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ACOUSTIC POSITIONING SYSTEM FOR UNDERWATER NEUTRINO TELESCOPES

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ABSTRACT

Neutrinos are elusive particles expected from a multitude of astrophysical sources. There is increasing demand and effort for the building of large neutrino 'telescopes' which might provide new insights not only in classical astronomy, but also in dark matter searches and studies in cosmic ray and high energy physics. Most of the telescopes are based on the underwater or under-ice detection of the Cherenkov light produced by muons; charged particles into which neutrinos can decay. For the underwater facilities, it is essential to have a position calibration system based on acoustics with which to monitor the position of the optical sensors with 10 cm precision. Constraints such as deployment in deep water, a very large instrumented volume and a large number of elements to be monitored - at reasonable cost with minimum system complexity - make the positioning system a challenge in itself. As a start point, the system for the 0.1km² ANTARES telescope is presented, followed by details of some concepts and R&D activities for the design of the acoustic positioning system of a much larger, cubic kilometre-scale neutrino telescope.

INTRODUCTION

The neutrino is an elementary particle, the study of which has brought a new insight (some would claim a new era) not only in particle physics, but also in astrophysics. For this reason there is an increasing demand and effort for achieving large neutrino telescopes, not only for classical astronomy, but also for dark matter searches, cosmic ray studies and high energy physics. Neutrinos interact only very weakly with matter, and are therefore difficult to detect. Sophisticated systems of sensors, sometimes operating in harsh environments, have been designed and developed for their detection. Most of these telescopes are based on underwater or under-ice Cherenkov light detection.

The frame of the study presented here is KM3NeT [1], a future deep-sea neutrino telescope and research infrastructure for deep sea sciences in the Mediterranean sea. The telescope is intended to detect high energy neutrinos from astrophysical sources. The KM3NeT design is being pursued by a pan-European consortium of 37 institutes under a three-year European Union-funded study which commenced in February 2006. This study will address all aspects of the infrastructure design, construction and operation, leading to a detailed final design report. The following phase will be a four- to five-year period for construction and deployment leading to an operational infrastructure around 2012.

The very low interaction probability of neutrinos dictates a very large detection volume in order to have a statistically significant number of events in a reasonable time (several years' operation). In addition, the numbers of high energy neutrinos from sources of astrophysical interest is expected to be much lower than the numbers of low energy neutrinos produced by the interactions of copious charged cosmic rays in the Earth's atmosphere. For this

reason a great depth of sea water or ice is needed above a neutrino telescope to avoid it being swamped by cosmic ray background.

The detection principle relies on a (very infrequent) interaction between a neutrino and an atomic nucleus in or close to the detector. This generates a muon, which has an electric charge. Travelling through water close to the speed of light, the muon radiates blue luminescence called Cherenkov radiation, which will be detected in a three dimensional array of highly sensitive light sensors called photomultipliers. Knowing the time and the position of the illuminated photomultipliers, it is possible to reconstruct the muon trajectory and therefore the incoming neutrino direction. The amount of light collected - the number of photomultipliers with signals - can in some cases help estimate the neutrino energy.

Very large underwater neutrino telescopes need real-time measurement of the positions of their optical sensors, since these are attached to some partially-mobile, non-rigid structure. Undersea currents can displace the optical sensors by up to several meters from their nominal positions. For accurate muon reconstruction, it is necessary to know sensor positions with an accuracy of the order of 10 cm, and for this a position calibration system is required. This positioning system has to handle a large volume and number of elements to be positioned. It must be integrated into the telescope; within a reasonable cost and have minimal complexity. In this sense, it is a new, unique problem, and therefore there is no standard solution.

In this communication a brief description of the positioning system of ANTARES telescope is presented, as well as some ideas and R&D activities for the design of the acoustic positioning system of a much larger, at least cubic kilometre-scale, neutrino telescope.

THE POSITIONING SYSTEM FOR ANTARES

The ANTARES collaboration is deploying a 0.1km^2 underwater neutrino telescope at 2500 m depth in the Mediterranean Sea near Toulon (France). The telescope will consist of 12 flexible detection lines of 450 m height, spaced at 70 m intervals on a seafloor grid. Each line contains 75 photomultipliers [2] located inside glass spheres (optical modules) arranged in 'triplets' at 25 levels ('storeys'), starting at 100 m above the sea floor. Five lines are already deployed and operational, and it is expected that the telescope will be completed during 2008.

The lines are anchored on the sea bed and held in tension by buoys. However, the upper ends of the lines undergo drifts of several meters due to underwater currents. The muon reconstruction relies on the knowledge of the relative positions of the photomultipliers within an accuracy of around 10 - 20 cm. For this purpose, a calibration system is deployed in the telescope in order to obtain information on the line shapes, together with the positions and orientations of the optical modules.

