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A reconstruction method for neutrino induced muon tracks taking into account the apriori knowledge of the neutrino source

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ABSTRACT

Gamma ray earthbound and satellite experiments have discovered, over the last years, many Galactic and extragalactic gamma ray sources. The detection of astrophysical neutrinos emitted by the same sources would imply that these astrophysical objects are charged cosmic ray accelerators and help to resolve the enigma of the origin of cosmic rays. A very large volume neutrino telescope will be able to detect these potential neutrino emitters. The apriori known direction of the neutrino source can be used to effectively suppress the ^{40}K optical background and increase significantly the tracking efficiency through causality filters. We report on advancing filtering and prefit techniques using the known neutrino source direction and first results are presented.

1. Introduction

The future Mediterranean very large volume neutrino telescope, KM3NeT, will be one of the world's largest particle detectors and will provide a research infrastructure for a rich and diverse deep-sea scientific program [1,2]. Various astrophysical sources are expected to produce high-energy neutrinos that can be detected with KM3NeT. The most promising candidate neutrino sources are Galactic point-like (or with a small angular size) sources. The observation of neutrinos emanating from such sources would bring unique new insights on the nature of cosmic accelerators and resolve the enigma of the origin of cosmic rays. Observations by gamma ray earthbound and satellite experiments have revealed many such astrophysical objects, in which high-energy processes at and beyond the TeV energy level take place. However, measurements with gamma rays alone cannot clearly distinguish whether the accelerated particles are leptons or hadrons. Only the observation of neutrinos from a source can unambiguously establish the hadronic nature of that source.

However, the Galactic sources are generally expected to have a cut-off in their energy spectra in the range 1–10 TeV. The signal produced by neutrinos in this energy range could be lost among the ^{40}K optical background, resulting in low track reconstruction efficiency. In this work we report on advancing triggering, filtering and prefit techniques that use the apriori known direction of the neutrino source to effectively suppress the ^{40}K optical background and enhance the detection efficiency for neutrinos from Galactic sources for which the direction is known from their gamma ray emission.

2. Detector description and simulation framework

In the present study the telescope layout considered is the one optimized during the KM3NeT Design Study [2], exhibiting optimal sensitivity in discovering astrophysical point sources emitting neutrinos with an energy spectrum of E^{-2} and either a high energy cut-off or no cut-off at all. According to this layout, the KM3NeT detector will consist of 12320 photo-sensors distributed over 308 Detection Units (DUs). The photo-sensor unit is a digital optical module (DOM) consisting of a 17-in. diameter pressure resistant glass sphere housing 31 3-in. photomultiplier (PMT) tubes [3]. A DU is a vertical structure which carries photo-sensors and devices for calibration and environmental measurements, arranged vertically on 20 Storeys. Each Storey consists of a bar with one DOM at either end. The horizontal distance between the centers of the DOMs is 6 m. The vertical distance between Storeys is 40 m, while the position of the lowest Storey is 100 m above the seabed. The bars have an orientation orthogonal to their neighbors. The distribution of the positions of the DUs on the seabed (the so-called footprint) is homogeneous. The footprint forms a roughly circular shape and has a typical DU density corresponding to an average distance between neighboring

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detection units of about 180 m. The total instrumented volume of the detector is 5.8 km^3.

For the present study we have simulated the detector signal produced by neutrinos using the HOURS (Hellenic Open University Reconstruction and Simulation) physics analysis package [4]. We have used a generic neutrino flux distributed isotropically (in a 4π solid angle) on the Earth's atmosphere, with an energy distribution following a power law spectrum, with a spectral index of -2.0, in the range of 15 GeV–100 PeV.

In the following, the signal produced by the secondaries of a neutrino interaction event in the vicinity of the neutrino telescope is described by a collection of active DOMs (hits), $h_i(t_i,\vec{H}_i,m_i)$ $(i=1,..,N_{hit})$. Each hit is described by the first photon arrival time, t_i, the active DOM's position, $\vec{H}_i$, and the multiplicity, m_i. The hit multiplicity is the number of active 3-in. PMTs of a DOM within a time window of 10 ns. A level one (L1) coincidence trigger is defined to fire/be activated for $m_i>1$.

A random background rate of 5 kHz is assumed for each 3-in. PMT, including dark current, ^{40}K decays, and bioluminescence. In addition to random coincidences, an L1 hit (with multiplicity $m=2$) rate of 500 Hz is assumed on each DOM, due to genuine coincidences from ^{40}K decays.

For each signal event, produced by a neutrino emanating from a known astrophysical point source, we assume that the direction vector, $\hat{d}$, of the muon track coincides with the source direction. In order to estimate the fake signal produced by implying in the analysis a certain direction, we assume for background events (atmospheric neutrinos and atmospheric muon bundles) a random (fake) candidate muon track direction distributed isotropically in a 4π solid angle.

3. Background filtering

The filtering technique of the ^{40}K optical background is based on a causality criterion that uses the assumed direction vector, $\hat{d}$, of the muon track generated by the incident neutrino. The arrival time, t_i, of a photon emitted by the muon with the Cherenkov angle, θ_c, to a DOM located at position $\vec{H}_i$ satisfies the relation

$$ct_i=a_i+b_i\tan\theta_c \tag{1}$$

where $a_i=\hat{d}\cdot(\vec{H}_i-\vec{V})$, and $b_i=|\vec{H}_i-\vec{V}-a_i\hat{d}|$ is the vertical distance of the DOM to the muon track. $\vec{V}$ is the position vector of the pseudo-vertex, corresponding to the position of the muon when the time measurement started.

