Searches for flaring and periodic neutrino emission with three years of IceCube data

THE ICECUBE COLLABORATION[1]

[1] *See special section in these proceedings*

Juan.Aguilar@icecube.wisc.edu

Abstract: Neutrinos provide a unique opportunity to study cosmic-ray acceleration processes, and their arrival times may provide additional insight about their sources. We present the results of searches for time-dependent neutrino emissions using three years of data (between April 2008 and May 2011) collected by the IceCube detector. The neutrino arrival time is used to enhance the discovery potential for sources with non-steady emission compared to that achieved by time-integrated searches for the same sources. Three different analyses are presented. An untriggered scan over one year of IceCube data has been performed using a maximum likelihood method that seeks to identify the point in the sky with the most significantly clustered events both in space and time. In the second search, a selection of flaring gamma-ray sources observed by the Fermi experiment and TeV telescopes were considered as promising sources. The gamma-ray lightcurves for each source were used to search for a coincident neutrino flux, under the assumption that neutrinos and gammas are produced at the same time in pp or p-gamma interactions. Finally, we searched for periodic neutrino emission coming from a selected catalog of binary systems and microquasars with known periodicities established from X-ray, gamma-ray and radio spectrum observations. The results of all the searches are compatible with fluctuations of the background.

Corresponding authors:
J. A. Aguilar[1],
A. Christov[1], T. Montaruli[1], M. Rameez[1]

[1] *University of Geneva, Geneva, Switzerland*

Keywords: neutrino telescope, astrophysical neutrino sources, time dependent searches

1 Introduction

IceCube is a cubic-kilometer neutrino detector installed in the ice at the South Pole [1] between depths of 1450 m and 2450 m. The detector construction started in 2005 and finished in 2010. Neutrino event reconstruction relies on the optical detection of Cherenkov radiation emitted by secondary particles produced in neutrino interactions in the surrounding ice or the nearby bedrock. The completed detector has 86 vertical strings of optical modules.

In this paper we present three searches for flaring astrophysical neutrino sources with the IceCube neutrino telescope data, enhancing the sensitivity by using timing information. In contrast to time integrated searches [2], the analyses presented here aim for further reducing the background of atmospheric neutrinos and muons by adopting the idea of correlations in the neutrino arrival times.

One of the searches presented here is untriggered as the considered time correlations are among the neutrinos themselves. This untriggered "All Sky Time Scan" looks for any possible neutrino flare in the entire sky and no information from independent observations is used. Similar triggered analysis, the "Search for Periodic Neutrino Emission From Binary Systems", assumes the period is fixed by photometric observations and the search is performed in the phase domain of the binary system. The two approaches are conceptually akin, one scanning in time and the second (equivalently) in phase; one considering the whole sky while the second only the direction of the selected binary systems.

The remaining triggered searches make use of the information obtained from gamma-ray observations. In this case we followed two approaches triggered by multi-wavelength measurements. They differ by what kind of multi-wavelength information is available. Namely "Time Dependent Searches for Flares with Extensive Coverage" uses the Fermi-LAT lightcurves which provide continuous monitoring. In contrast, the "Time Dependent Searches for Flares with Sporadic Coverage" are driven by flares reported by TeV range experiments where the data is available only for short time windows.

For searches which do not benefit from the addition of several data samples we use the 79 string configuration only. This is the case of the "All Sky Time Scan" and the "Time Dependent Searches for Flares with Sporadic Coverage". For the other searches we combine the data taken between April 2008 and May 2011, spanning across the 79-String, 59-String and 40-String configurations of IceCube.

2 Data Selection

The event selection for data from the 40, 59 and 79 string configurations is described in detail in [4] and [5].

- IceCube took data in the partially completed IceCube 40-string configuration from April 2008 until May 2009. The final sample of events obtained contained a total of 36,000 events: 14,121 from the northern sky (dominated by atmospheric muon neutrino events) and 22,779 from the southern sky where very tight selection cuts have been applied to deal with the huge atmospheric muon rate.

