PROCEEDINGS OF SCIENCE

Realtime neutrino alerts and follow-up in IceCube

The IceCube Collaboration†
† *http://icecube.wisc.edu/collaboration/authors/icrc17_icecube*
E-mail: blaufuss@icecube.umd.edu

Since the detection of a diffuse flux of high-energy astrophysical neutrinos in 2013 by the IceCube neutrino observatory, their origin so far has remained unknown. With no steady sources of neutrinos observed in IceCube data, neutrinos produced during transient astrophysical events are a viable alternative. Identification of an electromagnetic counterpart that is coincident in time and space would be strong evidence of a source of neutrinos. To support these searches, IceCube has implemented a realtime search for potentially astrophysical neutrino candidates that includes alerts to the community for rapid follow-up observations. This contribution will highlight the realtime analysis system, the current realtime alerts now being produced, and some preliminary results from the first alerts.

Corresponding author: E. Blaufuss[1]*
[1] *Dept. of Physics, University of Maryland, College Park, MD 20742, USA*

35th International Cosmic Ray Conference — ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

*Presenter

PoS(ICRC2017)982

1. Introduction

The detection of a diffuse flux of astrophysical neutrinos by IceCube [1, 2] represented the "first light" in the new field of high-energy neutrino astronomy. The detection of neutrinos from a source would be a telltale sign of high-energy hadronic interactions, and could add to the understanding of the acceleration mechanism which produces the most energetic particles observed in the Universe, the highest energy cosmic rays [3]. Searches for point sources [4] in the IceCube data and dedicated follow-up searches [5] have failed to locate a potential source. By observing the location of these neutrinos long after the arrival of the neutrino, these searches have assumed a steady state source flux. If these astrophysical neutrinos are from a class of transient sources, more immediate follow-up observations are required.

Multimessenger astronomy, the combined observations in cosmic rays, neutrinos, photons of all wavelengths, and gravitational waves, represents a powerful tool to study the physical processes driving the high-energy universe. Neutrinos play an important role in this emerging field. Unlike photons and charged cosmic rays, the neutrinos' small cross section and absence of electric charge allow them to travel the cosmological distances necessary to reach Earth from source regions without absorption or deflection. Observation of these astrophysical neutrinos can provide critical directional information that can be used to direct rapid, follow-up observations. Several models [7, 8] predict emission from flaring objects or other transient phenomena, requiring a fast start to follow-up observations.

IceCube is a cubic-kilometer neutrino detector [9] installed in the ice at the geographic South Pole, Antarctica between depths of 1450m and 2450m. Detector construction was completed in 2010, and the detector has operated with a $\sim$99% duty cycle since. IceCube does not directly observe neutrinos, but rather the secondary particles produced in the neutrino interaction with matter. IceCube detects these particles by observing the the Cherenkov light emitted as they travel through the Antarctic glacial ice. The ability to accurately determine the direction of a neutrino event recorded in IceCube is highly dependent on the ability to reconstruct these secondary particles.

These secondary particles can produce two distinct classes of signals within IceCube: tracks and cascades. Track events are produced by muons, arising mainly from the charged current interaction of muon-type neutrinos, which produce $\mathcal{O}$(few)km long light paths as they transit the detector. These tracks can be reconstructed with a directional uncertainty less than 1°, but with large energy uncertainty since an unmeasured fraction of their energy is deposited outside the instrumented volume. Shower events are produced by the charged current interaction of electron and tau-flavor neutrinos and by neutral current interactions of all neutrino flavors. Shower events tend to deposit all their energy within $\mathcal{O}$(10)m, producing a relatively isotropic light emission. These shower events tend to have good energy resolution ($\delta E/E \sim$15% [10]), but have typical angular resolutions on the order of $10-15°$ [11].

Given the depth and the size of IceCube, the observed event rate for penetrating atmospheric muons is approximately 2.7 kHz. The neutrino detection rate (a few mHz) is dominated by atmospheric neutrinos, created in the air showers when cosmic rays interact with the Earth's atmosphere. The first challenge for the realtime alert system is to find a pure sample of neutrino events, and the second is to identify the small fraction of these neutrinos that are likely to be astrophysical in origin.

