SWIFT Follow-Up of IceCube neutrino multiplets

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[1]*See special section in these proceedings,* [2] *see [1]*

Abstract: The search for neutrinos of astrophysical origin is among the primary goals of the IceCube neutrino telescope. Point source candidates include galactic objects such as supernova remnants (SNRs) as well as extragalactic objects such as Active Galactic Nuclei (AGN), Supernovae (SNe) and Gamma-Ray Bursts (GRBs). To increase the sensitivity of the search for high-energy neutrinos from SNe and especially GRBs an X-ray follow-up with the Swift satellite has been developed. Upon the detection of two or more neutrinos from a common direction and within a short span of time, IceCube will trigger the satellite to scan the same direction for a transient X-ray counterpart, e.g. an X-ray GRB afterglow. In addition to typical GRBs the program is sensitive to SN shock breakouts, slightly off-axis GRBs and orphan GRB afterglows. The online event selection in IceCube as well as the X-ray observation strategy will be presented.

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1 Introduction

1.1 Scientific Motivation

It may be possible to observe high energy neutrinos from astrophysical sources similar to GRBs that are not detectable via prompt electromagnetic emissions. Such objects could be GRBs with narrow jets that don't point directly towards earth [2] or choked GRBs [3] for which the jet may fail to penetrate the stellar envelope. In these cases, despite the lack of prompt γ-rays, the source is likely to be visible in X-rays from shock breakout after 10^3 s, and to exhibit an optical counterpart similar to that seen in core collapse supernovae [4]. While no firm estimate exists, the number of these dark bursts might be up to 100 times larger than γ-bright bursts [5]. Therefore, the search for transient neutrino sources can play an important role in the search for (γ-dark) GRBs, and may provide insights into the origin of the high energy cosmic rays. While an optical follow-up can be conducted by ground based telescopes (e.g. ROTSE [6]), satellites such as Swift are uniquely capable of rapid follow up with X-ray observations.

NASA's Swift Explorer Mission is ideally suited for studying the electromagnetic radiation from violent astrophysical events, such as GRBs. Three telescopes are supported by the Swift platform. A wide field of view instrument, the Burst Alert Telescope (BAT), monitors for the prompt γ-rays from a GRB. In response to a burst, Swift will slew into position to image the BAT error region with the X-Ray Telescope (XRT) and UltraViolet and Optical Telescope (UVOT). In this program the XRT will be used.

1.2 Overview of the program

The X-ray Follow-Up with Swift is a multimessenger approach developed by the Swift and the IceCube collaborations to detect GRBs. It uses the IceCube neutrino telescope at the South Pole to look for signal-like neutrino-multiplets (i.e. at least two neutrinos from the same direction within 100 seconds) to trigger follow-up observations with the Swift satellite in the X-ray band. The implementation of the program makes use of the existing neutrino event selection of the Optical Follow-Up Program [7] (OFUP) at the South Pole. Neutrino multiplets are reconstructed and identified online in quasi-real time with a typical latency of about 5 minutes. This low latency opens the possibility to search for fast decaying X-ray afterglows from (GRBs). Additional latency is expected on the Swift side, due to communication constraints with the spacecraft, the orbital position of Swift, and human-in-the-loop requirements for spacecraft commanding. Depending on the visibility of Swift to a ground relay station, the additional delay will be between 30 minutes to 4 hours. It is worth noting that the typical X-ray afterglow associated with long GRBs is visible to Swift for days and sometimes weeks.

2 Alert chain

Swift is in high demand amongst the scientific community. Hence only limited observing time is available for the Ice-Cube follow-up program. The current implementation of the OFUP program results in about 25 neutrino-multiplet triggers per year in IceCube. Most of these are due to background consisting of atmospheric neutrinos and about 25 % atmospheric muons. For short Swift follow-ups, the number of IceCube alerts can be decreased to approximately 7/year with very little loss in signal efficiency. This is achieved by using a likelihood method, as described in section 2.1. Extensive follow-ups over a time span of at least a week can then be performed at a rate of about one per year based on a quick evaluation of the first available X-ray data, as described in section 3.1.