- From May 2009 until May 2010 59 strings were operational. The final data sample for the 59-string configuration has a total number of 107,569 events, among which almost 2/3 come from the southern sky. The rest are neutrino candidates in the northern sky.

- From May 2010 until May 2011 IceCube took data with 79 strings. The final sample contains 109,866 events where 50,857 are coming from the northern sky and 59,009 are located in the southern sky.

The detector performance was evaluated within the scope of the time integrated searches, a brief description of it and the related references are included in [2].

3 Method

This analysis uses an unbinned maximum likelihood ratio test [3]. The significance of an excess of neutrinos above the background for a given direction can be calculated using this method. Both the reconstructed direction of the event and the reconstructed visible muon energy are used in order to discriminate between signal and background [4]. This method has been demonstrated to provide superior sensitivity over simple directional clustering based methods, as the signal events have a harder energy spectrum compared to the atmospheric neutrino and muon backgrounds. The method is identical to the time integrated searches up to the point where the arrival time of the events is used to discriminate against background. To make use of the timing information in the likelihood a time "Probability Density Function" (PDF) is introduced. Depending on the search this PDF can have different forms, Gaussian, box or following the shape of an lightcurve.

3.1 All Sky Time Scan

For each direction in the sky, the likelihood function is maximized with respect to the number of signal events n_s, the power law index γ and in addition specifically for this search the mean t_0 and the width σ_w of a Gaussian function in time. The Gaussian function is a possible parametrization of a sudden increase in the emission of a source. This term is designed to identify events which are signal-like (i.e. clustered in the time). The ratio of the likelihoods between the best fit hypothesis and the null hypothesis ($n_s = 0$) forms the test statistic. The maximum likelihood is evaluated for each direction in the sky on a grid of $0.1^\circ \times 0.1^\circ$, much finer than the angular resolution of the detector. To evaluate the background test statistic distribution, the analysis is performed repeatedly on scrambled data sets, wherein the arrival time of the events is randomized but all other event properties are fixed (i.e. the null hypothesis). The post-trial p-value is the fraction of scrambled data sets containing at least one grid point with a likelihood ratio higher than the one observed in the data. During a fixed period of time, larger number of narrower flares are possible than wider flares. This introduces an effective trial factor that makes this search method more sensitive to narrower flares than wider ones. To avoid being biased towards narrow flares, we introduce a marginalization term $\sqrt{2\pi}\hat{\sigma}_w/T$ to penalize very narrow flares. The test statistic is defined as:

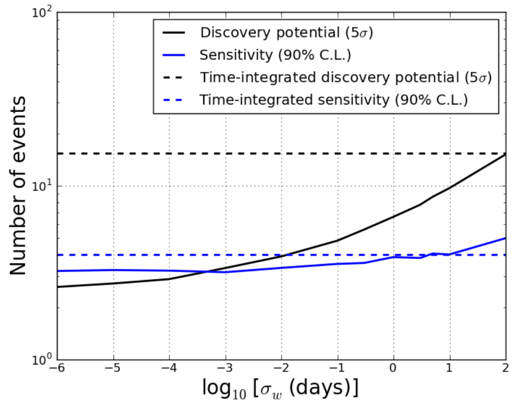

Figure 1: Discovery potential (for 5σ discovery) and sensitivity (90% confidence level) for the "All Sky Time Scan" in terms of the number of signal events needed as a function of the width σ_w of the Gaussian flare. For comparison the time integrated results are shown.

$$\log \lambda = \log \left(\left(\frac{\sqrt{2\pi}\hat{\sigma}_w}{T} \right) \frac{\mathscr{L}(\hat{\gamma}, \hat{n}_s, \hat{t}_o, \hat{\sigma}_w)}{\mathscr{L}(n_s = 0)} \right)$$

where the parameters with hats denote the fitted values, T is the total livetime of the detector.

