Abstract

Point source searches with the ANTARES neutrino telescopes usually examine up-going neutrinos, restricting the search on the Southern hemisphere. This is done in order to reject the atmospheric muon background which is down-going. This report examines the sensitivity of ANTARES to point sources using down-going neutrinos. For that, down-going cosmic neutrinos and atmospheric muons were simulated. Their signature on the detector was examined and discriminating methods were used in order to reject the background. Finally, limits have been set in the expected flux. The limit set is less than an order of magnitude higher from the limit set for up-going neutrinos in the common area.

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References
The interest of humanity in astronomy dates back to antiquity where people made the first naked-eye observations of the sky, separating the planets from the stars. From that point until modern times the gross majority of the methods used to probe the Cosmos were based on photons. Initially the optical spectrum was used, until in 1931 Karl Jansky observed that the Milky Way was a source of radio emission [1]. Contemporary astronomy extends from radio waves to gamma rays.

The greatest strength of photons is that they are electrically neutral and stable. Thus, photons are able to travel cosmological distances without decaying and they point directly back to their production source. Nonetheless, they have also some disadvantages. The most important is that photons interact with interstellar matter and with the cosmic microwave background through pair production. This makes certain areas of the universe invisible to high energy photons. Furthermore, photons reveal only the outer layer of stars but they do not provide direct access to the inner workings of them.

To tackle the problems that photons face, alternative messengers have to be used, protons being among them. It is known that high energy protons are produced at various sites in space. Although protons are also stable particles, they are charged so they are deflected by magnetic fields they encounter. Subsequently, their origin information is lost. An alternative messenger that does not encounter the shortcomings of protons and photons is the neutrino. Neutrinos were first postulated by Wolfgang Pauli in 1930 in an attempt to preserve the conservation of momentum, angular momentum and energy in beta decay.

The advantages that neutrinos have as messengers when compared to photons and protons are many. Unlike both messengers neutrinos are not affected by the GZK cutoff [2]. Neutrinos, like photons, are electrically neutral, so they maintain their origin information. Last but not least, neutrinos have a very small interaction probability and because of that, they can penetrate regions opaque to photons, giving valuable information about the inner working of stars.

Not everything is in favor of the neutrinos though and one of their advantages is also their greatest weakness: The small cross section leads to a small probability
of interacting with matter at Earth. This means that large detectors are needed in order to capture a significant number of neutrinos.

**Purpose of the study**

The detection of point sources producing neutrinos is one of the main goals of a neutrino telescope. Although photons with energies up to $10^{15}$ eV have been observed, their production mechanism remains unknown. If these sources produce photons by purely leptonic processes, like synchrotron radiation from electrons or inverse Compton scattering, neutrinos will not be produced. If, on the other hand, the photons are produced by hadronic processes there will be an abundance of neutrinos. This leads to the conclusion that a possible detection of high energy neutrinos would lead to a confirmation of hadronic processes on the source and would furthermore confirm the mechanism of high-energy cosmic ray production.

When neutrinos interact with nucleons, leptons of the corresponding flavor are created. Muons are the most appropriate for point source detection because they travel a long distance inside the detector revealing their direction. However, muons produced by cosmic neutrinos are only a small fraction of the muons that can be detected; the majority of muons are produced by the interaction of cosmic rays with the atmosphere; i.e. atmospheric muons. The main difference between cosmic and atmospheric muons is that the former reach higher energies than the latter.

In order to avoid being overwhelmed by the background formed by atmospheric muons, neutrino detectors are placed in sites that are hard for low energy particles to reach, like deep sea (for ANTARES) or ice (for IceCube). In spite of that, many atmospheric muons still reach the detector, but all of them come from the upper part; i.e. down-going. Therefore, analysis is usually restricted on particles originating from below the detector covering the Southern hemisphere. An extension to the Northern hemisphere, though, is still desirable and would help to extend the field of view of the ANTARES telescope. This report focuses on simulation studies of down-going neutrinos and atmospheric muons to examine the visibility of a point source on the Northern hemisphere. Similar searches with down-going neutrinos, covering the Southern hemisphere, have also been conducted by the IceCube experiment [3].
CHAPTER
ONE

COSMIC RAYS & SOURCES

The interest in the neutrino detection is intensified due to their correlation with highly energetic charged particles originating in space named cosmic rays. This chapter discusses the relation between cosmic rays and neutrinos as well as the sources of these particles.

1.1 Cosmic Ray Composition and Flux

Cosmic rays are mainly protons. Helium nuclei, electrons and heavier nuclei are also cosmic rays, though less abundant. When cosmic rays arrive at Earth, they interact with nuclei in the atmosphere producing a cascade of particles known as air showers.

The energy spectrum of the cosmic rays can be described by the power law

\[ \frac{dN}{dE} \propto E^{-\gamma}, \]  

where \( \gamma \) is the spectral index. The observed spectrum is shown in Figure 1.1 multiplied by \( E^{2.7} \) in order to display the features of the steep spectrum which are otherwise hard to discern. The spectral index has the value \( \gamma = 2.7 \) except in the region between \( 10^{15} \) eV and \( 10^{19} \) eV where its value changes to \( \gamma = 3.0 \).

The main mechanism of particle acceleration at astrophysical sources is considered to be shock acceleration or first order Fermi acceleration, as it is also known. A detailed explanation can be found in [5]. The shock acceleration predicts that the accelerated particles will have a spectrum with a power-law dependence of \( E^{-2} \). The observed cosmic ray spectrum is steepened because high energy cosmic rays are more likely to escape from the Galaxy [6], creating the final dependence of \( E^{-2.7} \).
1.2 Neutrinos

In the case that cosmic rays interact with matter, neutrinos will be produced. This implies that the sources of cosmic rays will also be sources of neutrinos.

1.2.1 Neutrino production

It is generally accepted that neutrinos in galactic sources are produced by interactions of cosmic ray protons. The main production channel is via charged pion production, e.g.

\[ p + p \rightarrow \begin{cases} \pi^0 + p + p \\ \pi^+ + n + p \end{cases} \]  \hspace{1cm} (1.2)

Pions can also be produced in objects with a dense photon gas, for example through a \( \Delta \)-resonance:

\[ p + \gamma \rightarrow \begin{cases} \Delta^+ \rightarrow n + \pi^+ \\ \Delta^+ \rightarrow p + \pi^0 \end{cases} \]  \hspace{1cm} (1.3)

The first process contributes to the neutrino flux through the decay of the \( \pi^+ \) and the latter to the gamma-ray flux through the decay of \( \pi^0 \). Then, through the decay of charged pions into muons and the subsequent muon decay, neutrinos
are produced:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_e, \]
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu, \]
\[ \pi^0 \rightarrow \gamma + \gamma \]  \hspace{1cm} (1.4)

Charged and neutral pions are produced in equal amounts, meaning that the expected amount of photons and neutrinos are roughly the same.

There are also other other processes which contribute to the neutrino flux, such as the free neutron decay \( (n \rightarrow p + e^- + \bar{\nu}_e) \) and various meson decays. Since the main cosmic neutrino production mechanism is through proton interactions, the cosmic neutrino spectrum is expected to be \( E^{-2} \)-dependent (see previous section).

