Antares first muons with the first line

Thierry Stolarczyk, on behalf of the Antares collaboration

CEA Saclay, DSM/Dapnia, Service de Physique des Particules, 91191 Gif-sur-Yvette, France

Abstract: The Antares collaboration is building a high energy neutrino telescope in the Mediterranean Sea, 40 km off the French coasts. By end 2007, the detector will be a 3-dimensional array of 12 lines equipped with 900 photomultipliers, installed on a 200 x 200 m^2 area at a depth of 2500 m. On March 2nd, 2006, the first of the twelve lines was successfully connected to the deep undersea junction box, and since then data arrive at the shore station continuously. First results on detector operation and downgoing muon detection are presented.

Introduction

The sky has been observed from antiquity with photons. The second half of the last century has seen the birth of astronomy outside the visible light domain and in particular γ ray astronomy. Each time a new wavelength has been used, unexpected phenomena were observed. Our view of the Universe today reveals objects such as supernova remnants, pulsars, micro-quasars in the Galaxy, extragalactic γ ray bursters and active galactic nuclei, all emitters of very high energy photons.

Significant progress has been made during the last century in understanding these new objects, helped in that by multi-wavelength observations. However, photon observations have their limitations. Because of their interaction with the infrared or cosmological diffuse backgrounds or with intergalactic matter, they cannot travel more than 10 Mpc above 10^{14} eV. Another view of the sky is given by cosmic rays. This is particularly true with the new generation of ground observatories that will detect particles up to 10^{20} eV. They could help to elucidate the origin of cosmic rays on which scientists have been debating for tens of years. However, here again, the fact that protons are subject to interaction with diffuse photon backgrounds on their path to the detector limits the observation depth to 50 Mpc at 10^{20} eV. Moreover, being deviated by intergalactic magnetic fields, they are of little help in point-source searches at lower energies, in particular for transient sources. The neutrino appears to be an excellent candidate for high energy astronomy: it is neutral and insensitive to magnetic fields. It essentially does not interact with matter. It makes the Universe totally transparent over a wide energy range.

High energetic photons are usually interpreted as being the result of electron acceleration. High energy neutrinos should be produced from the interaction of accelerated protons on the surrounding matter ($p + A/\gamma_{amb} \rightarrow \pi^\circ + \pi^\pm + \ldots$ followed by $\pi^\pm \rightarrow \mu\ \nu_\mu$ and $\mu \rightarrow \nu_\mu\ \nu_e\ e$, where A represents the surrounding matter and γ_{amb} the ambient low energy photon field). Under these assumptions, part of the high energy photon flux could also be due to proton interactions from the $\pi^\circ \rightarrow \gamma + \gamma$ decays.

Possible sources of high energy neutrinos in the Galaxy are binary stars with a neutron star or a black hole accreting matter from its companion. The accretion process creates plasma waves in the strong magnetic field of the compact object, leading to stochastic acceleration at high energies. The interaction of these particles with the accreting matter or the companion star would then produce high energy neutrinos.

Explosions of massive stars in the Galaxy (supernovae) produce an expanding shell of matter which is known from radio observations to accelerate high energy particles. Protons inside supernova shells can be accelerated by a first order Fermi mechanism. The interaction of these protons with the shell gives neutrinos.

Active galactic nuclei are galaxies hosting a super massive black hole (10^6 to 10^{10} solar masses) accreting matter at a rate of a few solar masses per year. Part of the absorbed energy is then released in a jet of accelerating electrons, these electrons being further able to give energy to ambient photons (the inverse Compton process). Electrons are accelerated by the Fermi process that should apply to protons.

Gamma ray bursts are the most violent phenomena in the Universe. The energy released in the few tens of seconds of the emission is estimated to be up to 10^{45} J. A possible interpretation of such an event is that a compact object emits matter that further expands relativistically in the surrounding medium. This would naturally produce high energy neutrinos.

