Electronics and DAQ of the ANTARES Neutrino Telescope

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Abstract--**ANTARES is an underwater Neutrino Telescope to be deployed in the Mediterranean Sea, starting in 2003. In this paper, we illustrate the detector design with emphasis on the electronics and data acquisition solutions. A brief introduction to the scientific motivations of this project and a summary of the past and present activities are also provided.**

I. Introduction

ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) is an underwater neutrino telescope which will be operated at a depth of 2400 m in the Mediterranean Sea. It consists of an array of 900 photomultiplier tubes (PMTs) by which the faint light pulses emitted by fast particles propagating in the water may be detected. Based on such measurements, ANTARES will be capable of identifying neutrinos of atmospheric as well as of astrophysical origin. In addition, the detector will serve as a permanent monitoring station for geophysics and sea science investigations.

This paper is organized as follows: the next section is a brief introduction to the scientific investigations which may be performed with ANTARES; Section III illustrates the overall design of the telescope; Section IV illustrates in some details the electronics and data acquisition of the detector; finally, Section V briefly summarises the current status of this project and the latest progress made by the ANTARES Collaboration.

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Nice pictures, animations and a vast, updated documentation on the ANTARES activities are available at http://antares.in2p3.fr/

II. Neutrino Observations With ANTARES

Neutrino observations may open a new window on the Universe and shed light on the most puzzling aspects of conventional Astronomy and Astroparticle Physics. Neutrinos, in fact, can only suffer the so-called "weak" interaction. As a consequence, they can propagate through large regions of interstellar or intergalactic space while experiencing no significant scattering. They may even escape from the very dense regions at the centres of stars or galaxies. In addition, they will be insensitive to the magnetic fields encountered along the way. Therefore, even neutrinos produced in very thick sources at very large distances may reach the Earth and, if detected, point back straight to their sources.

No other known particle exhibits such properties: charged particles, in fact, are curved by magnetic fields and do not point back to their sources. Photons may not penetrate through dense regions of matter. In addition, at very high energies the distance that charged particles and photons can propagate in space may be severely limited by the interactions on the cosmic microwave background (and on the diffuse infrared background in the case of photons).

Several sources of high-energy neutrinos are believed to be active both in the Galaxy and beyond. In fact, any source of high-energy cosmic rays should give rise to a neutrino component, through production and decay of intermediate mesons. The list of candidate neutrino sources includes binary systems containing neutron stars or black holes, young supernova remnants and, outside the Galaxy, active galactic nuclei and gamma-ray bursters.

The decay of massive particles or of metastable relics has been sometimes proposed to explain, in a "top-down scenario", the existence of cosmic-ray particles with extreme energies, i.e. above the so-called GZK cutoff [1]. It is important to point out that an associated production of neutrinos is expected to take place also in this case.

Neutrino observations may also provide a clue to understanding the nature of dark matter: neutralinos, which are among the most widely advocated candidates for non-baryonic dark matter, would tend to accumulate toward the centres of massive objects, such as the Earth, the Sun, or even