### 1.3 Sources

Cosmic rays can be of both galactic- and extra-galactic origin. This section discusses some of the most prominent neutrino and cosmic ray sources.

#### 1.3.1 Galactic sources

**Supernova remnants**

When the core of an massive star stops the nuclear fusion which fuels it, it goes through a gravitational collapse creating either a neutron star or a black hole while it releases a huge amount of energy. The sudden explosion expels the star’s outer layer. This outer layer forms a shockwave in which particles passing through it accelerate via *shock acceleration* reaching an energy of about \( 10^9 \) GeV. The interaction of these particles with interstellar matter is expected to produce neutrinos via the decay of charged and neutral pions as in Eq. 1.4.

**X-Ray binaries**

X-Ray binaries consist of a small object, like a neutron star or a small black hole, accreting matter from a massive stellar companion. The most prominent kind of X-Ray binary for neutrino emission is the *Microquasar* which emit a relativistic jet.

In this jet, protons get accelerated and they interact with photons. It it thought that neutrinos of energy up to \( 10^5 \) GeV could be produced in these sources [7]. Another mechanism increasing the neutrino flux from these sources would be the interaction of heavier nuclei with photons. In that case, the accelerated nuclei interact with photons creating neutrons which subsequently produce neutrinos as they interact with matter [8].
1.3.2 Extragalactic sources

Active galactic nuclei (AGN)

Active Galactic Nuclei (AGN) are the compact regions in the centres of galaxies. They are the most luminous objects known as well as possible sources of high-energy neutrinos. An AGN consists of a supermassive black hole (\( > 10^8 \, M_\odot \)) surrounded an accretion disc which is fed by a dust torus around it. Perpendicular to the accretion disc are two relativistic jets which are driven by the energy produced from the infalling of the matter to the black hole. In 10\% of the AGNs the jets are big enough to be studied (radio-loud AGN). The production of neutrinos is possible from both the accretion disc and the emitted jets. The jets radiate strongly in radio waves and this radiation reaches gamma rays which are produced by inverse Compton scattering and synchrotron radiation.

The most prominent king of AGN for neutrino emission is a Blazar. Blazars are considered the brightest objects in the universe and the sources of TeV energy \( \gamma \)-rays. A blazar flare duration ranges from less than an hour to a month and they may be the source of the highest-energy cosmic rays and, in association, provide observable fluxes of neutrinos from TeV to EeV energies [9].

Gamma-Ray bursts (GRB)

Gamma-Ray Bursts were discovered by accident in 1960’s by US satellites. The satellites were searching for nuclear bomb explosions behind the moon, since they speculated that Soviet Union was testing weapons in that area. Instead, they discovered powerful emissions of gamma rays from space which were named Gamma-Ray Bursts. GRBs are short and rare but extremely powerful bursts of gamma radiation.

The most prominent mechanism for the gamma-ray production is the fireball model. In this model a massive star collapses, or two compact ones merge, creating an explosion which sends huge blast waves though space with speeds close to the speed of light. A fraction of about 10\%, of the released energy is expected to be be neutrinos of energy around \( 10^{14} \, GeV \) produced by photomeson production [10].
CHAPTER TWO

THE ANTARES DETECTOR

ANTARES stands for Astronomy with a Neutrino Telescope and Abyss environmental RESearch and it is a neutrino telescope located in the Mediterranean Sea about 40 km south of France at a depth of 2.4 km. ANTARES extends the neutrino search in the region of the Milky Way, in contrast with the ongoing experiments at the South Pole.

The main motivation behind the experiment is neutrino astronomy. However, the scientific program of ANTARES incorporates searches for dark matter [11], neutrino oscillations and magnetic monopoles [12] among other particle physics topics. Apart from the interest that it creates in particle physics and astrophysics, the location of ANTARES in the deep sea and its permanent high-bandwidth connection to the shore, provides opportunities for innovative measurements in other scientific fields like oceanography, marine biology and seismology. Instruments for research in these fields are distributed on every active line of the detector and are also located on a further 13th line specifically dedicated to the monitoring of the sea environment.

2.1 Detection principle

Neutrino telescopes deployed in water use an indirect detection method, meaning that neutrinos are not directly observed; instead the products of their interaction with the material surrounding the detector produces Čerenkov light which can be detected. The basic principle is that from a given neutrino flux a fraction of them will weakly interact with nuclei either with a Neutral Current \((\nu + N \rightarrow \nu + X)\) or a Charged Current \((\nu + N \rightarrow l + X)\) interaction. The signature left in the detector depends on the kind of interaction as well as the flavor of the neutrino. Figure
Chapter 2. The ANTARES Detector

2.1 shows the cross section for CC and NC interactions for both neutrinos and antineutrinos. It can be seen that, since the CC cross section is higher, neutrinos will undergo CC interactions more often.

In both interaction types, a high energy neutrino interaction will result in the fragmentation of the target nucleon into hadrons. Because of the aforementioned high energies, the hadrons will also produce Čerenkov photons. Since the interaction length of hadrons in water is about 80 cm, after this distance they will also interact and new hadrons will be formed, something that ends up in the repetition of the above procedure until the energy of the hadrons is too low for any further continuation. The total length of this hadronic shower is typically a few interaction lengths. Due to the small absorption length the hadronic shower will be detected only if it is close, or inside, the detector. Furthermore, since the distance between the detector’s detection units (Photomultiplier Tubes) is large compared to the size of the hadronic shower, it will cause a signal in only a small number of them.

Apart from the hadronic shower, a CC interaction will furthermore produce a lepton which has its own signature based on its flavor:

- An electron neutrino interacting with a nucleon via charged current interaction will produce an electron. The electron will lose energy fast through the emission of bremsstrahlung photons. If these photons have high energy they will convert to $e^+ e^-$ pairs. These particles will undergo the same cycle, leading to an electromagnetic shower to accompany the hadronic one.

- A tau lepton originating from a $\nu_\tau$ interaction produces a Čerenkov cone. The distance it covers before it decays is very limited since, at PeV energies, it travels about 100 m. Then, the interaction of the tau neutrino will yield a second hadronic shower along with the original one. In 17% of tau decays a muon is produced which will cover a large distance.

- Muon neutrinos transfer, on average, 1/2 of their energy to the muon while antimuon neutrinos transfer 3/8 of their energy to the antimuon [13]. A muon produced by a $\nu_\mu$ interaction can travel a long distance before losing its energy since a typical energy loss is about 0.2 GeV/m. This implies that high energy muons produced outside the detector will also be detected. The change in direction of a relativistic muon’s track due to multiple scattering is very small and it is usually neglected. By detecting the intensity and the arrival time of these photons the direction of the passing muon is inferred. The angle between the neutrino and the produced muon is given by the approximation formula [14]

$$\delta \phi \approx \frac{1.5^\circ}{\sqrt{E_\nu [TeV]}}$$

(2.1)

Since angle difference is inversely proportional with the square root of the energy, high energy muons point back to the neutrino’s production source with a very high accuracy. This, combined with the large distance they travel, makes them the most suitable leptons for point source detection.
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Figure 2.1: Cross-section for deep inelastic neutrino scattering. Neutrino CC cross-section is plotted with a solid line while the antineutrino is plotted with short dashes. The NC cross section for neutrinos is plotted with long dashes and the antineutrino uses the dotted one. The CC cross section is higher which means that they have a higher probability. Figure taken from [15].