The expected performance of this search is illustrated in Fig. 1 which shows that on scales bellow one day this approach is more powerful than the time integrated search. For this search the most significant deviation from background is at 343.45° r.a. and -31.65° dec. The best-fit parameters for this deviation are $\hat{\sigma}_w = 1.8$ days and $\hat{t}_0$ corresponding to the 27^{th} of September 2010. The pretrial p-value for this point is 1.07×10^{-5}. The post-trial p-value was determined to be 66% and therefore it is compatible with background fluctuations.

3.2 Search for Periodic Neutrino Emission from Binary Systems

For certain binary systems such as microquasars, the time period is known from X-Ray, Gamma Ray and Radio spectrum observations. Microquasars are binary systems in which one of the bodies is either a compact black hole or a neutron star. Neutrinos could be produced in these systems in relativistic jets [8]. These jets are narrow and precess with the same time period as the binary system. The neutrino flux at earth from these sources depends upon the orientation of these jets with respect to the atmosphere of the massive star and our line of sight, and is hence expected to be high only during a narrow window during the orbit. We can use the knowledge of the period to enhance the discovery potential. The phase is calculated for each IceCube event from the period start T_0 as defined by Fermi LAT [9] and the known period of the system.

This search also uses the marginalization. We then search for events clustered together in this phase space, rather than time. The width and the phase are fitted. The list of sources and their periods can be found in Table 1.

Figure 2 indicates the discovery potential and sensitivity of this search in terms of number of signal events. The search is very powerful for flares of width of $1/100^{th}$ of

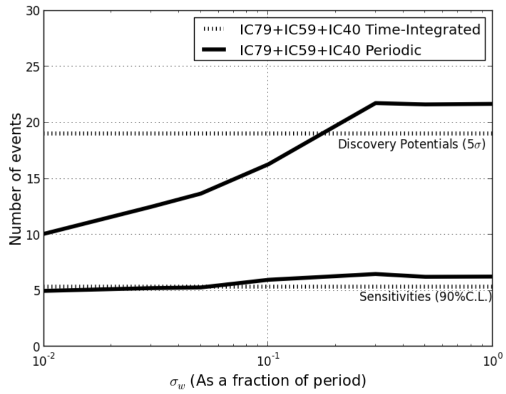

Figure 2: Discovery potential and sensitivity versus the duration of the flare divided by the period for the search for periodic neutrino emission from binary systems in terms of the number of signal events for the source GRO J0422+32

a period while for much wider flares, the time integrated search is preferable due to the penalty introduced by additional degrees of freedom in the fit.

Source	Period(days)	p-value
Cygnus X-1	5.599829±0.000016	0.45
Cygnus X-3	0.199679 d±0.000003	0.22
GRO J0422+32	0.212140±0.000003	-
GRS 1915+105	30.8±0.2	0.49
LSI + 61 303	26.496±0.0028	-
SS 433	13.08227±0.00008	-
XTE J1118+480	0.1699339±0.0000002	-
HESS J0632+057	320±5	-

Table 1: Candidate sources for the Periodic Neutrino emission search. The p-values are pre trial, "-" means underfluctuation.

In the search for periodic neutrino emission, the most significant observation was from the source Cygnus X-3. This Gaussian fitted flare was observed at a phase of 0.79 with a width of $\sigma_W = 0.042$ in terms of the fraction of the period, close to the peak of the gamma-ray flare as reported by Fermi around 0.8 [9]. The post-trial p-value of the Cygnus X-3 was found to be 80.5%, well compatible with the background hypothesis.

3.3 Time Dependent Searches for Flares with Extensive Coverage

This search targets a set of astronomical objects (FSRQs, blasars, etc.) which were observed in flaring state during the period of interest by the Fermi-LAT [6]. The tested hypothesis is that the neutrino emission follows the intensity of the photon emission. The Fermi-LAT provides continuous monitoring which allows for direct use of the lightcurves. We use the lightcurves to select flaring states following the selection criterium that the flux is above 10^{-6} photons cm^{-2}s^{-1} for energies above 100 MeV. Then the lightcurves are used as input for building a time PDF.

