Calibration Systems of the ANTARES Neutrino Telescope

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Abstract—**The ANTARES collaboration is deploying an underwater neutrino telescope at 2500 m depth in the Mediterranean Sea. The experiment aims to detect high-energy cosmic neutrinos using a 3D array of 900 photomultipliers (PMTs) distributed in 12 strings. These PMTs will collect the Cherenkov light induced by charged particles produced in neutrino interactions with the surrounding matter. Cosmic neutrino detection allows us the study of the possible sources of extra-terrestrial neutrinos.**

This work reviews the calibration systems (positioning and timing) devised for the detector. Spatial positioning is performed through an acoustic system and a set of tiltmeters and compasses. The time calibration is done first on-shore, in the laboratory using pulsed laser light distributed via a fibre optics and then in-situ with a system of Optical Beacons. In addition, an echo-based system built into the clock, whose signal is distributed throughout the detector and an LED within each Optical Module (OM), is used.

Two lines have been deployed by September 2006. Analysis of the first line, deployed on March 2006, has shown a resolution of about 0.5 ns in time and 10 cm in the OM positioning. With this performance the expected angular accuracy of the detector is better than 0.3º for $E_\mu > 10$ TeV.

I. Introduction

THE ANTARES [1] detector is located at 40 km off the Toulon coast. By September 2006, there are two complete lines (Lines 1 and 2), and one instrumentation line (MILOM), already deployed and taking data steadily. A standard line is composed by 25 storeys with 3 PMTs each. The 10'' PMTs are housed in the Optical Modules [2]. The OM looks downwards at 45º and is made of pressure-resistant glass sphere which protects the PMT [3] from the high pressures. The clock signal, slow control commands, HV supply, and the readout, arrive at the OMs via the electronic boards housed in the Local Control Module (LCM) container made of titanium. Each line is anchored to the seabed by the Bottom String Socket (BSS) which is in charge of controlling the line giving the power supply, etc. while a buoy at the top gives them

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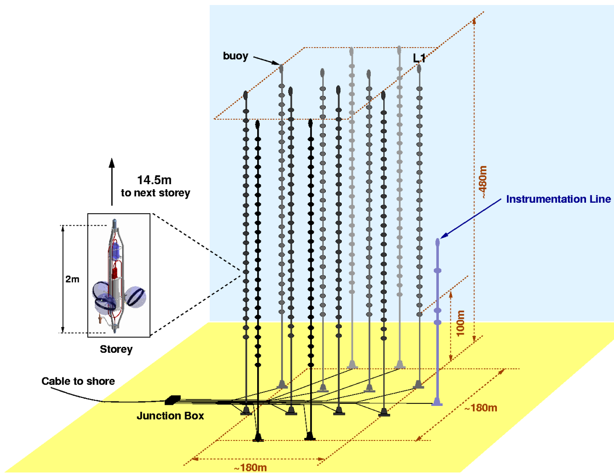

Figure 1: A general view of the ANTARES detector placed at the seabed. It is composed by 900 PMTs distributed along 12 lines.

vertical support.

The connection between the shore station and the detector is made by an electro-optical cable of 40 km. This cable links with the junction box which splits the connection to the BSS of the 12 lines.

The aim of the detector is to reconstruct the tracks of the particles created after a neutrino interaction. The track reconstruction in ANTARES relies basically on the arrival times of Cherenkov photons to the Optical Modules and the position of the OMs. Therefore, both the positioning accuracy of the detector and the timing resolution of the signals are closely related to the pointing power of the telescope, and are of the utmost importance.

An angular resolution for muon tracks better than 0.3º for $E_\mu > 10$ TeV (Fig.2) will require a high level of precision in the timing resolution. The main contributions to the uncertainties in the relative timing come from the transit time spread (TTS) of the signal in the photomultipliers (~ 1.3 ns) and the optical properties of the sea water such as light scattering and chromatic dispersion (~ 1.5 ns for 40 m distances) [4]. Therefore, all electronics and calibration systems are required to contribute less than 0.5 ns to the relative time resolution to guarantee the expected angular accuracy.