IceCube is sensitive to astrophysical neutrinos from the entire sky (4π steradians), making it an ideal trigger for follow-up observatories around the globe. Given the modest field of view of most follow-up instruments, track events from astrophysical neutrino interactions are preferred for realtime follow-up alerts. The smaller directional uncertainties of track events also help to limit coincidental discoveries when sensitive telescopes are pointed at unexplored regions of the sky.

This contribution presents a summary of IceCube realtime system, which has enabled rapid identification and public notification following the detection of neutrino event candidates. Two neutrino event selections are used to generate the public notifications. First, a search for track-like starting events [12] is used to identify high energy neutrino interactions that occur within the IceCube instrumented volume and produce an outgoing track (HESE track alerts). Second, a high-energy track search, adapted from a selection used to identify cosmogenic neutrino candidates [13] identifies through-going track events likely of astrophysical origin (EHE track alerts). Alerts issued in the first year of operation are presented, as well as an outlook toward future extensions of these alerts to new classes of astrophysical neutrinos.

2. IceCube Realtime Alert System and Active Alerts

Given the remote location of the IceCube detector, all data collection, processing and filtering is automated. The IceCube realtime alert system [14] is also fully automated, as shown in Figure 1. Neutrino selections are hosted in the online event filtering system and identify neutrino alert candidates in realtime. For each alert candidate, two messages are generated. The first contains a brief summary of the event information and the second, a larger message that can take longer to transfer north, contains the full event information.

Once the brief summary message is in the north, alerts are automatically issued to Gamma-Ray Coordinates Network (GCN[1]) via the Astrophysical Multimessenger Observatory Network (AMON[2]). The full event information is used to start data quality checks and refined direction reconstructions of the event. These refined reconstructions improve the angular resolution by more than 50% and provide a measure of the energy loss within the detector volume. Additionally, data quality and visual checks of the event information are used to ensure the event is consistent with an astrophysical neutrino signal and not rare backgrounds, such as atmospheric muons that are not detected in veto regions. Results from these checks and follow-up reconstructions are completed within a few hours of the alert and result in an updated alert notification in the form of a GCN circular.

2.1 HESE Track Alerts

The IceCube high-energy starting event (HESE) search has resulted in a clear detection ($>6.5\sigma$) of astrophysical neutrinos [6]. HESE events are identified as high-energy events that deposit a substantial amount of charge measured by the IceCube DOMs ($\geq$6000 photoelectrons), and reconstruct with an event vertex within the instrumented detector volume. In 4 years of data, 54 HESE neutrino events have been identified, with 14 of these being track-like. Given the better angular resolution of tracks, only the track-like events identified online are considered for HESE alerts.

[1] *https://gcn.gsfc.nasa.gov/*
[2] *http://amon.gravity.psu.edu/*

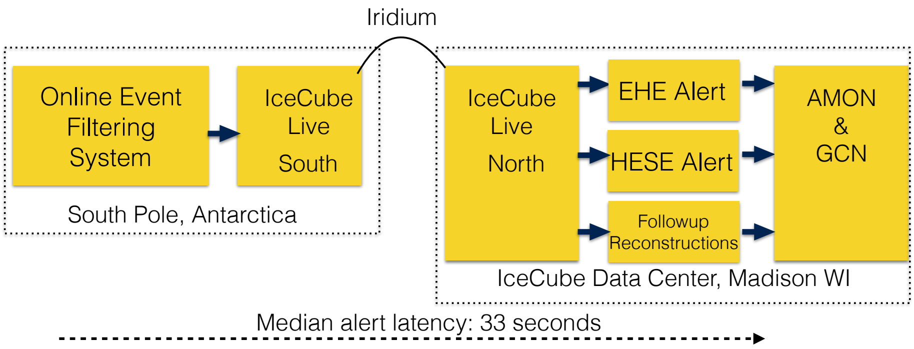

Figure 1: Overview of the realtime alert system. Events satisfying alert criteria are identified in the online event filtering system that operates in realtime at the detector site in Antarctica. Event summaries and event data are transferred to the north via the IceCube Live experiment control system [9] over an Iridium satellite connection. Once in the north, alerts are formatted for distribution to GCN via the AMON network. Additionally, full event information for each alert is used to trigger automated followup event reconstructions. Median latency for alerts, comparing the time of the neutrino event to the alert being issued, is 33 seconds.

