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Application of Kalman filter methods to event filtering and reconstruction for neutrino telescopy ☆

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ABSTRACT

Event reconstruction in underwater neutrino telescopes suffers from a high background noise due to the ^{40}K decays. Adaptive algorithms are able to suppress automatically such a noise and therefore are considered as good candidates for track fitting at the KM3NeT environment. In this note we describe an iterative event filtering and track reconstruction technique, employing Kalman filter methods and we present results from a detailed simulation study concerning the KM3NeT detector. We evaluate the accuracy of this technique and we compare its efficiency with other standard track reconstruction methods.

1. Introduction

The KM3NeT consortium is currently working on a conceptual design for a future Mediterranean neutrino telescope, which will have an instrumented volume of a scale of 1 km^3 [1,2]. The main background counting rate in the optical modules of an undersea neutrino detector originates from the decay of radioactive elements in the water. Sea water contains small amounts of the naturally occurring radioactive potassium isotope, ^{40}K. This isotope decays mostly through β-decay releasing electrons that produce Cherenkov light and produce a steady, isotropic background of photons with rates of the order of 100 Hz per square centimeter of photocathode area. Although the induced number of photoelectrons per photomultiplier during the time it takes a muon to pass the detector (a few microseconds) is moderate there is still a chance that these hits may mimic the signature of a muon or a shower or, more importantly, contaminate the hit pattern of a neutrino-induced event. This random background can be reduced by coincidence methods to an acceptable level. But even after the application of such methods the level of the contamination is of the order of the signal itself. Adaptive algorithms are able to suppress automatically such a noise and therefore are considered as good candidates for track fitting at the KM3NeT environment. Adaptive algorithms, based on Kalman filter methods, are extensively used in accelerator particle physics experiments, for event filtering, track reconstruction and vertex definition [3].

2. KM3NeT detector simulation

2.1. Detector description

In this study, the neutrino telescope was assumed to consist of 80 strings, 125 m apart, in hexagonal geometry as in the IceCube detector [4]. Each string was carrying 60 storeys, with a vertical distance of 17 m between them. Each storey of the detector consisted of two Optical Modules (OMs), one looking up and the other looking down, while the OM consisted of 20 cylindrical PMTs 3 in. in diameter inside a 17 in. benthos sphere, covering 2π in solid angle [5,6]. Detailed Monte Carlo description[1] of the MultiPMT OM has shown a directional sensitivity with a median of about 20°. Fig. 1 presents the probability distribution function of the space angle between the active PMT's direction of the OM and the wavefront direction of incidence. The information of the directionality of the hits can be used to form a direction likelihood for each reconstructed event. This likelihood can be used as a candidate track quality criterion.

2.2. Simulation

The track reconstruction resolution and efficiency of the techniques described in this note were quantified by a Monte Carlo study using KM3Sim [7], a GEANT4 [8] based simulation package to describe the passage (energy losses, electromagnetic shower production, multiple scattering, Cherenkov light emission)

☆ This work is in the framework of the KM3NeT Design Study.

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[1] The description included the absorption length and the refractive index of the benthos and PMT glass, as well as the optical properties of the Gell used for the optical coupling.

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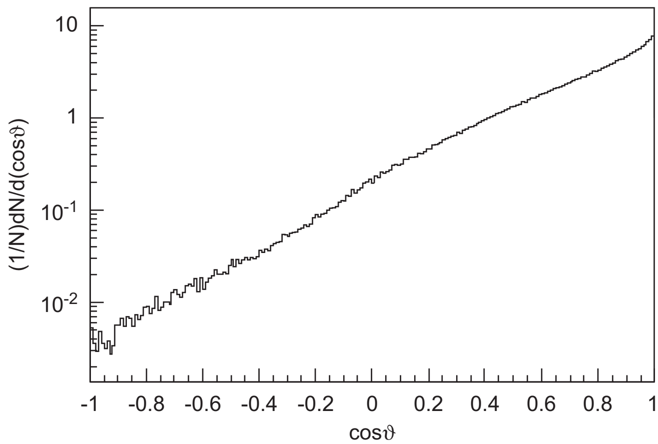

Fig. 1. The PDF of the space angle between the active PMT's direction of the MultiPMT OM and the direction of the incident wavefront.

