Measurement of the atmospheric neutrino energy spectrum
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CHAPTER 2

THE ANTARES DETECTOR

The spectrum of atmospheric neutrinos falls very steeply as a function of energy as discussed in the previous chapter. In addition, the small neutrino interaction probability results in low rates at the surface of the Earth. Therefore, very large detectors need to be built in order to detect neutrinos, especially at the highest energies. The basic idea consists of building a three dimensional array of light detectors inside an appropriate transparent medium [Mark 61]. The detector must be simple and cost effective since the instrumented volume has to be large. The medium needs to be transparent in order to allow for the detection of the muon’s Čerenkov radiation and to make the reconstruction of the muon direction possible. The detector also has to be shielded against the high flux of atmospheric muons. For this reason, neutrino detectors are often built deep underground or, as in the case of ANTARES, at the bottom of the sea. The ANTARES detector is optimized to detect upward going neutrinos that have traversed our planet, using the Earth as an absorber for other high energy particles, in particular muons.

In section 2.1 we briefly discuss neutrino interactions and different event topologies. Section 2.2 describes the propagation of the muon produced in the charged current neutrino interaction. In the following 3 sections the ANTARES detector is described in detail. Sections 2.6 and 2.7 address the data acquisition and triggering. The calibration methods used in ANTARES are described in section 2.8. Finally, the current status of the ANTARES detector and other neutrino telescopes are presented in the last 2 sections.

2.1 Neutrino interactions

Neutrinos, being electrically neutral, interact only through the weak force. At higher energies, relevant for the study of cosmic neutrinos, the neutrino interaction cross section is dominated by the deep inelastic scattering off the target nucleons. At 6.4 PeV the $\bar{\nu}_e e \rightarrow W^-$ channel is open, leading to $W^-$ production. This is known as the Glashow resonance [Glas 60]. However, the main channels are the charged-current (CC) and neutral-current (NC) deep inelastic scattering. In the former case, a neutrino of arbitrary flavor produces a hadronic cascade and a lepton of the same flavor through the...
2. The ANTARES detector

exchange of a $W^\pm$ boson with a target-nucleon $N$,

\begin{align}
\nu_l + N &\rightarrow l^- + X, \\
\bar{\nu}_l + N &\rightarrow l^+ + X.
\end{align}

(2.1.1) (2.1.2)

In the neutral-current case the neutrino exchanges a $Z$ boson with the target-nucleon $N$, producing a cascade $X$,

$$\nu + N \rightarrow \nu + X.$$  

(2.1.3)

The diagrams of the charged and neutral current processes are shown in figures 2.1 and 2.2 respectively.

![Figure 2.1: Charged current neutrino interactions. A neutrino of arbitrary flavor interacts with a nucleon producing a hadronic cascade and a lepton. In the case of anti-neutrinos a positively charged lepton of the same flavor is produced. Different flavors give rise to different event topologies.](image)

![Figure 2.2: During a neutral current interaction a neutrino scatters elastically by the exchange of a $Z$ boson with the nucleon, leading to a hadronic cascade.](image)

Depending on the neutrino flavor, the lepton detection signature in the detector can differ significantly. Muon neutrinos ($\nu_\mu$) produce muons that in turn manifest themselves as long tracks inside the instrumented volume. Electrons on the other hand, produced by electron neutrinos ($\nu_e$), initiate electromagnetic showers that, unless they happen inside the detector, are unlikely to be detected. A high energy electron coming from
a charged current neutrino interaction has a high probability to radiate bremsstrahlung photons after a few centimeters of water. The larger the change in acceleration of the electron, the larger the energy of the bremsstrahlung photon. For electrons of a given energy, bremsstrahlung losses are higher for propagation materials with higher atomic number. An electromagnetic shower is rapidly initiated and as soon as the energy of the constituents of the shower falls below a certain threshold energy, the shower production stops. For a 10 TeV electron, the shower length, defined as the distance within which 95% of the total energy has been deposited in the medium, is only around 7.5 meters, very small compared to the average distance between the photomultiplier tubes used to detect Čerenkov light. Tau neutrinos ($\nu_\tau$) can give rise to a variety of signatures. Taus from charged current neutrino interactions travel some distance before they decay and produce a shower. Their decay length is $l_\tau = \gamma c t_\tau \sim 50(E_\tau/\text{PeV})$ m. Due to their short lifetime they can travel from a few meters to a few kilometers. Depending on whether the primary and decay showers are inside or outside the detector, the event topology will be different. The most striking is the “double bang” signature where both showers connected by a track are visible within the detector [Lear 95]. The NC channel gives the same signature for all neutrino flavors and part of the energy is unobserved with the outgoing neutrino.