Up to now no high energy neutrino source has been discovered. Detecting neutrinos from already known sources would help to understand better the origin of the high energy phenomena. Because neutrinos make the universe transparent, sources with no photonic counterpart could also be discovered. The discovery of such neutrino sources would imply the presence of proton acceleration and help in answering the long standing question of the origin of the high energy cosmic rays.

The detector

The principle of neutrino telescopes is based on the detection of the Cherenkov light that upward going muons leave behind in a large instrumented volume of water or ice at great depths. These upward going muons result from the interaction of neutrino-muons with the Earth's crust. The typical path of a high energy muon in the rock is a few kilometres so that even a relatively modest sensitive volume (100 m being a typical scale) can indirectly detect the neutrinos from the much larger interaction volume (of a 10 km scale) below the detector. The phenomenon can be observed because of the total darkness at these abyssal depths. Neutrino telescopes are mainly sensitive to the 1 TeV-1 PeV energy range.

The ANTARES detector, being placed at 43° N in the Mediterranean, observes the sky in the southern hemisphere through the Earth. It covers a complementary region compared to the South Pole neutrino detector IceCube [1]. In particular it includes the Galactic Centre, a region that reveals high energy phenomena as recently shown by the Hess high-energy γ observatory [2].

ANTARES could also give information on the dark matter problem by observing the low-energy neutrinos (10 to 100 GeV) produced from the annihilation of WIMPs gravitationally trapped at the centre of the Earth, the Sun or the Galaxy.

The interaction of cosmic rays in the atmosphere creates showers of particles among which only muons and neutrinos are penetrating enough to reach the detector. The downward atmospheric muon flux is a potential background although reduced by order of magnitudes by the water above the detector. Interactions of atmospheric neutrinos coming from above give a negligible contribution to the downward muon flux. By contrast, those produced at the antipodes mimic the cosmic signal. Fortunately they have a harder spectrum and they become rapidly negligible as their energy increases, usually above 10 TeV.

An extra background is the continuous faint light coming from two distinct origins: firstly the Cherenkov light of MeV electrons resulting from ^{40}K beta-decay in the sea water; secondly the contribution from the bioluminescent abyssal fauna.

ANTARES is also a multidisciplinary underwater-science infrastructure continuously recording various types of data for studies relating to oceanography – including observation of the deep marine environment and bioluminescent phenomena – and geophysics. One example of this is the seismograph installed there, which has been recording Earth tremors for the past year.

An artist's impression of the layout of the ANTARES neutrino telescope is shown in Figure 1. The detector consists of 12 lines spread over a 200 x 200 m^2 area and spaced by around 65 metres, at a depth of 2500 metres. Each line has a total height of ~450 m. They are weighted to the sea bed and held nearly vertical by a buoy at the top. A line has a total of 25 storeys each comprising 3 optical modules. They consist of 10 inch photomultipliers housed in glass spheres that detect Cherenkov light. They are oriented 45° downward to increase the sensitivity to upward going tracks [5][7]. The first storey is 100 metres above the sea bed, and the spacing between storeys is 14.5 metres. Each storey comprises a titanium electronic container where the analogue electrical outputs of the photomultipliers are digitised in a custom built microchip with an analogue ring sampler architecture (simply called ARS in what follows). Each readout channel comprises two ARS working in a token ring mode to reduce the dead time. The signal is then treated in real time by a data acquisition card. The result is finally sent to the bottom of the line through optical fibres.