The position calibration system [3] is composed of a High-Frequency Long Baseline (HFLBL) acoustic system with transponders at the corners of a 300 m square on the sea floor, emitter-receivers on the seafloor anchors of each line and receiving hydrophones at several different heights along each line. Using tone signals at narrow bands in the 40-60 kHz range this system gives the positions of these elements of the line to within few centimetres accuracy. In addition, each storey contains a tiltmeter and compass to provide the local tilt angles (pitch, roll and heading) for each optical module. From these two systems, in principle, it is possible to reconstruct the shape of the line. Additional instrumentation determines the sound velocity and the height-dependent water current profile; parameters which have an important role in the calibration of the positioning system itself.

The line reconstruction is based on a mechanical model which takes into account the different forces on the line; buoyancy, weight and the effects of sea current. This gives an inclination for each storey, and integrating this expression gives the 3-D equation of the line form. Using as inputs the positions of hydrophones, the tilts and headings from compasses and tiltmeters, and the geometrical constants of the different parts of the line, the position and orientation can be found with sufficient precision to allow the muon reconstruction. The only free parameter of the model is the depth-dependent sea current, which is obtained from the fit to the data of the

positioning system in this model. Although the positioning system for the 5 lines already implemented is still being tuned, our experience with it suggests that it will be possible to reach the accuracy required in the specification of the calibration system.

THE POSITIONING SYSTEM FOR KM3NeT

KM3NeT will be at least 20 times larger than ANTARES. It will not be a simple scaling of ANTARES; the cost and complexity would be too large to make it feasible. This argument is also valid with respect to the positioning system. Therefore it is necessary to find a new design for the positioning system which maintains the accuracy and reliability needed, while keeping the cost, maintenance and complexity under control. Another aspect which complicates the design is the large uncertainty in the description of the telescope itself. Since it is being designed now, it is not completely clear yet which mechanics, optical modules and line spacing will be used in the final design. Moreover, the specifications of the positioning system, such as the position resolution needed, are not completely fixed. However, it is not possible to wait for a final design before starting to develop the positioning system, since this would delay the telescope construction. In this sense, several ideas based on the ANTARES positioning system are being studied by the KM3NeT consortium as part of the design task. These are described below.

One possibility in adapting the ANTARES system to KM3NeT would be to substantially reduce the number of acoustic emitter-receivers. Instead of using one on each line, it might be sufficient to equip only around 20% of the lines. However, this will imply working over longer distances, which probably requires lower sound frequency. Naturally, this implies a worsening in time resolution and therefore in position resolution. In order to overcome this problem, we plan to optimise the algorithms and signal processing for both signal detection and position reconstruction. One option is to use wideband technologies instead of tone signals. With this in mind, we have tried different signals: MLS (Maximum Length Sequences), TSP (Time Stretched Pulses), and sine sweeps.

MLS has given relatively poor results; it seems that the transmitted acoustic power is too low for piezoelectric transducers, and could not be used for long distances. More promising results are obtained using TSPs and sine sweeps [4]. As an example, Figure 1 shows the results of a simulation which compares two 10 ms linear sine sweep signals partly masked by noise. (left: with a spectrum from 39 to 40 kHz, right: from 20 to 40 kHz). The top traces show simulated transmitted signals; the bottom traces show the results after the deconvolution (a zoom to the region of interest). We note that a much better time resolution is obtained in the case of the wider spectrum signal. These results suggest that use of these kinds of signals with a wide frequency spectrum will allow better position resolution than possible with the use of tone signals. This improvement might allow the use of lower frequency signals. Before including this in the final design of the telescope, the results must be confirmed in a prototype positioning system.

