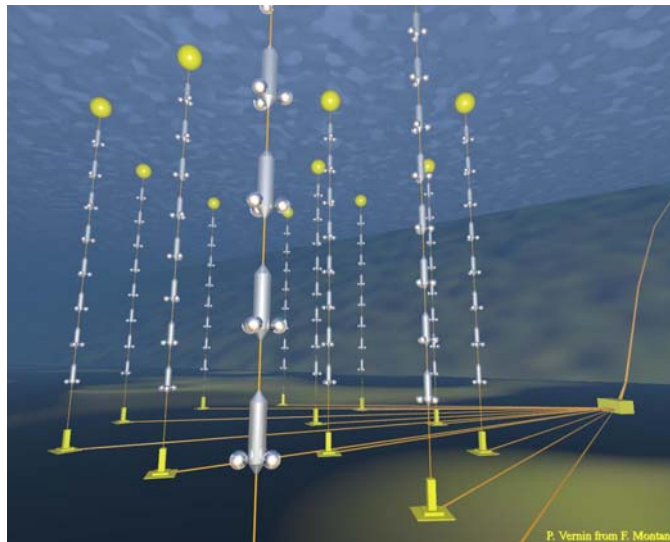
Figure 1. Artist's impression of the neutrino telescope, showing the detector lines, the seabed interlinks cables, the junction box and the MEOC cable to the shore. For clarity, the number of storeys per line is reduced and items are not drawn to scale.
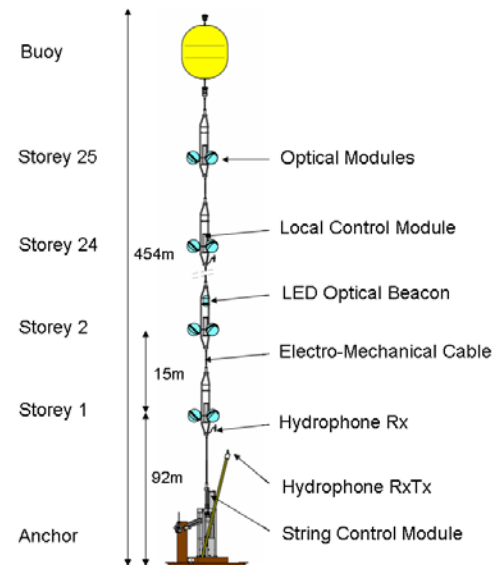
Figure 2. Schematic of an ANTARES detector line. For clarity, only 4 of the 25 storeys are shown and the cable lengths are not drawn to scale.

The electrical supply system has a similar architecture to the readout system. The submarine cable supplies ~4400 V, 10 A AC to a transformer in the junction box. The sixteen independent secondary outputs from the transformer provide ~500 V, 4 A AC to the lines via the interlink cables. At the base of each line a String Power Module (SPM) power supply shares the same container as the SCM. The SPM distributes 400 V DC to the MLCMs and LCMs in the line, each of which contains a Local Power Box (LPB) to provide the various low voltages required by each electronics card.

The 45 km undersea MEOC cable links the detector to the shore station in La Seyne-sur-Mer which houses the computer farm for the onshore event filtering. After this selection the data are sent via a standard telephone network data link to be recorded at a computer centre in Lyon.

3. Stages in the detector construction

In 1996 the ANTARES Collaboration started R&D activities towards the construction of a neutrino telescope. The first operations were the deployment and recovery of autonomous mooring lines to measure the properties of the water and environment at the ANTARES site which is located off the French coast at 42° 48'N 6° 10' E. In these site evaluation campaigns [2, 3], comprising more than 60 line deployments, extensive measurements were made of light background from bioluminescence, bio-deposition, sedimentation and light attenuation.

The earliest test line in the ANTARES program which was connected to a readout system on shore was deployed in November 1999 and is referred to as the "Demonstrator Line". This line used an old, existing, undersea cable donated by France Telecom, connecting the line to a recording station in Marseille. Located on a special site near Marseille at a depth of 1200 m, the line was operated for a few months and proved various concepts of the design, in particular the acoustic positioning system, and included reconstruction of cosmic ray muons with 7 optical modules [4].