In order to use the Fermi-LAT lightcurve as time PDF we apply a denoising procedure, the so called Bayesian Blocks method, implemented as described in [7]. The method takes a parameter F_B which affects how sensitive the method is to fluctuations in the lightcurve. Small values cause the resulting PDF to follow almost every point in the lightcurve while for big values the method will ignore important structures in the lightcurve. To determine the optimal value for the parameter F_B a series of tests were done, using real Fermi-LAT exposure data to simulate realistic background noise and injecting Gaussian shaped flares. The width, the height and the multiplicity of the flares was varied and for these different configurations the performance was evaluated in terms of the rate of finding a fake flare and the rate of finding the injected flare. The criterium for "finding a flare" was the denoised lightcurve to exceed three times the standard deviation of the background noise. In Fig. 3 an example of the performance of the Bayesian Blocks method is shown as function of the parameter F_B. After evaluating the performance for various flare scenarios the value of the parameter F_B was fixed at 5.0 for this analysis. At this value the fake flare rate drops significantly while the success rate for the injected flares stays high. Example of the resulting denoised lightcurve together with the original data is shown in Fig. 4.

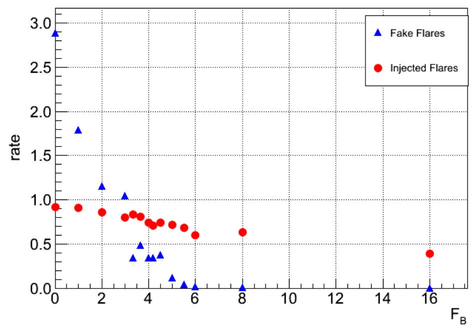

Figure 3: Example of the performance Bayesian Blocks method as function of the parameter F_B. In this example one Gaussian shaped flare was injected with width of two days and height of 10^{-6} photons cm^{-2}s^{-1}. On the vertical axis is the rate of finding a flare, i.e. the number of flares found divided by the number of lightcurves simulated. The blue triangles indicate the rate at which fake flares are found. In red circles we show the rate for finding the injected flare. The value of F_B chosen to be used for the analysis is 5.0

For each candidate source the likelihood function is maximized with respect to the number of signal events n_s, the power law index γ, the time lag and time PDF threshold. The time lag parameter allows for a time offset between the flare time and the event arrival time up to ±0.5 days. The last fit parameter, the time PDF threshold, makes it possible to modify the tested hypothesis, stating that only above this threshold the neutrino flux follows the photons. As the threshold is varied, the time PDF is redefined, setting it equal to zero bellow the threshold and normalizing to one what is left above the threshold. Time scrambled data sets are used to obtain the post-trial p-value. This search uses up to three years of IceCube data depending on the activity of the flaring sources.

There were 26 sources selected as flaring during the 79 string measurement period, 6 flaring in both the 59 and the 79 string measurement period and 2 with flares occurring throughout all three, 40, 59 and 79 string measurement pe-

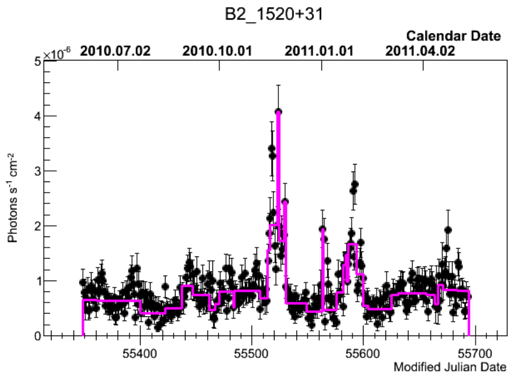

Figure 4: Example of a denoised lightcurve (solid line) together with the original data (black data points) for the blazar B2 1520+31.

riods. The source with the most significant deviation from background was the Seyfert 2 galaxy NGC 1275 at 49.95° r.a. and 41.51° dec. Fig. 5 shows the time PDF threshold resulting from the likelihood function maximization together with the time PDF and the IceCube event weights considering only the spacial and energy contribution to the likelihood, as function of time.

