

## Search for neutrinos from transient sources with the ANTARES telescope and optical follow-up observations

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**Abstract:** The ANTARES telescope is well suited to detect neutrinos produced in astrophysical transient sources as it can observe a full hemisphere of the sky at all the times with a duty cycle close to unity. Potential sources include gamma-ray bursts (GRBs), core collapse supernovae (SNe), and flaring active galactic nuclei (AGNs). To enhance the sensitivity of ANTARES to such sources, a new detection method based on coincident observations of neutrinos and optical signals has been developed. A fast online muon track reconstruction is used to trigger a network of small automatic optical telescopes. Such alerts are generated twice per month for special events such as two or more neutrinos, coincident in time and direction, or single neutrinos of very high energy or in the specific directions of local galaxies. Alert triggers are followed by the TAROT, ROTSE and ZADKO optical telescopes and by the SWIFT/XRT telescopes. Results on the optical images analysis to search for GRB in the prompt images and core collapse SNe will be presented.

**Keywords:** high energy neutrino, GRB, optical follow-up.

### 1 Introduction

Detection of high-energy neutrinos from an astronomical source would be a direct evidence of the presence of hadronic acceleration and provide important information on the origin of the high-energy cosmic rays. Transient astronomical phenomena, such as Gamma-Ray Bursts (GRB) [1] and core collapse supernovae (ccSNe) [2], offer very promising perspectives for the detection of cosmic neutrinos as, due to their short duration, the background from atmospheric neutrinos and muons is strongly reduced. As neutrino telescopes observe a full hemisphere of the sky (even the whole sky if down-going events are considered) at all times, they are particularly well suited for the detection of transient phenomena.

To improve the detection sensibility to transient sources, a multi-wavelength follow-up program, TAToO, operates within the ANTARES Collaboration since 2009 [3]. This method, earlier proposed in [4], is based on the optical follow-up of selected neutrino events very shortly after their detection by the ANTARES neutrino telescope. ANTARES is able to send alerts within one minute after the neutrino detection and with a precision of the reconstructed direction better than 0.5 degrees at high-energy ( $E > 1 \text{ TeV}$ ). The optical follow-up is performed by the TAROT [5] and ROTSE-III [6] telescopes. Since February 2009 to December 2012, 83 alerts have been sent, all of them triggered by the two single neutrino selection criteria. After a commissioning phase in 2009, more than 80 % of the alerts had an optical follow-up. The main advantage of this program is that no hypothesis is required on the nature of the source, only that it produces neutrino and photons.

In this paper, the first results on the analysis of the early follow-up images associated to eight TAToO alerts are pre-

sented. A brief description of the ANTARES experiment and the alert system are summarized in section 2 and 3 respectively. The observation strategy and the optical data analysis are described in section 4 and 5 respectively. Finally, section 6 outlines the results of this search.

### 2 The ANTARES experiment

The ANTARES experiment [7] aims at searching for neutrinos of astrophysical origin by detecting high-energy muons ( $\geq 100 \text{ GeV}$ ) induced by their neutrino charged current interaction in the vicinity of the detector. Due to the very large background from down-going cosmic ray induced muons, the detector is optimized for the detection of up-going neutrino induced muon tracks.

The ANTARES detector is located in the Mediterranean Sea, 40 km from the coast of Toulon, France, at a depth of 2475 m. It is a tridimensional array of photomultiplier tubes (PMTs) arranged on 12 slender detection lines, anchored to the sea bed and kept taught by a buoy at the top. Each line comprises up to 25 storeys of triplets of optical modules (OMs), each housing a single 10" PMT. Since lines are subject to the sea current and can change shape and orientation, a positioning system comprising hydrophones and compass-tiltmeters is used to monitor the detector geometry. PMT signals are digitized offshore and time-stamped using an external GPS signal giving the absolute timing at the location of the detector, allowing an absolute time accuracy better than  $1 \mu\text{s}$ . The onshore data acquisition system collects the data from all the individual PMTs of the detector and passes them to the filtering algorithms based on local "clusters" which search for a collection of signals compatible with a muon track crossing the

detector. All hits within a few microseconds around these clusters define an “event” and are kept for further online and offline reconstructions. Events are typically available less than one minute after the crossing of the detector by a high-energy muon. The ANTARES neutrino telescope is fully operational since May 2008[8].

