Search for multi-flares of high energy neutrinos from Active Galactic Nuclei with the IceCube detector

THE ICECube COLLABORATION\textsuperscript{1}, \textsuperscript{2}

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Abstract: Active Galactic Nuclei (AGN) are among the best candidates for sources of high energy cosmic rays. Their relativistic jet is expected to exhibit variability with flare durations ranging from minutes to several days. One of the properties is the extreme variability of their electromagnetic emission at different wavelengths, which may be associated with the acceleration of different particles in the jet. Here we present a statistical test to look for two or more flares separated in time (multi-flare) from selected AGN classes such as Flat Spectrum Radio Quasars (FSRQs) and BL-Lacs. This method does not rely on the detailed knowledge of the EM light-curves at a given wavelength, and it allows a time lag between the EM flares and the possible neutrino flares, which is predicted in some emission models. The duration of the potential neutrino flares is a result of this approach, not an input. An extension of this method performs an additional stacked flare search using a list of promising neutrino sources belonging to the same AGN class and selected from the 2nd Fermi-LAT AGN catalog. The performance and results of the method and its extension applied to one year of IceCube data in its 79-string configuration (IC79) are presented.

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1 Introduction

The origin of cosmic rays, especially at primary energies above $\sim 10^{18}$ eV, remains the subject of intense research since their discovery. Active Galactic Nuclei (AGN) are believed to satisfy the necessary conditions to emit charged particles at such high energies \cite{ref1}. Within the context of hadronic models, neutrinos should be produced in interactions of these particles inside the AGN jet \cite{ref2, ref3}. One of the aims of the IceCube neutrino observatory is to be sensitive to this high energy neutrino flux. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic south pole between depths of 1450 m and 2450 m \cite{ref4}. Detector construction started in 2005 and finished in 2010. The reconstruction of neutrino-induced events relies on the optical detection of Cherenkov radiation emitted by secondary particles produced in neutrino interactions in the surrounding ice or the nearby bedrock.

In order to distinguish astrophysical neutrino signal events from background events generated in the atmosphere (neutrinos and muons), energy and direction reconstructions have been used in several searches for localized excesses (time-integrated methods \cite{ref5, ref6}). An additional way to improve signal-background discrimination is the use of arrival time information to reduce the effective background. AGN are known to show time variability at different wavelengths and in various time scales \cite{ref7}. The associated neutrino emission may exhibit similar variability and this is used in time-dependent methods to improve the detection probability with respect to time-integrated approaches. One such method aims to find a significant set of events clustered in time at any point in the sky (untriggered search \cite{ref8, ref9}). Another approach takes into account information extracted from $\gamma$-ray light-curves in the GeV band for a set of selected AGN. This method defines periods of high $\gamma$-ray states where neutrinos are expected simultaneously (triggered search \cite{ref8, ref9}).

Here we describe two additional time-dependent methods that are sensitive to a set of neutrino events which form not only a single flare, as assumed in the untriggered search, but are distributed in several weak flares \cite{ref10}. These multiple flares need not be synchronous with the $\gamma$-ray light curve as considered in the triggered search, permitting large time delays or different durations as proposed in some emission models \cite{ref11, ref12}.

The event selection for these two analyses is the same used in time-integrated searches with the 79-string configuration of IceCube going from May-2010 until May 2011 \cite{ref6}. It consists of 109866 events (50857 arriving from the northern sky and 59009 arriving from the southern sky) with a median angular resolution better than 1° for neutrino energies larger than 1 TeV at which the current analyses are sensitive (see Ref. \cite{ref6} for details).

2 Method

A point-source of astrophysical neutrinos is expected to manifest itself in the data as a clustering of events in space (around the position of the source candidate $\vec{x}$) which have a different spectral index ($\gamma_\nu$) from the atmospheric neutrino and muon spectra. Time-integrated searches \cite{ref5} are based on a likelihood built with background and signal probability density functions (PDFs) evaluated
for each event $i$ of the data sample. These PDFs depend on the event reconstructed direction ($\vec{x}_i$) and energy ($E_i$). The signal PDF, $S_i(x_i, \gamma)$, is calculated from simulations while the background PDF, $B_i = B^\text{Space}(\vec{x}_i)B^\text{Energy}(x_i, E_i)$, is constructed directly from data. The likelihood to be maximized is defined as:

$$
\mathcal{L}(n_s, \gamma, \vec{x}) = \prod_{i=1}^{N} \left( \frac{n_s}{N} S_i(x_i, \gamma) + \left(1 - \frac{n_s}{N}\right) B_i \right),
$$

