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# Track Reconstruction and Background Rejection for the Baikal Neutrino Telescope

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## Abstract

We describe procedures to reconstruct muon tracks in the Baikal Neutrino Telescope including effective filtering of badly reconstructed events. Special attention is payed to reject downward going muons faking upward going muons from neutrino interactions. It is shown that a rejection factor of $10^6$ – as it is needed to operate a neutrino telescope at 1100 m.w.e. depth – can be obtained with a 200 PMT array. We present first results from NT-36, the 1993 array consisting of 36 PMTs. We observe satisfying agreement between Monte Carlo results and experimental data. This gives us confidence to our simulations of the full detector.

The crucial question in running an underwater detector as a neutrino telescope is whether one can reject the background of downward atmospheric muons faking upward moving muons. At 1 km depth, downward muons exceed the upward moving muons from interactions of atmospheric neutrinos by a factor of $10^6$.

The expected median angular resolutions for deep underwater detectors like the Baikal telescope NT-200 [1,2] are of the order of $1^\circ$. However, the zenith mismatch angle distribution from a simple fit alone is characterized by a long tail. Following only the usual fit procedure, fake events in NT-200 would exceed the events due to neutrinos generated in the atmosphere by several orders of magnitude.

We adopted the following reconstruction procedure:

- preliminary analysis including several causality criteria and a 0th approximation,
- $\chi^2$ minimum search,
- application of criteria to reject badly reconstructed events.

The toolset of these criteria implies the following cuts:

i) upper limit on the minimum $\chi^2$,
ii) upper limit on the time residuals of each individual PMT,
iii) upper limit on the maximum distance of a PMT to the reconstructed tracks,
iv) lower limit on the product of probabilities, $P_{nohit}$, of non-fired PMTs not to respond to a naked muon,
v) rejection of "quasi-peripheral" events, i.e., events with a reconstructed track crossing the array volume but not intersecting the polygon spanned by the fired PMTs,

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vi) upper limit on the large semi-axes of error ellipses in the error matrix obtained from the fit,
vii) upper limit on the angular error obtained from the error matrix,
viii) lower limit on the planarity (i.e. rejection of events where all PMTs lay in a plane)
ix) lower limit on the main axis of the tensor of inertion of the PMTs hit,
x) exclusion of zero correlation or full correlation between fitted track parameters.

For the NT-200 array, we have generated and analyzed about $2 \cdot 10^6$ events from single atmospheric muons [3]. No event was found which passed all criteria and was reconstructed as an upward event, corresponding to a preliminary upper limit of about $3 \cdot 10^2$ for the number of fake events per year (Fig.1). This compares to about 250 events per year passing all criteria and being due to atmospheric neutrinos from the lower hemisphere. Most of the fake events are expected to concentrate near the horizon. Regarding only muons within a certain cone around the opposite zenith, the upper limit of the signal-to-background ratio should be much better.

In the following, we present results obtained with NT-36 (see the talk of G.V.Domogatsky). NT-36 is the first operating deep underwater detector alloing full spatial reconstruction of muon tracks. It gives the first possibility to check experimentally the numerous methods of track reconstruction and background rejection developed in our collaboration. The detector consists of 36 PMTs arranged in pairs. The PMTs of one pair are switched in coincidence, so actually the 36 PMTs define a lattice of 18 space points ("channels"). It turned out that some of the criteria developed for NT-200 are not very effective for such small arrays, that's why we have used only criteria i-iv, ix and x up to now.

Fig.2 shows the time residual of channel 7 after the fit. Good agreement between MC calculations and experiment is observed if in addition to single muons also muon bundles are included in the MC calculations. Actually, the average number of muons per event giving at least one hit is 1.6 for NT-36. Since multi-muon events do not correspond to the model underlying the $\chi^2$-procedure, most of them are rejected by the criteria applied after the fit.

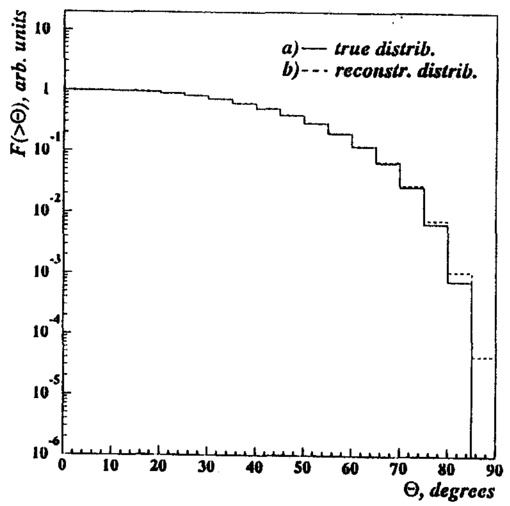

**Fig. 1:** The number of atmospheric muons in NT-200 as a function of zenith angle $\theta$ (integral distribution). (a) generated, (b) after reconstruction procedure.