### 3 ANTARES neutrino alerts

The criteria for the TATO trigger are based on the features of the neutrino signal produced by the expected sources. Several models predict the production of high energy neutrinos greater than 1 TeV from GRBs [1] and from Core Collapse Supernovae [2]. Under certain conditions, multiplet of neutrinos can be expected [9]. 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 TAROT and ROTSE telescopes ( $\approx 2^\circ \times 2^\circ$ ).

Atmospheric muons, whose abundance at the ANTARES detector [10] is roughly six orders of magnitude larger than the one of muons induced by atmospheric neutrinos, are the main background for the alerts and have to be efficiently suppressed. Among the surviving events, neutrino candidates with an increased probability to be of cosmic origin are selected [11].

To select the events which might trigger an alert, a fast and robust algorithm is used to reconstruct the calibrated data. This algorithm uses an idealized detector geometry and is independent of the dynamical positioning calibration. A detailed description of this algorithm and its performances can be found in [12]. This reconstruction allows to reduce the rate of events from few Hz down to few mHz. This algorithm is then coupled to a more precise reconstruction tool [13] which allows to confirm the neutrino nature of the event and to improve the angular resolution. With this system, ANTARES is able to send alerts in few seconds ( $\approx 3 - 5$  s) after the detection of the neutrinos.

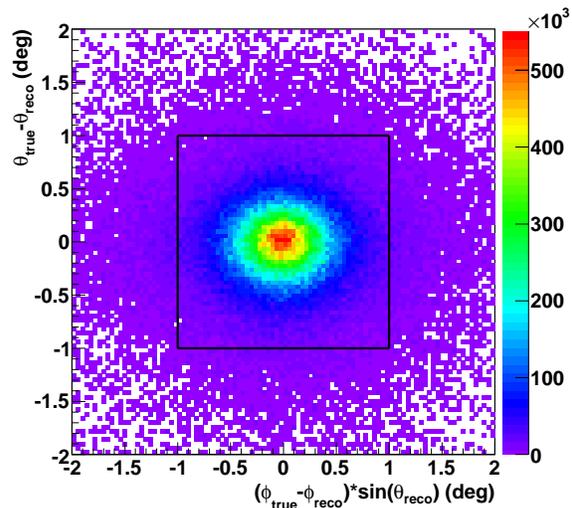
Three online neutrino trigger criteria are currently implemented in the TATO alert system [15]:

- the detection of at least two neutrino-induced muons coming from similar directions ( $< 3^\circ$ ) within a pre-defined time window ( $< 15min$ );
- the detection of a single high-energy neutrino induced muon.
- the detection of a single neutrino induced muon for which the direction points toward a local galaxy.

The main performance of these three triggers are described in table 1. For the highest energy events, the angular resolution gets down to less than  $0.3^\circ$  (median value). Figure 1 shows the estimate of the point spread function for a typical high energy neutrino alert.

### 4 Observation strategy of the robotical telescopes

ANTARES is organizing a follow-up program in collaboration with the TAROT and ROTSE telescopes. The TAROT [5] network is composed of two 25 cm optical robotic telescopes located at Calern (France) and La Silla (Chile). The ROTSE [6] network is composed of four



**Figure 1:** Bi-dimensional angular resolution. The black square corresponds to the TAROT telescope field of view ( $\approx 2^\circ \times 2^\circ$ ).

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  $2 \times 2$  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 about twice per month. With the current settings, the connected telescopes can start taking images with a latency of the order of  $\approx 20$  s with respect to the neutrino event (T0) including the telescope slewing.