The leading order differential cross section for the neutrino CC interactions is given by [Povh 02]:

$$\frac{d^2\sigma_{\nu N}}{dx dy} = \frac{2G_F^2 m_N E_\nu}{\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2} \left[ x q(x, Q^2) + x(1 - y)^2 \bar{q}(x, Q^2) \right],$$

where $G_F$ is the Fermi coupling constant, $m_N$ and $M_W$ are the masses of the nucleon and the W boson respectively, $Q^2$ represents the square of the four momentum transfer between the neutrino and the nucleon, $q(x, Q^2)$ and $\bar{q}(x, Q^2)$ are the parton distribution functions for quarks and anti-quarks, and finally $x = Q^2/2m_N(E_\nu - E_l)$ and $y = (E_\nu - E_l)/E_\nu$ are the Feynman-Bjorken variables. The (anti-)neutrino-nucleon cross sections are shown in figure 2.3. The cross section rises linearly with the neutrino energy up to around $10^4$ GeV. Above this energy, it is possible for the invariant mass $Q^2$ to be larger than the W-boson rest mass resulting in a decrease in the slope of the cross section. The slope still remains substantial through the scaling violations of the quark distribution functions.

## 2.2 Muon propagation

If the muons that are produced by the CC interaction of the neutrino in the vicinity of the detector are energetic enough they can reach the instrumented volume. The signal they create allows for their directional reconstruction. The angle between the parent neutrino and the resulting muon can be small, especially at higher energies. This means that the muon retains the neutrino directional information to a good approximation. Consider the momentum transfer from a neutrino $\nu$ with momentum $p_\nu = (E_\nu, \vec{p}_\nu)$ to
Figure 2.3: The total CC cross-section for neutrinos (left) and antineutrinos (right). The shaded band indicates the ±1σ uncertainties. [Coop 08], [Gand 98].

the nucleon N,

\[ Q^2 = -q^2 = (p_\nu - p_l)^2, \]  

(2.2.1)

where \( p_l \) is the four momentum of the final state lepton. Neglecting the masses of the neutrino and the produced lepton we end up with,

\[ Q^2 = 4E_\nu E_\mu \sin^2 \frac{\Delta \theta}{2}, \]  

(2.2.2)

where \( \Delta \theta \) is the angle between the neutrino and the outgoing lepton. The kinematically allowed region is given by the Bjorken \( x \) as \( 0 \leq x \leq 1 \). The momentum transfer can be expressed as \( Q^2 = sxy = 2E_\nu m_\mu xy \). The produced lepton will only have a fraction of the parent neutrino energy, i.e. \( E_\mu = (1 - y)E_\nu \), thus the following empirical relation, determined from Monte Carlo simulations, can describe the angular difference between the parent neutrino and the produced muon directions,

\[ \Delta \theta \leq 1.5^\circ \sqrt{E_\nu [\text{TeV}]}. \]  

(2.2.3)

Since neutrinos are not deflected by galactic or extra-galactic magnetic fields it is possible to trace the detected muon back to its source and thus use the detector as a pointing device, i.e. a telescope.

### 2.2.1 Čerenkov radiation

When a charged particle travels through a medium it polarizes the atoms around its trajectory. These electric dipoles are symmetrically oriented around the track when the particle is moving with a speed \( u \) smaller than the speed of light \( c/n \) in the medium, where \( n \) is the index of refraction of the medium under consideration. If \( u > c/n \) this symmetry is broken and dipole radiation is emitted, known as Čerenkov radiation [Cere 37]. Čerenkov light is emitted at a fixed angle, creating a cone of light around the particle’s track, and this fact makes it useful for reconstruction purposes. The
2.2 Muon propagation

Figure 2.4: Schematic view of Čerenkov light emission. As the charged particle propagates faster than the speed of light in the medium, radiation is emitted under a fixed angle $\theta_C$.

Čerenkov angle can be calculated with the help of figure 2.4 as follows. Consider a charged particle traveling with velocity $u_l = \beta \cdot c$ emitting spherical waves of light along its trajectory. A spherical wave emitted at point A will reach point C at the same time as the charged particle arrives at point D. The cosine of the angle $\Theta_C$ is given by:

$$\cos \Theta_C = \frac{AC}{AD} = \frac{t \cdot c/n}{t \cdot \beta \cdot c} = \frac{1}{\beta \cdot n}, \quad (2.2.4)$$

where for relativistic particles ($\beta \simeq 1$) and water as the propagation medium ($n = 1.33$) the value of this angle is about $41.2^\circ$. The spherical waves emitted at every point on the trajectory collectively create a wavefront in the shape of a cone.

The number of Čerenkov photons emitted per unit track length $x$ and wavelength $\lambda$ is [Jack 99]:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi \alpha Z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2}\right), \quad (2.2.5)$$

where $Z$ is the charge of the particle and $\alpha$ the electromagnetic coupling constant. In the optical part of the spectrum ($350 \text{ nm} \leq \lambda \leq 600 \text{ nm}$) which is of interest to us, this amounts to almost 200 emitted photons per cm.

As the muon propagates through the medium, the Čerenkov light it produces is affected by absorption and scattering. The absorption is characterized by the absorption length $\lambda_{abs}$, which is the average distance at which a fraction of $(1 - 1/e)$ of the photons is absorbed. Correspondingly, scattering is characterized by the scattering length $\lambda_s$ in
the same way. Absorption and scattering are discussed in more detail in sections 2.5.1 and 3.1.2.