Track events are classified online by a "signal-trackness" parameter [14] that uses the likelihood values returned from track and shower reconstructions to assign a numerical measure of how consistent each HESE event is with being a track. Events with a signal-trackness value $\geq$0.1 are classified as tracks.

Based on measured background event rates, and expectations based on the measured HESE neutrino flux [6], 4.8 alerts are expected per year. Of these, 1.1 are expected to be astrophysical, while 3.7 are from atmospheric background events, primarily rare cosmic ray muon events. Given their track nature these events have good angular uncertainty, as shown in Figure 2, based on simulated HESE event samples. Here, the median angular difference between the alert direction and true direction is 0.55° (1.89° for 90% inclusion) for tracks with a reconstructed track length $>$200 m.

2.2 EHE Track Alerts

The extremely-high-energy (EHE) neutrino alert stream is based on an offline search for cosmogenic neutrinos that resulted in the serendipitous discovery of the first observed PeV-scale neutrinos [15]. The standard EHE analysis searches for neutrinos with energies of $\sim$ 10 PeV to 1 EeV, where the expected event rate in the most optimistic case is $\sim$1 event per year [13]. To move this analysis into the realtime framework the event selection was modified in order to increase the sensitivity to astrophysical neutrinos, specifically neutrino energies in the 500 TeV to 10 PeV range, which are track events with good angular resolution.

The EHE alert selection requires a minimum deposited charge of $\sim$4000 photoelectrons (NPE) detected in IceCube DOMs, as well as at least 300 DOMs registering a signal. A cut on deposited charge that strengthens with zenith angle for well reconstructed tracks is then applied [14] (see Figure 3) to reject events likely to be from atmospheric origins.

A "signalness" value is calculated for each track event, which reflects how likely each event is to be of astrophysical origin relative to the total background rate. This value is calculated from the

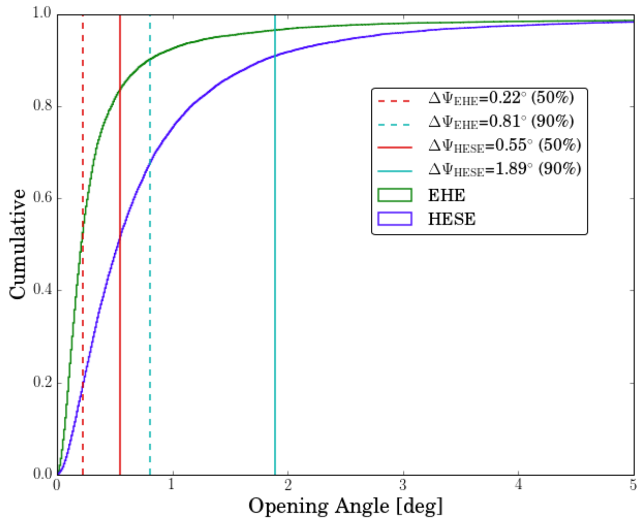

Figure 2: The cumulative distribution for the opening angle showing the radius containing 50% and 90% of simulated events for the HESE and EHE selected neutrino events. Figure adapted from [14].

expected number of astrophysical signal events for each energy and zenith combination relative to the total expected number (signal and background) of events, and is shown in Figure 3.