The flavour ratio of high energy cosmic neutrino flux is typically $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 2 : 0$. However, due to neutrino oscillations, the flavor ratio of neutrinos observed at the Earth is $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$. Although the flux of the three flavors is the same, the probability of a muon neutrino detection is higher due to the large path length of the muons they produce in interaction with matter.

2.1.1 Čerenkov radiation

Čerenkov radiation is emitted when a charged particle’s speed is greater than the speed of light in the medium. The velocity for Čerenkov radiation is given by the formula

$$\beta \geq \frac{1}{n},$$

(2.2)

where $n$ is the medium’s refractive index. The number of Čerenkov photons emitted by a particle with unit charge per unit track length and per unit wavelength is given by

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

(2.3)

where $\alpha$ is the fine structure constant. A relativistic particle emits about 100 photons for every centimeter of travel with wavelengths between 400 nm and 500 nm. About 200 photons are emitted for the same distance with wavelengths ranging from 285 nm to 400 nm.
The emission angle is related to the particle’s velocity and the refractive index of the medium that it is travelling in:

\[ \cos \theta_c = \frac{1}{n \beta} \]  

(2.4)

The energy range of the ANTARES is bigger than 10 GeV. Thus, the detectable particles are relativistic ($\beta \approx 1$). For this energy range the angle of the emitted photons is $\theta_c \approx 42.5^\circ$. Since the angle of the Čerenkov light cone is known, the reconstruction of the particle’s track is possible.

### 2.1.2 Photon detection

When a photon hits the photocathode of a PMT, it may liberate an electron with probability equal to the quantum efficiency of the PMT. This electron, referred to as a photoelectron (p.e.), induces an amplified electrical signal on the anode of the PMT. When the amplitude of this analogue signal crosses a voltage threshold, which is applied to exclude small signals due to currents inside the PMT and its typical value is 0.3 p.e., the signal is digitized by a front-end chip called Analogue Ring Sampler (ARS) [16]. The ARS measures the charge contained in the PMT signal by integrating the anode current over a time interval of 25 ns. The integrated charge is a measure for the intensity of the radiation on the PMTs and a higher charge value indicates the existence of a higher number of photons. Since the number of emitted photons is related with the energy of the passing particle, a higher charge implies the passage of a high energy particle.

### 2.2 Detector layout

Figure 2.2 shows a sketch of the detector’s layout. Čerenkov light is detected by 875 Optical Modules (OM). Each OM consists of a 43 cm diameter pressure-resisting glass sphere with one hemisphere painted black and the other one having a Photomultiplier Tube (PMT) glued to its inside with a transparent silicone rubber gel. Inside the sphere are also high voltage electronics necessary for the PMT’s correct operation.

Three OMs grouped together form a “floor”. The latter is a mechanical structure which includes a titanium container, and a Local Control Module (LMC), housing offshore electronics and processors. The OMs are mounted in such a way that they point downwards at an angle of 45°.

The detector consists of 12 lines paced about 60 m apart. The layout of the lines on the seabed is shown in Figure 2.3. The lines are held to the seabed with a weight on the bottom and a buoy on the top. Each line has a length of 448 m with the first 100 m of being uninstrumented to allow the development of the Čerenkov cone. Above that height a floor is located every 14.5 m. This brings the number of floor in each line to 25 and the total number of OMs on the whole detector to 875.
Figure 2.2: A schematic layout of the ANTARES detector.

Figure 2.3: The picture shows the position of the strings on the seabed.

The strings are connected to a junction box which transfers the data to the shore through a 40 km cable. It should be noted that no data reduction is used and all collected data are taken to the shore where specific triggers are applied.

2.3 Triggering

The ANTARES trigger software identifies the signal from a muon within large amounts of background noise. It is a very extensive software and contains several types of trigger algorithms and as well as a large number of parameters. The trigger software is applied to the data after their arrival to the shore and before they are written to disk [17].

The first step of the process is the registration of all hits of the event, i.e. zeroth
level (L0). At the same time, the charge and time of the hits are calibrated. Then, the first level (L1) follows. This is based on the logical assumption that the signal is more likely to have a higher charge and that it is more possible to generate hits on close-by PMTs. Consequently, L1 searches for two kind of hits:

- Events having a large charge, varying from 2 to 10 photoelectrons, with 3 p.e. being the default value and
- Locally coinciding hits, which are hits that occur in a time window of 20 ns on two different PMTs on the same floor.

The trigger software is based on a selection of appropriate L1 hits. In this report two trigger algorithms were used: The 2T3 cluster and the 3N cluster of hits which are described below. The 1T3 cluster is also described since 2T3 is based on it.

The 3N trigger: 3N is the standard trigger algorithm. It is activated in case there are five L1 hits in a time window of 2.2 $\mu$s with times consistent with a passing muon.

The 1T3 trigger: This is based on two L1 hits among two adjacent or next-to-adjacent storeys. The time window is set to 100 ns in the case that the two storeys are adjacent, and to 200 ns in the case of next-to-adjacent storeys [18].

The 2T3 trigger: The trigger expects two 1T3 clusters in the whole detector in a time window of 2.2 ms. The location of these clusters is not important, they can be either on the same line or on two different lines. In the former case, three L1 hits on three adjacent storeys can lead to a triggered event.

### 2.4 Muon Track Reconstruction

The task of the reconstruction software is to find estimates for the position and the direction of the muon’s track. This is done primarily by using the measured arrival times of Čerenkov photons at the PMTs. The reconstruction algorithm used in this report is named "Aart-Strategy". A detailed description can be found at [19] and [20].

Let $\vec{p}$ be the position of the muon at arbitrary time $t_0$ and $\vec{d}$ its normalized direction while $\vec{q}$ is the position of the hit at the PMT. Since the direction can be parametrized in terms of the azimuthal and zenith angles $\theta$ and $\phi$ respectively, the task of the reconstruction algorithm is to provide the estimates $\hat{p}_x, \hat{p}_y, \hat{p}_z, \hat{\theta}$ and $\hat{\phi}$ which describe the track.

In order to calculate the arrival time of Čerenkov photons at the PMTs, a vector $\vec{u} = \vec{q} - \vec{p}$ can be defined with parallel and perpendicular components $l = \vec{l} \cdot \vec{d}$ and $k = \sqrt{\vec{u}^2 - l^2}$ respectively, as shown in Fig. 2.4.
Then, the theoretical arrival time of the light at a PMT will be

\[ t^{th} = t_0 + \frac{1}{c} \left( l - \frac{k}{\tan\theta_c} \right) + \frac{1}{u_g} \left( \frac{k}{\sin\theta_c} \right), \]  

(2.5)

with \( u_g \) the group velocity of light in water. In the equation above the second term describes the time the muon needs to reach the point of the light emission while the third term is the required time for the light to travel from that point to \( \vec{q} \).