In 2001 the construction of the actual detector started with the deployment of a new cable between the final site and the shore station in La Seyne-sur-Mer. This cable, the present MEOC, was deployed on the seabed in Nov. 2001, initially with only a loop-back container at the sea end and in Nov. 2002 the end of the cable was brought to the surface, connected to the junction box and redeployed. Since this date the battery operated slow control in the junction box has sent to shore measurements of various parameters in the housing showing perfect operation of the MEOC and JB system for more than 5 years.

During 2003, prototypes approaching the final technology of the detector were operated. Two lines were deployed and connected between November 2002 and March 2003: the "MIL", an instrumentation line and the "PSL", a short optical detector line with 15 optical modules. These lines, which were operated in situ until May and July 2003 respectively, again proved the validity of various aspects of the design but indicated as well certain problems with loss of optical transmission in the line cables and leaks in the cables and containers. Nevertheless, the PSL was able to measure the counting rates in the optical modules, in particular the rates of bioluminescence, over a period of ~4 months.

After the experiences of the MIL and PSL lines some significant changes were made to the detector design and a line incorporating these changes, the "MILOM" was deployed in the sea from the ship CASTOR on 18 March 2005 with the connection using the Remote Operated Vehicle VICTOR on 12 April 2005. The successful operation of this line for several months in 2005 is described in reference [5].
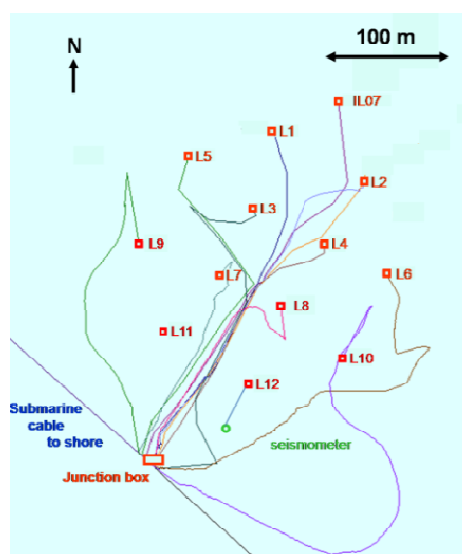

Figure 3. Seabed layout of the ANTARES detector.

The final detector lines have been deployed and connected between February 2006 and May 2008. The lines were deployed using the ship CASTOR and connected on the seabed at different dates using the submarine Nautile or the ROV Victor of IFREMER. The first detection line was deployed on 14 February, 2006 and connected two weeks later. A second detection line was put into operation in October of the same year. A further three lines were connected in January 2007, with another five connected in December 2007. The apparatus reached its complete configuration with the last two lines being deployed in early 2008 and connected on 29 May 2008. The final layout of the lines on the sea bed is illustrated in figure 3.

4. Calibration and comprehension of detector

With the detector construction complete and the first data available, the priority for the collaboration is in understanding and calibrating the detector. These activities have many aspects ranging from alignment in position and time calibration, to estimations of detector efficiency as well as optimization of event reconstruction software in the context of real data.

An example of the data from the acoustic positioning system is shown in figures 4a and 4b. The first plot shows the x-y displacement in the horizontal plane of the five hydrophones at different heights along the line and the second the absolute value of this displacement as a function of time from July to December 2007. The detailed analysis of this data is still in progress but it is already demonstrated that the statistical precision of the acoustics positioning system is well within the 10 cm required.
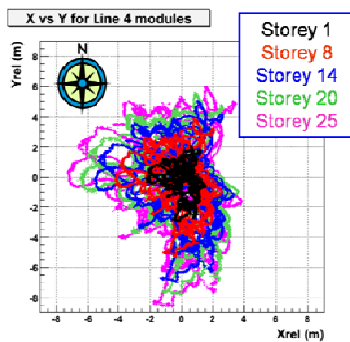
Figure 4a. Displacement in the horizontal plane for the hydrophones on 5 storeys in line.
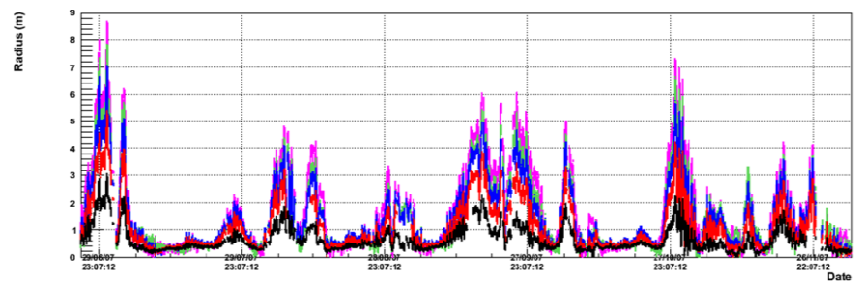
Figure 4b. Time dependence of the radial displacement of the hydrophones. The colours correspond to the different hydrophones as indicated in the inset in figure 4a.
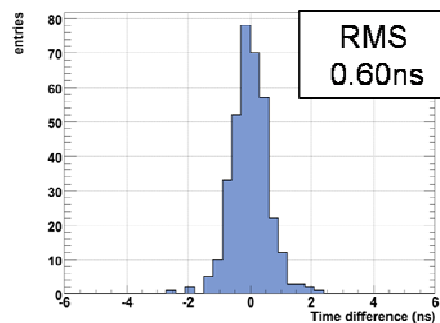