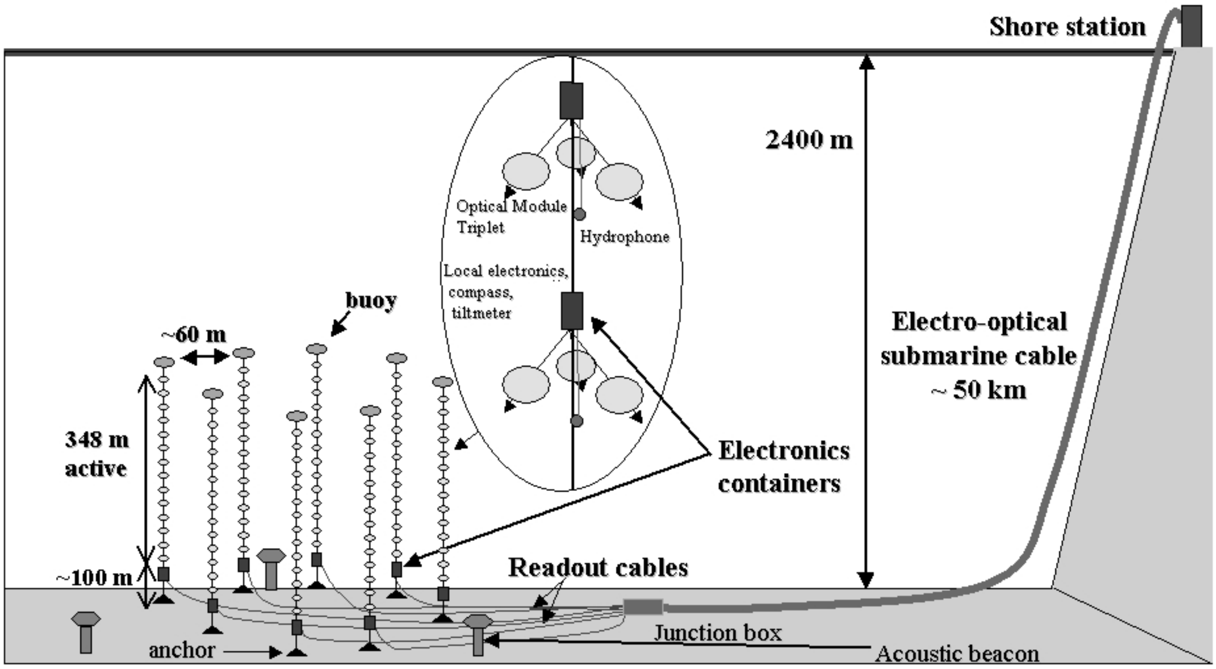

Fig. 1. Schematic view of a part of the detector (the full configuration will consist of 10 strings). The magnified view encompasses two storeys.

the Galaxy [2]. An observed excess of neutrinos coming from such objects would therefore provide evidence for existence of neutralinos. Inferences on the neutralino mass could also be made on the basis of the angular distribution of the detected events.

Finally, recent observations of atmospheric neutrinos have provided evidence for neutrino oscillations [3]. The design of the ANTARES detector is such that the oscillation pattern can be studied for values of the pathlength/energy ratio between about 60 and 1200 km/GeV. This investigation can provide a measurement of the oscillation parameters, complementary to the observations of the existing atmospheric neutrino detectors.

However, the detection of neutrinos is not easy. A massive detector with a very good background rejection is needed. Charged cosmic rays constitute a large background to neutrino observations which has to be filtered out. An underwater (or under-ice) detector currently provides the only feasible approach to Neutrino Astronomy: The water above the detector acts as a shield against charged cosmic rays coming from above, while the Earth itself will stop any other particles but neutrinos coming from below. Neutrinos interacting in the volume of the detector or in its surrounding may produce muons which, when propagating at a speed larger than the speed of light in the water, will radiate Cherenkov light in the water. ANTARES will record the location and arrival times of these light pulses: the tracks of the secondary muons will be precisely reconstructed from such measurements, providing information on the propagation directions of the parent neutrinos.

III. DETECTOR DESIGN

The detector consists of an array of 900 optical modules (OM) arranged in 10 strings. Each string will be anchored to the seabed and stretched taut by a top buoy. The minimum distance between two strings will be of about 60 m. The detector will have an effective area of 0.1 km^2.

Each string is composed of 30 'storeys', each equipped with 3 OMs oriented at 45^o with respect to the vertical. The storeys are spaced at 12 m from one another, the lowest one being located about 100 m above the seabed. The total height of the string is therefore of approximately 450 m, with an 'active' height of 348 m.

Each OM consists of a PMT, various sensors and the associated electronics housed in a pressure-resistant glass sphere. Hamamatsu R7081-20 PMTs will be used: these hemispherical phototubes have excellent features such as a large photocathode area (10" diameter), low transit time spread (~3.8 ns), high gain (10^9 maximum), good Peak/Valley ratio (larger than 2), low dark current rate, low incidence of pre- and after-pulses [4].

Each storey is controlled by a Local Control Module (LCM). A String Control Module (SCM), located at the basis of each string, interfaces the string to the rest of the detector.

A network of submarine cables supports the power distribution from the shore, the detector control and data acquisition. All offshore data and signal communications take place over optical fibres. A 50 km Main Electro-Optical Cable (MEOC) links the telescope to the onshore station. This cable is equipped with a copper coaxial conductor for power distribution and 48 optical fibres for digital communications, which include a master clock signal delivered from onshore, data and slow control connections with each string. This cable terminates at a junction box, from which separate cables serve the detector strings.

