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AN UNDERWATER DETECTOR AND SOFTWARE FILTERS FOR BACKGROUND

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Abstract

A common problem of the neutrino detection is the cut of the background. To this aim, a simple method has been successfully employed to a Monte Carlo simulation of a large-scale neutrino detector, hopefully giving useful suggestions to the problem of the 'km^3 detector'.

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1 Introduction.

The underwater detector is composed by a matrix of optical elements (in the following, OM's) with high sensitivity optical sensors - photomultiplier tubes (PMT). Unlike conventional detectors in high energy physics water Cherenkov detectors do not measure directly the trajectories of particles, but rather detect secondary light and reconstruct these trajectories *off-line*. The fit procedure requires the minimization of the quantity

$$\chi^2 = \sum_{i=1}^{N_{hit}} (\frac{t_i^{exp} - t_i^{cal}}{\sigma})^2, \tag{1}$$

where N_{hit} is the number of hitted OM's, t_i is the hit time in OM i, t_i^{cal} is the predicted time of arrival of the light from the track at OM i and σ is the instrumental time resolution.
The predicted time in each hitted OM i is taken as that for a minimum ionizing track by ignoring light from μ accompaniations and photon multiple scattering. The $t^i_{cal}(\mathcal{R}_0, \vartheta, \varphi)$ depends on parameters of muons trajectory (the coordinates $\mathcal{R}_0(x_0, y_0, z_0)$ and the angles ϑ, φ) and calculates with respect to the time when the muon is in the pseudo-vertex position $\mathcal{R}_0$.
This procedure bases on the following assumptions:
a) there is not any background;
b) the time response t_i^{ex} of the OM i corresponds to time of arrival of the light at OM i; c) Cherenkov light is emitted by 'naked' muon only.
In practice, the situation is more complicated. In salt water of oceans or seas there is significant optical background which causes an increase in OM noise rate. Moreover, the PMT has the time resolution and dark current noise. For large scale detectors where several hundreds or thousands of OM's are deployed this noise can pose severe technical problems in event triggering and reconstruction.
However, the noise problem can be solved by using special hardware, for example, use two OM's switched to a local coincidence instead of individual OM's. This brings the disadvantage that the required number of PMT's is doubled and due to the coincidence condition the mean visual range becomes smaller (due to increase of the effective threshold amplitudes). The advantages are much easier signal processing and possible use of simple and fast reconstruction algorithm without the need of sophisticated noise reduction algorithms.
This report describes the algorithm developed to reduce significantly the background.

2 The PMT and the optical background.

One of the source of the background hits is the dark current transit-time-accuracy of the PMT. A single photo-electron peak is visible in the distribution of dark noise. The probability of dark current amplitudes, for example, of Hamamatsu 2018 PMT more than 3 $p.e.$, is of $0.01 \div 0.03$. The noise rate at $0°$ C is of 10 kHz at 1 p.e. This PMT reaches a transit-time-accuracy (FWHM) of about 6 ns for 1 p.e. signals in full illumination and a pulse-height accuracy (FWHM) of 120%. The probability of the pre-pulse is $P \simeq N_{pe}\omega_p$, where N_{pe} is the number of photo-electrons emitted by the photocathode and $\omega_p \simeq 0.01 \div 0.03$. The pre-pulse outspreads the main pulse in 50 ns. The probability of the late-pulse is $P \approx \omega_\ell^{N_{pe}}$ where $\omega_\ell \approx 0.01 \div 0.02$ and it can be delayed up to 100 ns. The pre-pulses and late-pulses can be regarded as background hits since in this cases the time response of the OM does not correspond to the time of arrival of the light at the OM.