Concerning the absolute time calibration, the purpose is to fix a specific time for each neutrino event with respect to the

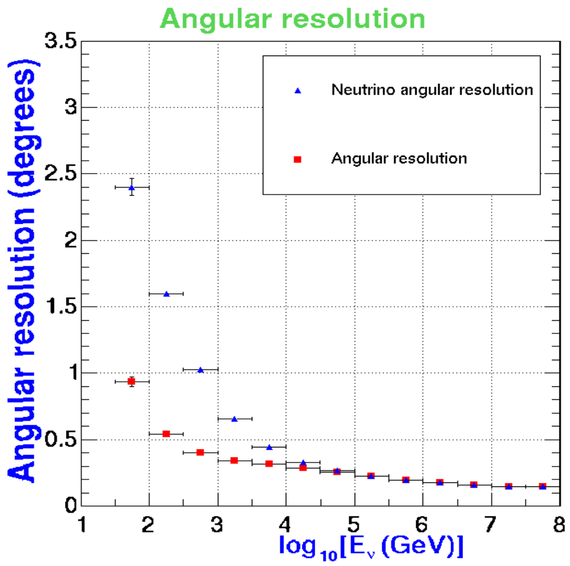

Figure 2: ANTARES expected angular resolution vs. neutrino energy.

universal time. An accuracy of 1 ms is enough in ANTARES for any conceivable physics goal such as gamma ray bursts, flares or supernova explosions. The main uncertainties in the absolute timing come from the time offsets and fluctuations in the path common to all the signals, i.e., the 40 km electro-optical cable between the junction box and the shore-station. The absolute timing is known interfacing the Master Clock on-shore station with a card receiving the GPS Clock. The resulting accuracy is of the order of 20 µs in average and does not exceed 100 µs.

In the positioning system, a relative resolution of ~ 10 cm is needed due to the fact that our precision should be better than the uncertainty of the Cherenkov light detection (0.5 ns is equivalent to 11 cm of light travel path in water). Considering the absolute positioning, we have to know the 3 geographic position coordinates (latitude, longitude and altitude) of the detector with respect to a fixed local reference frame defined by 3 string anchors. The absolute positioning precision desired is a few arc-minutes in latitude-longitude, and a few meters in depth. This is known by means of an acoustic system, pressure sensors and the GPS reference.

II. Time and Amplitude Calibration

Several calibration and monitoring systems have been devised for the ANTARES time calibration in order to measure the time offsets and the timing resolution. The signal amplitude calibration is also important for time precision through the walk effect.

The systems can be classified according to the place where they will be finally performed, that is: "in-situ" calibration systems and on-shore calibration systems before deployment.

A. In-situ calibration systems

These are the time calibration systems that operate in the sea. Some of the measurements and tests performed by these systems will be redundant with respect to those performed on-shore. However, the different environmental conditions in water might change the expected values of the calibration parameters already measured in the laboratory.

The in-situ systems and methods are: 1) The internal clock, 2) The internal LED calibration, 3) Optical Beacons, and 4) Atmospheric muons.

1. The internal clock

A high-precision (20 MHz) clock signal is generated on-shore and distributed afterwards throughout the detector. This signal provides a common reference to all the LCMs. The clock calibration system is based on an echo of the clock signal in different parts of the detector. The idea is to get the round-trip time from the delay between the moment when the signal is sent and the moment when the answer arrives. The half round-trip time for each LCM gives the clock-phase which allows the LCM to be synchronized with a time precision around 100 picoseconds. Another feature of this system is the synchronization with respect to the Universal Time by assigning the GPS time to the data.

2. The internal LEDs

Every OM has an internal blue LED (472 nm) glued on the back of the PMT to illuminate, pulsed by the clock, the photocathode from inside the OM. The aim of this system is the monitoring of the transit time (TT) of the PMTs. This is done by flashing the internal LED at a rate of about 100 Hz and measuring the difference between the OM signal arrival time with respect to the LED flash emission time. The

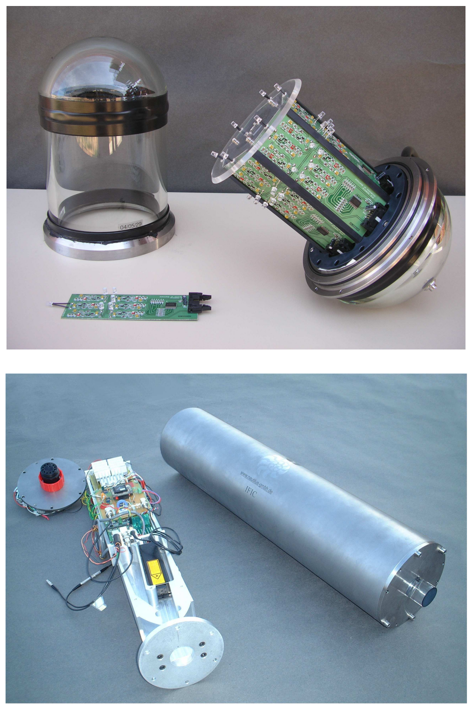

Figure 3: The ANTARES Optical Beacons with their containers. In the top part the LED Beacon, its light emission time is known with an internal PMT. In the bottom part the Laser Beacon, its light emission time is known with an internal built-in photodiode.

variation of this difference with time monitors the possible TT variation.