(1)

where $n_s$ (the number of signal events) and $\gamma$ (the signal spectral index) are free parameters. $N$ is the total number of events considered. For a point-source analysis this is the number of events in a declination band around the source candidate position $\vec{x}$, during the considered data live time. The final significance is calculated from a test statistic (TS) defined as the ratio between the null and the best-fit hypothesis: $-2 \log(\mathcal{L}(n_s = 0)/\mathcal{L}(\hat{n}_s, \hat{\gamma}, \vec{x}))$, where $\hat{n}_s$ and $\hat{\gamma}$ maximize the likelihood [5].

The variability in AGN electromagnetic emission may be exploited to further reduce the atmospheric background. For this purpose time-dependent methods such as the untriggered, triggered [6], and multi-flare searches [10], include additional signal, $S^\text{time}$, and background, $B^\text{time}$, PDFs dependent on the event arrival time $t_i$. These methods differ in the functional form of the signal time PDF. In the untriggered search for example, $S^\text{time}$ is a Gaussian function with its width and centroid taken as free parameters in the likelihood maximization, whereas in the triggered search it is modeled from Fermi light-curves [6].

2.1 Multi-flare method for a single source

The first step in the present analysis is the construction of time intervals $j$ with duration $\Delta t_j$. The intervals are defined by the arrival times of consecutive "signal-like" events, i.e. $S_i/B_i > 1$, where $S_i$ and $B_i$ only include space and energy information. The region around the declination of the source candidate $\delta_s$ is defined as $\delta_s \pm 5^\circ$. The background PDF is assumed to be flat in time, $B^\text{time}(t_i) = 1/\Delta T_{\text{Data}}$. Here $\Delta T_{\text{Data}}$ is the length of the search time window, namely 80 days around the flare alert selected for each source, see section 4. Within this declination band and time search window there are on the order of 2000 events from which about 2% are "signal-like" (depending on $\delta_s$).

The signal time PDF is defined as $S^\text{time}(t_i, \Delta t_j) = 1/\Delta t_j$ if the event $i$ is inside the time window $j$ and zero otherwise. In the second step the test statistic $T S_{j}$ is calculated for each time window, $\Delta t_j$, and then used to rank it in an ordered list. In the final step the algorithm selects from this list a subset of $M_{\text{opt}}$ time windows. For this purpose a global likelihood is defined using a modified signal term:

$$
S^\text{opt}_i(\vec{x}_i, \gamma) = \sum_{j=1}^{M} w^{j} \times S_i(x_i, \gamma) \times S^\text{time}(t_i, \Delta t_j),
$$

(2)

where $w^{j} = T S_{j}$ and $M$ is the index running over the elements of the ordered list. A global test statistic is then calculated as:

$$
T S(M) \equiv -2 \log \left[ \frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s, \hat{\gamma}, \vec{x}, M)} \right].
$$

(3)

Starting from the time window that provided the largest value of $T S_{j}$, i.e. $M = 1$, and following with the next in significance, the final number of $M_{\text{opt}}$ time windows that constitute the potential multi-flare signal is chosen according to the maximum of $T S(M)$ [10]. The resulting flare activity time, $\Delta T(M_{\text{opt}})$, is defined as the time interval between the arrival time of the first event in the first time window and the arrival time of the last event in the last time window (see sub-figure in the upper-left of Figure I). The final significance is estimated from Monte Carlo simulations by applying the same analysis to a large set of scrambled datasets (trials) [10][13].

2.2 Multi-flare stacking method

An extension of the multi-flare method was developed to consider several flaring sources that belong to a particular AGN category (FSRQs or BL-Lacs) in a single statistical test. The signal term in the likelihood is replaced by the weighted sum of the contribution of each source $k$ [5]:

$$
S^\text{Stacking}_i = \sum_{k=1}^{N_s} W_k(\gamma, \vec{x}_k) \times S^\text{opt}_k(\vec{x}_k, \gamma, M_{\text{opt}}, k) / \sum_{k=1}^{N_s} W_k(\gamma, \vec{x}_k),
$$

(4)

where $N_s$ is the number of sources in an AGN category and $W_k(\gamma, \vec{x}_k)$ is the relative detector acceptance calculated from simulations as the number of events expected from a source at a certain location in the sky $\vec{x}_k$ following a differential energy spectrum proportional to $E^{-\gamma}$. The signal
As an illustrative example two simulated neutrino flares \(\gamma\) in the previous section, the spectral index, \(\gamma\), is required to achieve a p-value less than 2 potential, defined as the average number of signal events between the individual flares. Figure 1 shows the discovery activity time for 5 of the selected FSRQs (see section 4) showing that the multi-flare algorithm in this case accounts for the sum of signal events produced in all the sources in the category.

