Positioning system of the ANTARES neutrino telescope

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Elsevier use only: Received date here; revised date here; accepted date here

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Abstract

The ANTARES neutrino telescope consists of 12 string lines housing the optical detectors. Sea water currents may result in drifts for these strings by several meters from the vertical. However, muon track reconstruction is based on precise arrival time measurement of Cherenkov photons to the Optical Modules (~1 ns) and knowledge of the Optical Module positions with respect to a fixed reference system with a corresponding resolution of ~20 cm.

The relative positioning of the detector is monitored combining two systems: an acoustic system giving the 3D-position of five hydrophones along the line and a set of tiltmeter-compasses giving the local tilt and orientation of each Optical Module storey. With this information, a global fit of the string shape leads to the 3D-positioning of the detector within the requirements. In this paper, the positioning system is described, and the performance and results for the first years of operation in ANTARES are shown.

PACS: 29.90.+r, 43.30.Xm

Keywords: ANTARES; Neutrino telescope; Underwater position monitoring; Acoustic positioning system

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1. Introduction

The ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) Collaboration has built a large area water Cherenkov detector in the deep Mediterranean Sea, optimised for the detection of muons coming from high energy astrophysical neutrinos. It is, at present, the largest neutrino telescope in the northern hemisphere [1, 2]. The detector, which is located at 2500 m depth in the Mediterranean Sea, 40 km off shore from Toulon (France), has a surface area of ~0.1 km^2. It is composed of 12 vertical lines of about 450 m height and 70 m spacing, holding nearly 900 photomultiplier tubes housed in pressure resistant glass spheres (Optical Modules, OMs). Besides the OMs, a set of calibration sensors (optical beacons, acoustic transducers, tiltmeters and compasses) and a data acquisition system are needed. All this results in a large inter-related network of sensors looking for high energy cosmic neutrinos. The telescope has just become fully operative with the connection of the last detector lines in May 2008.

The detection method of the telescope is based mainly on the estimation of the trajectory and energy of neutrinos by detecting the Cherenkov light from the particles induced by the neutrino interaction, especially muons. The muon track is reconstructed from the arrival time of the Cherenkov photons at the photo-sensors. The quality of the reconstruction of the track direction depends on the timing resolution of the photo-sensors and on the knowledge of the photo-sensor position. ANTARES is expected to achieve very good angular resolution (< 0.3º for muons above 10 TeV). The pointing accuracy of the detector is mainly determined by the overall timing accuracy of each event, which is a quadratic sum of terms due to the precision with which the spatial positioning and orientation of the OMs is known; the accuracy with which the arrival time of photons at the OMs is measured and the precision with which local timing of individual OM signals can be synchronised with respect to each other. In order to determine accurately these parameters positioning and timing calibration systems are used. This paper describes the design and development of the ANTARES positioning calibration system, as well as the experience and results obtained with this system, taken into account the behaviour and first data from the first 5 lines deployed. The timing calibration system is described and discussed elsewhere [3].

2. Positioning calibration system

The ANTARES detector has a string structure anchored on the sea bed and maintained vertical by a buoy. Since it is not based on fixed rigid structures, water current flows can drift the buoy by several meters, and therefore move the OM positions from their ideal geometry. However, the reconstruction of the muon trajectory is based on the differences of the arrival times of the photons between OMs and is thus highly sensitive to the distances between the OMs. In order to achieve the best performance of the reconstruction, it is necessary to monitor the relative positions of all OMs with an accuracy better than 20 cm, equivalent to the ~1 ns precision of timing measurements. The reconstruction of the muon trajectory and the determination of its energy also require the knowledge of the OM orientation with a precision of a few degrees. In addition, a precise absolute positioning of the whole detector has to be guaranteed as well in order to point to individual neutrino sources in the sky.

To attain a suitable precision on the overall positioning accuracy, a constant monitoring of two independent systems is used:

- A High Frequency Long BaseLine acoustic system (HFLBL) giving the 3D position of hydrophones placed along the line. These positions are obtained by triangulation from emitters anchored in the base of the line plus autonomous transponders on the sea floor.
- A set of tiltmeter-compass sensors giving the local tilt angles of each OM storey with respect to the horizontal plane (pitch and roll) as well as its orientation with respect to the Earth magnetic north (heading).

The shape of each string is reconstructed by performing a global fit based on all these information. The relative positions of the OMs are then deduced from the reconstructed line shape and from the geometry of the OM frame.

This reconstruction requires the knowledge of two parameters: the water current flow and the sound velocity in sea water. For this, different oceanography instrumentation has been deployed as well: Acoustic Doppler Current Profilers (ADCP), to monitor the water current flow along the full height of the detector strings; Conductivity-Temperature-Depth (CTD) sensors, to monitor the temperature and salinity of the sea water at various depths (from these measurements, it is possible to determine the sound velocity); and Sound Velocimeters to monitor directly the sound velocity in sea water.

2.1. The line shape model

The reconstruction of the line shape is based on a model which predicts the mechanical behaviour of the line under the influence of the sea water flow taking into account the weight and drag coefficients of all elements of the line. The zenith angle Θ in one point of the line can be computed from the vertical forces F_Z (buoyancy minus weight) and the drag horizontal forces $F_\perp=\rho C_W A v^2/2$ where ρ is the density, A is the cross-section area of the element considered, v is the sea current velocity, and C_W is the drag coefficient, which was determined by a hydro-dynamical study of the storey in the IFREMER pool facility. Since $\tan(\Theta)=dr/dz$, the position of the radial coordinate *r* as a function of the vertical coordinate *z* can be obtained by integration along the line, resulting in the expression:

$$r(z) = a\,v^2\,z - b\,v^2\ln[1-cz] \qquad (1)$$

where a, b and c are known mechanical constants, whereas the sea current velocity coordinates $v(v_X, v_Y)$ are treated as free fitting parameters in the model. Additionally to the physical constants of the lines mentioned, the input for the fits of expression 1 comes from the acoustic system monitoring, which gives a few positions along the lines associated to the hydrophones, and the compass-tiltmeter system, which monitor the local tilt and heading angles of each storey with OMs.