![Figure 2.4: Geometrical relation between the muon track and point \( \vec{q} \) where the hit is measured. Point \( \vec{p} \) is the muon position at time \( t_0 \). \( k \) and \( l \) are the components of the vector \( \vec{v} = \vec{q} - \vec{p} \) perpendicular and parallel to the track respectively. The dashed line is emitted at the Čerenkov angle \( \theta_c \). Figure taken from [19].](image)

The first step in the track reconstruction algorithm is selecting all coincidence hits and all hits with an amplitude of three or more photoelectrons and applying a Linear prefit on them. This fit assumes that the hits are on the muon’s track and performs a straight-line fitting on them.

From the result of this prefit various possible tracks are generated and they are used as starting points for the next step which is applied to selected hits with time residuals less than 150 ns and with a distance smaller than 100 m to the track.

For this set of hits the track parameters are recalculated using M-estimates. This method calculates the time residual \( r_i \) as a function of the track parameters:

\[ r_i = t_i - t_i^{th}(\hat{p}, \hat{d}), \]  

(2.6)

where \( t_i \) is the time of the \( i \)th hit and \( t_i^{th} \) is calculated using formula (2.5). The estimates of these parameters are given by those parameters for which the following is maximal:

\[ Q = \sum_{i=1}^{N} g(r_i(\hat{p}, \hat{d})), \]  

(2.7)

The above procedure is first called with \( g(r) = -2\sqrt{1 + r^2/2} + 2 \), named \( L1-L2 \) [21]. Then the same method is called with \( g(r) = \ln L(r) \) where \( L \) expresses the probability density function of finding a hit with residual \( r_i \). The solution with the highest
likelihood in the end of the procedure is considered the most accurate one and is used as a starting point for the final fitting process. The later uses hits with time residuals less than 250 ns and distances smaller than 300 m from the track.

The last stage of the parameter estimation uses the Maximum Likelihood estimator which tries to find the track parameters that yield the highest probability of the observed data. The probability density function (PDF) gives the probability of observing the event given the track parameters. In the case that all hits are uncorrelated the normalized PDF can be written as

$$P(event|track) = \prod_i P(t_i|t_i^0, a_i, b_i, A_i), \quad (2.8)$$

where $A_i$ is the amplitude of the hit, $a_i$ is the cosine of the angle of the incident photon on the PMT and $b_i$ is the distance travelled by that photon.

**Quality cut**

In order to reject events which are poorly reconstructed, one may cut the value of

$$\Lambda = \log(L)/NDOF. \quad (2.9)$$

In this equation, NDOF is the Number of Degrees of Freedom, indicating the number of compatible solutions found by the algorithm, and $L$ is the value of the likelihood function at the fitted maximum.

### 2.5 Background

There are various sources that produce light apart from the muons produced by cosmic neutrinos. These sources constitute the background that has to be isolated and rejected in order to separate the light coming from the signal and are discussed in this section.

#### 2.5.1 Background photons

Potassium ($^{40}$K) is the most abundant radioactive element found in sea water. It has two different decay modes which both can be responsible for Čerenkov radiation:

$$^{40}K \rightarrow^{40}Ca + e^- + \bar{\nu}_e$$
$$^{40}K \rightarrow^{40}Ar^* (+\bar{\nu}_e) \rightarrow^{40}Ar + \gamma.$$ 

This effect is well understood and can be simulated by Monte Carlo. The expected rate is $34 \pm 7$ kHz [22]. Another source of background light is organisms, like bacteria, which are present at the ANTARES site. This is known as bioluminescence.

The combination of bioluminescence and $\beta$-decay of Potassium create a baseline of around 60 kHz which has been included in the simulations.
2.5.2 Atmospheric muons

Muons are the most numerous charged particles at sea level. Most muons are produced by interactions of cosmic rays high in the atmosphere, at an altitude of around 15 km, and lose about 2 GeV to ionization before reaching the ground [4]. Atmospheric muons are always down-going and, since they are produced by cosmic rays, follow the same energy spectrum. A simulation of the atmospheric muon background is analyzed in detail in section 3.3.

2.5.3 Atmospheric neutrinos

Many neutrinos are produced by the interaction of cosmic rays with the atmosphere; i.e. atmospheric neutrinos. The only difference they possess from cosmic neutrinos is their energy spectrum which is steeper when compared with the energy spectrum of cosmic neutrinos.

Most atmospheric neutrinos with energies below $10^5$ GeV are produced by the decay of pions and kaons while neutrinos of higher energy are usually produced by charmed meson decay. Since atmospheric muons are of low energy, they were not taken into account in this study.
3.1 The SeaTray Software Framework

For the simulations, the SeaTray software framework was used. It is an adoption from IceTray, used by the IceCube collaboration, and it was changed to take into account the geometry of the ANTARES detector and the water properties at this region.

The simulation chain followed by SeaTray is divided in three parts. A more detailed description can be found in [23] and [24]. In the first part, the cosmic particles are generated at the surface of the Earth and then propagated to the detector's vicinity. The second step comprises the generation of particles created by the neutrino, like muons and their propagation from the position they were generated to and through the detector. On the third step the secondaries and tertiaries are generated (such as electrons and Čerenkov photons) and their interaction with the detector's components is simulated.

3.1.1 Neutrino Generator

The Seatray project Neutrino Generator (NuG) is used for the generation of the primary neutrino flux. NuG is a version of Anis [25]. It generates random energies following a power law spectrum on the Earth's surface. The user has control on almost all aspects of the generation (such as the number and flavor of the particles, their energy range, azimuth and zenith angles, etc.). The cross section implemented in the generator is valid for neutrino-nucleon interactions in energy ranging from $10 \text{ GeV}$ to $10^{12} \text{ GeV}$ and it is able to simulate all three flavors of neutrinos.
Chapter 3. Signal & Background Simulation

Figure 3.1: The detector geometry used in Neutrino Generator. The cylinder’s size varies according to the neutrino’s energy. The detector is represented by the rectangle and it is always fully contained inside the cylinder.

NuG starts by performing a complete propagation of the neutrino through the Earth, in case the event is up-going, or the water surrounding the detector for down-going events, which means that it simulates the propagation of every generated neutrino through the Earth including all neutrino-nucleon interactions.

Once the neutrino has been propagated and reaches the detector vicinity, it is forced to interact inside a specified detection volume. This detection volume is a cylinder coaxial with the incoming neutrino and fully contains the detector. A graphic representation of the detection volume is shown in 3.1. There, a neutrino or a charged lepton is produced along with a hadronic shower according to the interaction probabilities. Each of these interactions is assigned a weight which is described in the following section. Figure 3.1 depicts the detector when a neutrino enters the detection volume.

**Neutrino flux and event weighting**

The cylinder mentioned in the previous section has length $L$ and it is coaxial with the incoming neutrino. The probability density function that the neutrino entering the cylinder will interact after traveling a distance $x$ along the axis of this cylinder is given by

$$P_{\text{int}}(x) = N_A \rho \sigma e^{-N_A \rho \sigma x}$$  \hspace{1cm} (3.1)

where $N_A$ is Avogadro’s number, $\rho$ the Earth’s density, and $\sigma$ the total neutrino-nucleon cross section. The exponential takes into account the probability that a neutrino will cover the distance until the point $x$ inside the cylinder.