A schematic view of the ANTARES detector and of the submarine connections is shown in Fig. 1.

The installation site is about 40 km off the coast of Toulon, France. A sky coverage of 3.5π sr, including the galactic centre, is possible from this location.

IV. Electronics and DAQ

A. Requirements and Constraints

The most compelling requirements that the electronics and data acquisition network for a complex installation such as ANTARES have to fulfil are a large bandwidth for data transmission, low power consumption and a very high reliability.

The data bandwidth requirements are mainly set by considerations about the background levels expected for the ANTARES installation. In fact, the data due to particle events as well as the slow control information contribute negligibly to the data flow from the detector to shore. There are two main sources of optical background at the water depths involved: radioactive decay of the ^{40}K dissolved in the sea water and the light flashes due to bioluminescence activity. The former will give rise to a constant pulse rate in the optical modules (approximately 60 kHz for the ANTARES PMTs), while the latter may cause light bursts, of duration up to a few seconds, during which the pulse rate from a single PMT may reach the level of the MHz. The typical data flow expected from the detector is of the order of 7.5 GB/s. ANTARES is designed to sustain such a high data rate by means of the Dense Wavelength Division Multiplexing (DWDM) technique described in the following.

Power consumption should be kept at minimum for two main reasons: power is provided by the onshore station, therefore increasing the power needs will affect the structure (and consequent cost) of the main electro-optical cable as well as of the entire offshore network. Secondly, the power dissipated offshore will affect the temperature balance inside the electronics containers, and higher temperatures may negatively affect the lifetimes of the components. The maximum power dissipated inside the offshore electronics containers will be about 30 W.

Concerns about the reliability and long-term functionality of the detector have received a large attention in the design of the ANTARES telescope. Access to the instrumentation is impossible, once the detector is installed, unless an entire string is recovered. This procedure, however, is time-consuming and costly. Three major solutions have been adopted in order to improve the overall reliability of the detector. Firstly, the network has been designed so as to minimize the impact of single point failures: the most sophisticated functions are performed by components distributed along the whole detector, while mainly passive operations are performed at the "network nodes" such as the main junction box and the SCMs. Secondly, only very well-known and tested components will be used in the offshore electronics. Thirdly, a detailed test and qualification scenario has been developed for the string production: every major step in the integration of the strings will be marked by a qualification test of the instrumentation being assembled. In addition, all of the equipment to be used in the offshore electronics will undergo an Accelerated Stress Test, in order to get rid of the infant mortality and increase the MTTF of the surviving components.

B. Front-End Electronics

The full-custom Analogue Ring Sampler (ARS) has been developed to perform the complex front-end operations [5]. This chip samples the PMT signal continuously at a tunable frequency up to 1 GHz and holds the analogue information on 128 switched capacitors if a threshold level is crossed. The information is then digitized, in response to a trigger signal, by means of an integrated dual 8-bit ADC. Optionally the dynamic range may be increased by sampling an attenuated anode signal and the signal from one of the dynodes.

A 20 MHz reference clock will be used for time stamping the signals. A Time to Digital Converter (TVC) is used to interpolate between clock pulses. This system allows a timing precision better than 1 ns to be achieved.

The ARS is also capable of discriminating between simple pulses due to conversion of single photoelectrons (SPE) from more complex waveforms. The criteria used to discriminate between the two classes are based on the amplitude of the signal, the time above threshold and the occurrence of multiple peaks within a time gate. Only the charge and time information is recorded for SPE events, while a full waveform analysis is performed for the other events.

Two ARS chips, in a "token ring" configuration, will serve a single PMT. A third chip will be used for triggering purposes.

C. Trigger

The trigger function of the detector may be useful in order to decrease the amount of data to be transmitted to shore. A simple and flexible trigger system has been designed for this purpose, based on three levels of trigger (L0, L1 and L2). All of the options available may be remotely controlled and all of the parameters (thresholds, coincidence windows, time delays) set from the shore station.