It is well known that ^{40}K and bioluminescence are the main sources of the light background in ocean or sea salt water. A typical isotropic photon flux is $\Phi \equiv 200$ quanta$/cm^2/sec$. The rate of ^{40}K is a constant incoherent source of signals with a rate of $R \equiv$ 20-50 kHz (Hamamatsu 2018 PMT), and an amplitude threshold $\mathcal{A}_{th} \simeq 0.8 \div 1.2$ p.e. The detections of amplitudes higher than 1 p.e. is generally unlikely - more than 98% of registered signals are 1 p.e..

An important feature of bioluminescence is that the emission of light can be stimulated mechanically. The peak emission lies in the region of maximum water transparency. The emission duration ranges from short ms-pulses up to several minutes. Intensities can be small, exceeding the photons due to ^{40}K only short distances ($\sim m$) up to the emission of more than 10^{12} photons. The pulses often show a fast rise-time and a long decaying tail. Intensity-depth relationship in the Pacific Ocean (> 2 km) was found to decrease roughly exponentially with depth as $\sim \exp^{-h/h_0}$ where $h_0 \sim 0.8 \div 1.0$ km.

Studies of the depth dependence indicate that the bioluminescent background is roughly equal to the radiogenic light background at 4 km depth, for stationary detectors. Based on data with SPS [1], we estimate that the single rates of Hamamatsu PMT at $\mathcal{A}_{th} \sim 1$ p.e. are: $R(^{40}K) = 20.6$ kHz and R(bio)$= 57.3^{+3.1}_{-10.3}$ kHz at depth of 4 km.

3 The underwater detector and the algorithm of background filtering.

To test the algorithm of background filtering we simulated the response of the underwater detector to *'naked'* muons. The chosen configuration (see Fig. 1) of the detector is an hexagonal tower made of 7 strings (1 in the centre and 6 on the vertices of the hexagon) with distance between the strings equal to 16 m. Each string consists of 6 pairs of OM's with a vertical spacing of 20 m. The PMT's of each pair look into opposite directions, one down-one up, in order to achieve a 4π sr sensitivity for the detector. So, this structure is 100 m high with a diameter of 32 m and contents a total of 84 PMT's. We simulated the response of the detector by

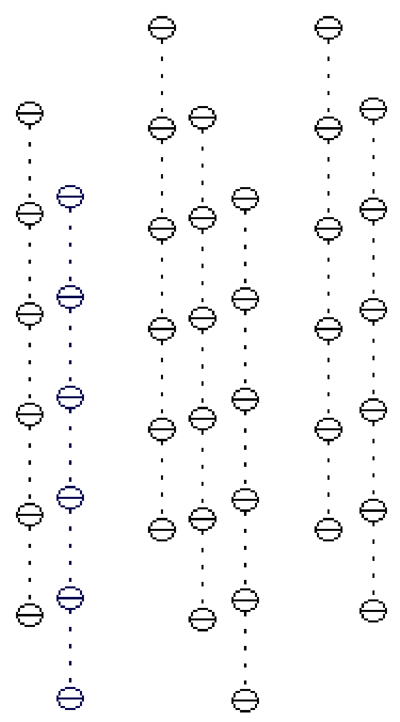

Figure 1: *Sketch of the underwater detector.*

taking into account the timing distribution (Gaussian distribution with $\sigma = 2.5$ ns at $\mathcal{A} = 1$ $p.e.$) as well as the pre-pulse and late-pulse of the Hamamatsu 2018 PMT. Time window for the trigger conditions determined by the the size of this detector was taken equal to 500 ns. For this time window the background hits due to ^{40}K, bioluminescence and dark noise of PMT's was simulated randomly. The rate for ^{40}K as well as for bioluminescence was chosen of 20 kHz with the amplitude of 1