Figure 5. Time difference between adjacent optical modules within a storey for light pulses sent from a calibration optical beacon below.

The timing calibration of the optical modules is made initially during the line assembly with a system of fibre optics distributing light pulses simultaneously to each optical module. In the sea this initial timing calibration is controlled and if necessary adjusted using a system of optical beacons [6] on the detector lines. Figure 5 shows a sample distribution from this system, indicating that the timing

resolution of the detector electronics is within the design specification. Together with the data from the position calibration these results illustrate that it will be possible to attain the detector design angular resolution of ~0.3° for high energy neutrinos.

5. Data analysis status

Although not complete the detector calibration is adequate to allow data analysis to begin and already extensive studies have been made. An essential aspect of the reconstruction of the data from an undersea neutrino telescope is the treatment of the optical light background noise. This noise has two components: radioactive decay of ^{40}K in the sea water and bioluminescence from a range of living organisms. In the ANTARES data the latter component has strong time variations and figure 6 shows the median counting rate in two example optical modules in the first line deployed during 26 months of operation. It can be seen that in spring 2006 the rates were hundreds of kHz while after July 2006 the rates have been much lower with only short periods above 100 kHz which are in general associated with periods of high sea current.
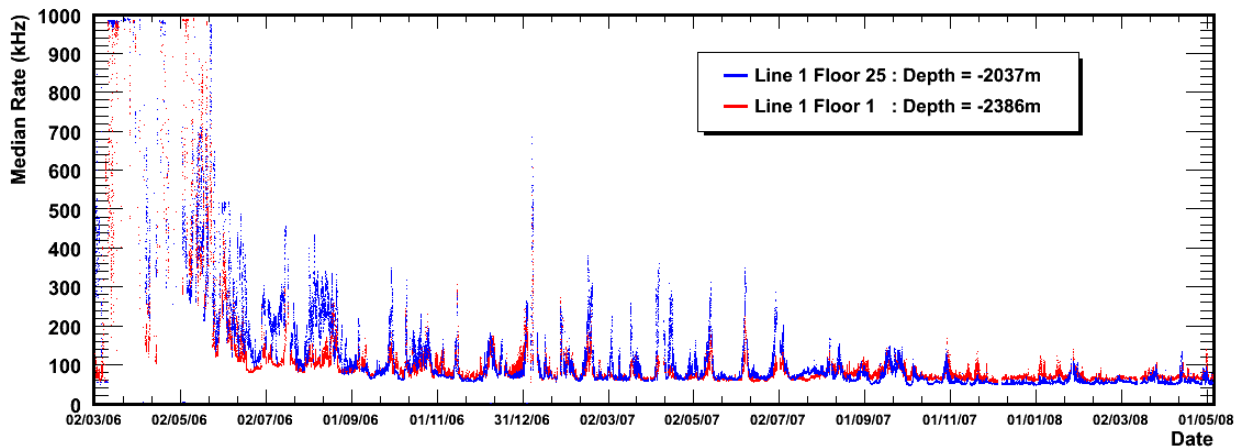

Figure 6. Median counting rate in two examples OM in line 1 between March 2006 and May 2008.

After reconstruction, the majority of events are due to atmospheric muons. These events represent a background to the neutrino events if badly reconstructed in direction and not recognized as such. In addition, these events, being numerous, provide a method to calibrate the detector and measure detection efficiencies. However, since the apparatus is optimized for the detection of upward-going particles with downward-orientated photomultipliers, the systematic errors on efficiency estimates with downward muons and upward neutrinos are different. The present status of the studies of the detector detection efficiency leads to systematic errors of about ±30% for muons using selection cuts appropriate for high muon efficiency. The expectation is that that for neutrinos with the present understanding of the detector the efficiency sytematics would be less by a factor 2.