3. Calibration with Optical Beacons

The Optical Beacons [5], LED and Laser (Fig.3), are devices which emit light pulses through the water to illuminate the OMs and provide a known time reference that allows the overall calibration of the detector. The LED Beacon contains 36 individual LEDs arranged in groups of six on six boards which are placed side by side forming an hexagonal cylinder. The LEDs emit blue light of 472 nm. Each light pulse of one LED gives a maximum output of typically 160 pJ (4×10^8 photons per pulse). The intensity of the LEDs can be modified as well as the number of LEDs fired.

The Laser Beacon uses a diode Q-switched Nd-YAG laser to produce pulses of ~ 1μJ of 532 nm of wavelength which means ~ 10^{12} photons.

On the detector there are four LED Optical Beacons distributed uniformly along every line, and one Laser Beacon on the base of two lines. They provide a common light source to all the OMs. With them, the relative time offsets among OMs can be estimated and compared with respect to the values obtained in previous on-shore measurements. In addition, positioning cross-checks and studies of the light transmission in water can also be performed. The emission time is known by means of a small internal PMT and an internal photodiode for the LED and Laser Beacon respectively.

4. Atmospheric muons

The relative time offsets can also be monitored using the ~ 10000 downward atmospheric muons per day, expected in the ANTARES detector. The distributions of the time residuals of the hits (difference between the measured time and the time expected from the track fit) will be used as a monitoring system which will show whether the offsets used in the reconstruction are accurate enough.

B. On-shore calibration system

The on-shore calibration systems are necessary in order to check that all the detector components work properly before the line is deployed in the sea. Moreover, they allow us to obtain the first set of calibration parameters which will be compared with the calibration made in-situ. For most of these measurements the OMs are placed in a dedicated dark room (or in dark boxes). A laser system providing a common light signal by optical fibre to every OM is used. The light coming from the laser is divided by a 1-to-16 optical splitter in order to illuminate 15 OMs individually. The end of the fibre is attached to a kind of flowerpot which encloses the OM (Fig. 4). Inside the flowerpot a diffuser spreads the light before illuminating the PMT photocathode. The laser used in the dark room is similar to the one used in the Laser Optical Beacon. Several tests and measurements are done with this system:

Figure 4: General view of the laser and optical fibre OM calibration by fibre optic system at the dark room.

1. Time-offset measurements

The aim of this measurement is the relative time offsets among the OMs of the detector which appear when an external synchronous signal flashes them simultaneously. In other words, to compute the time differences resulting from different transit time and electronics associated to each OM.

In order to measure the differences of the time response of each OM, a reference time, synchronous with the laser light emission, is needed. This reference signal is provided by a photodiode internal to the laser which is read by an independent LCM_ref, exclusively built for the dark room calibration measurements. The time difference between the OM signal and the LCM_ref signal gives the time offsets between OMs. All the time offsets values are referred to a particular OM. The time offset of the LED Beacon PMT is also calculated with this system and referred to a particular OM.

2. TVC calibration

The Time-to-Voltage Converter (TVC) of the readout chip [6] (the Analogue Ring Sampler, ARS) provides the time measurement with an accuracy of ~ 0.3 ns. The TVC is read by an 8-bit ADC. The calibration of the TVC on shore, as well as off-shore, is done using random hits.

3. Front end threshold

This calibration aims to measure the discriminator threshold response computing the efficiency curve (S-curve) for different levels of input voltage test signals (equivalent 0, 1, 1.5 photoelectrons). This allows us to know the response function of the dedicated DAC in order to choose the appropriate threshold in mV or p.e. units.

Once in situ, the thresholds are measured using the p.e. from the background light (^{40}K radioactivity of the sea water, bioluminescence, and the glass sphere radioactivity).

4. Charge calibration

The charge is also read with the ARS chip by an 8-bit ADC following an Analog-to-Voltage Converter (AVC). In this test the values of pedestal and the p.e. peak of the PMT charge spectrum, are measured. This is necessary to convert the charge (ADC channels) values into p.e. units. The methodology of this test is similar to the one performed in the ARS threshold test, i.e., tuning by steps the input laser signal.