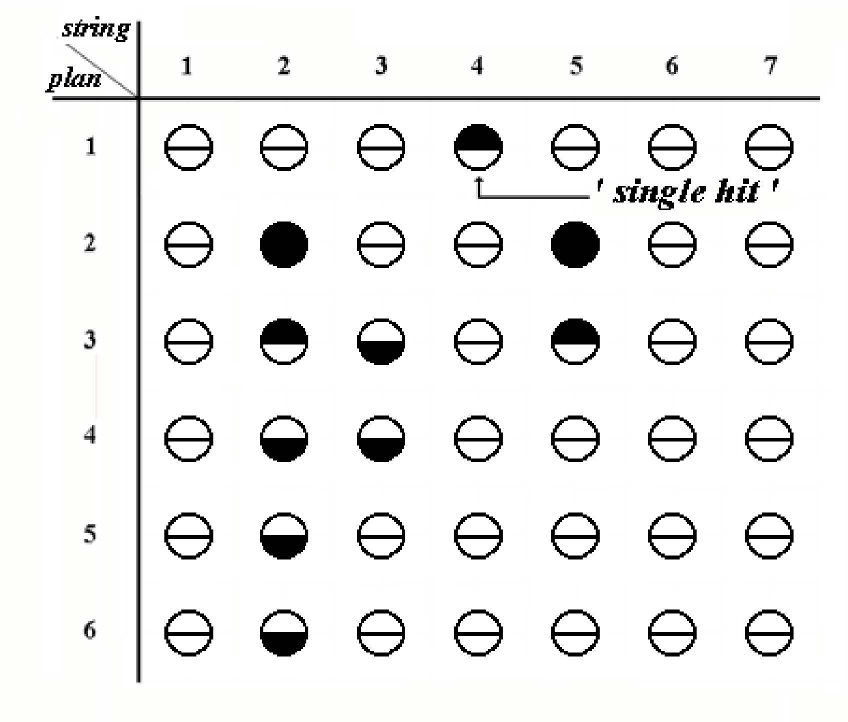

Figure 2: *The example of the* single *hit.*

p.e.. We have made runs assuming two variants for single PMT noise rate: one with the rate of 60 kHz (so called OLD variant) and the other with the rate of 5 kHz (so called NEW variant). The hits due to background, pre-pulse or late-pulse will be called BAD hits, while the other hits will be the GOOD ones.

The trigger conditions were the following:

◇ the number of hitted OM's, $N_{hit} \geq 12$

◇ the number of hitted strings, $N_{st} \geq 3$

◇ the number of hitted plans, $N_{pl} \geq 2$ (if N_{pl}=2, more than 4 OM's on each plan at least).

FILTER1.

1) If event passed the trigger for each pair of the hitted OM's the following conditions

are tested:

$$| t_i^{ex} - t_j^{ex} | < \frac{n\mathcal{R}_{ij}}{c} + m\sigma_{PMT} \quad (2)$$

where $t_{i(j)}^{ex}$ is the hit time in OM i (j), $\mathcal{R}_{ij}$ is the distance between OM i and OM j, $n = 1.32$ and $m = 1.5$ have been found after optimization. The condition (2) requires that $\Delta t_{ij} =| t_i^{ex} - t_j^{ex} |$ does not exceed the time that the Cerenkov wave front to pass between the $i-th$ and the $j-th$ OM's.
For the matrix elements one gets

$$a_{ij} = \begin{cases} 1 & \textit{if condition (2) is fulfilled} \\ 0 & \textit{otherwise} \end{cases}$$

2) After testing all pairs of the hitted OM's the maximal S_{max} and the minimal S_{min} elements of the array

$$S_i = \sum_{j=1}^{N_{hit}} a_{ij} \quad (3)$$

are determined, as well as the corresponding numbers of OM's:

$$S^{max} \to i_{max} \text{ and}$$

$$S^{min} \to i_{min}.$$

3) If the amplitude of the $OM_{i_{min}}$ $\mathcal{A}_{i_{min}} < 3$ $p.e.$, the $OM_{i_{min}}$ toss out from the following analysis and otherwise the hit time $t_{i_{min}}^{ex}$ regards as OM with pre-pulse and are corrected as