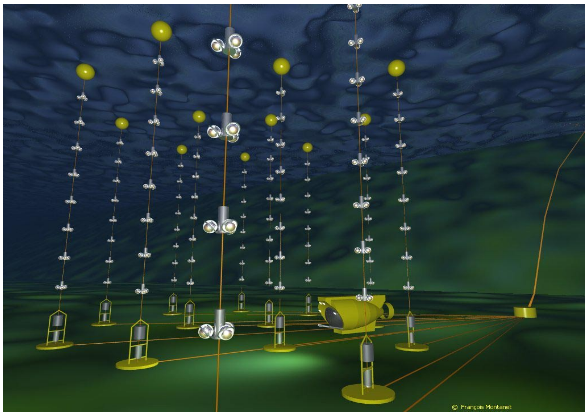

Figure 1: Artist's impression of the ANTARES neutrino telescope on the sea floor, showing the detector lines, the seabed interlink cables, the junction box and the cable to the shore. In this illustration for clarity, the number of storeys per line is reduced and many items are not drawn to scale (© F. Montanet, CNRS/IN2P3 and UFJ).

Each line anchor is connected to a junction box on the seabed via an electro-optical cable. In the junction box the outputs from up to 16 lines are gathered onto a 40 kilometre electro-optical submarine cable and sent to the experiment shore station in the town of La Seyne-sur-Mer, in France. Since no filtering is made offshore, the data stream is mainly composed of background hits. On shore, a computer farm selects from the data the periods of time containing storeys in coincidence, suspected to contain physical tracks. These events are stored on disks for further selections and analysis. The knowledge of the fired photomultiplier positions and the arrival time of the Cerenkov photons allow the reconstruction of the muon trajectory thus giving information on the parent neutrino.

The lines are flexible and so move in the sea current, with movements being 5 metres at the top for a typical sea current of 5 cm/s. The positions of the optical modules are measured with an acoustic positioning system with components at discrete positions on the line and on the sea bed, together with tiltmeters and compasses on each storey of the line. The positioning system gives a real time measurement, typically once every few minutes, of the position of every optical measurement with a spatial precision better than 10 cm.

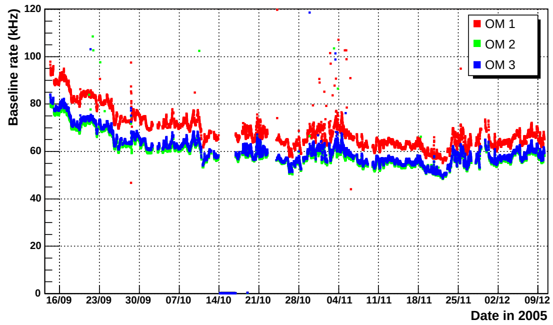

Figure 2: Baseline rates for the three optical module of an instrumented prototype during autumn 2005.

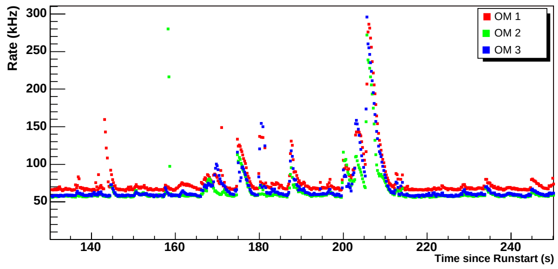

Figure 3: Example of counting rates for the three optical modules located on the second storey of an instrumented line over a period of 120 seconds.

During the extensive trials carried out in the R&D phase (1996-1999), the properties of the selected site have been carefully studied. Absorption and scattering lengths are of about 60 and 300 metres in the blue wavelength, and of about 26 and 100 metres in the UV wavelength, respectively [4]. The loss in transmission due to biological fouling and sedimentation deposits on the surface of the optical modules is less than 1.5% per year [6]. The optical background was also monitored. The 10 inch ANTARES photomultipliers have a continuous rate of 60 to 100 kHz on top of which some short bursts are due to episodic fauna activity [8]. The optical background measured during autumn 2005 with the instrumented line is shown on Figure 2 for what concern the continuous component. The Figure 3 shows an example of the burst activity over a period of two minutes.

Expected performances

The Figure 4 shows the expected evolution of the angular resolution (the difference between the reconstructed and Monte Carlo generated angles) for muons and neutrinos versus the neutrino energy. At lower energy, the neutrino angular resolution deteriorates because the emitted muon is no longer collinear with the incident neutrino. Above 100 TeV the resolution is better than 0.3° for both muon and neutrino and is mainly limited by the light diffusion in water and the discrete energy loss of muons.