Since this interaction probability is really small, NuG would be very CPU-intensive and inefficient if it used it for the simulations. Instead, NuG forces every neutrino to interact. Then, on the same cylinder, the probability density of the neutrino interacting at the point $x$ is given by

$$P_{\text{gen}} = \frac{1}{L}.$$  \hspace{1cm} (3.2)
This is not the real probability, however, so each event is assigned a weight that re-weights the event with the real probability of happening:

$$W_{\text{int}} = \frac{N_A \rho \sigma e^{-N_A \rho \sigma x}}{1/L}.$$  \hfill (3.3)

The same procedure must be applied to the flux. NuG generates events based following a power law. In order to simulate a desired physical flux, each event has to be weighted. For that, NuG provides a quantity named OneWeight which includes the above weight, the generation area $A$, the spectral index $\gamma$ of the simulation, the energy range $E_{\text{min}} - E_{\text{max}}$ and the simulation’s solid angle range $\Omega$. OneWeight is given by

$$\text{OneWeight} = \frac{W_{\text{int}}}{E_{\nu}^{\gamma}} \int_{E_{\text{min}}}^{E_{\text{max}}} E_{\nu}^{-\gamma}dE \ A \ \Omega \ [\text{GeV cm}^2 \ \text{sr}]$$  \hfill (3.4)

Then, the weight of each individual event will be given by

$$\text{weight} = \frac{\text{OneWeight}}{N_{\text{evs}}} \times \phi(E_{\nu}) \times \text{LiveTime}.$$  \hfill (3.5)

where $\phi(E_{\nu})$ is the desired flux, $N_{\text{evs}}$ the total number of events in the simulation and LiveTime is the time that the simulation covers in seconds.

### 3.1.2 Muon Monte Carlo propagator

The muons that were generated are propagated inside the detector’s volume by Muon Monte Carlo (MMC) described in detail in [26] and [27]. The detector’s response is based on the amount of light deposited by the muon, which is related to the material that the muon passes through. To simulate the muon’s behavior, MMC is aware of the properties of the material around the detector and the energy loss mechanisms of leptons. It is designed to work with muons and tau leptons in energies ranging from $10^{5.7}$ MeV (which is the muon’s rest mass) to $10^{11}$ GeV.

MMC implements all main energy loss mechanisms: ionization, Bremsstrahlung, pair production and photonuclear interactions. The average energy loss of a muon is given by

$$\frac{dE}{dx} = a(E) + b(E)E$$  \hfill (3.6)

where $a(E)$ is the energy loss due to ionization and $b(E)$ is the energy loss due to remaining three processes. The energy losses as a function of energy in pure water are shown in Figure 3.2.

### 3.1.3 Hit Constructor

The Hit Constructor is the last step in the simulation chain of the SeaTray Framework. It examines the tracks provided by MMC, selects the ones that can produce
Figure 3.2: Muon energy losses in pure water. Curve a shows the energy loss due to ionization while curve b describes the term $b(E)E$. Curve c is the final sum. Figure is taken from [28].

light, generates Čerenkov photons and propagates them to the PMT’s surface. Thereby taking into account the quantum efficiency and the angular acceptance of the PMT, it examines if a hit will be created [24]. The propagation of the photons is done using the program Photonics, described in [29].

3.2 Cosmic Neutrino Simulation

3.2.1 Flux

The signal is represented by cosmic neutrinos from point sources. As it was discussed earlier (see section 1.2), the cosmic neutrino spectrum is derived from the spectrum of the interacting protons which is proportional to $E^{-2}$.

In order to have some normalization, the spectrum used in this report is the Waxman-Bachcall bound [30, 31]. This is $E^{-2}$-dependent and has the value

$$\frac{d\Phi}{dE} = 2 \times 10^{-8} \left( \frac{E}{\text{GeV}} \right)^{-2} \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$  \hspace{1cm} (3.7)

This flux model includes both neutrinos and antineutrinos.
3.2.2 Neutrino Energies and Angles

With the use of NuG, which was described in paragraph 3.1.1, $10^6$ muon neutrinos and antineutrinos were generated on Earth’s surface with a spectral index $\gamma = 2$. The energies of the simulated particles ranged from $10^4$ GeV to $10^9$ GeV since lower energy events would be rejected by the separation of signal from the background. The events were weighted with the flux described in the previous section.

Figure 3.3 shows the energies of the neutrinos at the interaction point inside the cylinder. Only neutrinos that underwent a charge current interaction are shown. It can be seen that the spectrum is less steep than the one expected for the current spectral index. This behavior is expected: Neutrinos and antineutrinos of higher energy have a higher cross section making the more probable to interact (see Figure 2.1).

![Figure 3.3](image_url)

**Figure 3.3:** Energies of the simulated neutrinos weighted by the Waxman-Bahcall flux. The total number of events per year for the energy range shown is 43.66.

The neutrinos were generated isotropically with azimuth angles ranging from $0^\circ$ to $360^\circ$ degrees. The zenith angle of the generated particles starts from $0^\circ$ degrees, indicating muons that move directly downwards, and reaches $90^\circ$ degrees, in which case the generated neutrinos move parallel to the surface of the Earth at the point of the detector. Figure 3.4 depicts the cosine of the zenith angle of the simulated neutrinos with a charged-current interaction. It can be seen that, although the neutrino production was isotropic, most of the neutrinos that interacted were traveling close to the horizon, having a cosine value close to zero. The reason is that these neutrinos pass through a thicker layer of water than the ones that move directly downwards which cross around 2.5 km, therefore the probability to interact increases.
Chapter 3. Signal & Background Simulation

3.2.3 Muon energies

From the generated neutrinos and antineutrinos, 75.66% had a charged-current interaction, producing a muon or an antimuon respectively at a random vertex point with energies as depicted in the left plot of Figure 3.5. The produced particles then traveled down to the detector’s vicinity losing energy in-between and arriving at the latter with energies shown in the right plot of the same figure.

The same plots also include the energies of the muons that were reconstructed and they are marked by the filled area. The Monte Carlo simulation yielded 43.66 muons per year from which 10.55 were reconstructed. The majority of the events is lost by the triggering while the reconstruction fails for only a small number of triggered events.

The reconstruction efficiency for muons as a function of their energy at the interaction point is presented in figure 3.6. High-energy muons create a bigger amount of radiation, which leads to a higher probability of them being detected.

3.3 Atmospheric Muon Simulation

The vast majority of particles detected by a neutrino telescope are muons produced in Earth’s atmosphere by the decay of charged mesons generated by the interac-
Chapter 3. Signal & Background Simulation

3.3 Atmospheric muon energies

The generation of events does not use weights, therefore, the user is not able to change the primary energy spectrum. This leads to an inability to simulate different models, with the advantage of the software becoming very light-weight and fast. The simulation used here covers 30 days of events with a multiplicity ranging from 1 to 100 and 71 days of events with multiplicity from 100 to 1000. All the figures in this section were scaled to simulate one year of data taking. Figure 3.7 shows the multiplicity after scaling.