Two hits $h_i(t_i,\vec{H}_i,m_i)$ and $h_j(t_j,\vec{H}_j,m_j)$ produced by direct photons on two different DOMs according to Eq. (1) satisfy the following relation, in which $\vec{V}$ is eliminated:

$$\frac{c\Delta t-\hat{d}\cdot\Delta\vec{H}}{\tan\theta_c}=\Delta b \tag{2}$$

where $\Delta t=t_i-t_j$, $\Delta\vec{H}=\vec{H}_i-\vec{H}_j$ and $\Delta b=b_i-b_j$. If we project the DOM's positions on a plane perpendicular to the assumed direction $\hat{d}$, then from simple geometry and using Eq. (2) we have the relation

$$|\Delta b|=\left|\frac{c\Delta t-\hat{d}\cdot\Delta\vec{H}}{\tan\theta_c}\right|<|\Delta\vec{H}-(\hat{d}\cdot\Delta\vec{H})\hat{d}|. \tag{3}$$

According to Eq. (3) we form the causality criterion to be satisfied by the two hits

$$|c\Delta t-\hat{d}\cdot\Delta\vec{H}|<\tan\theta_c|\Delta\vec{H}-(\hat{d}\cdot\Delta\vec{H})\hat{d}|+ct_s \tag{4}$$

where $t_s=10$ ns is inserted in order to relax the causality requirement, due to light dispersion and time jitter effects. In order to limit the number of noise hits satisfying this criterion, we also require the longitudinal distance between the two DOMs along the direction of the muon track to be

$$|\hat{d}\cdot\Delta\vec{H}|<800\ \text{m} \tag{5}$$

while the corresponding lateral distance should be less than one absorption length[1]:

$$|\Delta\vec{H}-(\hat{d}\cdot\Delta\vec{H})\hat{d}|<67.5\ \text{m}. \tag{6}$$

Eqs. (4)–(6) define the causality condition that has to be satisfied by any two hits.

In order to use this condition as criterion for background filtering, for every hit, h_i, we calculate the following sum:

$$M_i=\sum_{j=1}^{N_{hit}} m_jC(h_i,h_j)$$

where m_j is the multiplicity of the hit h_j defined in Section 2, while $C(h_i,h_j)=1$ if the causality condition is satisfied by the two hits, or 0 otherwise. If $M_i<5$ the hit h_i is rejected. When we apply this filtering technique we achieve a 99.7% rejection of the noise hits, while more than 90% of the signal hits survive.

4. Triggering and prefit

For every three hits on different DOMs, that when combined in pairs satisfy the causality condition, a pseudo-vertex, $\vec{V}$, can be found analytically, as described in the following. Using Eq. (1) we calculate that

$$ct_i=\hat{d}\cdot(\vec{H}_i-\vec{V})+b_i\tan\theta_c\Rightarrow$$
$$c_i+z'=b_i(i=1..3) \tag{7}$$

where

$$z'=\frac{\hat{d}\cdot\vec{V}}{\tan\theta_c} \tag{8}$$

and $c_i=(ct_i-\hat{d}\cdot\vec{H}_i)/\tan\theta_c$.

Then, we define a new coordinate system with the z-axis parallel to the assumed direction $\hat{d}$, the origin at the point defined by $\vec{H}_1$, and the xz-plane defined by the z-axis and the point defined by $\vec{H}_2$. The base vectors of this coordinate system are

$$\hat{x}=\frac{1}{p}(\vec{H}_2-\vec{H}_1)-\frac{1}{p}[\hat{d}\cdot(\vec{H}_2-\vec{H}_1)]\hat{d}$$
$$\hat{y}=\frac{1}{p}\hat{d}\times(\vec{H}_2-\vec{H}_1)$$
$$\hat{z}=\hat{d}.$$

In this frame, the projections of the three hits that we consider on the xy-plane are: $\vec{H}_1(0,0)$, $\vec{H}_2(p,0)$, $\vec{H}_3(q,r)$, where the values of p,q and r can be estimated easily from the positions of the hits. The unknown pseudo-vertex $\vec{V}(x,y,z)$ is expressed as follows:

$$\vec{V}=\vec{H}_1+x\hat{x}+y\hat{y}+z\hat{z} \tag{9}$$

where from Eq. (8)

$$z=\hat{d}\cdot(\vec{V}-\vec{H}_1)=z'\tan\theta_c-\hat{d}\cdot\vec{H}_1. \tag{10}$$

Taking into account that b_i in Eq. (7) is the vertical distance of the hit position from the track, then the x, y, z' satisfy the following set of equations:

$$b_1^2=(c_1+z')^2=x^2+y^2$$
$$b_2^2=(c_2+z')^2=(x-p)^2+y^2$$
$$b_3^2=(c_3+z')^2=(x-q)^2+(y-r)^2,$$

[1] This is the maximum absorption length for wavelength 440 nm.