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NEUTRINO DETECTION OF TRANSIENT SOURCES WITH OPTICAL FOLLOW-UP OBSERVATIONS

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Abstract. The ANTARES telescope has the opportunity to detect transient neutrino sources,such as gamma-ray bursts,core-collapse supernovae,flares of active galactic nuclei. To enhance the sensitivity to these sources, a new detection method based on coincident observations of neutrinos and optical signals has been developed. For this purpose the ANTARES Collaboration has implemented a fast on-line muon track reconstruction with a good angular resolution. These characteristics allow to trigger a network of optical telescopes in order to identify the nature of the neutrino sources. An optical follow-up of special events, such as neutrino doublets, coincident in time and direction, or single neutrinos with a very high energy, would not only give access to the nature of their sources but also improve the sensitivity for neutrino detection. The alert system is operational since early 2009, and as of September 2010, 22 alerts have been sent to the TAROT and ROTSE telescopes.

Keywords: Antares, neutrino astronomy, transient sources, optical follow-up

1 Introduction

The ANTARES neutrino telescope (Aslanides et al. 1999) is located in the Mediterranean sea, 40 km south of the french coast of Toulon, at a depth of about 2500 m below sea level. The detector is an array of photomultipliers tubes (PMTs) arranged on 12 slender vertical detection lines. Each string comprises up to 25 floors, i.e. triplets of optical modules (OMs) housing each one PMT. Data taking started in 2006 with the operation of the first line of the detector. The construction of the 12 line detector was completed in May 2008. The main goal of the experiment is to detect high energy muons induced by neutrinos of astrophysical origin interacting in the vicinity of the detector.

The detection of high energy cosmic neutrinos would be the only direct proof of hadronic acceleration processes in astrophysical objects,implying the identification of the sources of ultra high energy cosmic rays without ambiguity. Among the possible astrophysical sites, those that have transient nature such as gamma ray bursts (GRB) or core collapse supernovae (ccSNe), offer one of the most promising perspectives for the detection of cosmic neutrinos thanks to the almost background free search. The emission of neutrinos is predicted by several authors in correlation with other multi-wavelength signals. Their detection could help for example to constrain GRB models, such as the fireball model (Piran 1999). This model tells us how the GRBs operate but important questions still remain such as which processes generate the energetic ultra-relativistic flows or how the shock acceleration is realized.

In contrary to the current gamma-ray observatories, a neutrino telescope can survey at any time a full hemisphere if only up-going events are analyzed and even 4π sr if down-going events are considered. More importantly no assumption is made on the nature of the source and the mechanisms occurring inside.

In this paper, we discuss the implementation of a strategy for the detection of transient sources (Kowalski and Mohr 2007; Dornic et al. 2011; Basa et al. 2009). This method is based on the optical follow-up of selected neutrino events.

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2 ANTARES neutrino alerts

In order to allow a successful detection, the neutrino trigger has to be set according to the expected neutrino signal emitted from the considered sources. Several models predict the production of high energy neutrinos (10-100 TeV) from GRBs (Waxman and Bahcall 1997; Meszaros and Waxman 2001; Dermer and Atoyan 2003; Razzaque et al. 2003) as well as 1-10 TeV neutrinos from Core Collapse Supernovae (Ando and Beacom 2005). If such sources are close enough, bursts of neutrinos can be expected as discussed in (Razzaque et al. 2005).

Two on-line neutrino trigger criteria are currently implemented in the alert system: the detection of at least 2 neutrino-induced muons coming from similar directions within a predefined time window, or the detection of a single high energy neutrino-induced muon.

To select the events which might trigger an alert, a fast and robust algorithm is used to reconstruct the raw data. This algorithm uses an idealized detector geometry and is independent of the dynamical positioning calibration. 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. A detailed description of this algorithm and its performances can be found in Antares (2010). The resulting direction of the reconstructed muon track is available within about 5 ms and the obtained minimal χ^2 is used as fit quality parameter to remove miss-reconstructed tracks.

To select the alert candidates, first the atmospheric muon background is suppressed. In a second step, a selection of neutrino candidates having a high probability to be of cosmic origin is performed.

