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Underwater Acoustic positioning in ANTARES

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The ANTARES collaboration is deploying a 2500 m deep underwater neutrino telescope in the Mediterranean Sea off shore from Toulon (France). The detector will consist of 12 vertical lines of 450 m height and about 70 m spacing, holding a grand-total of nearly 900 photomultipliers. Lines are anchored on the sea bed and maintained vertically by buoys, however, they undergo drifts of several meters due to underwater currents. The 0.2 degrees angular resolution for the muon reconstruction relies on the knowledge of the relative positions of the photomultipliers within an accuracy of 10 cm. The positioning of the detector is primarily based on underwater acoustic techniques. Every detector line is equipped with 6 hydrophones allowing for long range triangulation of their relative positions with a 3 cm accuracy. Absolute positioning of the detector is performed by acoustic triangulation of the line anchors from a surface ship equipped with a DGPS antenna.

1. Introduction

The ANTARES [1] detector is an underwater deep sea neutrino telescope currently in deployment. It is located at 2500 m depth in the Mediterranean Sea off shore from Toulon (France). In Spring 2005 a first step was achieved with the deployment of two prototype lines: MILOM and LINE0. In its final stage the detector will consist of 12 vertical lines of 450 m height and about 70 m spacing, holding a grand-total of nearly 900 photomultipliers. The Cerenkov light emitted by high energy muons (above few GeV) originating from neutrino deep inelastic scattering is detected by the photomultipliers optical modules.

ANTARES lines have similar mechanical structures. They are anchored on the sea bed and maintained vertically by buoys. Due to underwater currents they undergo drifts of several meters. Since the angular resolution for the muon reconstruction relies on the knowledge of the relative positions of the photomultipliers within an accuracy of 10 cm it is important to monitor these motions. Therefore the detector will be equipped with several positioning devices. Because light has a 60 meters attenuation length in water long range location relies on acoustic techniques.

Equipped with both acoustic positioning modules and optical modules, as well as with oceanographic probes and calibration devices, the MILOM line appears as an important test-bench for the validation of all these techniques.

2. The GENISEA-ECA Acoustic Relative Positioning System

The GENISEA-ECA [2] acoustic relative positioning system is one part of the global positioning of the detector. Its goal is to provide accurate relative positions, within a few cm, of a few distributed points along lines. These precise positions are used to constrain a global fit of the shape of lines including data from tilt-meters and compasses distributed regularly, with 15 m spacing, along the lines.

To achieve its goal the relative positioning system has two kinds of components. The first ones are acoustic modules among which we distinguish emitter-receiver (RxTx), located on anchors of ANTARES lines, receiver solely (Rx), located on upper levels of lines together with Transponders located on separate structure on the sea bed.

Acoustic modules transduce electrical commands to sound waves and reciprocally. The transducing part will be referred to as hydrophone in the following. It is made of a hemispherical piezo-ceramic of about 1 cm diameter. In addition to an hydrophone, acoustic modules include 3 (Rx) or 6 (RxTx) dedicated electronic boards located in a standard ANTARES titanium container. These boards take in charge the 'logic' of the positioning.

Transponders are autonomous devices, powered by batteries with 3 years of lifetime, and acoustically remote controlled by the RxTx modules. They have their own containers and electronics. The autonomous transponders are deployed on the sea bed around the lines at some 300 m distance each from another. They enable positioning during the early deployment phase of the ANTARES detector. In addition, compared to the spacing of 70 m between two lines relative errors on distances to transponders are usually lower than between two hydrophones on lines. Hence they also provide additional accuracy on the overall relative positions for the full detector.

The second kind of devices are oceanographic probes. They fall in three sub-entities as following : direct sound velocimeters (Sv), conductivity, temperature and pressure probes coupled to a direct sound velocimeter (Sv-CTD) and single pressure probes. The pressure sensors are located on anchors to constrain their relative depths. The positioning procedure is based on triangulation of the relative positions of hydrophones from the distances separating them. Distances are measured from the travel time of acoustic waves between hydrophones. Therefore one needs sound velocimeters to convert acoustic travel times into distances. In sea water sound velocity is dependant on three main properties: salinity, temperature and depth [3]. In the Mediterranean Sea temperature is stable after a few hundred meters depth with a value of 13.2 °C at the ANTARES site. Sound speed variations are then dominated by pressure variations. In a sufficient approximation for our purpose, sound speed can be considered as linear with depth. At this first order of approximation the distances d_{ij} between two hydrophones i and j, located at depth z_i and z_j, is computed from the travel time t_{ij} as :

$$d_{ij} = t_{ij}(c_s(z_i) + c_s(z_j))/2 \tag{1}$$

where c_s is the velocity of sound. Because sound velocity varies in the volume of the detector, sound velocimeters are distributed among lines to sample these variations.

The relative positioning is operated as following. The ANTARES clock system regularly sends Major synchronisation signals to Rx and RxTx acoustic modules with a period of a few minutes. Between two successive Major signals up to 20 Minor signals are sent to acoustic modules. Each Minor signal triggers the emission of a single RxTx acoustic module at a specified frequency. All other Rx, RxTx modules start listening to the emitter at the given frequency. By repeating this while alternating the emitting RxTx modules, in the time interval of two Major signals, one gets the full set of distances required for the triangulation of hydrophones positions. Transponder are a particular case. As they are autonomous from ANTARES lines they don't get the clock signal. They are configured via acoustic modem commands to answer to an RxTx acoustic interrogation frequency at a Transponder specific response frequency. The delay between two successive Minor signals is set by the travel time of acoustic waves between acoustic modules, which can reach a few seconds when using Transponders. Variations of distances between line elements are usually seen to be small enough on the time scale of a Major cycle, less than 1 cm, so that one can neglect those.