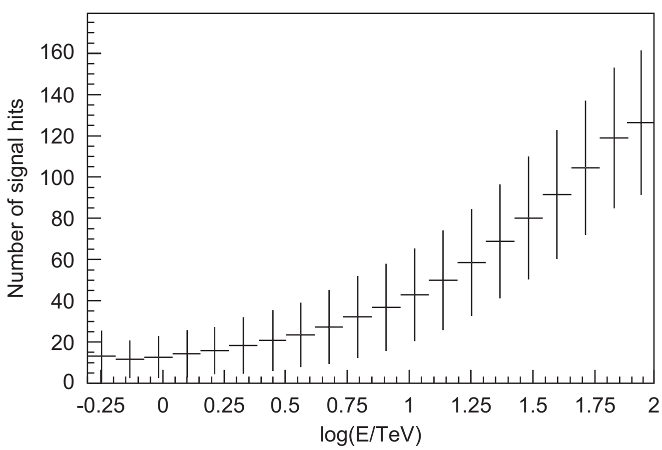

Fig. 2. The mean number of active OMs as a function of muon energy. The vertical error bars represent the RMS of the number of active OMs.

of muons through the water, the optical background generation due to the ^{40}K radioactive decays and optical photon absorption.[2] In this study muons generated in the energy range from 500 GeV to 100 TeV were fully simulated. Fig. 2 presents the mean number of signal hits versus the muon energy. A constant background noise of 6.4 kHz on each 3 in. PMT was assumed, due to PMT dark current and ^{40}K decays. To reduce the number of noise hits to an acceptable level the coincidence of 2 PMTs in an OM was required in a time window of 20 ns. This results in a background noise of 310 Hz per OM. The maximum distance any muon can travel in the detector is 1500 m leading to a maximum time window of 4.5 μs. Subsequently each simulated event contained on average 13.5 noise hits.

3. Muon track reconstruction

3.1. Initial prefit and filtering

The stage before the actual track reconstruction is a prefit and filtering based on the clustering of track segments. A track segment is defined as the line between the positions of two active OMs and a candidate track is defined as a track which passes between these two points in space if at least 4 other hits are consistent with this track (the corresponding residual must be between −60 and 60 ns). If no candidate track is found the event is rejected. The next step after the definition of all the candidate tracks is the clustering in direction. For each candidate track the number of other neighbouring candidate tracks with a maximum space angle of 15° is found. The track with the largest number of neighbours is chosen as the best candidate solution. Hits with residuals between −40 and 40 ns are considered consistent with the best candidate solution, while the rest are rejected. Fig. 3 presents the filtering efficiency of this rejection technique. The filled (open) circles represent the percentage of noise hits before (after) the application of the prefit.

[2] The absorption length we have used has a maximum of 60 m at 480 nm. Optical photon scattering was not included in the simulation.

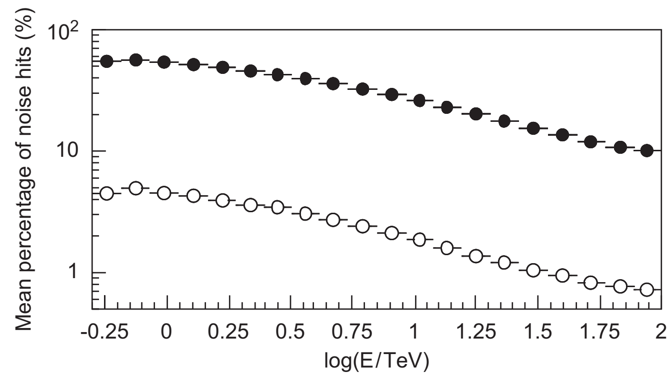

Fig. 3. The mean percentage of noise hits before (black dots) and after (open circles) the application of the prefit rejection technique.

3.2. χ^2 fit

The arrival time of the selected hits is used in a χ^2 minimization in order to estimate the track parameter vector, $\boldsymbol{x} = (\boldsymbol{V}, \theta, \phi)$, where the vector $\boldsymbol{V}$ is the pseudovertex, while θ and ϕ are the zenith and the azimuth angles of the muon track, respectively. The χ^2 estimator is defined as

$$\chi^2 = \sum_{i=1}^{N_{\rm hit}} \left(\frac{t_i^{\rm exp} - t_i}{\sigma_i} \right)^2 \tag{1}$$

where $N_{\rm hit}$ is the number of the hits used for the track reconstruction, $t_i^{\rm exp} \equiv t_i^{\rm exp}(\boldsymbol{x})$ is the expected arrival time of the ith hit, assuming that the pulse is the PMT response to the Cherenkov light produced by a muon track with parameter vector $\boldsymbol{x}$, t_i and σ_i are the arrival time and the error of the ith hit, respectively. The $t^{\rm exp}$ is evaluated as

$$t^{\rm exp} = (L + D \cdot \tan(\theta_c))/c \tag{2}$$

$$L = \boldsymbol{d} \cdot (\boldsymbol{h} - \boldsymbol{V})$$

$$D = |\boldsymbol{h} - \boldsymbol{V} - L \cdot \boldsymbol{d}|$$

where $\boldsymbol{h}$ is the position vector of the active OM, $\boldsymbol{d}$ is the direction unit vector of the track and θ_c is the Cherenkov angle.

3.3. Kalman filter

A way to perform both track fitting and background noise filtering is the Kalman filter technique. In the most general formulation Kalman filter can incorporate process noise (multiple