3 Performance

As an illustrative example two simulated neutrino flares separated in time (double-flare) are considered as a signal hypothesis. This configuration may not be observed in the untriggered search because the assumed single Gaussian time structure is less efficient for large time gaps between the individual flares. Figure 1 shows the discovery potential, defined as the average number of signal events required to achieve a p-value less than \(2.87 \times 10^{-5}\) (one-sided 5\(\sigma\)) in 50% of the trials, as a function of the flare activity time for 5 of the selected FSRQs (see section 4) in dashed lines. The discovery potential is approximately constant and below the time integrated search for the range of flare activity times tested in this example. This feature of the method represents an improvement in the sensitivity for large time gaps when compared with the untriggered approach (see more details on this feature in Ref. [13]).

For the stacking case we consider a category of 5 flaring sources (FSRQs). Each source contributes with a double-flare structure located in a different time window. Signal events are injected in each location and chosen time window following a Poisson distribution with mean 6 (30 in total) and an \(E^{-2}\) energy spectrum for 10\(^5\) simulated trials. Figure 2 shows the resulting best fit parameters. The centroid of this 2D distribution is located approximately in \(\delta_i = 30\) and \(\gamma_i = 2\) showing that the multi-flare algorithm is able to recover on average the parameters of the injected signal. Figure 1 shows the improvement in the discovery potential for the stacking case (filled triangles showing discovery potential per source) compared to the single source case (dashed lines showing individual source discovery potentials). Each source has to contribute with less signal events on average to reach the 5\(\sigma\) threshold in the stacking approach than if analyzed separately. Figure 3 shows the resulting discovery potential per source as a function of the total number of stacked sources for different flare activity times. Adding sources improves the discovery potential as is expected from a stacking analysis.

4 Source selection

A list of promising AGN candidates is selected in order to reduce the large trial factor that would be implied in an all-sky scan. There are several theoretical models predicting high energy neutrino emission from AGN. In Ref. [14] hard-spectrum BL-Lacs are selected as source candidates for IceCube whereas in Ref. [2] FSRQs bright in the GeV range are the promising objects without any assumption on the spectral index. The proton blazar model described in Ref. [3] predicts that the low synchrotron peaked BL-Lacs (LBL) are more likely to produce a significant neutrino emission than the high synchrotron peaked BL-Lacs (HBL). Data from the second Fermi Catalog has shown that LBLs have on average softer energy spectra than HBLs [7] and that FSRQs present a cutoff at a few GeV. In Ref. [15] a list of potential neutrino-loud AGNs is provided. In order to include these predictions in the selection of promising sources, data from the Fermi catalog was used to define the following criteria:

- **BL-Lacs**: Average flux \([1 - 100\ GeV] > 8 \times 10^{-8}\) photons cm\(^{-2}\) s\(^{-1}\) AND spectral index < 2.3
- **FSRQs**: Average flux \([0.1 - 1\ GeV] > 1 \times 10^{-9}\) photons cm\(^{-2}\) s\(^{-1}\)