As for threshold calibration, pedestals and p.e. peaks can be measured again in situ using the background light.

III. Positioning Systems

The relative positioning in ANTARES is done using two independent systems: an acoustic system which exchanges signals in the 40-60 kHz range, and a set of tiltmeter-compass sensors.

The *acoustic system* is composed by an array of transponders (RxTx) placed in known positions on the seabed, and receiver hydrophones (Rx) distributed uniformly along the lines (Fig. 5). The transponders are placed on the anchor of every line and, in addition, several autonomous pyramids have been also deployed to this end. The travel time of the acoustic signals exchanged between the receiving hydrophones and the emitters fixed at the bottom is measured. This allows real time localization in space of the Optical Modules by triangulation with a precision of ~10 cm. A good knowledge of the sound velocity is crucial in order to achieve accurate position calculation. In the sea water, the sound velocity depends on the temperature, the salinity and the pressure. These parameters are measured by the instrumentation.

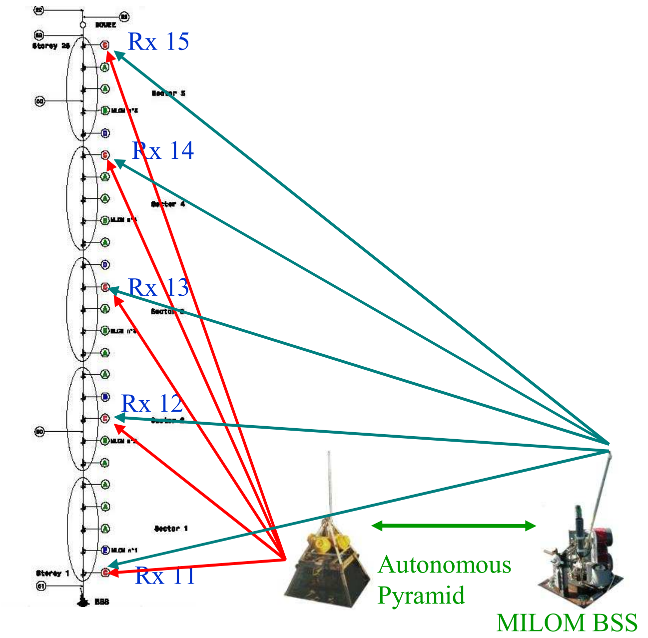

Figure 5: Sketch of the signal exchanges by the acoustic system.

The *tiltmeter-compass sensors* are located on each storey of every line, inside the LCM. The tiltmeter provides information about the pitch and the roll angles of the storey with a precision of ~ 0.2º. The compass gives the heading of the triplet of OMs in each storey, that is, the angle between the magnetic north and one OM used as reference. This heading angle is known with a precision better than 1º.

IV. Results

The calibration system has been tested using the instrumentation line (MILOM) [7] and the first standard line (Line 1), already deployed and operating.

The tests performed with the time calibration systems have shown the expected behaviour.

The *clock calibration system* has been tested as well. It has been shown that the time delay between the shore station and every storey is provided with a precision of ~ 100 ps.

Fig. 6 shows the results of the *internal LED* runs from the instrumentation line, MILOM, with the line already in the sea for a time period of six months. The internal LED confirmed that the transit time of the Optical Modules remains stable within 0.5 ns.

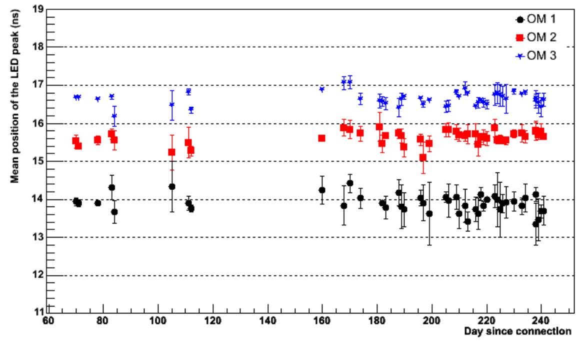

Figure 6: Mean values of the arrival times of the OM signals induced by an internal LED flash with respect to the flash time emission, during 170 days of the instrumentation line (MILOM) connection.

The *Optical Beacons* were flashed and the time offsets were measured with them. The values obtained were compatible with the ones computed in the laboratory. In addition, with this system it was possible to show that the timing resolution achievable for a single Optical Module is ~ 0.4 ns. Effects concerning Optical Modules orientation and light scattering were also noticed and are being studied.

