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OPTICAL FOLLOW-UP OF HIGH ENERGY NEUTRINOS DETECTED BY THE ANTARES TELESCOPE

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Abstract. The ANTARES Collaboration has completed in 2008 the deployment of what is currently the largest high energy cosmic neutrino detector in the Northern hemisphere, covering a volume of about 0.01 km^3. To enhance the sensitivity of the ANTARES detector to transient sources, such as Gamma Ray Bursts (GRBs), Core Collapse Super Novae (CCSN), flaring active galactic nuclei (AGN) and microquasars, a method based on coincident observations of neutrinos and optical signals has been set up. The observation is triggered whenever a high energy singlet or a burst of neutrinos event in space and time coincidence is detected by the ANTARES telescope: the selection of events is such that alerts are sent with a frequency of about twice per month. The system is operational since 2009 and since then, about 40 alerts have been sent to the telescopes network, about 30 of them being followed. The optical follow-up system will be described and first results on the optical images analysis searching for GRBs will be presented.

Keywords: Neutrino astronomy, Transient Sources, Optical Follow-up

1 Introduction

The production of high-energy neutrinos has been proposed for several kinds of astrophysical sources, such as gamma-ray bursts, supernova remnants, active galactic nuclei and microquasars, in which the acceleration of hadrons may occur. Transient sources offer a unique opportunity to detect high energy neutrinos, the background of atmospheric muons and neutrinos being strongly reduced in the narrow observation time window. For example, several authors predict the emission of neutrinos in correlation with multi-wavelength signals, e.g. the Fireball model of GRBs (see Piran 1999).
The ANTARES Collaboration has completed in May 2008 the deployment of a neutrino telescope that is located about 2500 meters deep, offshore Toulon, France (see Ageron 2011a). The PMTs are arranged on 12 detection lines, each comprising up to 25 triplets of PMTs (floors), regularly distributed on 350 m, the lowest floor being located at 100 m above the sea bed. The main goal of the experiment is to search for neutrinos of astrophysical origin, by detecting high energy muons ($\geq$100 GeV) induced by their neutrino charged current interaction in the vicinity of the detector. Due to the large background from downgoing cosmic ray induced muons, the detector is optimised for the detection of upgoing neutrino induced muon tracks.
In this paper, the implementation and the first results of a strategy for the detection of transient sources of high energy neutrinos is presented. This method, earlier proposed in Kowalski & Mohr (2007), is based on the optical follow-up of selected neutrino events very shortly after their detection by the ANTARES neutrino telescope. The alert system is known as "TAToO" (Telescopes and ANTARES Target of Opportunity) and it is described in Ageron (2011b).

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2 ANTARES neutrino alerts

Several theoretical models predict the production of high energy neutrinos with energies higher than 1 TeV from transient sources like GRBs and Core Collapse Supernovae (see for example Waxman & Bahcall 1997; Ando & Beacom 2005). Under certain conditions, multiplet of neutrinos can be expected, as discussed in Razzaque & et al. (2005). Two online neutrino trigger criteria are currently implemented in the TAToO alert system: the detection of at least two neutrino induced muons coming from similar directions within a predefined time window, and the detection of a single high energy neutrino induced muon.

A basic requirement for the coincident observation of a neutrino and an optical counterpart is that the pointing accuracy of the neutrino telescope should be at least comparable to the field of view of the optical telescopes, namely TAROT and ROTSE (see Boer & et al. 1999; Akerlof & et al. 2003), having a field of view of about $2° \times 2°$.

To select the events which might trigger an alert, a fast and robust algorithm is used to reconstruct the ANTARES events (see Aguilar & et al 2011). The principle is to minimize a χ^2 which compares the times of selected hits with the expectation from a Cherenkov signal of a muon track. The resulting direction of the reconstructed muon track is available within about 10 ms and the obtained minimal χ^2 is used as fit quality parameter to remove mis-reconstructed tracks. This algorithm uses a simplified detector geometry, that does not take into account the actual shape of the detector as well as the storeys orientation and lateral extension.

Neutrino events selection criteria have been established on the basis of Monte Carlo simulations of both signal and background events. Figure 1 shows the angular resolution of the online algorithm as a function of the neutrino energy. This resolution is defined as the median of the space angular difference between the direction of the incoming neutrino and the reconstructed neutrino-induced muon. For neutrinos with an energy higher than a few tens of TeV, an angular resolution of 0.4 degree is achieved.