Hydrophones relative positions are computed from distances using an iterative algorithm based on singular value decomposition (SVD) [4]. Recurrent measurement of distances are performed with a period of some minutes. Because the global motion of a line is small in that time interval it is a good first guess to use previous step hydrophone and sound velocimeter positions in order to compute distances for the new step by the iterative SVD algorithm. By using a redundant set of distance measurements a cross check for the accuracy and systematic errors is given by the residuals on the relative positions.

Past [5] and recent deployment with the MILOM have shown that a few millimetres standard deviation is achieved on distances measured with the GENISEA-ECA relative positioning system. However main causes of uncertainties are systematics. For the accuracy we require on the distances, a few cm over several hundred meters, ambient sound speed variations, due to underwater currents mostly, are of importance. Typical values of sound speed at the ANTARES site are 1540 m/s. Hence an accuracy of some tens of cm/s is required on sound velocity measurements. This is achieved with modern sound velocimeters which are calibrated to an accuracy of 5 cm/s at IFREMER [6]. Because of the critical role that sound velocity plays on the accuracy, two types of sound velocimeters are used. Sv perform a direct measurement of local sound velocity from the travel time of an ultrasonic sound wave between two acoustic mirrors. Sv-CTD allow for a cross check by computing the expected value of sound velocity from salinity, temperature and depth.

Sound gradient is of 1.65 $cm \cdot s^{-1} \cdot m^{-1}$ which implies that the relative depths of the hydrophones and sound velocimeters have to be known within some ten meters accuracy, prior to any triangulation. Since underwater current are moderate in usual conditions, less than 5 cm/s on average, drifts of line top buoys are small. The lateral deflexion of a several hundred meters long line is only of a few meters leading to small vertical displacement of their elements. Hence the knowledge of the mechanical structure of lines, in addition with surface positioning measurements and depth measurements from pressure probes is enough in most cases. Last, but not least, travel times have to be measured with an accuracy of some ten μs. Therefore the relative positioning sends relatively high frequency sine acoustic waves. The acoustic signals are in the range of frequencies from 44 kHz to 65 kHz and have a configurable duration, some ms. Calibrated corrections of threshold delay at detection as well as electric synchronisation delay between modules are taken into account.

Former studies [5] have shown that a 3 cm systematic standard deviation on hydrophone positions can be achieved. Hence we are confident in the possibility of achieving an overall accuracy of 10 cm leading to a 0.2 degrees angular resolution for the muon reconstruction. However particular effort has to be given in hunting systematic corrections. Further studies are currently in progress with the deployment, in June 2005 of two more autonomous Transponders. With currently 2 Transponders, one RxTx module on the bottom of the MILOM line, and one Rx module, at the first floor of the line, 100 m above the sea bed, the relative acoustic positioning procedure can be validated.

3. The Surface Positioning system

The absolute positioning of the ANTARES detector is performed by acoustic triangulation of bottom underwater beacons from a surface ship equipped with a differential GPS antenna. Elements of the detector lying on the sea bed are located relatively to the ship by acoustic triangulation. Simultaneously the absolute geocentric position of the ship is measured by the DGPS receiver. Repeating this for different positions of the ship one computes the frame transformation giving the geocentric coordinates of bottom acoustic beacons. This is performed by the dedicated software WINFROG [7]. Accuracies of about 1 m are achieved on geodetic positions of anchored elements.

Each anchor of an ANTARES line is equipped with two acoustic release transponders allowing for absolute triangulation as well as recovery of the lines. These beacons can be triggered by an acoustic command in order to release the line from the anchor. In addition there are five reference acoustic beacons [8] lying on the sea bed in a radius of 1.5 km distance surrounding the ANTARES detector area. The large spacing provides an increased relative accuracy on the positioning. To compensate for stronger sound absorption on longer range lower frequencies acoustic waves are used. The acoustic signal varies from 8.5 kHz to 15.5 kHz, with 10 ms duration, each beacon having its characteristic frequency for identification. The autonomous transponders are also equipped with long range release beacons for absolute positioning and recovery.

The positions of line anchors as well as autonomous transponders are known from both the surface positioning system and the relative positioning systems, but in two different coordinates frames. From these positions one computes a frame transformation giving the absolute position of ANTARES lines.

Particular attention is given to the fact that this frame transformation, a rotation and a translation, is norm conservative. Hence the relative angular accuracy from the relative positioning is not affected by the lower accuracy on absolute positions.

4. Conclusions

Underwater acoustic techniques play a key role in the operation of the ANTARES detector. In addition to allowing for location of the different parts of the detector they also provide crucial information during sea operations. Acoustic waves are used to probe kilometric deep sea reaches. Furthermore they also allow for distant remote control and weak data flow transmission. Overall accuracies of 10 cm can be achieved on relative positions leading to a 0.2 degrees angular resolution for the muon reconstruction. A global bias of about 1 meter is expected on geodetic positions.

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