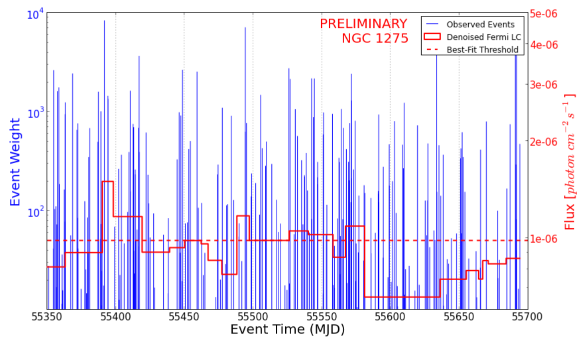

Figure 5: In red solid line and using the red scale on the right is drawn the time PDF for NGC 1275 obtained from Fermi-LAT data. Again using the red scale on the right, the red dashed horizontal line indicates the threshold resulting from the likelihood function maximization. The blue vertical lines are drawn at the times of measured IceCube events and the height indicates the event weights on the blue left scale. Events in the periods when the PDF is above the threshold are contributing to the significance.

The pre-trial p-value for this source was 0.058 which was translated using the scrambled datasets into post-trial p-value of 95% and therefore well compatible with background fluctuations.

3.4 Time Dependent Searches for Flares with Sporadic Coverage

There is yet another interesting set of sources, which show no distinct activity structure in the Fermi-LAT lightcurves but were reported to The Astronomer's Telegram to be flaring by higher energy experiments like H.E.S.S., MAGIC or VERITAS. For these sources the Fermi-LAT lightcurve did not pass the criterium of flux is above 10^{-6} photons $cm^{-2}s^{-1}$ and therefore the time PDF is just a box function in time with duration defined as the reported flare time plus one day margin before and after. The selected sources and the corresponding limits for the time PDF are listed in Table 2. Here only the number of signal events n_s and the index of the power law γ are free parameters in the maximization of the likelihood function. This search is carried out with data from the 79 string configuration since the flares reported previously were already analyzed with the corresponding data samples.

Source	ATel num.	Period in MJD
1ES 0806+524	3192	55615-55617
HESS J0632+057	3153, 3161	55598-55602
1ES 1215+303	3100	55562-55564

Table 2: Source candidates selected for the "Time Dependent Searches for Flares with Sporadic Coverage".

Only one out of the three sources, namely 1ES 0806+524 at 122.46° r.a. and 52.32° dec, does not under-fluctuate. The pre-trial p-value for this source is 0.24 which using repeated analyses on time scrambled data translates into post-trial p value of 0.73 .

4 Conclusions

We presented the results of different time-dependent searches of neutrinos in IceCube. The test hypothesis differs from the time-integrated searches where a steady neutrino emission is assume. The triggered searches use gamma-ray and optical information to drive the search of neutrinos in a multi-messenger fashion. The "All-Sky Time Scan" on the other hand, is the most general time-dependent search where the only assumption taken is that a neutrino flare can be well described by a Gaussian-profile in time. None of the searches presented in this contribution had shown a significant deviation from a background only hypothesis. The IceCube telescope is now taking data with its final configuration and high stability in the data is expected. Some of the searches described here will be applied in almost real-time, releasing on-line information on neutrino uxes observed during ares, or, in the lack of a discovery, providing limits useful to constrain models together with photon observations.

References

[1] R. Abbasi et al., Nucl. Inst. Meth. A, 2010, 618 : 139.
[2] IceCube Collaboration: latest results on point and extended neutrino source searches, these proceedings.
[3] J. Braun et al., Astropart. Phys., 2010, 33 : 175.
[4] R. Abbasi et al., ApJ., 2011, 732 : 18.
[5] M.G. Aartsen et al.,Search for time-independent neutrino emission from astrophysical sources with 3 years of IceCube. In preparation (2013).
[6] http://www-glast.stanford.edu/
[7] J. D. Scargle, J. P. Norris, B. Jackson, J. Chiang, arXiv:1207.5578
[8] M. Reynoso et al, Mon.Not.Roy.Astron.Soc. 387 (2008) 1745-1754
[9] A. Abdo et al., SCIENCE 326 1512F (2009)