2.2.2 Muon propagation

The muon loses energy while passing through matter. The main processes involved are ionization, which is considered a continuous energy-loss process, and a series of stochastic processes that play an important role at higher energies. These processes are pair production, photo-nuclear interactions and Bremsstrahlung radiation emission. Additionally, the direction of the muon is affected by multiple Coulomb scattering off atomic nuclei. The energy-loss of the muon as well as the propagation of the Čerenkov photons will be examined in detail in chapter 3. The stochastic nature of these radiative energy-losses makes the reconstruction of the energy of the particle a challenging task.

2.3 The ANTARES project

The ANTARES collaboration (fig. 2.5) was formed in 1996 with the objective to construct and operate a neutrino telescope in the Mediterranean sea [Amra 00]. The collaboration consists of physicists, engineers and sea scientists from 29 institutes and 7 European countries. The first ANTARES line was deployed in spring of 2006 [ANTA 09], and the telescope was completed in May 2008 with the deployment of the last line.

Figure 2.5: The location of the institutes in the ANTARES collaboration.

The ANTARES detector is located approximately 42 km south of Toulon in France, at a depth of 2475 m on the bottom of the Mediterranean sea. It is currently the largest

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1 Astronomy with a Neutrino Telescope and Abyss environmental RESearch
2 France, Germany, Italy, the Netherlands, Romania, Russia, Spain, Morocco
neutrino telescope in the northern hemisphere and is sensitive to a large part of the southern sky, including most of the galactic center region.

2.4 Detector layout

The ANTARES detector consists of 12 vertical strings, each one holding photomultiplier (PM) tubes for Čerenkov light detection. ANTARES comprises 885 detector units, called optical modules (OM) [ANTA 02], shown in figure 2.7. The OM is a sphere containing the PM tube. A single storey consists of three such optical modules mounted on the optical module frames (OMF). Five storeys complete a single ANTARES sector. The optical modules point downwards at a 45° angle with respect to the vertical. The OMF is a mechanical structure which, in addition to the OM’s, supports a titanium container holding the local control module (LCM) and housing offshore electronics and processors. Five storeys together constitute a sector which is an individual unit in terms of power and data transmission. A line is a chain of 25 OMF’s, i.e. 5 sectors, linked by an electro mechanical cable (EMC). The distance from storey-to-storey is 14.5 m and the first storey of each line is located 100 m from the bottom of the sea. The reason for this is to leave enough space to allow for the development of the Čerenkov cone from upgoing particles. The inter-line spacing varies between 65-70 m. A schematic view of
The ANTARES detector

Figure 2.7: Schematic view and photo of the ANTARES optical module. The PM tube is glued on the inside of a pressure resistant glass sphere. A penetrator is used for the electrical connection of the PM tube with the rest of the detector. The tube is shielded against the Earth’s magnetic field. Additional LED components are used for the calibration of the PM tubes’ signals.

The detector is given in figure 2.8. Each line is anchored to the bottom of the sea with the bottom string socket (BSS) and a dead weight, and is held vertical by a buoy at the top. Every BSS contains a string control module (SCM), a string power module (SPM), calibration instruments and an acoustic release system. The acoustic release system allows for the recovery of the complete line. The SPM houses the power supplies for all sectors in a line while the SCM contains electronics for slow control. The full configuration is octagonal as seen in figure 2.9. In each sector, one LCM is the master LCM (MLCM) and its role is to handle data distribution between all LCM’s in the sector. A Dense Wavelength Division Multiplexer (DWDM) multiplexes the data signal from the 5 sectors onto one pair of optical fibers. Data and power are transmitted between the lines and the shore via the 40 km long main electro-optical cable (MEOC) connected to the junction box (JB), and interconnecting link cables (ILC). Data arrives onshore in a PC farm located at the shore station (La Seyne sur Mer) where the ANTARES control room is located and data filtering is applied. Filtered data are copied and stored remotely at a computer center in Lyon once a day. The instrumentation line (IL07) contains oceanographic sensors for measurements of environmental parameters. Line 12 and IL07 contain hydrophones which are used to test the feasibility of acoustic neutrino detection. The IL07 and the top sector of Line 12 do not contain OM’s.

Each OM consists of a pressure resistant glass sphere, 43 cm in diameter and 15 mm thickness. It contains a Hamamatsu R7081-20 hemispherical PM tube with a diameter of 25 cm and an effective sensitive area of 440 cm$^2$. Each PM tube has 14 amplification stages and a nominal gain of $5 \times 10^7$ at a high voltage of 1800 V.
The wavelength sensitivity range of the PM tubes is 300-600 nm. The peak quantum efficiency (QE) is 23% at light wavelength of 350-450 nm. The charge resolution and transit time spread (TTS) of the PM tubes are 40% and $\sim 1.5$ ns respectively. The dark count rate at the 0.25 photoelectron level is about 2 kHz. Each PM tube is surrounded by a $\mu$–metal cage to minimize the influence of the magnetic field of the Earth on its response. The high voltage is provided by an electronics board mounted on each PM tube’s socket. Each OM also contains an LED calibration system explained in more detail in section 2.8. The PM tube is glued to the outer glass sphere by means of a transparent silicon rubber gel. The glass hemisphere behind the PMT is painted black and contains a penetrator which provides the power and data transmission connection to the outside.