2.1 IceCube candidate event selection

For the optical follow-up program, the singlet data rate achieved by the OFUP filter [7] is $R_s \approx 2mHz$, reaching a 75% pure (atmospheric) neutrino sample. Using this data sample, multiplets are selected if more than one neutrino is detected within $\Delta t = 100s$ and from the same direction within the reconstruction uncertainty of $\Delta\Psi = 3.5°$. These two conditions reduce the detected number of co-incident neutrinos from the isotropic background of atmospheric neutrinos to about 25 false positives per year.

Given the limited observing time available with Swift, an additional test-statistic was developed to select the subset of these multiplet triggers which are most likely to have astrophysical origins and be detectable by Swift follow-up observations. As the derivation is beyond the scope of this paper, it is only described and motivated here. We begin with the following definitions:

$$
\begin{aligned}
\sigma_q^2 &= \sigma_1^2 + \sigma_2^2 \\
\sigma_w^2 &= \left(\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2}\right)^{-1} \\
cos\psi &= \hat{r}_1 \cdot \hat{r}_2
\end{aligned}
\tag{1}
$$

where $\sigma_{1/2}$ are the reconstruction uncertainties of the participating neutrinos that arrive from the (reconstructed) directions $\hat{r}_{1/2}$ with an angular difference of ψ. Assuming a circular follow-up region, the test statistic

$$
d = \frac{\psi^2}{\sigma_q^2} + 2\ln(2\pi\sigma_q^2) - 2\ln\left(1 - e^{-\frac{\theta_A^2}{2\sigma_w^2}}\right) + 2\ln\left(\frac{\Delta t}{100s}\right)
\tag{2}
$$

tends to small values for signal-like doublets and larger values for background-like events (figure 1). It takes various effects into account.

- The first two terms act together. While the first term favors events with a small angle ψ, indicating neutrinos from the same direction and possibly source, it also introduces a penalty for small reconstruction
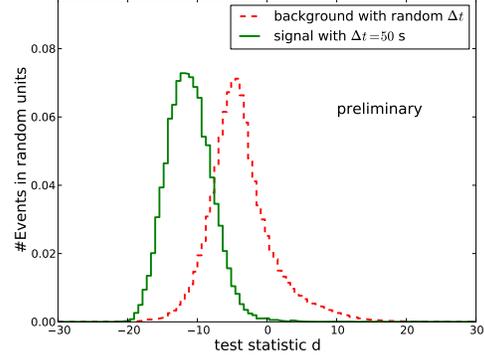

Figure 1: The distribution of the test statistic used for down-selection of OFU alerts, shown here for signal from astrophysical sources with an E^{-2} spectrum (solid line) and background doublets (dashed line). For background, Δt is assumed to be evenly distributed over 0 - 100s while a signal with $\Delta t = 50$ s is assumed.

uncertainties. The qualitative explanation is that two neutrinos for which the error regions do not overlap are more likely background than signal. As a consequence the first term tends also to small values for large combined reconstruction uncertainties σ_q. The second term counteracts this effect, introducing a penalty for large uncertainties. Thus, the two first terms favor well reconstructed events from the same direction.

- The third term introduces the tiled Swift field of view with a radius of $\theta_A \approx 0.5°$. It favors those events with small errors for which, in the case of a signal, the reconstructed doublet direction is expected to be relatively close to the source direction, thus minimizing the possibility of observing a region of space during a follow-up which does not include the actual source within the FoV and supporting the first two terms in selecting well reconstructed events. The value of θ_A reflects a tiled field of view of Swift (section 2.2).

- The time difference Δt between two neutrinos is considered in the fourth term. Normalized to the 100 s time window of the trigger, small values are reached for small time differences assuming they are an indicator for a neutrino bundle of an astrophysical source.