The lowest level of trigger, L0, is generated by any OM when its signal meets the (remotely configurable) trigger conditions. If no further level of triggering has been activated, the data from each OM generating an L0 trigger are sent to shore; otherwise, the data are momentarily stored by the ARS into a pipeline from which they can be retrieved and sent to the DAQ if a request arrives within a preset time window.

The L1 trigger is generated when preset conditions on the signals from OMs from the same storey are met: the data from the relevant storey are then acquired. The L1 trigger signal is also daisy-chained along the string, in such a way that coincidences from consecutive storeys may be formed.

An L2 trigger signal is generated when proper coincidences occur between L1 signals from different storeys or strict requirements are satisfied by the OM signals of a single storey. Whenever a L2 signal is generated, a global Readout Request (RoR) is broadcast to the whole detector. The distribution of such request works as follows: the L2 signal is sent from the storey where it has been generated to the junction box, which in turn generates and distributes the RoR request to all strings.

The RoR signal is also sent, along the MEOC, to the shore in such a way that the L2/RoR rate can be monitored. It is also possible to distribute RoR requests directly from the shore.

D. Offshore DAQ

A single processor is in charge of the data acquisition and slow control (SC) at the LCM level: the choice has been for the low-power RISC Motorola MPC860P running the VxWorks OS. The MPC860P features a 100 Mb/s Ethernet controller, up to 4 Serial Communication Controllers (SCC) and a Serial Peripheral Interface (SPI). The Ethernet port will be used for external data/SC communications, while one of the SCC ports will be used to implement an RS485 serial bus, with MODBUS protocol, for local (i.e., internal to the module) slow control communications. The processor boots from a flash memory.

The interface between the ARSs and the DAQ processor is provided by an FPGA (Altera APEX20K200E), which receives the data from the front-end chips, temporarily stores them into internal buffers and then moves them to the DAQ memory (a SDRAM). The processor will be in charge of retrieving the data from the DAQ memory and sending them toward the shore station. The FPGA code is stored on a dedicated EEPROM.

From the point of view of the data acquisition and control, the detector is organized with a star topology. Independent communications with any strings take place along different optical fibres. The data from the different sectors of a string are sent toward shore implementing a DWDM technique with standard ITU optical wavelengths with 400 GHz frequency spacing. The selected wavelengths lie in the region between 1535 nm and 1560 nm. In each sector the gateway to the network is performed by a Master LCM (MLCM), which features a DWDM laser for data transmission to the shore and a 1 Gb/s Ethernet switch for communications with the DAQ processors inside the MLCM itself and the other LCMs of the sector.

The data coming from the different sectors are merged by a DWDM multiplexer in the SCM and then injected into a single fibre toward the shore station. On the shore, the reverse process is implemented with a passive DWDM demultiplexer. Similarly, the network supports the data transfer from shore to the offshore electronics.

E. Onshore DAQ

Depending on the operational mode of the detector, data rates of about 50 Mb/s to 1 Gb/s are expected from each string. A fast data processing system will be used to decrease the rate of data to be recorded. This system will consist of a Linux-farm of about 100 PCs. The data flow through this system will be managed through the IP addressing of the Ethernet protocol: the offshore modules choose the destination address where to send their data packets depending on the time stamp. Consequently, each onshore processor will process the data collected in the whole detector in defined time windows (10 ms of duration, typically).

It will be also possible to have a continuous record of 10-100 s of data temporarily kept in memory in such a way that they can be saved to disk in case of a (delayed) external trigger signal.

If very loose trigger conditions are used offshore, the onshore filtering program will have to produce a data reduction of the order of 10^3. Therefore, the rate of data to be stored on disk is not expected to exceed 7.5 Mb/s. The onshore station will be accessible from the outside world through a high bandwidth (100 Mb/s) data link.

F. Slow Control

The main functions that have to be performed by the slow control system are the following:

- control all detector subsystems (power distribution, OMs, calibration and monitoring devices) and set up the desired configurations;
- monitor detector parameters (voltages, currents, temperatures, …);
- collect calibration data for time alignment and space positioning;
- download software into programmable devices, if necessary;
- manage databases for detector configuration, settings, command logfiles, calibration data;
- provide online information for monitoring and alarm.