In order to set the cuts used for our neutrino selection, we have analyzed the data registered by ANTARES in 2008 corresponding to 173 active days of data taking. During this period, around 600 up-going neutrino candidates were recorded. In order to obtain a good angular resolution*, we only select reconstructed events which trigger several hits on at least 3 lines. The curve labeled "on-line algorithm" of figure 1 shows the median angular resolution as a function the neutrino energy for events selected by the high energy criteria. For the mean energy given by the selection cuts, the angular resolution is around 0.95°. The asymptotic resolution of 0.6° can be achieved when considering the highest energetic events.

An estimation of the energy in the on-line reconstruction is indirectly determined by using the number of hits of the event and the total amplitude of these hits. In order to select events with an energy above around 5 TeV, a minimum of about 20 storeys and about 180 photoelectrons per track are required. These two different trigger logics applied on the 2008 data period select around twenty events (Dornic et al. 2009).

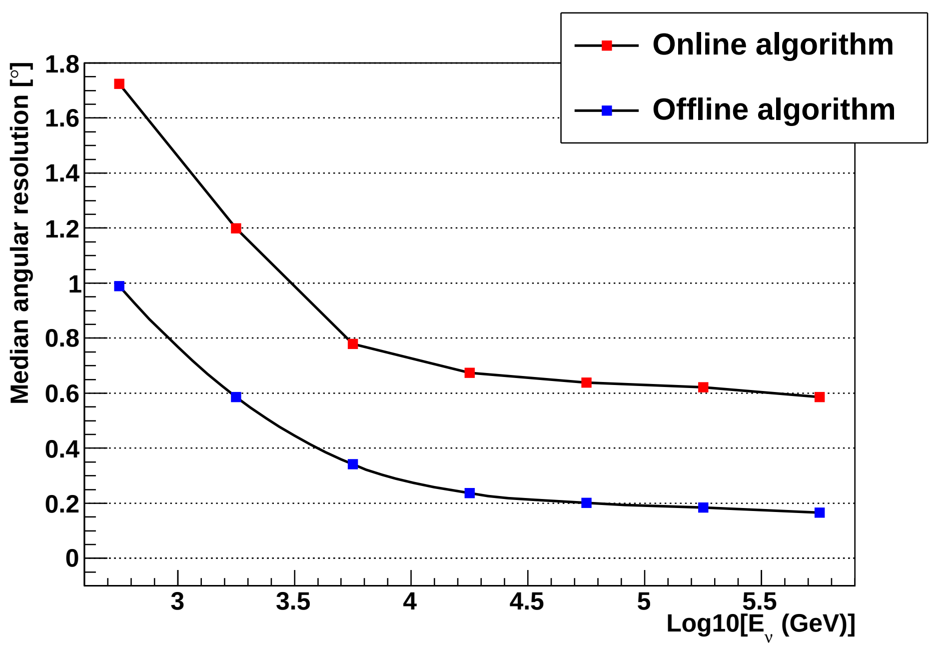

Fig. 1. Angular resolution obtained for both on-line and offline reconstructions as a function of the neutrino energy.

*The angular resolution is defined as the median of the space angular difference between the incoming neutrino and the reconstructed neutrino-induced muon.

Figure 2 shows the estimation of the point spread function for a typical high energy neutrino alerts. Around 70% of the events are contained in the field of view of a typical robotical telescope ($\approx 2°x2°$). With a larger delay (few tens of minutes after the time of the burst), we are able to run the standard reconstruction tool which provides a much better angular resolution using the dynamical positioning of the detector lines. Simulations indicate that, with this algorithm, ANTARES reaches an angular resolution smaller than about 0.3-0.4° for neutrino energies above 10 TeV.