3.3.1 Atmospheric muon energies

The bundle’s energy when it enters the can is shown in the left plot of Figure 3.8. The total number of events per year before the triggering is $4.53 \times 10^9$, however, this is lowered to $4.22 \times 10^8$ after the triggering and reconstruction. MUPAGE
propagates particles to the detector only if their energy when they reach sea level is higher than 500 GeV [32]. This leads to a sudden drop in the frequency of events with low energy. Also, the simulation does not include events with energy higher than $10^6$ Gev. If they were included, the distribution would continue to higher energies following with the same steepness.

As shown in the right of Figure 3.8, no events with energy lower than 50 GeV were reconstructed.

**Figure 3.6:** Muon efficiency for signal as a function of the muon’s energy at the interaction point. The fluctuation on higher energies is due to a lack of statistics.
Figure 3.7: Event multiplicity for MUPAGE-generated background for both multiplicity categories. The multiplicity of the events that were triggered and reconstructed is also shown. The events with multiplicity below 20 are almost 2 orders of magnitude more frequent than the rest.

Figure 3.8: Left plot: Bundle energy for background events for both high and low multiplicity. Right plot: Reconstruction efficiency for atmospheric muons. The increase in efficiency would continue with the same curvature if higher energy events were included.
As Figure 4.1 shows, background events overshadow the signal almost completely. The signal’s spectrum below $10^4$ GeV is unrealistic and appears like that because neutrinos were not simulated in this energy range. Also, the background stops abruptly on $10^6$ GeV, whereas in a realistic situation the event rate would continue falling with the same rate.

Despite this vast difference in the number of events, the discovery of point sources is still a viable option. This is because the background events will be spread out across the sky in contrast to the signal events which will originate from the same point. Should the missing background events be included, the result would not change since it would increase the number of background events by some hundreds.

Still, the rejection of the atmospheric events as much as possible while keeping the high-energy neutrino-induced events is a necessity. The rejection is based on the examination of a set of parameters which characterize an event: The zenith angle of the muon, the quality of its reconstruction, the number of hits induced in the PMTs and the total charge of the event.

### 4.1 First set

The first set of cuts places some limitations on the various quantities to guarantee that the events have a high energy, are well reconstructed and originate from low zenith angles where the cosmic muons dominate.
Chapter 4. Signal & Background Separation

4.1.1 Angular cuts

The right plot of Figure 4.2 shows the cosine angles of the muons constituting the signal. The muon angle distribution does not resemble the neutrino distribution since it does not show all muons but only those that passed the trigger logic and the reconstruction. A small number of muons appears to be up-going, creating a small tail between cosine values of -0.05 and 0. This is due to neutrinos moving almost parallel to the horizon which have a small probability of creating a muon moving upwards according to equation (2.1). In the reconstructed angle distribution appear events which have been reconstructed as up-going.

In the same figure, the left plot depicts the distribution of the background’s cosine of the zenith angle. Again, the “true MC” plot includes only the events that were reconstructed. Each entry in the histogram represents a muon bundle.

In contrast with cosmic muons, the atmospheric muon flux increases with zenith angle, having no particles in low angles. That led to the rejection of events with a cosine bigger than 0.4. Also all events that appear to be up-going were rejected. These two cuts lowered the number of background events from $4.22 \times 10^8$ to $2.26 \times 10^7$. Simultaneously, 5.26 out of 10.53 signal events survived.

4.1.2 Quality cut

The event reconstruction is performed with the use of Aart strategy which provides a parameter quantifying the quality of the reconstruction (see 2.4). This algorithm...
Chapter 4. Signal & Background Separation

Figure 4.2: Comparison between the cosine value of the true muon’s zenith angles and the reconstructed values for the signal (left) and the background (right). Only events that got reconstructed are shown. On the reconstructed angles one can notice that a more significant number of events are reconstructed badly and appear as up-going. Signal events originate mainly from the horizon while the background event spectrum increases with the angle. All particles with cosine below zero or greater than 0.4 were rejected.

will give a good angular resolution by cutting in the $\Lambda$ variable. A strict $\Lambda$ cut will select events which are better reconstructed and reject misreconstructed events. Figure 4.3 presents the $\Lambda$ values for signal and background events. The reconstruction performs worse when compared with up-going events. This is due to the PMTs pointing $45^\circ$ downwards. Selecting events with $\Lambda > -6$ guarantees that events that pass this step are well reconstructed. Something like that is obligatory in a point source search since badly reconstructed events will point to a wrong direction. This cut reduced the number of background events from $2.26 \times 10^7$ to $8.80 \times 10^6$ and the signal events from 5.26 to 4.10.

Figure 4.3: $\Lambda$ value for the reconstructed muons induced by cosmic neutrinos (left) and atmospheric muons (right). Events with $\Lambda < -6$ were rejected.
4.1.3 Number of hits and event charges

After summing the charges on all PMTs for each event, one ends up with the total charge of the event. These distributions of the charge are presented on Figure 4.4 for signal and background. Events with an event charge less than $10^{2.5}$ were rejected, something that reduced the background from $8.80 \times 10^6$ to $4.27 \times 10^5$ and the signal from $4.10$ to $2.17$.

The number of hits in the events, is shown in Figure 4.5. The background noise of 60 kHz increases the number of hits since it creates at least 15 hits in each event. The bump at $\log(N_{\text{hits}}) = 1.5$ is due to background noise (see section 2.5.1). In the same plot it can be seen that the reconstruction algorithm is able to reconstruct all events with more than $10^{2.5}$ (≈315) hits while only a small percentage of events with less than 100 hits were reconstructed. All events that had less than $10^{2.4}$ hits were rejected.
From the first set of cuts, $1.26 \times 10^5$ out of $4.99 \times 10^8$ background events per year selected. The downside is that a 8.74 signal events are rejected, with only 1.81 events per year surviving.

4.2 Second set

After the first category of cuts, the background still dominates. The second set of cuts was based on the parallel examination of all the quantities on which the cuts are based ($\Lambda$, number of hits, charge and zenith angle) as a function of the rest. Regions where the background is much higher than the signal are being rejected. Figures 4.6 and 4.7 present the six plots that were used in this process after the first category of cuts was applied. The red lines on each plot mark the rejected area. The process required trial-and-error, something that made the final cuts different than the choices that should be made based solely on the first look on the plots.

The first row of Figure 4.6 shows the charge versus the cosine of the zenith angle. It can be seen that the highest concentration of background events lies in the area with zenith angle above $20^\circ$ and charge less than 650 p.e.. The cut placed excludes events with $\cos(\text{zenith}) > 0.35$ and charge smaller than 1000 photoelectrons. This reduced the background from $1.26 \times 10^5$ to $7.79 \times 10^4$ and the signal from 1.79 to 1.68.

Similarly, based on the plots on the second row of Figure 4.6, the cut affected all events with $\Lambda$ less than $-5.5$ and a logarithm of charge lying below 2.8. This cut dropped the background greatly from $7.79 \times 10^4$ to $4.33 \times 10^4$ and the signal from 1.68 to 1.52 events per year.

The linear relation in between the charge and the number of hits on an event is clearly visible in the third row of the same figure. Because of this relation, no cuts we based on this plot.

