FIRST NEMO TOWER FOR ASTROPHYSICAL RESEARCH

Deepsea Positioning Accuracy

The Italian Istituto Nazionale di Fisica Nucleare (INFN) is developing a large underwater apparatus to investigate new frontiers in astrophysical research. The NEutrino Mediterranean Observatory, NEMO, consists of a 3D-array of optical sensors capable of detecting the primary source of extremely high-energy neutrinos. This article covers underwater positioning techniques: system architecture, technical, advanced and data processing aspects, and preliminary data analysis.

The first prototype, NEMO Phase 1, was deployed in December 2006 off the coast of Catania. A set of synchronous acoustic beacons was installed in the sea at a depth of 2,000m to position a large number of optical modules. The system, comprising up to five synchronous, seabed beacons and a number of acoustic, digital receivers mounted inside the pressure housings, offers sub-metric accuracy. INFN partner ACSA Underwater GPS has introduced new technology for use in this system: Time Spectral Spread Codes, (TSSC). Up until now astronomical knowledge has been possible thanks to light observation, photons, but several major workings of the universe remain unobservable, including dark matter and the inner workings of stars. The neutrino is electrically neutral and unaffected by magnetic fields, stable over very long distances and, unlike the photon, able to pass through matter; it could be a perfect informant concerning unexplored areas of the universe.

The Neutrino

The neutrino is the only particle capable of passing through the Earth. Thus a particle detected as coming from the Earth can be immediately correlated to a neutrino interaction consequence. This is so in the case of muons, which are detected by their Cherenkov light emission as they enter seawater The NEMO detectors aim to track muons, and thus the neutrinos that have passed through Earth. In this way, information about neutrinos will help improve our understanding of astronomical phenomena such as dark matter, supernovae, high-energy ray generation and so on.

Detection

High-energy cosmic neutrino astronomy is one of the most interesting frontiers of astrophysical research today. The observation of cosmic rays with energy up to 1020eV has shown the existence of cosmic objects able to accelerate protons to extreme energies. Unfortunately, such experiments are not currently able to identify the source of these. Many celestial bodies, today observable only via their electromagnetic emission, could accelerate particles at very high energies. Actually, theoretical models foresee that in some sources acceleration occurs of both electrons responsible for the observed non-thermal electromagnetic emission and protons. Acceleration of protons not hindered by competition with bremsstrahlung processes would prove to be efficient up to extreme energies (1019eV) and would greatly increase neutrino energy and photon production.

Protons with energy of approximately 1TeV have recently been observed from galactic supernova remnants (SNR-W28, SN-1006) and from the nearest active galactic nuclei to the Earth (Markarian 501 and Markarian 421). Nevertheless, the potential of gamma astronomy at these energies is limited. In fact, photons with energy higher than 1TeV are completely absorbed by cosmic radiation (so-called cosmic μ-wave background) and interstellar medium interactions within distances of about ten million light-years from the Earth. Hadrons too are unusable probes: neutrons have too short an average life, the heavy nuclei suffer fragmentation processes in their interactions with medium and interstellar radiation, and protons are deflected by the galactic magnetic field (~ mG), disallowing identification of emission source. Protons of elevated energy (>1019eV) are finally absorbed by interactions with the cosmic background radiation within 107 light-year distances.

Neutrinos would appear the preferred astronomical “probe” for very high astrophysical phenomena observation. They do not interact with radiation and have only weak inter–actions with matter: the weak interaction coupling constant is around 1013times smaller than the electromagnetic one. Neutrinos, therefore, can carry information originating from very remote space sources, at a time near to the big bang, or in regions next to black holes where radiation density and matter do not allow the escape of photons. The analysis of high-energy neutrino fluxes would allow the characterisation of physical processes occurring in active galactic nuclei, gamma ray bursts, microquasars and other foreseen sources.

NEMO

Various R&D projects are underway in the Mediterranean area based on underwater 3D-array optical sensors (1,2). For experimental requirements to be met it is necessary to install the optical sensor at a depth of around 3,000m and track its position with an accuracy of 15cm. Generally called “neutrino telescopes” these detectors require a volume of one cubic kilometre. As described above, NEMO is being developed by INFN off the Sicilian coast. The optic–al sensors are contained in a tower of four floors and overall height of around 200m from the seabed. The final NEMO tower configuration will have sixteen floors and be 800m high. The NEMO tower is deployed on the seabed in a folded configuration. The buoy is released using an acoustic remote control and it takes only few minutes for the tower to reach its final vertical configuration.