2.2 Swift Follow-Up

IceCube provides a median position resolution for selected events of less than one degree. However, the XRT field of view is only 0.4^o in diameter, which will cover only a fraction of the IceCube space angle distribution. Due to this
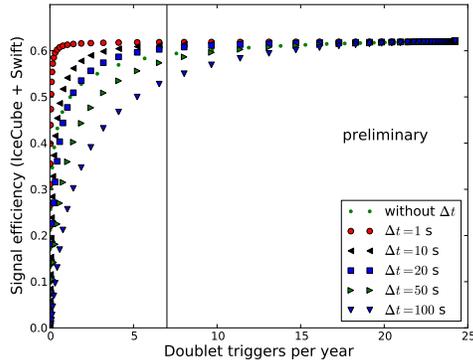
Figure 2: Displayed on the y-axis is the signal efficiency with which a real E^{-2} source that passed the OFUP selection criteria will pass the test statistic and lie within Swift's FoV. This is plotted vs the estimated number of doublet triggers per year. The effect of the Swift field of view is included, only accepting events within the FoV and reducing the acceptance to a maximum of 63%. It is displayed for four different cases assuming a signal with a time difference between the arriving signal neutrinos of Δt. The aim is to reduce the background to seven alerts per year.

limited coverage by the XRT field of view, we are forced to tile the follow-up region with seven pointings of Swift, thus creating an artificially larger field of view. Assuming a neutrino signal following an E^{-2} spectrum and centering the telescope pointings on the reconstructed direction, the fraction of sources that are actually positioned in the observed tiled field of view if is found to increase thus from only about 20% to 63% by tiling the follow-up region. At the same time the observation time for one pointing is reduced limiting the search to bright sources that are easily discovered in less than 1000 sec.

Figure 2 shows the signal efficiency for an astrophysical source with an E^{-2} spectrum relative to the optical follow-up filter as a function of the estimated number of doublet triggers per year. Starting with loose cuts on the test statistic (high positive values in figure 1) and 25 false positives a year, one can see the drop in the number of false positives as well as signal efficiency for tighter cuts (lower values of d in figure 1) reducing the background to zero doublets per year.

Based on figure 2 we decided to aim for triggering seven observable alerts for follow-up per year as the best compromise between background reduction and signal efficiency. This reduces the background by 72% while, in the case of an E^{-2} spectrum, there is only a loss of 10% (14%) for events arriving with a time difference of 50 (100) seconds relative to the maximum acceptance. Almost all doublets with a shorter time difference will pass the cut.

3 Expected Results

Swift orbits the Earth every 96 minutes, with the IceCube trigger region becoming visible each orbit for approximately 2000 sec. The spacecraft will be commanded to automatically observe the seven tiled fields as soon as they rise above the Earth limb, providing approximately 285 every orbit until a total of approximately 2000 sec per tile is achieved, typically taking between 12 hours and a full day to complete. In this way, any X-ray sources visible to Swift will be observed multiple times, generating a light curve. This information is critical for interpreting the nature of the source, possibly identifying a GRB via a typical GRB afterglow.

Two different significance tests are proposed. The level 1 test (section 3.1) provides a relatively quick test on the first day of data collected by Swift, to decide whether to initiate a multi-day follow-up program. The level 2 test (section 3.2), made on the full data set, provides a threshold for claiming a joint Swift-IceCube discovery of an X-ray afterglow in coincidence with an astrophysical neutrino source. The level 1 test is presented in its final form here, while the level 2 test is still under development.

3.1 Level-1 Significance Test

After several orbits, Swift may have detected one or more X-ray sources, with a position uncertainty that is typically on the order of a few arcsec, limited by the Swift XRT point spread function. The source position and an initial measurement of the flux are used to assess whether this is significantly above the expected X-ray background. The expected number of background X-ray sources depends strongly on the flux threshold. We will consider an X-ray source to have passed the level 1 significance test if it satisfies any of the following criteria for an (extra) galactic search.

A **Uncatalogued Sources:** The level 1 source is not in proximity to a catalogued X-ray object (i.e. not within $N\sigma$ ($N = 3$) of the combined Swift and catalog position uncertainty), is brighter than a flux threshold $S_A = (5 \cdot 10^{-12}) 1 \cdot 10^{-10}$ erg/(cm^2 s), and occurs in a region of the sky where the ROSAT Bright Source Catalog would have observed it had it been in its current state when surveyed.