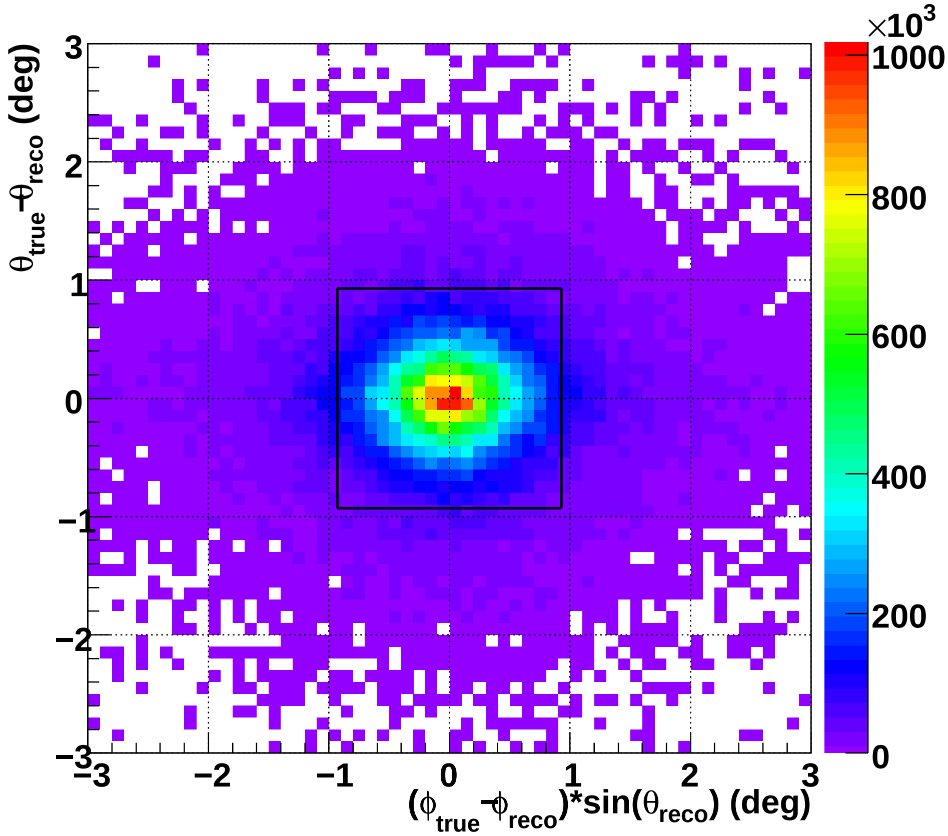

Fig. 2. Bi-dimensional angular resolution. The black square corresponds to the TAROT telescope field of view.

3 Observation strategy of the robotical telescopes

ANTARES is organizing a follow-up program in collaboration with the TAROT and ROTSE telescopes The TAROT (Boer et al. 1999) network is composed of two 25 cm optical robotic telescopes located at Calern (France) and La Silla (Chile). The ROTSE (Akerlof et al. 2003) 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 of 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 hemishpere (42.79 degres 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.

As it was said before, the rolling search method is sensitive to all transient sources producing high energy neutrinos. For example, a GRB afterglow requires a very fast observation strategy in contrary to a core collapse supernovae for which the optical signal will appear several days after the neutrino signal. To be sensitive to all these astrophysical sources, the observational strategy is composed of a real time observation followed by few observations uring the following month. For the real time observation (at T0), 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 around 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 more T0+16 and T0+28 days).

4 Optical image analysis

Once the images are taken, they are automatically processed (flat and dark subtraction) at the telescope site. Once the data is copied from the telescopes, a second analysis is performed off-line, combining the images from all sites. This off-line program is composed by three main steps: absolute astrometric and photometric calibration of the image, subtraction between each image and a reference one and light curve determination for each variable candidates. This program, originally developped for the supernovae search in the SuperNova Legacy Survey (SNLS) project has been adapted in order to look for transient objects in the large field of view taken into account the image quality of the TAROT and ROTSE telescopes. Cases like variable PSF due to the atmospheric conditions or the lower quality images on the CCD edges have to be optimized in order not to lose any optical information. Image subtraction is performed according the methods presented in Alard and Lupton (1998). Here, the image with the best seeing during the first night in case of GRB search or during the whole observations in case of SN search serves as reference. It is also planned that the image analysis step will be included at the end of the automatic detection chain.

5 Conclusions

The follow-up of golden events would improve significantly the perspective for neutrino detection from transient sources. The most important point of the rolling search method is that it is sensitive to any transient source. A confirmation by an optical telescope of a neutrino alert will not only give the nature of the source but also allow to increase the precision of the source direction determination in order to trigger other observatories (for example very large telescopes for the redshift measurement). The alert system is operational since early 2009, and as of September 2010, 22 alerts have been recorded. After a commissioning phase in 2009, all alerts had an optical follow-up in 2010. These numbers are conform to the rate of one or two alerts per months, as it is required by the optical telescope network. The program for the follow-up of ANTARES neutrino events is already operational with the TAROT and ROTSE telescopes. It would be also interesting to extend this technique to other wavelength observation such as X-ray or radio.

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