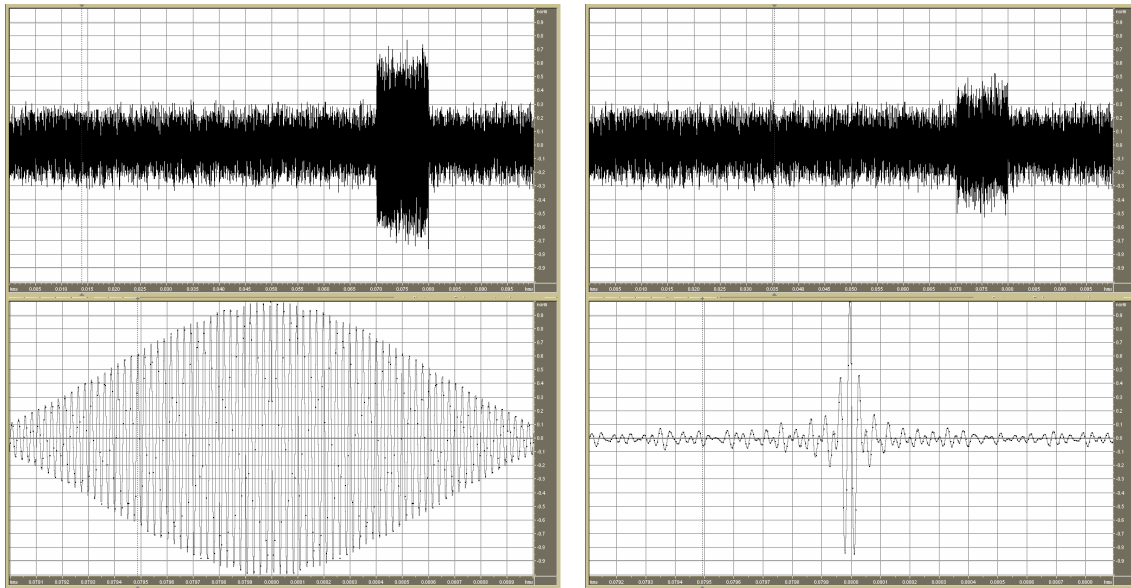


Figure 1.- Top plots show the intensity level as a function of time for two 10 ms linear sine sweeps signals partly masked by noise. (left: with a spectrum from 39 to 40 kHz, right: from 20 to 40 kHz). Lower plots show the intensities as a function of time after the deconvolution of the signals [4] (a zoom to the region of interest).

Since a large number of hydrophones will be needed in the KM3NeT telescope, it is important to reduce their unit cost. One option is to glue ceramic piezoelectric transducers to the inside of ANTARES-type optical module glass pressure spheres. Anton et al. [5] have shown that a similar configuration should be feasible for the acoustic detection of neutrinos, and it seems reasonable that it should be much easier for acoustic positioning purposes. We could imagine each optical module composed of a glass sphere with a photomultiplier as the light sensor and a piezoelectric receiver for acoustic positioning. This could have the advantage of obtaining the position and orientation of the optical module directly, perhaps without the need for compasses and tiltmeters.

In addition to being cheaper than commercial hydrophones, these are easier to implement, being protected from the high sea pressure by the sphere. A possible drawback might be lower sensitivity compared with conventional hydrophones. Care will also be needed to prevent interference between the electronics of the optical and acoustic systems in the sphere. With these concerns in mind, a prototype is being designed and will be built and tested in the near future.

Another ongoing study is related to a possible mixed acoustic-optical positioning system. Since an optical system is necessary to calibrate the photomultipliers, the idea is to include them in the positioning system. It would be a two-step system: the photomultipliers are located using optical calibrators, which are themselves located acoustically. In this scheme the actual (time-varying) positions of the optical modules would be found using short light pulses generated in 'LED beacons' installed on dedicated 'calibration' lines. Each optical module position would be determined by triangulation using light pulses received from several LED beacons. The position of each LED beacon would be determined by acoustic triangulation between hydrophones mounted on the beacon and fixed transponders on the sea bed similar to the system operated in the ANTARES neutrino telescope explained above.

Preliminary simulation studies suggest that a position resolution for optical modules of 25 cm could be achieved with this method. Further studies will investigate whether this position resolution can be improved by a fit to the positions obtained from the optical triangulation using the mechanical model of the line as a functional form input. This form would take into account the weight and drag coefficients of all elements of the line, predicting the mechanical form of the line, with only the height-dependent sea current velocity as a parameter.

CONCLUSIONS

We have illustrated the requirement for a positioning system in large underwater neutrino telescopes. Acoustics can play a major role in these systems, as has been demonstrated in the ANTARES telescope. However, due to the large detection volume and large number of elements in KM3NeT, the present-day ANTARES design cannot be used. Some ideas and preliminary studies to improve the positioning system through the use of wideband technologies, the use of piezoelectric hydrophones glued inside glass spheres and upon the viability of using an acousto-optic system have been presented.

ACKNOWLEDGEMENTS

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* Institutes that constitute the KM3NeT consortium are: Cyprus: University of Cyprus, Nikosia. France: CEA/Saclay; CNRS/IN2P3 (APC: AstroParticule et Cosmologie, Paris; CPPM : Centre de Physique des Particules de Marseille; ReS: Institut de Recherches Subatomiques, Strasbourg); University of Haute Alsace/GRPHE; IFREMER: Institut Francais de Recherche pour l'Exploitation de la Mer, Toulon. Germany: University of Erlangen; FTZ (University of Kiel): Forschungs- und Technologiezentrum Westkuste, Busum. Greece: HCMR: Hellenic Centre for Marine Research (Institute of Oceanography), Anavissos; HOU: Hellenic Open University, Patras; NCSR: National Centre for Scientific Research 'Demokritos', Athens; NAO/Nestor: National Observatory of Athens/Nestor Institute of Astro-particle Physics, Athens; University of Athens. Italy: CNR/ ISMAR, Istituto di Scienze Marine, La Spezia; INFN: Istituto Nazionale Fisica Nucleare (University of Bari; University of Bologna; University of Catania; University of Genova; University of Messina; University of Pisa; University of Roma1; LNS, Catania; LNF, Frascati); INGV: Istituto Nazionale di Geofisica e Vulcanologia, Rome; Tecnomare SpA, Venice. Netherlands: NIKHEF (FOM): National Institute for Nuclear and High Energy Physics, Amsterdam. Spain: IFIC: Instituto de Física Corpuscular (CSIC; Universitat de València Estudi General); Universitat Politècnica de València. UK: University of Aberdeen (Oceanlab); University of Leeds; University of Liverpool; John Moores University, Liverpool; University of Sheffield.

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