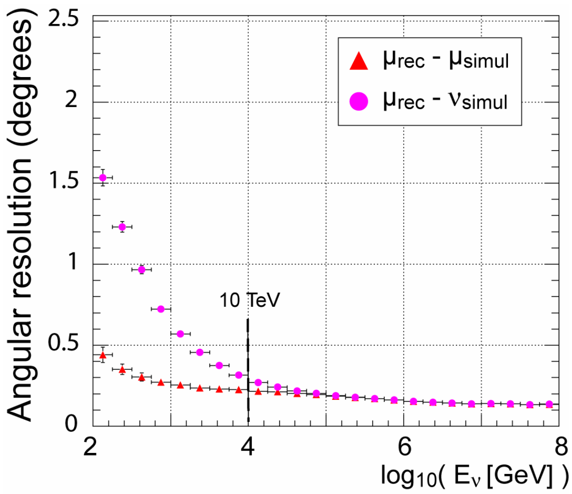

Figure 4: Angular resolution of the Antares detector as a function of the energy of the incident neutrino.

The event rate is related to the neutrino cross section and the efficiency to reconstruct muon tracks within a certain pointing accuracy. It can be quantified by the effective detector surface which is the ratio of detected muons per unit of time, divided by the incident neutrino flux. It increases with energy as the neutrino cross section does, and also because the muon range in the rock below the detector and the light produced by muons in water both increase with energy. However, because of the very small neutrino cross section, this area is very small: it reaches 1 m^2 for vertical upward going neutrinos at 100 TeV. It then starts to decrease due to the fact that the neutrino interacts early in the Earth and leads to a muon stopped before the detector (higher energy domains can be reached with nearly horizontal muons). The rates which are expected in ANTARES are of the order of 10^7 per year for downward going atmospheric muons, and 10^4 per year for upward going muons induced by atmospheric neutrinos. The high energy neutrino event rate predictions vary from a few to a hundred per year after background rejection [9].

Because neutrinos are hardly absorbed, the contribution of all neutrino emitters in the Universe, that is the high energy neutrino diffuse flux, is one of the first physical goal that should be achieved. Since most theoretical models predict a high energy neutrino emission to have an E^{-2} energy dependence (Fermi acceleration), the key point is to fight against the upward going atmospheric neutrino background, consisting of events with a softer spectrum ($E^{-3.7}$). Above 1 TeV, the muon energy loss rate becomes correlated with its energy and it can be estimated from the detected light and the muon visible path. The energy can then be obtained to within a factor 2 or 3 from this estimation, and the high energy signal can be isolated from the lower energy background.

Instrumented line operation

In March 2005 a so-called mini instrumented line (MILOM) equipped with three storeys was deployed [3]. Its primary goal is to monitor the environmental parameters and to illuminate the full detector for calibration purposes by means of several light emitters. Moreover a seismometer is linked by a 50 metre cable to the instrumented anchor. Since its deployment, it registered many earthquakes all around the world. The anchor holds a laser beacon and an acoustic positioning receiver-transmitter. The bottom storey lies 100 m above the sea bed and is equipped with a LED beacon, a conductivity-temperature probe, an apparatus for light transparency monitoring and a hydrophone acting as an acoustic positioning receiver. The middle storey, located a further 15 metres above, holds 3 optical modules and a sound velocimeter. Finally the top storey, at a further 50 metres above, has another LED beacon and an Acoustic Doppler current profiler.

The water current velocity recorded by the Doppler current profiler located on the MILOM top storey is displayed in Figure 5 as a function of time over a period of eight months. These measurements confirm that the water current usually remains small at the ANTARES site, with a velocity not exceeding 20 cm/s and with an average speed of about 5 cm/s.