With this selection we include most of the candidate sources listed in Refs. [2] [3] [14] [15]. In addition, for both source populations we require that the Fermi variability index is larger than 41.6 to select sources that are more likely to exhibit flaring periods [7]. The search time window for each AGN, \(\Delta T_{\text{Data}}\), is defined by taking into account photon flare alerts in the IC79 period reported in astronomer telegrams (Atels) [16] or other relevant references. It is restricted to \(\Delta T_{\text{Data}} = T_m \pm 40\) days where \(T_m\) is the midpoint of the flare time interval reported in each alert [10].
Table 1: Results for the selected variable AGN using the multi-flare analysis. All the p-values are pre-trial. If $\hat{\eta}_s = 0$ then no p-value or $\hat{\gamma}$ are reported.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>ra ($^\circ$)</th>
<th>dec ($^\circ$)</th>
<th>Atel ID</th>
<th>$I_n$ (MJd)</th>
<th>p-value</th>
<th>$\hat{\eta}_s$</th>
<th>$\hat{\gamma}$</th>
<th>$\Delta t$ (M$_{opt}$) (days)</th>
<th>Fluence u.l. (GeV/cm$^2$)</th>
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<tr>
<td>PKS 2326-502</td>
<td>FSRQ</td>
<td>352.317</td>
<td>-49.939</td>
<td>2783,3008</td>
<td>55415</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
<td>15.974</td>
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<tr>
<td>PKS B1414-418</td>
<td>FSRQ</td>
<td>217.012</td>
<td>-42.104</td>
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<td>55686</td>
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<tr>
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<td>278.413</td>
<td>-21.075</td>
<td>2943</td>
<td>55485</td>
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<tr>
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<td>FSRQ</td>
<td>278.413</td>
<td>-21.075</td>
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<td>3194,2385</td>
<td>55616</td>
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<td>2.3</td>
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<td>1.63</td>
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<tr>
<td>3C 279</td>
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<td>194.042</td>
<td>-5.794</td>
<td>2886</td>
<td>55467</td>
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<td>1.9</td>
<td>2.2</td>
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<tr>
<td>PKS 1329-049</td>
<td>FSRQ</td>
<td>203.015</td>
<td>-5.136</td>
<td>2728,2739</td>
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<td>2837</td>
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<td>FSRQ</td>
<td>349.497</td>
<td>16.153</td>
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<td>55520</td>
<td>-</td>
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<tr>
<td>4C+21.35</td>
<td>FSRQ</td>
<td>186.227</td>
<td>21.380</td>
<td>2684,2686</td>
<td>55364</td>
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<td>Ion 599</td>
<td>FSRQ</td>
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<td>29.247</td>
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<td>FSRQ</td>
<td>230.542</td>
<td>31.744</td>
<td>3050</td>
<td>55519</td>
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<td>1.8</td>
<td>2.0</td>
<td>0.418</td>
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<tr>
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<td>FSRQ</td>
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<td>38.171</td>
<td>3238</td>
<td>55635</td>
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<td>-</td>
<td>9.527</td>
<td>0.71</td>
</tr>
<tr>
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<td>FSRQ</td>
<td>248.809</td>
<td>38.171</td>
<td>3333</td>
<td>55368</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
<td>1.377</td>
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<td>-30.219</td>
<td>2944</td>
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<td>5.643</td>
<td>6.124</td>
<td>2800</td>
<td>55387</td>
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<td>10.836</td>
<td>3120,3129</td>
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<td>-</td>
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<td>-</td>
<td>3.792</td>
<td>0.83</td>
</tr>
</tbody>
</table>

5 Results

No significant set of events was found in the IC79 period. In Table 1 we list the results for each selected AGN: pre-trial p-values, best fit parameters $\hat{\eta}_s$ and $\hat{\gamma}$, and flare activity time, $\Delta t(M_{opt})$. The fluence upper limit (u.l.) is calculated by integrating the differential energy spectrum $\langle d\Phi/dE \sim E^{-3} \rangle$ over the 90% energy range and over the $\Delta t(M_{opt})$ time interval. Figure 2 shows the fluence upper limit as a function of the declination of the selected sources. It depends on declination since the IceCube sensitivity is different for different energy ranges accessible in each part of the sky [17]. The pre-trial p-value for the most significant AGN (PKS 1830-211) is 0.13 (0.93 post-trial) which is compatible with the expected background fluctuations.

The results for the multi-flare stacking search are shown in Table 2. The chosen categories also depend on the hemisphere in which the sources are located since IceCube is sensitive to higher energies in the southern sky [17]. The most significant category is the set of FSRQs located in the southern hemisphere ($\delta < 0^\circ$) with a post-trial p-value of 0.16 which is compatible with the background-only hypothesis. The fluence upper limits shown in Table 2 were calculated for the sum of the most significant time windows extracted for each source in each category (Table 1) divided by the number of contributing sources. We call this quantity the fluence upper-limit per source. These upper-limits are stronger than the ones extracted from the single-source analysis (Table 1) which again shows the advantage of the stacking procedure.

References

[6] IceCube Coll., paper 0550 these proceedings.
[9] IceCube Coll., paper 0649 these proceedings.