An integral part of the ANTARES detector is AMADEUS (ANTARES Modules for the Acoustic DEtection Under the Sea), a set-up of acoustic sensors, which is used for a feasibility study towards a future acoustic neutrino detector. It consists of six acoustic
storeys (AS) and 34 sensors. A detailed description of the acoustic components can be found in [Graf 08].

2.5 The site

During the R&D phase of the experiment, extensive measurements were carried out in order to determine environmental parameters and optical water properties [ANTA 04].

2.5.1 Water optical properties

The performance of the detector depends on the optical properties of sea water, since light propagation in a medium is affected by absorption and scattering. Absorption reduces the amount of light that reaches the OMs while scattering affects the path of the photons and their arrival time on the OMs. Absorption and scattering reduce the intensity of light as,

\[ I(x, \lambda) = I_0(\lambda)e^{-x/\lambda_{abs}(\lambda)}e^{-x/\lambda_s(\lambda)}, \]  

(2.5.1)

where \( x \) is the optical path travelled by light and \( \lambda_{abs} \) and \( \lambda_s \) the absorption and scattering lengths, respectively. The absorption length as a function of the photon wavelength is shown in figure 2.10. Figure 2.11 illustrates the wavelength dependence of the scattering length.
2.5 The site

2.5.2 Optical background

There are two background contributions to photon detection in sea water. The first one is the decay of the radioactive potassium isotope $^{40}$K,

\[
^{40}\text{K} \to ^{40}\text{Ca} + e^- + \bar{\nu}_e \quad (BR = 80.3\%), \tag{2.5.2}
\]

\[
^{40}\text{K} + e^- \to ^{40}\text{Ar} + \nu_e + \gamma \quad (BR = 10.7\%). \tag{2.5.3}
\]

The emitted electron energy in (2.5.2) can take values up to 1.33 MeV. A large fraction of these electrons is above the Čerenkov threshold for light production. The photons emitted in the electron capture process (2.5.3) have an energy of 1460 keV. These photons can lead to Compton scattering producing electrons above the Čerenkov threshold. The second optical background contribution comes from luminescence produced by various organisms (bioluminescence). Bioluminescence can give rise to optical background up to several orders of magnitude above the $^{40}$K contribution and these bursts can last for seconds. In figure 2.12 the typical counting rate on a PM tube, i.e. hit frequency, as a function of time is illustrated.

The fraction of time during which the instantaneous background rate exceeds the baseline rate by at least 20% is called burst fraction. After monitoring deep sea currents, it was found that the baseline component is correlated neither with the sea current nor with the burst frequency. However, long-term variations of the baseline were observed. A strong correlation between bioluminescence and sea current velocity has been observed, as shown in figure 2.13.

2.5.3 Sedimentation and biofouling

The optical modules are exposed to particle sedimentation and biofouling. This can adversely affect light transmission through the glass sphere of the optical module. Extensive in situ measurements have been performed in order to study this effect [ANTA 03]. The average loss of light transmission is small, estimated to be only around 2% at
Figure 2.12: Typical photomultiplier tube counting rate as a function of time. The almost flat background indicates the presence of potassium decay light while the bursts correspond to bioluminescence. Figure taken from [Amra 00].

Figure 2.13: Correlation between the burst fraction and the sea current velocity, measured at the ANTARES site. An increased bioluminescence activity is observed for higher current velocities. Taken from [Chia 10].

the equator of the sphere housing the photomultiplier tube, decreasing with increasing zenith angle. Additionally it exhibits a tendency to saturate with time. Even though the sedimentation rate at the site can be quite high, these sediments are washed away by the sea currents. The light transmission as a function of time is shown in figure 2.14.
2.6 Data acquisition

The role of the data acquisition (DAQ) system of ANTARES [Agui 07] is to convert the analogue signal recorded by the PM tubes into a digital format that can be used for physics analyses. This includes preparing the detector for data taking, converting the analog PM tube signal and transporting, filtering and storing the data. In addition, the run settings are archived. The DAQ system is a large network of processors, both on-shore and off-shore. The off-shore processors, integrated in custom made electronics, are connected to the on-shore processors (standard PC’s) by the electro-optical cable on the sea-bed. A schematic view of the data acquisition system is shown in figure 2.15.

2.6.1 Signal digitization

A photon hitting the photo-cathode of a PM tube can produce an electrical signal on the anode. The probability of an electron emission induced by a photon is given by the quantum efficiency (QE) of the PM tube and is a function of the incident photon wavelength. The wavelength dependence of the quantum efficiency is shown in figure 2.16.