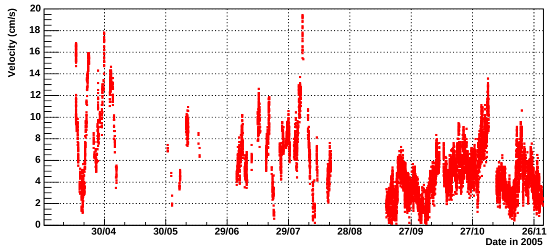

Figure 5 : Velocity of the water current flow measured by the Doppler current profiler, as a function of time over a period of eight months.

The Figure 6 shows the individual headings of the three storeys of the line measured by the compass in each electronics container, as a function of time for the same period. Although each storey has its own relative orientation due to the uncontrolled alignment in construction, the rotation changes affect, in general, the whole line. As expected, the top storey shows a larger rotation amplitude than the others. The measurements also indicate that the two lower storeys, separated by a shorter cable of 12.5 m, tend to remain at a constant orientation with respect to each other. Some correlation between the storey rotations and the water direction changes can also be noticed, especially when the current velocity is large as during the first days of November 2005.

An essential element to achieve the expected angular resolution presented in Figure 4 is a real time measurement of the position in space of the optical modules with a precision of about 10 cm. This is obtained from the triangulation of acoustic signals from emitters on the sea bed and received by hydrophones on the lines. The Figure 7 displays the acoustic distance measured between the hydrophone on the MILOM anchor and one of these autonomous emitters. The acoustic system measurements show a resolution of a few mm and a stability of about 1 cm over a distance of 174.91 m, during two months of operation.

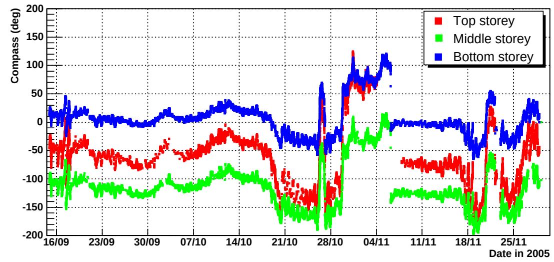

Figure 6 : Individual headings of the three instrumented line storeys, measured by the compass included in every electronics container, as a function of time during two months of monitoring.

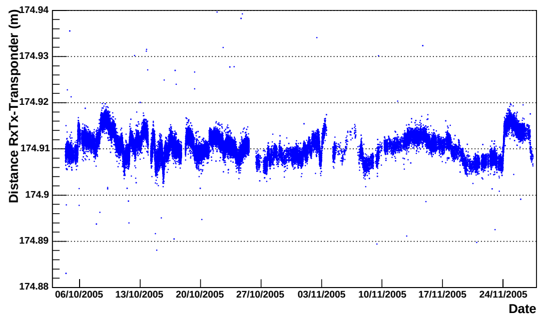

Figure 7 : Distance measured by the acoustic positioning system between the hydrophone on the instrumented line anchor and the autonomous emitter, both being fixed a few metres above the sea bed. The measurement is displayed as a function of time, during two months of operation.

In such measurement, the knowledge of the sound velocity is important to convert time measurement with the acoustic positioning system in distances.

The sound velocimeter records a value of about 1545 m/s with a very good stability. The sound velocity depends on the temperature, pressure and conductivity which are independently monitored. The temperature on site is 13.2°C with variations of 0.1°C at most on month scale.

An other key element to achieve the angular resolution is the timing precision. The specification for the timing resolution is such that it should be limited by the transit time spread of the photomultipliers ($\sigma \sim 1.3$ ns) and by the effect of scattering of the light. For this, all electronics and calibration systems are required to contribute less than 0.5 ns to the overall timing resolution. The complete timing resolution of the optical modules on the middle storey has been measured using the LED optical beacon installed on the first storey. This LED beacon contains 36 individual blue LEDs synchronised in time and arranged to give a quasi-isotropic light emission. A small photomultiplier internal to the LED beacon monitors the output light pulse timing and amplitude and provides the time reference of the light flash.