Moving to the first row of Figure 4.7 one can notice the excess of events that the background has on the upper left corner which is described by high zenith. Trial-and-error methods proved that the cut most reducing the background is to reject particles with cosine above 0.2 and $\Lambda$ smaller than -5.4. After this step, the background was reduced from $4.33 \times 10^4$ to $3.78 \times 10^4$ while the signal went from 1.52 to 1.39.

The next row depicts the values of the cosine of zenith angle against the number of hits of each event. It can be seen that the signal is much more dispersed than the background. This led to the decision to cut the particles with cosine above 0.25 and number of hits per event below $10^{2.5}$ (316 hits). The background was reduced from $3.78 \times 10^4$ to $1.78 \times 10^4$ and the signal from 1.39 to 1.31 events per year.

The plots on the last row compare the number of hits of each event with the $\Lambda$ value. The regions with the majority of events coincide. However, the scale shows that by rejecting the region below $10^{2.5}$ and $\Lambda$ less than $-5.3$, a much higher
Figure 4.6: Three dimensional histograms of the examined quantities after the first set of cuts. The rejected areas lie between the red lines and the axes. Since the relation between the number of hits and the charge induced is almost linear, no cuts were placed in the plots on the third row.
Figure 4.7: Three dimensional histograms of the examined quantities after the first set of cuts. The cuts are marked by the red lines. Everything inside this region is rejected. On the first row it can be seen that a significant part of the background is not rejected by the cut. It’s rejection was possible from the remaining cuts. In the third row it can be seen that in order to reject the majority of the background, the biggest part of the signal was also rejected. Given, though, the difference in the scale, this was advantageous since it affected the background much more.
percentage of background than signal is rejected. The number of events remaining after this cut is $1.35 \times 10^4$ while for the signal there are $1.26$ events per year.

4.3 Rejection summary

Events that met any of the following conditions were rejected:

- $\cos \theta > 0.4$ and $\log Q < 3 \text{ p.e.}$ and $\cos \theta > 0.35$
- $\log(N_{\text{hits}}) < 2.4$ and $\Lambda < -5.4$ and $\cos \theta > 0.2$
- $\Lambda < -6$ and $\log Q < 2.8 \text{ p.e.}$
- $\log Q < 2.5 \text{ p.e.}$ and $\cos \theta > 0.25$ and $\log N_{\text{hits}} < 2.5$
- $\Lambda < -5.3$ and $\log N_{\text{hits}} < 2.5$

where $\theta$ is the zenith angle, $Q$ the total charge of the event and $N_{\text{hits}}$ the total number of hits. Table 4.3 summarizes the event rates for each step of the procedure.

Figure 4.8 compares the background’s and signal’s energy spectrum after the cuts. It can be seen that low energy events are much more affected than the events having a higher energy. In the case that background events of higher energy were included the background event rate would change by some tens of events. This number is very small and would not affect the final results.
Chapter 4. Signal & Background Separation

Table 4.3: Comparison of the number of expected events before and after the cuts for background and signal events.

<table>
<thead>
<tr>
<th>Rate (yr$^{-1}$)</th>
<th>Background</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Cuts</td>
<td>$4.22 \times 10^9$</td>
<td>10.53</td>
</tr>
<tr>
<td>$0 &lt; \cos \theta &lt; 0.4$</td>
<td>$2.26 \times 10^7$</td>
<td>5.26</td>
</tr>
<tr>
<td>$\Lambda &lt; -6$</td>
<td>$8.80 \times 10^9$</td>
<td>4.10</td>
</tr>
<tr>
<td>$\log Q &lt; 2.4$</td>
<td>$4.27 \times 10^3$</td>
<td>2.17</td>
</tr>
<tr>
<td>$\log N_{hits} &lt; 2.4$</td>
<td>$1.26 \times 10^9$</td>
<td>1.81</td>
</tr>
<tr>
<td>$\cos \theta &gt; 0.35$ and $\log Q &lt; 3 \text{ p.e.}$</td>
<td>$7.79 \times 10^4$</td>
<td>1.68</td>
</tr>
<tr>
<td>$\Lambda &lt; -5.4$ and $\cos \theta &gt; 0.2$</td>
<td>$4.33 \times 10^4$</td>
<td>1.52</td>
</tr>
<tr>
<td>$\Lambda &lt; -5.5$ and $\log Q &lt; 2.8 \text{ p.e.}$</td>
<td>$3.78 \times 10^4$</td>
<td>1.39</td>
</tr>
<tr>
<td>$\cos \theta &gt; 0.25$ and $\log N_{hits} &lt; 2.5 \text{ p.e.}$</td>
<td>$1.78 \times 10^4$</td>
<td>1.31</td>
</tr>
<tr>
<td>$\Lambda &lt; -5.3$ and $\log N_{hits} &lt; 2.5$</td>
<td>$1.35 \times 10^4$</td>
<td>1.27</td>
</tr>
</tbody>
</table>
The potential for discovery of point sources is one of the major reasons for the construction of a neutrino telescope. Even if a $km^2$ detector would be needed to detect most neutrino sources, ANTARES is still able to place flux limits to various point source candidates which will allow the confirmation or rejection of existing models of neutrino emissions from these sources. Simultaneously, the sensitivity to unknown sources can be examined with for a possible discovery of up to now unknown phenomena. The discussion on this chapter focuses on setting an upper limit on the flux of point sources.

5.1 Search for point sources

In order to search for point sources, equatorial coordinates are used to map an object in the sky. Equatorial coordinates are declination and right ascension. Declination measures the distance of an object from the celestial equator while right ascension measures the angle of the object east of the apparent location of Sun’s center. Polaris, the Northern hemisphere’s pole star, has a declination of $90^\circ$ and it is the center of rotation. This means that its location in the sky is always the same and the rest of the sky “rotates” around it. Figure 5.1 shows the equatorial coordinate system.

After the coordinate transformation, a bin is defined around the coordinates of an astronomical object of interest and the number of events inside the bin are counted. An excess of events over the background expectation would indicate a cosmic neutrino signal. If the probability to have the counted events inside the bin assuming that they are caused only by background is low, then there is a probability of the bin including signal events. If there is no excess in events, then flux limits can be set.
In the following, the expected average limit for 90\%CL is computed. For that, the number of background events in a bin is calculated and then, the upper limit on the signal events is set at 90\%CL. This is followed by the limit computation.