The slow control offshore communication system shares the same network as for data acquisition. Communications between the offshore electronics modules and the onshore station will use the Ethernet standard with TCP/IP protocol and optical transmission with 400 GHz DWDM features. Communications inside the offshore electronics containers and between these and the external instruments connected will implement a serial MODBUS protocol (on a RS485 physical layer).

G. Positioning System

As explained in Section II, the reconstruction of the tracks of muons which cross the detector is based on the interpretation of the light pulses detected at given positions (i.e., the locations of the OMs) at specific arrival times. Hence, the pointing accuracy of the telescope depends critically on how well the OM positions are known and the arrival times are measured.

ANTARES is equipped with a hybrid positiong system. Each offshore electronics box is provided with a tiltmeter and a compass, giving information on the 3-axis orientation of the storey. An acoustic triangulation system provides measurements of the propagation times, hence 3-D distances, from acoustic transceivers located at the bases of the strings to hydrophones properly distributed along the strings. The shape of each string is then reconstructed by performing a global fit of all this information. Our previous experience with a prototype string shows that a relative positioning accuracy better than 10 cm can be obtained with such a system [6].

Standard GPS measurements and acoustic triangulation techniques will be used to absolutely position the detector with an accuracy of the order of 1 m.

H. Clock

The clock system has been designed to provide a low-jitter common clock reference for the whole detector. A 20 MHz master clock signal is generated onboard and distributed to each electronics box offshore by means of a dedicated optical fibre of the underwater network described previously. Digital data may be superimposed on the reference clock, thus providing a means of distributing common synchronised orders to the whole detector or to an addressable part of it. The time jitter measured for this system is of the order of 100 ps.

The clock network supports bidirectional transmissions. The return path is used to measure the propagation delay between the onshore clock system and the offshore electronics. This information is necessary for an accurate alignment of the OM signals. A full time calibration of the detector is performed by measuring also the PMT transit times and the detector offsets, in response to signals respectively from LEDs mounted internally to the OMs and from light beacons which illuminate large parts of the telescope. The return signal capability of the clock network is also used to send data to shore for test and debugging.

The onshore clock is synchronised to the GPS time with an accuracy of 100 ns.

V. ANTARES: PAST, PRESENT AND FUTURE

A. Past: R&D

The ANTARES Collaboration has conducted an extensive R&D programme toward the construction of an underwater neutrino telescope since 1996 [7]. The main achievements from such activities may be summarised as follows:

- the installation site has been selected: a flat region is available at the desired depth (2400 m) off the coast of Toulon, France at a distance not too large from the coast (~40 km). A bonus advantage of this site is the proximity to the excellent infrastructures of IFREMER;
- the installation site has been characterized during more than 20 survey campaigns: the submarine currents, the optical background, the sedimentation rate and the light transmission properties of the water have been extensively studied [8];
- a vast field experience with the operations of deployment and recovery of the strings has been accumulated. Tests of submarine connections have also been performed successfully;
- the neutrino telescope has been designed and its performances extensively simulated;
- a "demonstrator" string has been deployed and operated in deep water (1100 m) at a distance from the coast (~37 km) comparable to that of the 0.1 km^2 site. Detector control and data acquisition were performed over a long range electro-optical cable to the shore. The positioning system was extensively tested and a large data sample from single and multiple cosmic-ray muons (more than 50000 events) was collected and analysed [6].

B. Present: Final-Design Prototype String

The ANTARES Collaboration is currently involved in the construction of a final-design prototype string. This string will have the same mechanical structure as for the 0.1 km^2 strings and it will be equipped for one sector with final-design instrumentation. The prototype string will be deployed in spring 2002 and recovered after a few months of operations. This test is intended to validate the full production and installation operations of the strings of the telescope.

C. Future: 0.1 km^2 Detector

The first strings of the 0.1 km^2 detector will be deployed in early 2003. The plan is to have the installation complete, i.e. 10 strings deployed, in 2004. A further expansion (although not currently scheduled) of the telescope is possible up to 16 strings.

The ANTARES Collaboration is also involved in a joint study with the Italian NEMO (NEutrino Mediterranean Observatory) Group for the construction of a next generation underwater neutrino telescope with a sensitive volume of the order of 1 km^3 [9].

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