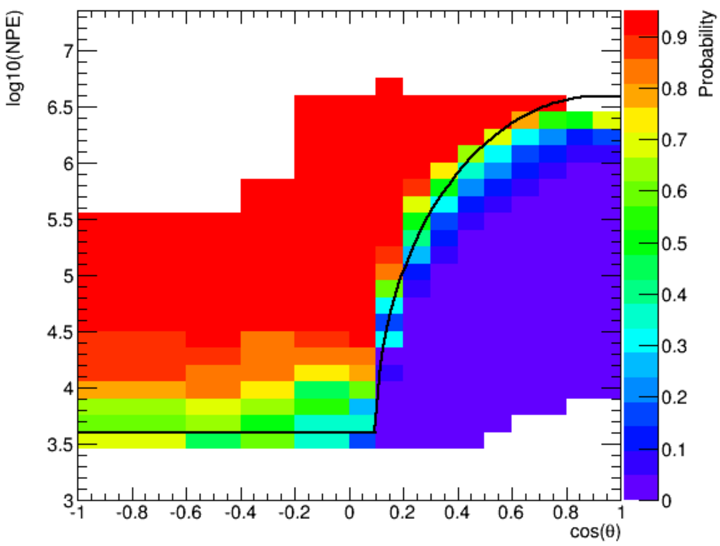

Figure 3: The two-dimensional signalness parameter dependng on the reconstructed zenith angle ($\cos(\theta)$) and total deposited charge (log10(NPE)) derived from simulated EHE alerts. Bins are only filled if a minimum threshold of signal events is met, and empty bins are indicated by white space. The black line represents the event selection criteria, with events above the line generating alerts. Figure adapted from [14].

The EHE track alerts are expected to issue ∼5 alerts per year. Of these alerts, 1.9 events will be from background events, primarily from high-energy atmospheric neutrino events, are expected.

2.5 - 4 alerts per year are expected from astrophysical neutrino events, depending on the assumed neutrino spectral index. As these events are through-going track events, the angular resolution is quite good. The median angular difference between the reported direction and true direction for a simulated sample of EHE alert candidates is 0.22° (0.81° for 90% inclusion).

3. Alerts Issued

Both the EHE and HESE event selections, as well as the software needed to handle the alerts were deployed to the IceCube detector site in early 2016. HESE alerts began operation in April 2016, and EHE alerts followed in July 2016. Since they began, nine alerts have been issued and are summarized in Table 1.

Each alert has generated follow-up observations that have been publicly reported to GCN or by Astronomer's Telegrams. No significant association with a transient source has yet been reported. Given the small cross section for neutrino interactions compared to other astronomical messengers, neutrinos that are created at extreme cosmological distances are still detectable at Earth. In this case signals in photons or gravitational waves are potentially too weak to be detected or show overlap with unrelated foreground objects that are detected in follow-up observations, but exhibit no flaring signal that would be expected from a transient source. Further follow-up observations will hopefully lead to a clear transient source detection, and a powerful hint to the underlying physics that drive the high-energy universe.

4. Future Outlook

Now that the alert system is in stable operation, new alerts are being considered beyond the HESE and EHE channels. Additional through-going track candidates are found in the diffuse muon-neutrinos searches [17], and are being investigated as a supplement to the EHE track alerts. A new class of starting events is also being developed that will identify 1-2 additional starting tracks per year as an addition to the HESE track alerts. The non-track HESE shower events are also potentially interesting to wide field observatories like HAWC and Fermi. Even though the angular uncertainties of these events is $\sim$10 - 15°, a coincidence in time and space could still constitute a significant detection.

In addition to these public alerts, IceCube also has several agreements with optical, x-ray, and gamma-ray observatories to perform observations based on IceCube observed multiplets. These multiplets, observed as as a cluster of events from the same direction on timescales of seconds to weeks, are dominated by accidental coincidences in the atmospheric background events. However, a neutrino detection from a gamma-ray burst, or an AGN flare would also trigger these follow-up observations. Searches for bursts of low energy neutrinos from nearby Supernova [18] are also performed as part of the SNEWS network [19]. Additionally, a fast-response neutrino point source analysis has been developed [20] to respond to external alerts from the wider astronomical community.

With the start of operation of the IceCube realtime alert system, the alerts generated by IceCube, and the potential discovery of transient astronomical sources in conjunction with them, the era of multi-messenger time domain astronomy has arrived. A clear multi-messenger detection

PoS(ICRC2017)982

of a source holds the potential to enrich our understanding of the most energetic cosmic phenomena, shed light on the mysterious origins of the highest energy cosmic rays, and provide a unique window into the cosmos.