$$t_{i_{min}}^{ex} \to t_{t_{min}}^{ex} + 50 \ \ ns. \quad (4)$$

The iterations 2), 3) and 4) continue until the condition

$$S^{max} - S^{min} = 1 \quad (5)$$

will be reached.
If the condition (5) is fulfilled, the *single* hits, that is the case when there is one hit on one string and one plan only (as shown in Fig. 2), are tossed out.
Moreover, the *isolated* hits, that are hits which are separable from the main group of the hitted OM's by the plan without any hitted OM's (as Fig. 3 shows) are tossed out.
If after the **FILTER1** procedure the trigger conditions are not fulfilled the event is discarded otherwise the **FILTER2** procedure starts.

FILTER2.

A fast, efficient preliminary track reconstruction algorithm *(pre-fit)* is used for the track fit [2]. Let the position vector of the muon at time t as from the basics of

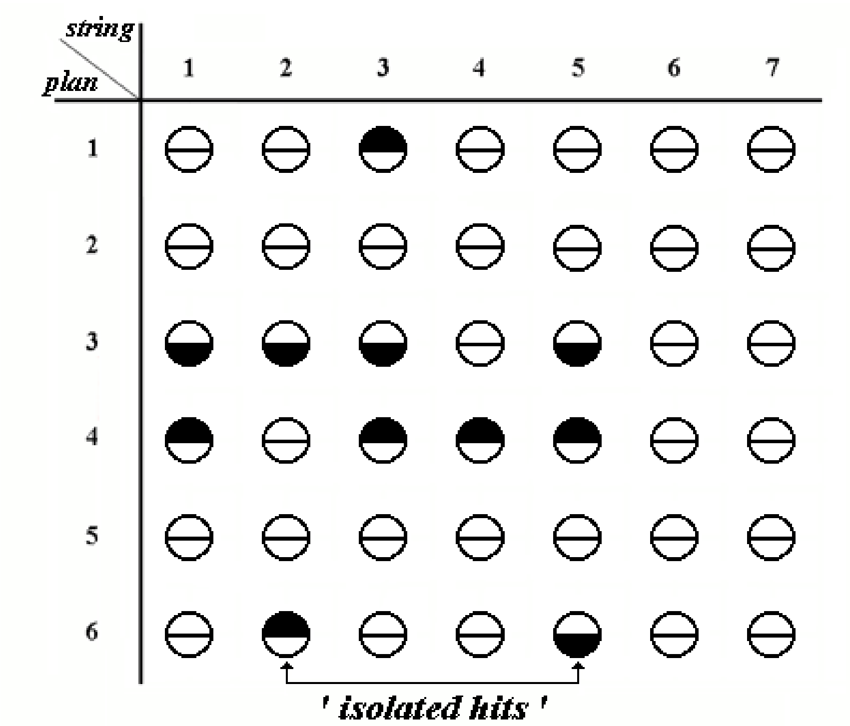

Figure 3: *The example of the* isolated *hits.*

physics

$$r = r_0 + vt \tag{6}$$

that the muon speed is c, so that the x^j and the v^j form a set of six symmetrical parameters.

Next let us define

$$\chi^2 = \sum_{j=1}^{3} \sum_{i=1}^{N} \mathcal{A}_i (x_i^j - x_0^j - v^j t) \tag{7}$$

where $\mathcal{A}_i$ is the measured amplitude of the *i-th* OM and N is the total number of hits after the **FILTER1** procedure. Differentiating this with respect to each one of the six parameters x_o^j and v_0^j and setting the results equal to zero give the following six equations for the best fit parameters

$$v^j = \frac{< x^j t > - < x^j >< t >}{< t^2 > - < t >^2} \tag{8}$$

$$x_0^j = < x^j > + v^j < t > . \tag{9}$$

Note that Eq. (8) just expresses the fact that the velocity is a measure of correlation between position and time.
Writing out the sums explicitly we get the following formulas that can be used in practice:

$$x_0^j = \frac{1}{D} \sum_{i \neq k}^{N} \sum_{i \neq k}^{N} \mathcal{A}_i \mathcal{A}_k [x_i^j (t_k^2 - t_i t_k) - x_k^j (t_i^2 - t_i t_k)] \tag{10}$$

$$v^j = \frac{1}{D} \sum_{i \neq k}^{N} \sum_{i \neq k}^{N} \mathcal{A}_i \mathcal{A}_k (x_i^j - x_k^j)(t_i - t_i t_k) \tag{11}$$

$$D = \sum_{i \neq k}^{N} \sum_{i \neq k}^{N} \mathcal{A}_i \mathcal{A}_k (t_i - t_i t_k)^2. \tag{12}$$

Using the found parameters of trajectory the time residuals for each hitted OM are calculated:

$$\mid \Delta t_i \mid = \mid t_i^{ex} - t_i^{cal} \mid \tag{13}$$

$$\overline{\Delta t} = \frac{1}{N} \sum_{i=1}^{N} \mid \Delta t_i \mid \tag{14}$$

$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (\mid \Delta t_i \mid - \overline{\Delta t})^2 \tag{15}$$

where t_i^{cal} is the predicted time of arrival of the light from the track at OM i. If $\mid \Delta t_i \mid > 36\ ns$ and $\mathcal{A}_i < 3\ p.e.$ the OM i is tossed out while the hit time t_i^{ex} pull accordingly to (4).

Also all OM's at distances $d > d_0$ from the pre-fit trajectory where the probability of the hits with $\mathcal{A} \geq \mathcal{A}_{th}$ is small are tossed out. The value of the parameters d_0 depends on water transparency and muon energy.
In our calculation for water transparency of 30 m, *'naked'* muons and $\mathcal{A}_{th}$=1 $p.e.$, we used $d_0 = 40\ m$.
The trigger conditions are tested if one OM has been tossed out by the **FILTER2** procedure, at least. If they are fullfilled, **FILTER1** and **FILTER2** procedures are repeated one more (*typically one time*); otherwise, the event is discarded.

4 Results.

FILTER1 and **FILTER2** procedures discard 32% events which passed the trigger condition in the case of OLD variant. In this case the total background rate R_{tot}=