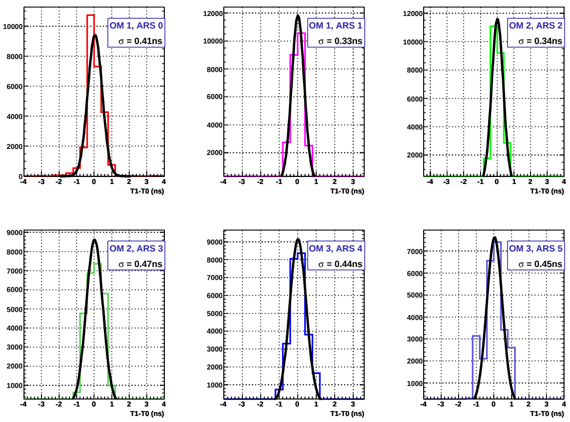

Figure 8 : Distribution of signal arrival times in the optical module (T1) with reference to the time of the LED Optical Beacon flash (T0). The measurement obtained by every ARS readout channel of the optical module triplet is shown. Each distribution has been centered to 0 by subtracting its mean value before the fit of a Gaussian function. The resulting resolution value (σ) is indicated in each panel.

The Figure 8 shows the distribution of signal arrival times in the three optical modules relative to the reference photomultiplier 15 m below. For every optical module, the measurement obtained by both ARS readout channels is shown. The contribution of the small photomultiplier inside the LED beacon is small (fast rise time of 0.8 ns), and so the measurement is dominated by the electronics of the optical module, the received amplitude making the transit time spread contribution negligible. As can be seen from the figure the timing resolution of all optical module readout channels is measured to be about 0.4 ns. The complete electronics contribution is smaller than 0.5 ns as required.

First muons detected with the first line

On February 14th 2006, the first line of the ANTARES detector was deployed. It was connected to the junction box on March 2nd, using the remotely operated Ifremer submarine, Victor [10]. Although the detector is designed to observe upward going muons from neutrinos which transverse the Earth, the angular acceptance of the photomultipliers is such that downward going muon tracks from cosmic ray interactions in the atmosphere can be observed as well.

The trigger condition applied in the present online computer farm is to require at least 5 pairs of optical modules to have signals coincident within 20 ns which could be causally connected with the same source, consistent with muon and light propagation speeds. This essentially suppresses the random hits due to the optical background. Figure 9 shows a display of two typical muon events together with their reconstructed fit. The display shows the recorded hits at the different heights (Z) along the line with the measured times relative to an arbitrary zero. All the hits within a 1 µs time window are displayed as crosses and those used in the event fit are surrounded by a red square. Black dots correspond to hits in coincidence as defined above. The muon track reconstruction is simplified in this case and consists of a simple least-square minimisation based on time and altitude of the hits and on the properties of the Cherenkov light (propagated as a coherent conic wave-front with an angle of about 42° with respect to the track). The optical background conditions at the bottom of the sea can vary significantly: there was a period of relative calm just after deployment in March; this was followed by two months of high bioluminescent activity, making data taking difficult. This optical background increase was previously observed last year and during the operation of a prototype in 2003. It seems related to higher sea currents and is a seasonal effect which was unexpected and is not well understood. From the end of May the optical background has fallen to a level that has allowed data taking, tuning of the detector and muon reconstruction.

Beside the success of reconstructing physical particles with the first line of the detector, the performance previously obtained with the mini-instrumented line deployed in 2005 has been reproduced. In particular, the line was illuminated by the optical beacon located on the first floor of the mini-instrumented line and gave the time resolution shown on Figure 10. The bottom plot shows the distribution of the time differences in the coincidence found between the optical beacon and the storey of the detection line at the same altitude. The distance between the two storeys is 70 metres. The distribution is basically Gaussian and has a width of 0.7 ns. The top plot is obtained in the same conditions with a storey at higher altitude on the detection line. The distance between the emitter and the optical modules is now 150 metres and the influence of the light scattering is visible in the distribution.