The performance of the neutrino detector will greatly depend on the ability to accurately position each optical detector in real time. In effect, though the towers are designed for stability and the deployment site chosen for its low current and environmental stability, sphere position is assumed to slowly oscillate around the vertical. Oscillations of the spheres have to be monitored to 15-cm accuracy, with high repetition rate (1s) during the overall functioning period of ten years.

Several constraints have to be taken into account for the design of the positioning system:

- the great number of optical detect–ors to be positioned: several thousand
- high accuracy and repetition rate for positioning
- small spatial volume available in towers for electronics
- low power consumption of electronic boards
- limited data flow relating to pos–itions circulating over fibres
- minimal duplication cost of equipment
- long lifetime of the project.

Due to the specific undersea waves propagation conditions, only acoustic waves can be used for long-distance (over 1km) measurement. The great number of positions to be monitored implies that the acoustic receptors be located at the position to be monitored, a minimum of four beacons be deployed around the area of tower deployment, and acoustic flows be one-way only (3).

Underwater Positioning

The positioning system is based on acoustic signal times of flight measurements at regular intervals (i.e. 1 second) between the reference beacons and the targets to be positioned where, firstly, the reference beacons integrate ultra-stable clocks and, secondly, targets are the hydrophones located nearby each individual optical sensor. Distances are calculated by converting “time of flight” into distances, knowing the sound velocity profile. Time of flight is the difference between the time of arrival (TOA) on the receiver hydrophone and the time of emission on the beacon (TOE). In order to achieve 15-cm accuracy in positioning the distances should be measured with higher accuracy. Thus the time of flight must be measured at accuracy better than 10-4s.

To achieve a high level of performance the positioning system needs to share a unique time reference (relative) at the beacons and at the receivers: designated Master Clock. Though the beacons have an ultra-stable clock, a monitoring station allows accurate measurement of its drift. Beacon position is accurately calibrated (15cm) using a sophisticated calibration procedure. Further, in order to be able to merge in post-processing positioning data together with Neutrino detection information, both need to be stored (time stamped) within a universal time reference such as the UTC: Universal Time Coordinate.

The amplitude of pendular motion cannot exceed 30 metres for the sixteen-floor tower. Depth variation is calculated by modelling, with the help of the embedded compass and tilt-sensor at each floor. Thus the fourth beacon has been installed on the tower base to handle depth measurements for depth-value calculation. The elevation between the tower base beacon and the receivers is given by the time of flight of the acoustic signal, knowing the sound velocity.
In this application ACSA has adopted a proprietary, patented technique known as TSSC (Time Spectral Spread Codes). All the beacons transmit acoustic pulses at the same frequency; this is a real cost advantage, as beacons are all identical except software configuration, and receivers require only one acoustic channel. In order to identify the beacons each has a unique orthogonal Time-Space pseudo-random signature. This very powerful technique also allows the attainment of high repetition rates without cycle ambiguity.

Accuracy

Beacon positions were calibrated to an accuracy of 15cm, see Figure 3, showing the clouds of positions and histogram of distance to mean position. The DRMS circle corresponds to the distance for which 63.2% of fixes lie in that circle. The radius of the circle is read on the histogram: around 3cm. This indicates the accuracy of the calibration of beacon positions. The position of the tower has been calculated to very high accuracy. Figure 4 shows the position of one hydrophone on the tower. As this hydrophone lies only 75m above the seabed, and as the structure was designed to be rigid, movement is reduced to the degree that it may be regarded as static during acquisition.
The Figure 5 shows the histogram of distance to mean position of the third-floor hydrophone 1. The DRMS circle corresponds to the distance for which 63.2% of the fixes lie in that circle. The radius of the circle is read on the histogram: around 10cm. This indicates the accuracy of the positioning system.

Concluding Remarks

Phase 1 of the NEMO project offers the opportunity to test and validate very high-tech equipment specially developed for this application. In terms of positioning, the system imagined by ACSA will have other applications in various fields.