2.2. The compass-tiltmeter system

The compass-tiltmeter system gives the local measurements of tilts (roll, pitch) and heading of storeys. The TCM2 sensor by Navigation Precision Inc. has been used. It has a measurement range of ±20° on 2 tilt axes and 360º on heading with an accuracy of 0.2° in tilt and 1.0° in heading. It also allows a compensation of parasitic magnetic fields. The sensor is integrated on a more general instrumentation board which is assembled in the ANTARES electronics container of the storey. The performance and the linearity of the sensor have been checked and good agreements with the specifications given by the manufacturer have been found.

2.3. Acoustic system

It is a High Frequency Long Baseline acoustic positioning system to monitor the position of five hydrophones, that is, five points along the line. The hydrophones are not uniformly distributed, but in storeys 1, 8, 14, 20 and 25 in order to monitor some strategic points of the line and minimise the uncertainties in the shape reconstruction. Additionally, there is a transmitter-receiver at the anchor of each line plus some autonomous transponders. Electronic boards manage the settings of the system, for emission, detection, filtering and recording. The signals used are tone bursts in the 40-60 kHz frequency range. Distances are obtained from the travel time measurement of the acoustic wave. Thanks to an excellent time resolution of the system of few μs, distances between fixed transducers are obtained with a stability better than 1 cm. The positioning is then determined by acoustic triangulation with respect to fixed emitters on the sea floor. A full detector positioning is obtained every 1-2 minutes, which is enough since the movements of the lines are quite slow. This system and its performance are described with more details in reference [4].

3. Results

Although the ANTARES detector has only been recently fully completed, the performance of the acoustic system has already been extensively studied with the first five detection lines which are in operation since January 2007. We will focus on the results of the first five lines for this period.

As an example of the behaviour of the acoustic positioning system, the horizontal displacements of the hydrophones of line 4 with respect to the anchor of the line for the period February-April 2007 is shown in Fig.1. It can be seen that hydrophone displacements are followed with an accuracy of a few centimetres. As expected, larger displacements are observed for the top storeys. The movement of the line is dominated by East-West heading of the Ligurian current. Very similar behaviour is observed for the other lines.

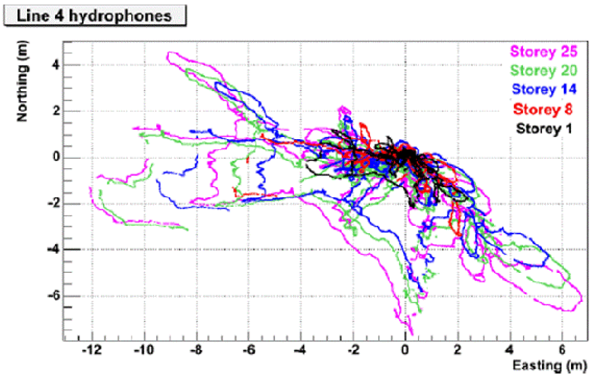

Fig. 1. Horizontal tracking of the hydrophones of line 4.

In order to evaluate the performance of the global positioning system, i.e. the line shape reconstruction based on the combined information of the compass-tiltmeter and the acoustic systems, we have compared the hydrophone positions given by the line shape fit with respect to the triangulated positions obtained from the acoustic system. In this comparison the acoustic information from the hydrophone under study is not used in the line shape reconstruction in order not to bias the comparison study. In Fig. 2, the difference in the X coordinate of the top hydrophone of line 4 obtained with the two methods compared for the period February-June 2007 is shown. A difference of less than 10 cm is observed, while similar behaviour is obtained for the Y coordinate as well as the rest of the lines. Since the top storey constitutes the worst scenario, we can conclude that it is possible to reconstruct the position of the OMs with a resolution better than 20 cm, as required.

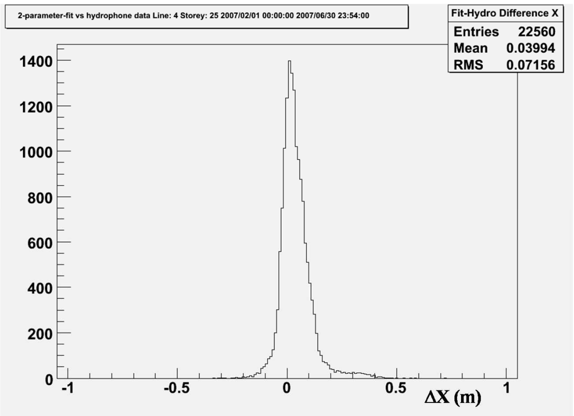

Fig. 2. Difference in the X coordinate of the line 4 top hydrophone from the line shape reconstruction and from acoustic positioning

4. Conclusions

The ANTARES positioning system is operational and within specifications. The required spatial reconstruction of 20 cm per Optical Module is achieved. The use of independent complementary systems allow cross-checks and to detect and solve possible systematic uncertainties. Due to the good performance and flexibility of the positioning system, it certainly provides a good starting point for the design of the positioning calibration system of a cubic kilometre neutrino telescope in the sea [5].

Acknowledgments

M. Ardid acknowledges the support from the Spanish Education and Science Ministry (Project FPA2007-63729).

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