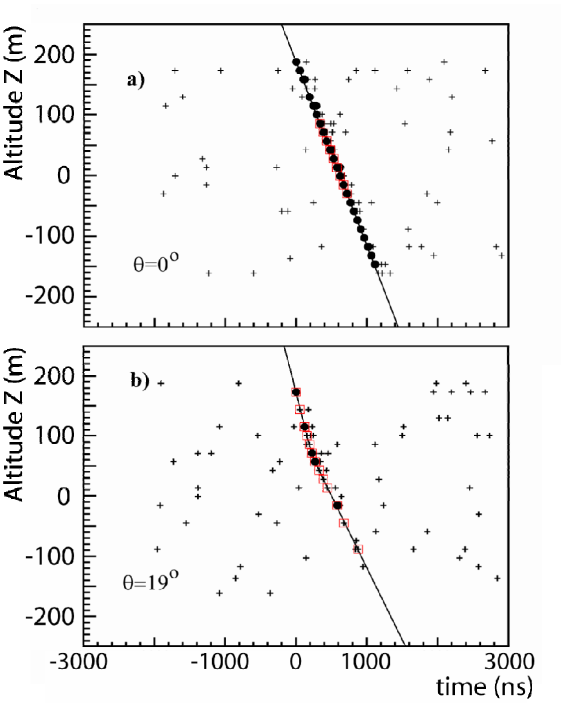

Figure 9 : Examples of reconstructed tracks using the data from the first ANTARES line: a) vertical downward going muon; b) downward going muon at 19 degrees from the zenith.

What's next?

The installation of the lines of the Antares detector has now started with the deployment and operation of the first line since March, the deployment of the second line end of July and its recent connection (September 21th, 2006). Two more lines will be connected by beginning of next year, 4 more next spring, and the last 4 end 2007. The Antares collaboration is involved into the KM3NeT design study. The corresponding consortium gathers, among others, the scientists of the NEMO, NESTOR and ANTARES collaborations. It has been funded by the European FP6 on the period 2006-2009 for the definition of a km^3-scale undersea neutrino telescope in Mediterranean.

Beside the success of Antares and many years of exciting results to come, the next generation of detector is therefore already under study.

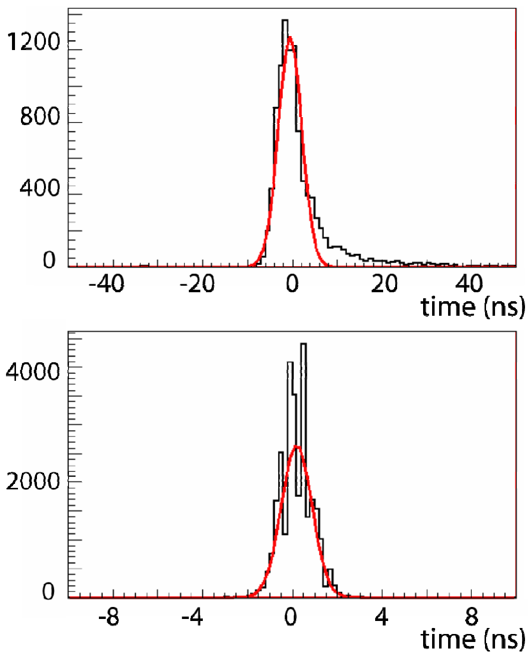

Figure 10 : The time differences in the coincidence found between the optical beacon on the instrumented line and two storeys of the first detection line. Bottom: storey at the same altitude (distance of 70 metres). The Gaussian width is 0.7 ns. Top: storey at a higher altitude (distance of 150 metres). The Gaussian width is larger (2.6 ns) and the influence of the light scattering is responsible for the tail at larger times.

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