Within the collaboration extensive effort is being applied to developing efficient reconstruction software. The existing default reconstruction code [7] was written based on Monte-Carlo simulation before the data was available. Knowledge of the real parameters of the detector and the background has motivated work to improve this software. Many ideas are being explored to gain efficiency mainly by improving the pattern recognition steps of the software to select the signal hits among the dominant noise background. In parallel work is in progress on the Monte-Carlo simulation using the actual detector information. An example of the present situation is shown in figure 7 using the data between March and December 2007, when the detector consisted of 5 active lines. The figure shows the data and Monte-Carlo simulations for atmospheric neutrinos and atmospheric muons using the default reconstruction code. For this figure, event selection cuts are applied to reject downward going muons and this leads to differences between data and predictions for muons which are larger than the sytematics quoted above for muon selection. The agreement for neutrinos (upward going muons), is however good. It can be seen that in the upward going hemisphere and up to a few degrees

above the horizontal the events are dominated by neutrinos with very small contamination from miss-reconstructed atmospheric muons. Another reconstruction algorithm has been developed which is more robust in a number of ways and can be used on the data before the full alignment and calibration is available. This algorithm is run online during the data taking. An example of event reconstruction with this newer algorithm is shown in figure 8 using the data taken between December 2007 and April 2008, when the detector had 10 active lines. In total in the already recorded data, there are more than 400 reconstructed neutrino candidate events.
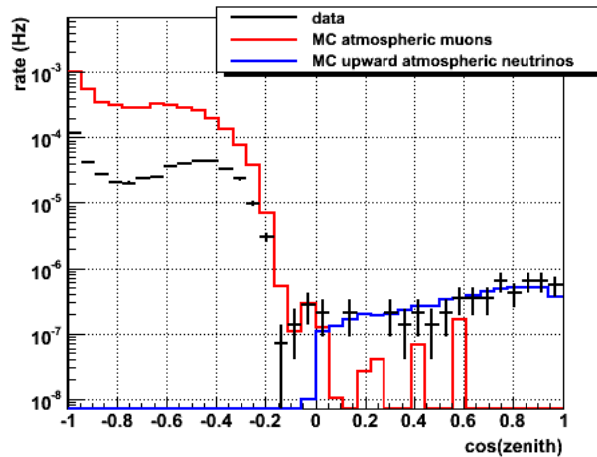
Figure 7. Azimuth angular distribution of reconstruction of data with 5 lines recorded between March and December 2007. This distribution uses the default reconstruction algorithm [7].
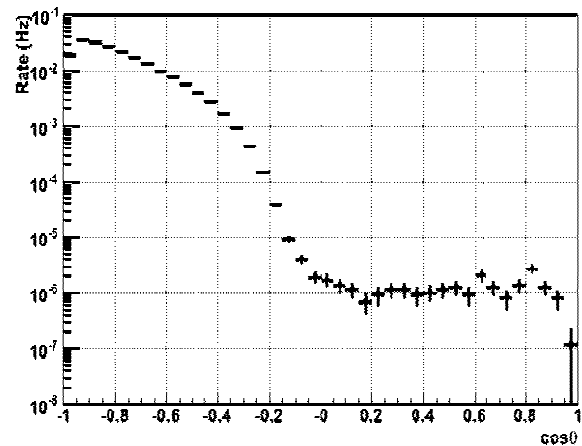
Figure 8. Distribution of reconstructed data with 10 lines recorded between December 2007 and April 2008. This analysis is an example of one of the new reconstruction algorithms being developed which applied online during data taking.

6. Conclusions

The construction of the ANTARES detector was completed in May 2008, making ANTARES the first undersea neutrino telescope and the largest neutrino telescope in the northern hemisphere. Clear evidence for the excellent precision of the detector components can be seen in the first data, showing that the detector operates within specifications and fulfills its design goals. Already, more than 400 candidate neutrino events have been identified.

The success of ANTARES finally proves the feasibility of a deep sea neutrino telescope which can benefit from the better optical properties of water compared to ice. This achievement represents a major landmark and encouragement for the construction of a km^3-scale neutrino telescope in the Mediterranean Sea [8].

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