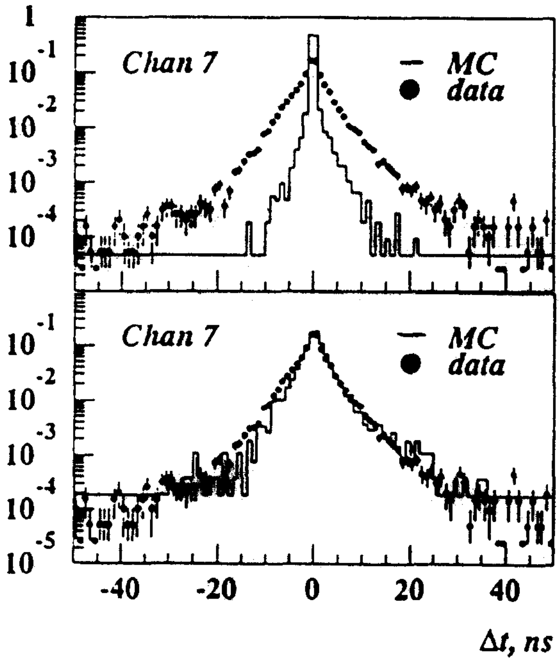

**Fig. 2:** Time residual after fit for channel 7 of NT-36. Points are the experimental data, lines are MC results with *a)* including only single muons and *b)* including also muon bundles.

Fig.3 shows the distribution of the zenith mismatch angle as obtained from MC calculations. The medium zenith mismatch angle is 2.9°. In fig.4, the zenith angle distribution of the reconstructed muons having passed all the cuts is shown. There remains a rest of $1.5 \cdot 10^{-3}$ of the initial sample which is reconstructed as upward going muons. Applying the same cuts to a MC sample of neutrino events one gets a reduction factor of 0.45. Thus the ratio of fake events to muons from atmospheric neutrinos is $10^6 \cdot 1.5 \cdot 10^{-3}/0.45 \approx 3 \cdot 10^3$.

All the cuts mentioned above basically reject events being candidates for large errors in the fitted parameters. They do not relate to the hemisphere which the muon comes from. Therefore, we finally applied a filter in the phase space of time differences between modules along one string which essentially acts as a "smooth" cut in the zenith angle. It rejects most muons from the upper hemisphere and cuts away only a few of the $\nu$-events just below horizon. Together with the standard criteria we got a rejection factor of $4 \cdot 10^{-5}$ for our experimental sample as well as for the sample of MC generated downward muon events, with a 30-percent survival rate for the MC neutrino sample. This yields $10^6 \cdot 4 \cdot 10^{-5}/0.3 \approx 1.3 \cdot 10^2$ as the ratio of fake events to true neutrino events.

It turned out that, by careful inspection of the remaining candidates for neutrino events, further fake events can be rejected. However, the remaining two orders of magnitude which are necessary to bring the fake events to the same level as the events from atmospheric neutrinos will be possible only with a bigger array. The results from NT-36 and their agreement with MC calculations support our confidence gained from simulations of NT-200 (see above), namely, that a 200 PMT array in 1 km depth can be operated as neutrino telescope.

## References:

1. S.D.Alatin et al., Nucl.Phys.B (Proc.Suppl.), 28A (1992) 491-495

2. I.Sokalski, Ch.Spiering (eds.), The Baikal Neutrino Telescope NT-200, Baikal-Note 92-03

3. I.A.Belolaptikov et al., Proc. 23rd ICRC, Calgary 1993, v.4, 577

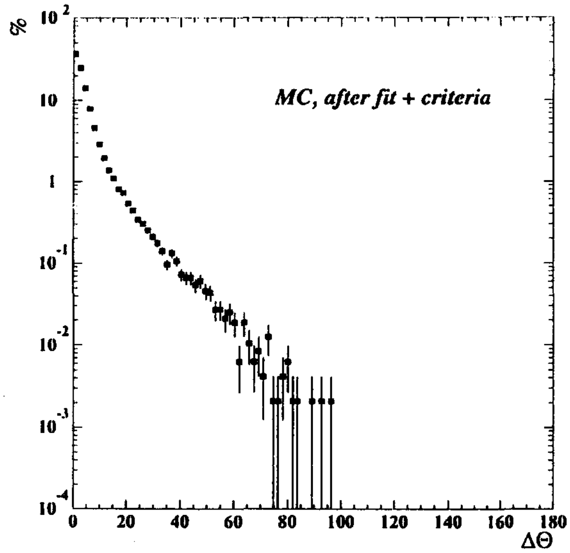

**Fig. 3:** Distribution of the zenith mismatch angle for NT-36 obtained from MC simulations.

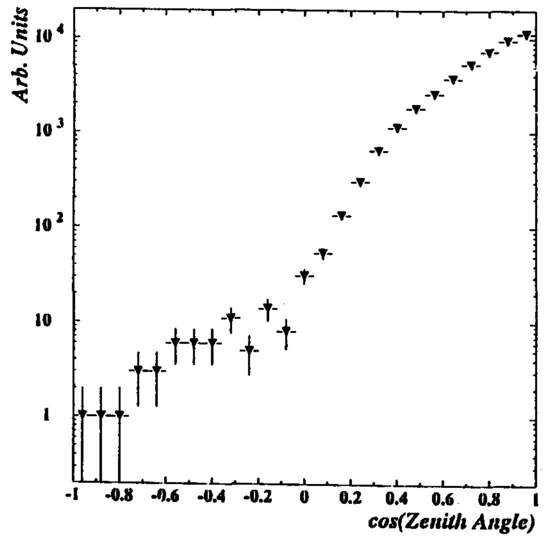

**Fig. 4:** Zenith angle distribution of reconstructed muons in NT-36 after application of rejection criteria (statistics of 1 day, 16 channels operating).