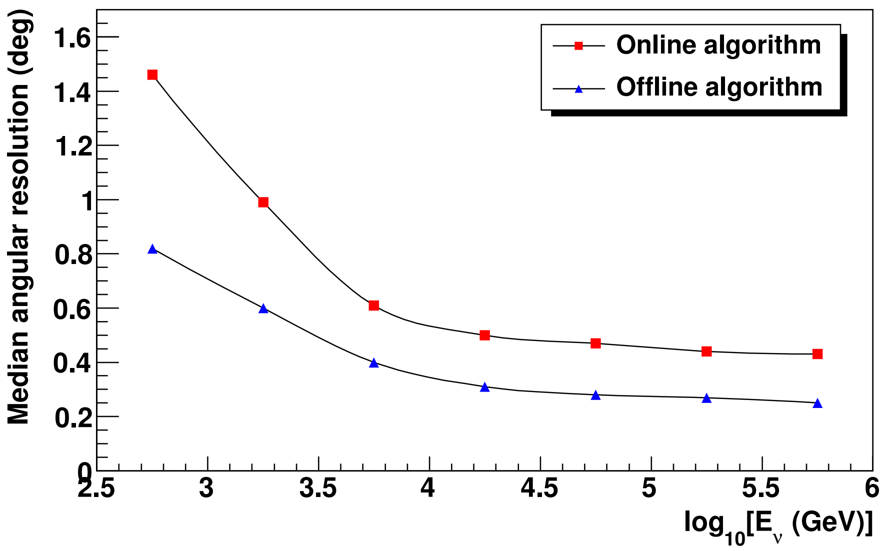

Fig. 1. Angular resolution obtained for both online and offline reconstructions as a function of the neutrino energy.

2.1 *Multi-neutrino trigger*

The typical signature of the transient emission of high energy neutrinos is expected to be a neutrino burst, i.e. a multiplet of neutrino events originating from the source in a short time window. A trigger for this event type is implemented as the detection of two upgoing events reconstructed with at least two lines in a 15 minutes time window with a maximum angular difference of $3°$. The time window was optimized to include most predictions of the neutrino emission by various models for transient sources. The $3°$ angular window was selected to match the convolution of the track reconstruction angular resolution and the field of view of the robotic optical telescopes ($\approx 2° \times 2°$). The accidental coincidence rate due to background events, from two uncorrelated upgoing atmospheric neutrinos, is estimated to be 7×10^{-3} coincidences per year with the full ANTARES detector. With such a small background, the detection of a doublet (triplet) in ANTARES would have a significance of about 3 (5) sigma.

2.2 High energy event trigger

Since the spectrum of cosmic neutrinos is expected to be harder than that of atmospheric neutrinos, a cut on the reconstructed energy could efficiently reduce the atmospheric neutrino background, while keeping most of the signal events. The selection of the alert candidates is based on two simple energy estimators: the number of storeys used in the track fit and the total amplitude (in photoelectrons) of the hits in the storeys.

The event selection for the high energy trigger has been tuned on atmospheric neutrinos in order to obtain a false alarm rate of about 25 alerts per year. This rate was agreed between ANTARES and the optical telescope collaborations. A requirement of at least 20 storeys on at least three lines and an amplitude greater than 180 photoelectrons will select around 25 high energy events per year (for the full configuration of the ANTARES detector). Simulations performed using an E^{-2} energy spectrum for signal events indicate energies higher than 10 TeV for the single high energy trigger. Figure 2 shows the estimation of the point spread function for a typical high energy neutrino alert. Around 70% of the events are contained in the field of view of a typical robotical telescope ($\approx 2° \times 2°$).

With a larger delay (few minutes after the time of the burst), an additional reconstruction algorithm is used to refine the result of the online strategy. This algorithm has been developed to search for point-like sources of high energy neutrinos (see Heijboer, A. J. 2004). Simulations indicate that, with this algorithm, ANTARES reaches an angular resolution smaller than about 0.3-0.4° for neutrino energies above 10 TeV (curve labeled 'offline algorithm' in Figure 1).