If the signal amplitude exceeds a certain voltage threshold, the signal is read-out and digitized by a custom application-specific integrated circuit, the Analogue Ring Sampler (ARS) [Fein 03]. The threshold is typically set to 0.3 photoelectrons to suppress the PM tube’s dark current although this can vary among different PM tubes. The ARS can
distinguish between single photoelectron pulses (SPE) and more complex waveforms. The criteria used to discriminate the two classes are based on the amplitude of the signal, the time above threshold or the occurrence of multiple peaks within the time gate. Only charge and time information is recorded for SPE events. In cases of large or double pulses, the ARS can sample the PM tube’s signal continuously with a tunable sampling frequency of 150 MHz up to 1 GHz holding the analog information on 128 switched capacitors. For physics data taking only SPE hits are used. A local clock is used by the ARS chips for the determination of the arrival time of the hit. The time resolution of the system is better than 0.4 ns. The charge of the analog signal is integrated and digitized by the ARS over a certain period of time using two 8-bit ADC’s. The integration gate is typically set to 40 ns. After this period, the ARS’s exhibit a dead time of around 200 ns. Each PM tube is read by 2 ARS’s operating in a token-ring scheme to minimize the effect of the dead time. The combined charge
and time information is called a level 0 (L0) hit. All 6 ARS chips in an LCM are read out by a Field Programmable Gate Array (FPGA) that arranges the hits produced in a time window into a dataframe and stores it in a 64 MB Synchronous Dynamic Random Access Memory (SDRAM). The complete set of dataframes from all ARS’s that correspond to the same time window is called a TimeSlice. A 20 MHz clock is used to provide a common time for all ARS’s. It is synchronized to the GPS time with an accuracy of 100 µs. Through the optical fiber network, all local clocks on the different storeys are synchronized with the master clock.

2.6.2 Data transmission

Each offshore CPU runs two programs controlling the data transmission. DaqHarness handles the transfer of dataframes from the SDRAM to the control room, while SCHarness handles the transfer of calibration and monitoring data (slow-control data). Transmission Control Protocol and Internet Protocol (TCP/IP) is used for communication between the CPU’s and for data transport. The LCM’s in a sector are connected to the MLCM in the same sector using an optical bidirectional 100 Mb/s link. These links are merged using the Ethernet switch of the MLCM into a single Gb/s Ethernet link. Each string is connected with an electro-optical cable to the junction box which in turn is connected to the shore station with the 40 km long electro-optical cable. The data are transported using dense wavelength division multiplexing technique (DWDM) [Seni 92]. Each sector and each string use a unique pair of wavelengths to transmit data along a single optical fibre to shore. The ControlHost package [Guri 95] is used for data transfer and communication among the processes in the DAQ system.

2.6.3 Data filtering and storage

All data, after the off-shore digitization, are transported to shore without any further selection. The total data output of the detector in periods of low bioluminescence (60-90 KHz per PMT) is 0.3-0.5 GB/s. Since most of it is optical background it has to be filtered appropriately. Trigger algorithms are applied to identify signals from
particles traversing the detector by searching for space-time correlations in the data. Such physics events selected by the DataFilter program, are subsequently written to disk with the program DataWriter. The DataFilter looks for a set of correlated hits in the full detector in a window of about 4 µsec. If an event is found, all hits during this time window are stored. If ANTARES receives external GRB alerts all detector activity is recorded for a few minutes. Data filtering or triggering is examined in more detail in the following section.

2.7 Trigger

Physics data taking runs in ANTARES last for about three hours. The average data rate of 625 MB/s for each detector string is reduced after filtering to \( \sim 0.15 \text{ MB/s} \) for the whole detector. The duration of the run along with the start and end times, as well as the trigger conditions are stored in the database. The majority of the data is optical background due to potassium decays or bioluminescence. This overwhelming background can be reduced by a factor of \( 10^4 \) on the first filtering (triggering) stage \cite{Jong 05a}. Such a reduction is achieved by searching for hits within 20 ns in different PM tubes of the same storey or single hits with an amplitude higher than 3 photo-electrons. Hits satisfying these criteria are called L1 hits. All other hits are called L0. This kind of selection is based on the assumption that background hits should be uncorrelated and signal hits correlated. Two recorded hits on two different PM tubes are considered causally related if they satisfy,

\[
|\Delta t| \leq \frac{n_g}{c} \cdot d,
\]

where \( \Delta t \) is the time difference between hits, \( d \) is the distance between the PM tubes and \( n_g/c \) is the group velocity of light in water. In this time window an additional \( \pm 20 \text{ ns} \) is included to allow for uncertainties in the hit positions, time and light scattering. Hits satisfying this condition constitute a cluster. If this cluster is large enough (typically 5 L1 hits) it is stored as a physics event. Physics events contain L1 hits that fired the trigger as well as all L0 hits in \( \pm 2.2 \mu s \) from the first and last L1 hit. The reason for this is that this is the time it takes for a relativistic muon to travel approximately 650 m i.e. traverse the detector. The hits contained in a physics event are illustrated in figure 2.17.