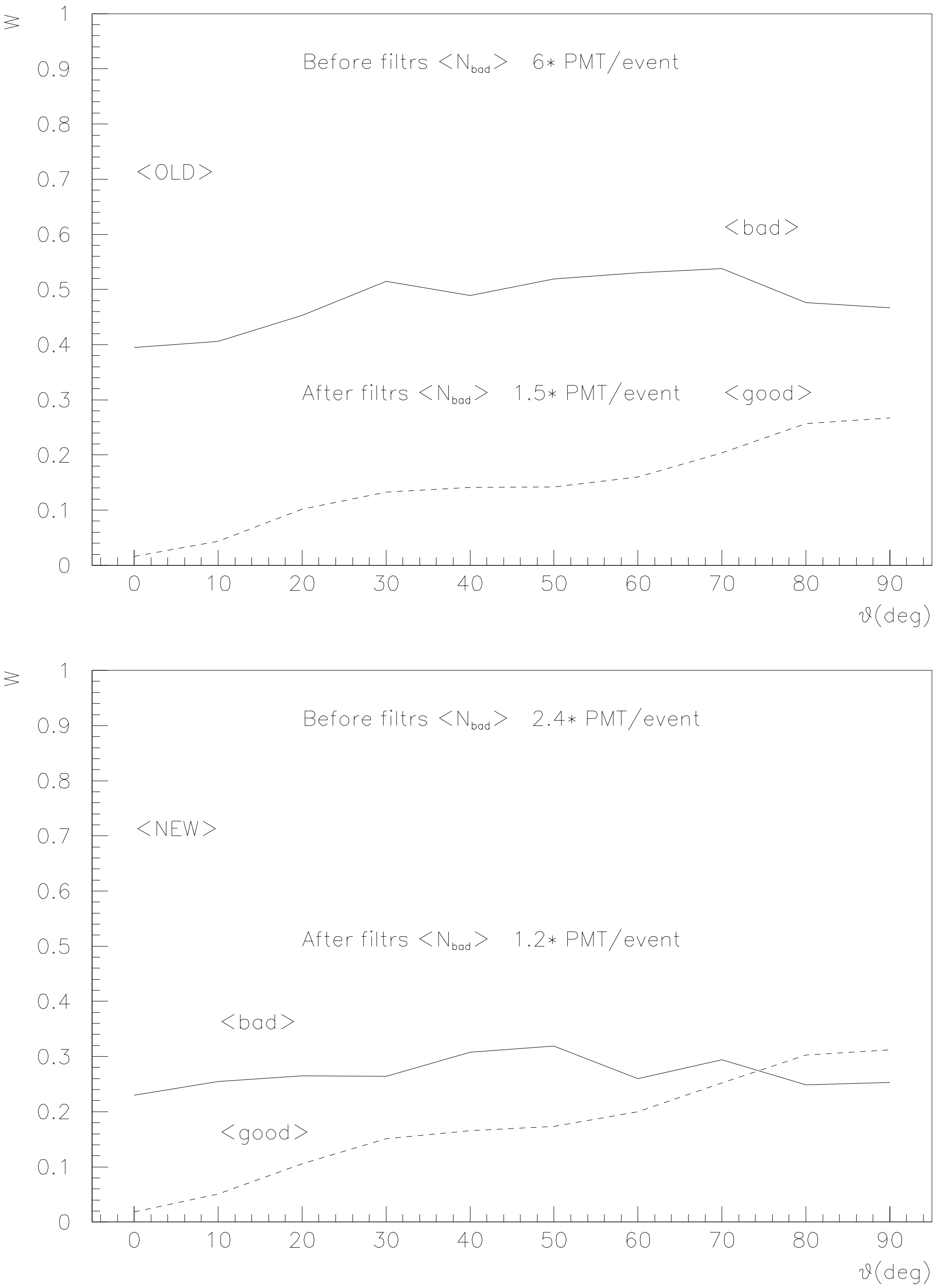

Figure 4: *Probability of maintenance of one BAD hit while one GOOD hit is tossed out.*

100 kHz and the mean number of BAD hits per event is N_{BAD}= 6. For the NEW variant (R_{tot}= 45 kHz) N_{BAD}= 2.5. After the filtering of 1.5 BAD hits remained at R_{tot}= 100 kHz and 1.2 at R_{tot}= 45 kHz. The dependence of the probabilities that one BAD hit remained and one GOOD hit tossed out, at least, is shown in Fig. 4 as function of zenith angle for both variants.
At R_{tot}= 100 kHz (R_{tot}= 45 kHz) in each the second (the third) event remained one BAD hit at least. The probability that one GOOD hit at least is tossed out increases with zenith angle in both variants but is less than 30%.
The efficiency of this algorithm is $\epsilon \geq 0.9$ at the ratio $N_{BAD}/N_{GOOD} \simeq 0.3 \div 0.4$, where N_{GOOD} is the number of GOOD hits per event.

5 Conclusions.

Simple filters have been developed to reduce the background significantly. Also they take into account the pre-pulses and late-pulses of the PMT's and allow to perform time corrections. For high energy events with large flux of light it should be important.
This procedure rejects the background hits with efficiency $\epsilon \geq 0.9$ at $N_{BAD}/N_{GOOD} \simeq 0.3 \div 0.4$ and the GOOD hits will remain with a probability larger than 70%.

References

[1] I. Badson *et al.*, Phys. Rev. **D4** (1990) 6313.

[2] V. I. Stenger, Preprint HDC-1-90, 1990.