In Fig. 7, the time differences between the MILOM LED Optical Beacon and 6 OMs of 3 different storeys are represented. The distribution in the OM which faces the MILOM is narrower than the one obtained for the OM looking

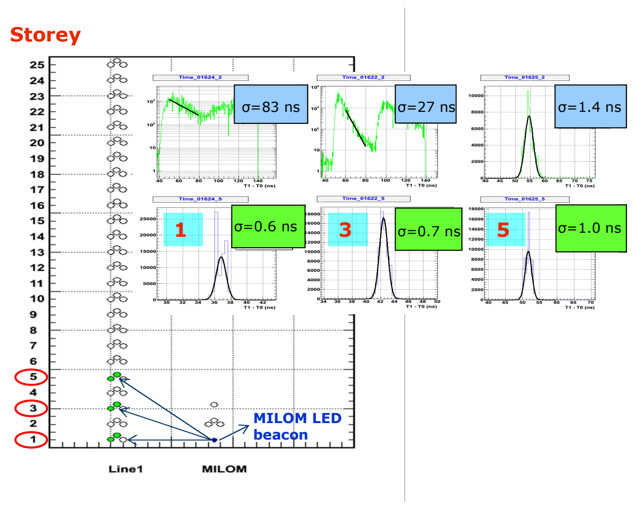

Figure 7: Time differences between the MILOM LED Optical Beacon (blue) and 6 OMs, 2 per storey (filled in green), located in different Line 1 storeys (1st, 3rd and 5th).

in the opposite direction. This is due to the fact that the OM in opposite direction only sees scattered light.

The acoustic system was tested using the MILOM BSS transponder which exchanges signals with the Line 1 receiver hydrophones. In Fig. 8, the distance between the transponders of the MILOM and the Line 1, as is computed by the acoustic

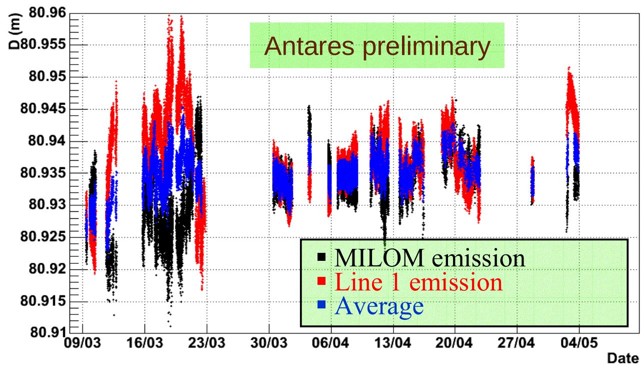

Figure 8: Distance between the instrumentation line (MILOM) and Line1 measured using the transponder located at the anchor of both lines. The stability of the position measurements for fixed points is of the order of ~ 1 cm.

signals, is shown. The stability is of the order of ~ 1 cm.

The tiltmeter-compass sensors have also been operating and their results has been used in order to reconstruct the line shape in combination with the acoustic system data (Fig. 9).

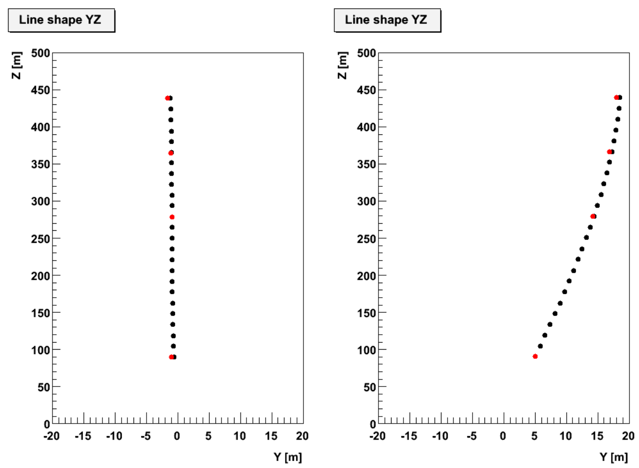

Figure 9: Line shape fit (black dots) with the measured hydrophones positions (red dots) for low (left) and high current (right) case.

V. Conclusion

The ANTARES calibration systems have been tested successfully both in the laboratory and in the sea. The results have proven that the aimed time resolution (0.5 ns relative, 1 ms absolute) and spatial resolution (10 cm) can be achieved. Therefore, the angular accuracy of the detector of about 0.3º for high-energy neutrinos is reachable.

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