In addition to this first level selection, a second trigger level (e.g. 3N trigger) can be applied. This includes a scan over a certain number of directions searching for coincidences compatible with the Čerenkov light emission hypothesis. The expected time of a Čerenkov photon is:

\[
t_i = t_0 + \frac{1}{c} \left( z_i - \frac{r_i}{\tan \theta_C} \right) + \frac{1}{u_g \sin \theta_C} r_i,
\]

where \( t_0 \) is simply an initial reference time on the muon track. The first term in equation (2.7.2) describes the distance along the track up to the point where the Čerenkov photon
was emitted and the second term is the path from the point of photon emission to the PM tube. This is illustrated in figure 2.18 for two illuminated PM tubes, where \( t_i = (t_1, t_2) \), \( z_i = (z_1, z_2) \), and \( r_i = (r_1, r_2) \). Two hits are considered compatible with the Čerenkov hypothesis if:

\[
|t_2 - t_1| \leq \frac{z_2 - z_1}{c} + \frac{R}{c} \tan \theta_C + 20 \text{ ns},
\]

where we used the assumption that \( \cos \theta_C = 1/n_g \). The 20 ns are added to account for uncertainties on the time calibration, light scattering, and position of the storey. Additional clusters can be formed by L1 hits. An example of this is the T3 trigger [Carr 07]. It accepts more background hits, increasing the sensitivity in the low energy region with the drawback of triggering on additional events that will be reconstructed badly i.e. it exhibits a higher efficiency at the expense of lower purity. A T3 cluster is defined as at least 2 L1 hits in 3 consecutive storeys within a time window of 100 ns for adjacent and 200 ns for next to adjacent storeys.

## 2.8 Detector calibration

The precision of track and energy reconstruction is strongly dependent on the precision of time, position and charge measurements. In this section, the calibration systems used in ANTARES are discussed.

### 2.8.1 Time calibration

The time calibration in ANTARES [Agui 11] is performed using pulses from LED and laser devices. A timing resolution on the recorded PM tube signals of 1 ns is required to
ensure the reliability of track and energy reconstruction. The internal clock calibration system measures the time offsets of each storey. It consists of the master clock on-shore and a bi-directional optical communication system connected to all LCMs. The relative offset of each local clock can be measured by using a calibration signal sent by the master clock and echoed back. The clock system assigns an absolute event time with a GPS master clock synchronization accuracy of 100 µs. The optical beacon system \cite{ANTA07} is used to calibrate the relative offsets between the PM tubes. Four blue (472 nm) LED beacons on storeys 2, 9, 15 and 21 of each detector line and two green (592 nm) laser beacons on the BSS of L7 and L8 are used for this purpose. The LED beacons are used for intra-line calibration purposes while the laser beacon, being much more powerful and able to illuminate all the lines, is used for inter-line calibration. An initial set of time offsets is determined in the laboratory prior to deployment. After deployment, these values may change due to different factors such as temperature changes or stresses in the cables. Using the optical beacon system they are monitored periodically and readjusted as necessary. A second calibration system consisting of a blue (470 nm) LED inside each OM is used to measure time offsets between the PM tube photo-cathode and the read-out electronics. Internal LED and optical beacon measurements reveal less than 0.5 ns contribution of the electronics to the photon arrival time resolution. Thus, time resolution is dominated by the transit time spread of the PM tubes which is about 1.5 ns, and light scattering and chromatic dispersion, which depends on the distance travelled by the photon. The calibration system just described provides a relative time calibration of better than 1 ns.
2.8 Detector calibration

2.8.2 Charge calibration

The integrated charge of the PM tube signal has to be converted into the number of photoelectrons that created this pulse. The relation between the signal amplitude and the number of photoelectrons is given by the transfer function of the Amplitude-to-Voltage Converter (AVC). This function is important for the measurement of the amplitude in the PM tube pulse, as well as for the correction of the time slewing of the PM tube signal i.e. the influence of the pulse amplitude and the pulse rise time on the threshold-crossing time, illustrated in figure 2.19. The first step in charge calibration is performed on the test bench where the AVC transfer function is determined. In order to do this, a pulse generator sends a direct signal to a pair of ARS’s operating in a token-ring scheme. The pulse has a triangular shape with 4 ns rise time and 14 ns fall time. The transfer function and the dynamic range of the ADC’s exhibit a linear behavior and can be parametrized by the slope and intercept of the function. In addition to the test bench calibration, regular in situ calibration runs have to be performed. These runs are used to determine the pedestal value of the AVC channel, namely the offset \( AVC_{0pe} \) value corresponding to zero photoelectrons, and the single photoelectron peak which is studied by looking at minimum bias events, since light from potassium decays and bioluminescence produce in their majority single photons on the photocathode level. The charge spectrum, ignoring contributions from the second and higher photoelectron peaks, can be described as [Jong 05b]:

\[
f(x) = Ae^{-a(x-x_{th})} + Be^{-\frac{(x-x_1)^2}{2\sigma^2}},
\]

where the first term corresponds to the contribution of the dark current. The second term describes the single photoelectron peak as a gaussian with mean \( x_1 \) and standard deviation \( \sigma \). The effects of the dynamic nonlinearity (DNL) of the AVC can be minimized by considering the integral of the AVC spectrum:

\[
\int_0^x f(x')dx' = \frac{A}{-a}e^{-a(x-x_{th})} + \frac{B}{\sqrt{\pi}} \Gamma \left( \frac{1}{2}, \frac{(x-x_1)^2}{2\sigma^2} \right),
\]
where $\Gamma$ is the incomplete gamma function. A fit on the integrated spectrum leads to the determination of the single photoelectron peak. The same procedure is applied to identify the pedestal region as shown in figure 2.20. The parametrization used is:

$$\frac{C}{\sqrt{\pi}} \Gamma \left( \frac{1}{2}, \frac{(x - x_0)^2}{2\sigma_0^2} \right).$$

(2.8.3)

Measuring the pedestal and single photoelectron peak values, the transfer function can be determined.

Charge measurements in AVC channels appear to be affected by time measurements in the TVC channel. This is known as the “cross-talk effect” and can be attributed to a cross-talk of the capacitors inside the ARS pipeline. Plotting AVC against TVC values, as shown in figure 2.21, makes it possible to determine the correction to be applied. After applying this correction most of the hits in a minimum bias event have a charge of one photoelectron.

Figure 2.20: Examples of integrated single photoelectron spectrum (left) and integrated pedestal spectrum along with the corresponding fits. Images taken from [Fehr 10].

Figure 2.21: Example of the cross-talk effect affecting the charge measurement channel [Agui 10].
Due to the spread of the PM tube gain, the photoelectron peak is described by a gaussian function with mean $ AVC_{1pe} $. If the parameters of the gaussian distribution for one photoelectron are $ \mu_1 $ and $ \sigma_1 $, then for the coincidence of $ N $ photoelectrons the parameters of the gaussian distribution are,

$$ \mu_N = N \cdot \mu_1, $$

$$ \sigma_2^N = N \cdot \sigma_1^2. $$

The transfer function is expressed as,

$$ Q \left[ p.e. \right] = f(AVC) = \frac{AVC - AVC_{0pe}}{AVC_{1pe} - AVC_{0pe}}, $$

where $ AVC $ is the corrected AVC value taking into account the “cross-talk effect”.

Light from potassium decay is also used to monitor how the detector response evolves with time. A gain drop of the PM tubes is observed and is attributed to the aging of the phototube. The charge pedestal value is almost constant in time, while the photoelectron peak drops by around 0.02 photoelectrons per month as can be seen in figure 2.22. The systematic error on charge calibration is estimated at around 30% [Fehr 10; Bare 09].

### 2.8.3 Position calibration

Due to the flexible nature of the lines, water currents can displace the position of the optical modules, especially on top storeys. As with timing and charge information, knowledge of the position of the optical modules is of high importance for a precise event reconstruction. For this purpose a High Frequency Long Baseline (HFLBL) acoustic
The ANTARES detector system is used to monitor the positions of five hydrophones along each line. The hydrophones are mounted on storeys 1, 8, 14, 20 and 25. A transmitter-receiver is installed at the anchor of each line and some additional autonomous transponders are used. The emitters send high frequency acoustic signals in the 40-60 kHz range and the distances are obtained by measurements of the travel times of the acoustic waves. The distances are used to triangulate the position of each receiver with respect to the emitters on the sea floor. Furthermore, a system of compasses and tiltmeters is used to measure the orientation and inclination of each storey. The shape of each line is reconstructed by performing a global $\chi^2$-fit based on a model of the mechanical behavior of the line under the influence of the sea currents. The relative positions of each OM are calculated from this fit using the known geometry of each storey. In order to determine these positions as accurately as possible, knowledge of the water current flow and the sound velocity in sea water is used. These are measured using acoustic doppler current profilers (ADCP) for the water current flow, conductivity-temperature-depth (CTD) sensors to monitor the temperature and salinity of the water and sound velocimeters to monitor the sound velocity in sea water. The relative positions of all the optical modules is monitored with an accuracy better than 20 cm [Ardi 09]. The horizontal movement of a line with respect to the BSS position is illustrated in figure 2.23. The absolute positioning of each anchored detector component is calculated with an accuracy of about 1 m by acoustic triangulation from a surface ship equipped with differential GPS.