B **Variable Sources:** The source is brighter than a flux threshold $S_B = (5 \cdot 10^{-13}) 1 \cdot 10^{-11}$ erg/(cm^2 s) and exhibits significant variability across the first day of Swift data, with the p-value of a fit to a flat light curve being lower than some critical value $P = 0.001$.

C **Active Catalogued Sources:** The level 1 source is within $N = 3\,\sigma$ uncertainty of the position of a catalogued object but the new measurement is $M = 10\times$ brighter than it appears in the catalog.

D **Poorly Catalogued Sources:** A source lies outside of the region covered by the ROSAT Bright Source Catalog (due to the low exposure time of ROSAT in that region) but is observed to be $\overline{M} = 10\times$ brighter than the threshold set by ROSAT for that region.

It is noted that there are significantly more serendipitous X-ray backgrounds in proximity to the galactic plane. As such, the analysis is carried out with different thresholds depending on galactic latitude (GL). Specifically, a higher threshold is used if $|GL| < 20°$.

Our intended goal is that the level 1 test will allow no more than one false positive per year. If an X-ray source passes the level 1 test, then additional Swift data is accumulated over the following $\approx$ 1 week, to determine a light curve and spectrum for the source. The full data set is then utilized for the level 2 test.

The level 1 tests will first be applied once two observations have been made on each tile (i.e. after two Swift orbits). The analysis will continue on the accumulating data until the level 2 observations are triggered or a total of 2000 sec have been observed for each tile. Otherwiese no further obserations or analysis will be carried out.

3.2 Level-2 Significance Test

Should an X-ray source be discovered that passes the level 1 test described above, a dedicated observing program will be initiated for that source. The tiled observations will be discontinued and Swift will take up a pointed observing mode, with the source at the center of a single XRT field of view (0.4° diameter). The level 2 test will determine the significance of all data accumulated over $\approx$ 1 week, in conjunction with the IceCube trigger data. Backgrounds will be significantly reduced from level 1 to level 2 by examining the larger data set, looking at additional features for transient behavior like the slope of the light curve.

It is anticipated that, for a given class of transient X-ray sources (GRB afterglow, AGN activity, etc), unambiguous identification of a source will be limited by an irreducible background of similar but unrelated events. A first estimate, based on the rate of BAT-triggered GRBs and the average light curve behavior, predicts that serendipitous GRB afterglows will be discovered only once per 3000 years with the Swift-IceCube program.

Numerous studies have placed limits on the number of untriggered GRBs, typically of order 100 times the rate of regular GRBs [5, 8, 9]. This would place a limit on the Swift-IceCube level-2 false positive rate of once per 30 years.

4 Current Status and Outlook

The program was approved by the IceCube collaboration at the beginning of 2011 and is running since February, 11th. Until the middle of May, one alert has been forwarded to Swift. The total latency between the neutrino events and the first observation by Swift was 90 minutes. All steps in the alert chain worked as planned and the event will be included in the final analysis of the program.

In the full km^3 sized IceCube detector a mean of about 10 neutrinos from GRBs per year and hemisphere are predicted to be detectable [10]. If the neutrino flux is equally distributed amongst the GRBs, then we estimate a combined Swift and IceCube detection rate for γ-bright GRBs of 0.013 per year. This number was derived by folding in various detection efficiency factors like, for example, the filter efficiency of the OFU program and the probability to classify the source with Swift. In the case where a 2-year joint Swift-IceCube program results in no detection, a conservative upper limit on the γ-dark GRB rate of 90 times the γ-bright GRB rate (90% c.l.) can be placed. This upper limit will improve significantly for model dependent analysis where a large fraction of the neutrinos are concentrated in a subset of the bursts [11].

A future extension to single neutrino events, applying a stringent high energy cut, is planned as an additional stream. Avoiding the doublet criteria for triggering a follow-up leads to an improved signal efficiency. Initial estimates suggest a detection rate of 0.25 γ-bright GRBs per year and a 2-year upper limit on the γ-dark GRB rate of 4.5 times the γ-bright GRB rate (90% c.l.). This limit is within the current theoretical prediction given in [5].

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