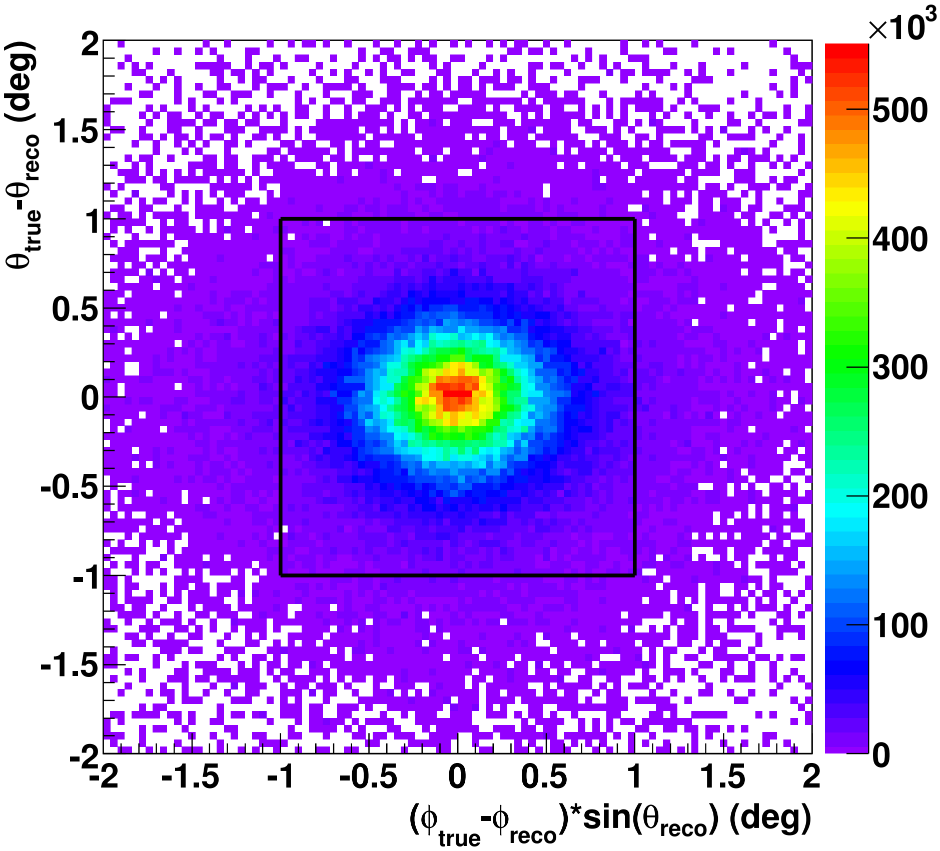

Fig. 2. Bi-dimensional angular resolution. The black square corresponds to the TAROT telescope field of view ($\approx 2° \times 2°$).

3 Observation strategy of the robotical telescopes

ANTARES is organizing a follow-up program in collaboration with the TAROT and ROTSE telescopes. The TAROT network is composed of two 25 cm optical robotic telescopes located at Calern (France) and La Silla (Chile). The ROTSE network is composed of four 45 cm optical robotic telescopes located at Coonabarabran (Australia), Fort Davis (USA), Windhoek (Namibia) and Antalya (Turkey). The main advantages of these instruments are the large field of view, namely about 2 x 2 square degrees, and their very fast positioning time (less than 10s). These telescopes are perfectly tailored for such a program. Thanks to the location of the ANTARES telescope in the Northern hemisphere (42.79 degrees latitude), all the six telescopes are used for the optical follow-up program. Depending on the neutrino trigger settings, the alert are sent at a rate of abour one or two times per month. With the current settings, the connected telescopes can start taking images with a latency of the order of one minute with respect to the neutrino event (T0).

To be sensitive to a wide range of transient sources, the TAToO observational strategy is composed of a real time observation, optimized to search for GRBs, followed by several observations during the following month, optimized to search for longer phenomena like CCSN. For the prompt observation, 6 images with an exposure of 3 minutes and 30 images with an exposure of 1 min are taken respectively by the first available TAROT and ROTSE telescopes. The integrated time has been defined in order to reach an average magnitude of about 19. For each delayed observation, six images are taken at T0+1,+2, +3, +4, +5, +6, +7, +9, +15, +27 days after the trigger for TAROT (8 images for ROTSE the same days plus T0+16 and T0+28 days).

4 Optical image analysis

Once the images are collected, they are automatically dark subtracted and flat-fielded at the telescope site. Once the data are copied from the telescopes, an offline analysis is performed combining the images from all sites. This off-line program is composed by three main steps: astrometric and photometric calibration, subtraction between each image and a reference one and light curve determination for each variable candidates. The choice of the reference image is based on quality criteria such as the limiting magnitude and the seeing. For the GRB search, the reference is chosen amongst the follow-up observations (few days after the alert) where no GRB signal is expected anymore, while for SN search, we consider the first night observation, or we use images of an additional observation, performed few months later, to have a better quality, in absence of a SN signal.

The ROTSE pipeline has been applied to five alerts from which optical images have been recorded during the first 24 hours after the neutrino alert sending. The minimum delay between the neutrino detection and the first image is around 70 s. No object has been found for which the light curve is compatible with a fast time decreasing signal.

5 Conclusions

The method used to search for an optical counterpart of candidate neutrino events detected by the ANTARES telescope has been presented. The TAToO system is able to trigger the observation with a network of optical telescopes within one minute from the detection of the neutrino candidate, with an precision on the alert position that is better than one degree. The quasi-online availability of a refined direction further improves the quality and efficiency of the alert system.

The alert system is operational since February 2009, and as of October 2011, about 40 alerts have been sent, all of them triggered by the high energy selection criterium. No doublet trigger has been recorded yet. After a commissioning phase in 2009, almost all alerts had an optical follow-up in 2010, and the live time of the system over this year is equal to the one of the ANTARES telescope, namely 87%. These numbers are consistent with the expected trigger rate, after accounting for the duty cycle of the neutrino telescope. The image analysis of five 'prompt' observations has not permitted to discover a GRB afterglow associated to the high energy neutrino. The analysis of the rest of the images to look for the light curve of a core collapse SN is still on-going.

The optical follow-up of neutrino events significantly improves the perspective for the detection of transient sources. A confirmation by an optical telescope of a neutrino alert will not only provide information on the nature of the source but also improve the precision of the source direction determination in order to trigger other observatories (for example very large telescopes for redshift measurement). The program for the follow-up of ANTARES neutrino events is already operational with the TAROT and ROTSE telescopes and results based on analysis of the optical images will be presented in a forthcoming paper. This technique could be extended to observations in other wavelength regimes such as X-ray or radio.

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