Figure 2.23: The horizontal displacement of the hydrophones on Line 11 with respect to the BSS (0,0) for a period of six months. The East-West tendency of the Line heading is due to the Ligurian current at the detector site. The top storeys of the line experience larger amounts of displacement due to the water current. Image taken from [Brow 09].
2.9 Detector history and status

During the period between 1996 and 1999 several site campaigns were performed, aiming to evaluate quantities such as the refraction index, scattering and absorption lengths as well as background rates. A 350 m line with seven photomultipliers was deployed at a depth of 1200 m from the end of 1999 until June 2000. Tests of acoustic positioning as well as the first atmospheric muon data measurements were performed. The MEOC was installed in October of 2001. In December 2002, the junction box and a prototype-sector-line (PSL) were deployed. It contained one LED beacon, a sound velocimeter, a pressure sensor, hydrophones and an acoustic transceiver. A mini instrumentation line (MIL), containing time calibration, positioning and monitoring devices was deployed in February 2003. During the next month, the prototype and the mini instrumentation line were connected to the junction box, where they stayed for the next couple of months. In March 2005, a mechanical test line (Line 0), containing all the mechanical elements of a full string but without the electronics, was built and deployed along with an improved mini instrumentation line (MILOM). The test line was recovered after two months. The first ANTARES complete line (Line 1) was deployed in February 2006 and in March of the same year it was connected and data taking started. In July 2006, Line 2 was deployed and it has been operational since September 2006. In January 2007, Lines 3, 4 and 5 were connected, making ANTARES the most sensitive neutrino telescope in the Northern hemisphere. By the end of 2007, Lines 6 to 10 were connected, effectively doubling the size of ANTARES. The last two lines were connected in May 2008, thereby completing the construction of the ANTARES telescope. On June 24th 2008, the cable providing power to the junction box broke down, interrupting the detector’s power supply. A sea operation took place on the 6th of September, the cable was repaired and data taking resumed normally. During the following years several lines have been non-operational and action had to be taken for their recovery and redeployment. Line 6 was disconnected from October 2009 until November 2010. Line 9 was not operational from July 2009 until November 2010. A problem with the cable connecting Line 10 did not allow data taking with this line from January 2009 until November 2009. Finally, Line 12 was disconnected from March 2009 until November 2009 and did not take data due to a cable problem during the period from September 2010 to November 2010.

2.10 Other neutrino telescopes

The ANTARES detector is not the only neutrino detector that has been constructed or is already operational. In this section, past, present and future efforts towards neutrino astronomy will be summarized.

The DUMAND project (Deep Underwater Muon And Neutrino Detection) \cite{Aoki98} started around 1976 with the goal to construct a neutrino telescope at 4800 m in the Pacific Ocean off Keyhole Point on the Big Island of Hawaii. The attempt however was not successful. After the connection of the prototype strings, short circuits occurred and the connection to the shore was lost. In 1996 funding was ceased and the project
The ANTARES detector was cancelled.

The BAikal neutrino telescope was the first working setup which proved the feasibility of optical neutrino detection technique, detecting several of these elusive particles in 1996. It was deployed in the Siberian lake Baikal \cite{Balk01} and consisted of 18 strings with 192 PM tubes (NT-200 setup) at a depth of 1 km. The 68.5 m strings were distributed in a circular geometry with a 22 m radius. This setup was extended in 2005 by 3 additional strings of 200 m length with 36 PM tubes (NT-200+ setup) at a distance of 100 m from the detector center to increase shower effective area. Contrary to ANTARES, fresh lake water gives no background contributions from $^{40}$K decays but a contribution from bioluminescence is present. In addition to that, maintenance operations are easier, using the frozen lake surface as a basis for these operations. On the other hand, the reduced absorption length as well as the small depth of the lake lead to more background from atmospheric muons.

AMANDA (A\textit{ntarctic M\textit{uon And N\textit{eutrino D\textit{etection Array}}}) \cite{Andr99} is located near the Scott-Amundsen South Pole station in the Antarctic Ice. In 1997, 10 strings were immersed in glacial ice at a depth of 1500-2000 m. 302 PM tubes, 8-inch in diameter were used. In 2000, the apparatus was enhanced to AMANDA-II adding 9 more strings reaching a total of 677 PM tubes. AMANDA was switched off in 2009.

The IceCube neutrino observatory \cite{Gold02} is the km$^3$-sized successor of AMANDA and has recently been completed in the Antarctic Ice. It is configured as a collection of 80 strings of over 1000 m length, separated by 125 m, with 4800 PM tubes in total. A complementary surface air-shower array, IceTop, serves as a calibration device. IceCube is already operational.

A number of projects exist in the Mediterranean aiming towards the construction of a cubic kilometer neutrino telescope. NESTOR (\textit{NE}utrino \textit{E}xtended \textit{S}ubmarine \textit{T}elescope with \textit{O}ceanographic \textit{R}esearch) \cite{Rapi09} is a Greek collaboration and it initiated the first project for a neutrino telescope in the Mediterranean sea. NEMO (\textit{NE}utrino \textit{M}editerranean \textit{O}bservatory) \cite{Amor07} is an Italian collaboration. The KM3NeT project \cite{Katz06b} \cite{Katz06a} is a joint effort of the ANTARES, NEMO and NESTOR collaborations to design and construct the next generation telescope with a size of about 5 km$^3$. 