Results and prospects of IceCube’s real time alert capabilities

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Abstract. The IceCube neutrino observatory is a 1 km$^3$ detector for Cherenkov light in the ice at the South Pole. Its recent results confirm the presence of an astrophysical neutrino flux of still unidentified origin. In addition to traditional analyses, IceCube now distributes alerts of interesting neutrino events in real time. Harnessing the continuous full-sky observation power to immediately react upon the detection of neutrino multiplets and single astrophysical neutrino candidates will increase the availability of simultaneous multi-messenger data. This approach boosts the discovery potential of astrophysical sources and can constrain models of their high-energy neutrino and gamma emission. The talk will present recent results and future prospects of the neutrino-triggered multi-messenger programs in IceCube.

1. Introduction
In the quest of astrophysics to further our understanding of cosmic phenomena, multi-messenger observations, here using neutrinos and photons, may help understand the accelerators of cosmic rays.

High-energy neutrinos can only be produced in hadronic interactions in conjunction with cosmic rays [1]. The arrival directions of the neutrinos reaching earth unabsorbed and undeflected point back to their origin likely coinciding with the sources of cosmic rays. However, the detection of neutrinos is complicated due to the small interaction cross-section and the susceptibility of ground-based neutrino telescopes to the background of neutrinos and muons produced in the atmosphere.

So far, the IceCube experiment has shown evidence for the existence of a diffuse astrophysical neutrino flux [2], the sources of which have yet to be identified. In addition to the search for steady sources [3], transient and variable objects present further possible source candidates. Simultaneous observations of neutrinos and photons during their various states of activity can improve the sensitivity to these sources and yield a more complete picture of their acceleration mechanisms.

Neutrino telescopes can observe the full sky around the clock with a duty cycle close to 100%. Optical, Cherenkov and X-ray telescopes are limited to their field of view of typically several square degrees. Thus, observations in e.g. gamma rays are only available for certain points of time in the past and the amount of data for times where correlated neutrinos are observed can be extended by using IceCube neutrino observations as a trigger for optical, gamma-ray and X-ray telescopes.
The time scales on which sources’ activities vary over several orders of magnitude, from milliseconds in the case of e.g. fast radio bursts (FRBs) over days to years in the case of active galactic nuclei (AGN) [4]. In order to cover all these cases, the so called Neutrino triggered Target of Opportunity (NToO) programs employ a highly automated analysis chain and alerts of neutrino flares can be generated without human intervention.

Currently, IceCube operates two of these NToO programs: the gamma-ray follow-up (GFU) and the optical and X-ray follow-up (OFU, XFU). After the description of the detector in Sec. 2, the operation of both programs is explained in Sec. 3. Section 4 closes with a summary.

2. The IceCube Detector
The IceCube neutrino observatory is a cubic-kilometer detector for Cherenkov light, installed in the ice at the geographic South Pole [5]. The construction of the detector, i.e. deployment of its 5160 optical modules, was completed in 2010.

Neutral current interactions produce a hadronic cascade in the ice and charged-current interactions of electron and tau neutrinos produce a short-lived lepton next to the hadronic cascade. Usually, these leptons cannot be resolved and the directional uncertainty of cascade events is of the order of tens of degrees, making them unsuitable for follow-up observations with optical or gamma-ray telescopes with a field of view one order of magnitude smaller.

However, charged-current interactions of muon neutrinos in the detector or nearby bedrock yield a muon traversing through the detector. The long lever arm of the track allows for the reconstruction of the direction of the muon and corresponding neutrino with a median precision of roughly one degree. For energies larger than 10 GeV, this resolution is better than the kinematic angle between the muon and the corresponding neutrino.

Thus, in the following, only muon tracks will be discussed.

The muon filter at the South Pole selects these events with a rate of 40 Hz. In order to suppress the background from atmospheric muons, the Online Level 2 filter uses likelihood reconstructions, which take into account photon propagation and the ice properties. As computing power at the South Pole is limited, computationally demanding reconstructions are only applied to events passing further cuts. After cuts on the likelihood fit quality, the event rate is reduced to 5 Hz. Afterwards, multivariate classifiers are employed to improve the neutrino purity to 90% at an event rate of 5 mHz.

3. Follow-Up Programs
Currently, there are two follow-up programs in operation. Both used to run their respective event selection and clustering analysis at the South Pole. Only clusters significant enough to yield an alert were sent to the North immediately through a satellite link, where they are distributed to the follow-up observatories via automatically generated emails.

The system is currently transitioning to transmitting every single track-like event passing a common event selection immediately through the Iridium satellite network. For each of these events, the most important reconstructed quantities, including direction, energy, fit quality and uncertainty estimates, are sent to the North, where multiple analyses run on the events from the stream. The searches for neutrino multiplets described in the following sections will be run in the North, where they can be updated and improved more easily.