### 5.1.1 Number of background events

Figure 5.2 depicts the rate of background events as a function of declination. The region below $\sin(\delta) \simeq -0.8 \ (\sim -48^\circ)$ is never visible by ANTARES with the use of downgoing neutrinos. Events that appear in this region before the cuts are misreconstructed, therefore they do not appear after the cuts have been placed. The region above $\sin(\delta) \simeq 0.8 \ (48^\circ)$ is constantly visible with downgoing neutrinos, something that leads to a small increase in the event rate. However after the cuts, events with a declination of $90^\circ$ are greatly reduced due to the effect of the angular cut (see section 4.1.1).
The number of background events as a function of declination is given the formula

$$\mu_{bg} = R_{bg}^\text{obs} \Omega_{bin} \Delta T$$  \hspace{1cm} (5.1)

where $\Omega_{bin}$ is the bin area, in this case $\pi \text{ sq. degrees}$, and $\Delta T$ the observation time which is taken to be a year. $R_{bg}$ (shown in Figure 5.2) is the rate of background events ever in a declination band over the width of this band:

$$R_{bg} = \frac{N_{\text{evs}}^{\text{band}}}{\Omega_{\text{band}}}.$$  \hspace{1cm} (5.2)

The width of the band is given by

$$\Omega_{\text{band}} = 2\pi \int_{\sin \theta_1}^{\sin \theta_2} d\sin \delta = 2\pi (\sin \theta_2 - \sin \theta_1)$$  \hspace{1cm} (5.3)

where $\theta_1$ and $\theta_2$ are the lower and upper angle of the band respectively. Figure 5.3 presents the number of background events as a function of declination.

### 5.1.2 Upper Limits

In the previous section, the number of background events in the bin as a function of declination of the bin was calculated. The next objective is the placement of upper limits on the expected number of cosmic neutrinos in each bin. This will then be used to calculate the sensitivity of the detector.

The first step is to calculate the expected number of events per bin as a function of declination in order to be 90% certain that this number is not due to a random
Figure 5.3: The average number of background events in a bin with radius $1^\circ$ as a function of declination.

background fluctuation. Suppose that $n_{\text{obs}}$ events are observed in a bin. The expected number of events $\mu_{\text{lim}} = \mu_{\text{bg}} + \mu_{\text{lim}}^{\text{sig}}$ will be given by

$$\sum_{n=0}^{n_{\text{obs}}} P(n|\mu_{\text{lim}}^{\text{sig}}) = 10\%.$$  \hspace{1cm} (5.4)

Then, the limit on the number of signal events can be found by the formula

$$< \mu_{\text{sig}} >_{90\%} = \sum_{n=0}^{n_{\text{obs}}} \mu_{\text{lim}}^{\text{sig}} P(n|\mu_{\text{bg}}).$$ \hspace{1cm} (5.5)

where

$$\mu_{\text{lim}}^{\text{sig}} = \mu_{\text{lim}} - \mu_{\text{bg}}.$$ \hspace{1cm} (5.6)

This is the number of events inside a bin of radius $1^\circ$ and area $\pi$ square degrees. To find the total number of events the source must emit in order to have $\mu_{\text{lim}}^{\text{sig}}$ events in the bin, one has to divide the above value with the binning efficiency.

The binning efficiency expresses the probability to have the coordinates of the reconstructed event falling on the same bin with the true coordinates and it is shown in the left of Figure 5.4. The bin is circular with the centre taken to be the event’s true coordinates. In this case, the bin radius used is 1 square degree, making the efficiency $\epsilon = 0.91$. 
Figure 5.4: The plot on the left shows the binning efficiency for downgoing neutrinos after the cuts. The bin is circular with the centre taken to be the event’s true coordinates. The plot on the right is the average number of signal events that can be excluded at 90% CL.

The limit on the average number of events the source emits is found by dividing the expected number of signal events with the binning efficiency. This value is shown in the right of Figure 5.4 as a function of declination.

5.1.3 Sensitivity

The last step of the process is to calculate the flux that will give a detectable number of cosmic neutrinos. As mentioned in section 3.2.1, the flux that was used is the Waxman-Bahcall diffuse flux:

$$\frac{d\Phi}{dE} = 2 \times 10^{-8} \left( \frac{E}{GeV} \right)^2 GeV^{-1}cm^{-2}s^{-1}sr^{-1}.$$  \hspace{1cm} (5.7)

The rate, as a function of declination, generated by such a flux appears in Figure 5.5. The sensitivity will be derived by the formula

$$\Phi_{90\%} = \frac{<\mu_{\text{sig}}^{90\%}(\delta)>}{A}.$$  \hspace{1cm} (5.8)

In this equation $<\mu_{\text{sig}}^{90\%}(\delta)>$ is the average number of events for 90%CL and A is the acceptance of the detector. Acceptance is defined as the ratio of the rate of detected events over the point source flux which generated them. It is depicted in the right plot of Figure 5.5 as a function of declination.

Figure 5.6 shows the sensitivity of the ANTARES detector at 90%CL as a function of declination.
Chapter 5. Performance

5.1.4 Effective Area

As it has been discussed before, not all the events reaching the detector can be measured and reconstructed. To describe the efficiency of the detector, a parameter named effective area can be used. Effective area shows the area that a detector should cover in order to be able to measure all events. The neutrino effective area is the ratio of the rate of selected events over the total incident flux arriving on Earth. It is described by the formula

\[ A^{\text{eff}}(E) = \frac{R_{\text{det}}^\nu(E)}{\Phi(E)} \]  

(5.9)

where \( \Phi(E) \) is the flux of neutrinos before they enter the Earth and \( R_{\text{det}}^\nu(E) \) is the rate of detected neutrinos. Figure 5.7 shows the effective area before and after the cuts.

**Figure 5.5:** The left plot illustrates the rate of cosmic neutrinos by a Waxman-Bachall flux as a function of declination. The area below -0.75 is never visible by ANTARES, therefore no events exist there. Although the area above 0.75 is always visible, it is also the area most influenced by the angular cuts. Therefore, there is an original rise on the flux at \( \sin(\delta) = 0.75 \) which declines fast due to the cuts. The plot on the right is the acceptance. Dividing the two plots yields the sensitivity.
Figure 5.6: The sensitivity of the detector for down-going events at 90%CL.

Figure 5.7: The effective area for down-going neutrinos. The straight black line is the effective area for the minimum flux value, the dotted red is the effective area for the maximum flux while the dotted black line is for a flux falling in between the other two values. The left plot depicts the effective area before the cuts while the plot on the right uses the cuts.
CONCLUSIONS

This study examines the visibility of point sources with the use of down-going neutrinos. To achieve that, the signal, consisting of cosmic neutrinos, and the background, which was mainly atmospheric muons, was simulated. Then their signature on the detector was examined which led to a cut placement in order to reduce the number of background events. Then a flux limit was set at 90%CL.

6.1 Comparison with other experiments

Various experiments have conducted point source searches, including MACRO [34], Super-Kamiokande [35], AMANDA-II [36] and IceCube [37]. Up to now only upper limits have been set since no point sources have yet been discovered. These limits are presented on Figure 6.1 along with the limit set by this study. The figure also includes the upper limit set by the ANTARES telescope for upgoing events. This limit is less than an order of magnitude below the limit set by this report. Unlike this report, the included studies were conducted with data and not simulations.

The IceCube observatory has set a much lower limit on the flux for the same region of the sky. This should be expected, given that IceCube is designed to be more sensitive in this region of the sky. The sensitivity of IceCube for down-going events is examined in [3]. The limit set by IceCube for down-going events is lower than the limit set by this work. This can be attributed to the larger size of the detector.
Figure 6.1: The limits set on the flux normalization constant by various experiments. The neutrino spectrum is assumed to follow an $E^{-2}$ distribution. This study is represented by the black line.
BIBLIOGRAPHY