Additional information regarding the alerts from IceCube is at *https://gcn.gsfc.nasa.gov/amon.html*, and requests for additional information should be directed to the IceCube realtime coordination group (`roc@icecube.wisc.edu`)

References

[1] **IceCube** Collaboration, M.G. Aartsen et al., *Phys. Rev. Lett.*, **115** (2015) 081102

[2] **IceCube** Collaboration, M.G. Aartsen et al., *Astrophys. J.*, **833** (2016) 3

[3] K.A. Olive et al., *Chin. Phys.*, **C38** (2014) 090001

[4] **IceCube** Collaboration, PoS(ICRC2017)997, *These proceedings*

[5] M. Santander, K. Satalecka, J. Dumm, et al., PoS(ICRC2017)618, *These proceedings*

[6] **IceCube** Collaboration, PoS(ICRC2015)1081 (2016)

[7] E. Waxman and J.N. Bahcall, *Phys. Rev. Lett.*, **78** (1997) 2292

[8] S. Razzaque, P. Meszaros, and E. Waxman, *Mod. Phys. Lett.* **A20** (2005) 2351

[9] **IceCube** Collaboration, M.G. Aartsen et al. *JINST*, **12** (2017) P03012

[10] **IceCube** Collaboration, M.G. Aartsen et al., *JINST*, **9** (2014) P03009

[11] **IceCube** Collaboration, M.G. Aartsen et al., *Phys. Rev. Lett.*, **113** (2014) 101101

[12] **IceCube** Collaboration, PoS(ICRC2017)981, *These proceedings*

[13] **IceCube** Collaboration, PoS(ICRC2017)975, *These proceedings*

[14] **IceCube** Collaboration, M.G. Aartsen, et al., *Astropart. Phys.*, **92**, (2017) 30

[15] **IceCube** Collaboration, M.G. Aartsen, et al., *Phys. Rev. Lett.*, **111** (2013) 021103

[16] **IceCube** Collaboration, M.G. Aartsen, et al., *Astrophys. J.*, **811** (2015) 52

[17] **IceCube** Collaboration, PoS(ICRC2017)1005, *These proceedings*

[18] **IceCube** Collaboration, R. Abbasi et al., *AandA*, **535** (2011) A109

[19] C Vigorito et a;, *J. Phys.: Conf. Ser.*, **309** (2011) 012026

[20] **IceCube** Collaboration, PoS(ICRC2017)1007, *These proceedings*

Alert:	160427A	160731A	160806A	160814A	161103A	161210A	170312A	170321A	170506A
Date	16/04/27	16/07/31	16/08/06	16/08/14	16/11/03	16/12/10	17/03/12	17/03/21	17/05/06
Time	05:52:32	01:55:04	12:21:33	21:45:54	09:07:31	20:06:40	13:49:39	07:32:20	12:36:56
RA (deg,J2000)	250.6	214.5	122.8	200.3	40.8	46.6	305.2	98.3	221.8
DEC (deg, J2000)	+9.3	-0.33	-0.8	-32.4	+12.6	+15.0	-26.6	-15.0	-26.0
Ang. Uncertainty (deg)	0.6	0.75	0.5	1.5	0.9	0.7	0.5	1.2	2.5
Dep. Energy	150 TeV	130 TeV	62 TeV	97 TeV	47 TeV	56 TeV	55 TeV	16 TeV	38 TeV
Alert Type	HESE	HESE/EHE	EHE	HESE	HESE	EHE	HESE	EHE	HESE
Signalness	0.92	0.91/0.85	0.28	0.12	0.30	0.49	$0.78^{\dagger}$	0.28	$0.35^{\dagger}$
Latency (sec)	81	41	37	42	37	27	59	13	1465
GCN Circular	19363	NA	19787	NA	20119	20247	20857	20929	21075

Table 1: Summary table of alert information from all IceCube EHE and HESE alerts sent since April, 2016. Name, date, time, right ascension (RA), declination (DEC), angular uncertainty, deposited energy, alert type, signalness measure, latency, and GCN circular reference is included for all alerts. Angular uncertainty values are listed for 90% containment radius, and any asymmetric error regions (available in the GCN circulars) have been averaged to a single value. Deposited energy is a preliminary measure of the energy detected within the IceCube instrumented volume [1] from the offline, follow-up reconstructions. Signalness values are the "signal-trackness" values for HESE alerts and the astrophysical signalness measure for EHE alerts. Signalness values marked with a † show signs of being consistent with expected non-astrophysical backgrounds. The large latency of 170506A was caused by a communication network outage. GCN circulars are available at `gcn.gsfc.nasa.gov`.