The median delay between the neutrino interaction in the detector and receiving the event in the North is 22 seconds.

3.1. Gamma-Ray Follow-Up
The gamma-ray follow-up is aimed in particular at catching flares from variable sources such as AGN. Out of the wide range of possible time-scales for their activity, this program considers neutrino clusters of up to 21 days in duration by running a time-dependent point source analysis
on a list of pre-agreed upon source candidates. The list is comprised of AGN in the northern hemisphere that have exhibited variable behavior in gamma rays in the past and are visible to the follow-up telescope.

The likelihood analysis considers the distance between the observed neutrinos and the source candidate, an estimation of the angular reconstruction uncertainty, the energy spectra of potential sources and background, and the detector livetime during the time window to be tested. Two quantities are fitted: The spectral index of the events and the most likely number of signal events among the events in the time window. Starting from the latest received event (the trigger), increasing time windows are considered in the search.

A likelihood ratio test of the best fit versus the null hypothesis (i.e. the likelihood given the best fitted spectral index and number of signal events divided by the likelihood assuming no signal events at all) is used to determine the most likely extent of the time window and to evaluate the significance of a possible cluster of neutrinos. In case the significance threshold is passed, the alert is forwarded to the MAGIC and/or VERITAS telescope (depending on the significance and visibility conditions, which may be impaired due to the moon or the zenith angle of the source w.r.t. the telescope up to 24 hours after the alert).

Since the inauguration of the program in March 2012, the significance threshold was passed 14 times. Three alerts have been sent to MAGIC and five to VERITAS. One alert has been followed up by each telescope. In both cases, no significant gamma-ray emission was observed.

In the past, this program relied on a cut-based event selection and a binned analysis. Now, an event selection based on multivariate classifiers has been developed that reaches a sensitivity comparable to offline analyses and covers the full sky (i.e. also the southern hemisphere). Together with the aforementioned likelihood analysis, the sensitivity has been much improved.
and is now close to that of the offline point source analysis for the majority of the sky as is shown in Fig. 1.

3.2. Optical and X-Ray Follow-Up
The optical and X-ray follow-up programs share the same event selection and alert generation technique. The selection of track-like muon events is similar to the one used in the GFU, but limited to the northern hemisphere and optimized equally to $E^{-1}$, $E^{-2}$ and $E^{-3}$ spectra (whereas the GFU is optimized for an $E^{-2}$ spectrum). The contamination of atmospheric muons and neutrinos is suppressed by placing a cut which requires that at least two neutrinos arrive within 100 seconds of each other and are separated by no more than 3.5 degrees. The very short timescale of the clustering is targeted at observing neutrinos from gamma-ray bursts (GRBs) and supernovae.

So far, more than two events matching these criteria have not been observed. A test quantity is calculated for doublets, taking into account the angular separation, the quality of the directional reconstruction, the telescopes field of view and the time interval. By placing a threshold on this test quantity, a rate of nine alerts per year to the Palomar Transient Factory (PTF [6]) and seven alerts per year to the Swift X-Ray Telescope [7] is achieved.

The most significant alert from the OFU program to PTF was sent on March 30th, 2012 [8]. Two neutrinos were recorded within 1.7 seconds, roughly one degree apart from each other. In the follow-up observation performed by PTF ten days later, the previously unknown core-collapse supernova PTF12csy was discovered 0.14 degrees away from the mean neutrino direction. In Fig. 2, the location of the neutrinos and the supernova are shown on the left and the result of the PTF observations and the earlier image from the Sloan Digital Sky Survey on the right.

As the age of the supernova was determined to be at least 169 days at the time of the observation, the detection is considered a coincidence and the neutrinos are likely unrelated to the supernova.

Figure 2. Left: Location of the two neutrinos that triggered the follow-up observation, which found PTF12csy. The gray boxes indicate the field of view of the CCDs used for PTF observations (CCD 03 was broken). Right: Result of the PTF observation after the IceCube trigger (NEW), a reference image taken at a later point in time (REF), the difference between both (SUB) and an earlier image from the Sloan Digital Sky Survey (SDSS). [8]
4. Summary and Outlook
The gamma-ray and optical/X-ray follow-up programs presented have established the feasibility of using IceCube as a trigger for multi-messenger observations. The IceCube event processing and transmission can be operated in a robust and stable manner, with alerts being generated with a very small delay.

In the future, upgrades to the event selection will improve the sensitivity of the existing programs. New follow-up opportunities may arise from new event selections that select high-energy track-like events starting in the detector. These types of events are more likely to be of astrophysical origin. Additionally, extremely high-energy muons starting in the detector will be available with a similar delay as the existing event selections. These new event classes are of interest to a broad range of follow-up observatories looking for counterparts in e.g. cosmic rays or gravitational waves.

References
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