As already mentioned, this 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 during the following month. 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, +45, +60 days after the trigger for TAROT (8 images for ROTSE the same days plus T0+16 and T0+28 days). Since one year, the follow-up has been extended to the 1 m ZADKO telescope [16] located in Australia with the same observational strategy as the one used for TAROT.

### 5 Optical image analysis

Once the images are taken, they are automatically dark subtracted and flat-fielded at the telescope site. Once the data is copied from the telescopes, an offline analysis is

**Table 1:** Performances of the three alert criteria. The third column corresponds to the fraction of events inside a  $2^\circ \times 2^\circ$  field of view assuming a flux of GRB [1] and ccSNe [2].

Trigger	Angular Resolution (median)	Fraction of events in fov	Muon contamination	Mean energy
Doublet	$\leq 0.7^\circ$		0 %	100 GeV
single HE	0.25-0.3 $^\circ$	96 % (GRB) 68 % (SN)	< 0.1 %	7 TeV
single directional	0.3-0.4 $^\circ$	90 % (GRB) 50 % (SN)	2 %	1 TeV

performed combining the images from all sites. This offline program is composed of three main steps: astrometric and photometric calibration, subtraction of each image and a reference one and light curve determination for each variable candidates.

Currently, two offline analysis pipelines are used: the ROTSE automated pipeline [17] and one specially adapted to the TAROT and ROTSE image quality based on the Poloka [18] program originally developed for the supernovae search in the SuperNova Legacy Survey (SNLS) project. 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. The choice of the reference is based on quality criteria such as the limiting magnitude and the seeing (i.e. mean size of the stars in the image). For the GRB search, the reference is picked among the follow-up observations (few days after the alert) where no GRB signal is expected anymore. For SNe search, the reference is either the first observation night or an additional image taken few months later to have a better quality in absence of a SN signal. It is also planned that the image analysis step will be included at the end of the automatic detection chain. The photometry is done using [19].

## 6 Results

This paper presents the analysis of the data taking from 01/01/2010 to 31/12/2012. ANTARES was running in a reduced configuration (10-11 lines) up to November 2010 and in the full configuration (12 lines) from this date. During this period, the efficiency of the ANTARES data taking was around 80 % which includes periods of maintenance and calibration of the detector.

During this period a total of 83 alerts were successfully sent to the telescopes, 65 of which benefit from at least 3 observations. For the remaining 18 alerts were not followed because of the telescope maintenance or due to the Sun position too close to the alert direction. Only 12 alerts had a good quality follow-up within less than one day (i.e. prompt follow-up). The lack of prompt observations is due to the telescopes observing efficiency upon the reception of the alert.

The two optical image analysis pipeline have been applied to these twelve 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 20 s. No object has been found for which the light curve is compatible with a fast time decreasing signal.

The limitation is most probably due to the sensitivity of the telescope and atmospheric conditions during the observation, which reduce the limiting magnitude. We define the limiting magnitude as the mean value of sources extracted at a Signal-to-Noise Ratio (SNR) of 5. Table 2 shows the

obtained limits along with the delay of the first image acquisition with respect to the neutrino detection. The limiting magnitude is further reduced when the direction is close to the galactic plane, which causes magnitudes to be dimmer and redder than they are (i.e., galactic extinction).

## 7 Conclusion

The method used by the ANTARES collaboration to implement the search for coincidence between high energy neutrinos and transient sources followed by small robotic telescopes has been presented. Of particular importance for this alert system are the ability to reconstruct online the neutrino direction and to efficiently reject the background. With the described ANTARES alert sending capability, the connected optical telescopes can start taking images with a latency of the order of  $\approx 20$  s. The precision of the direction of the alert is better than 0.5 degrees.

The alert system is operational since February 2009, and as of December 2012, 83 alerts have been sent, all of them triggered by the two single neutrino criteria. No doublet trigger has been recorded yet. After a commissioning phase in 2009, almost all alerts had an optical follow-up since 2010, and the live time of the system over this year is strictly equal to the one of the ANTARES telescope, 70-80%. These numbers are consistent with the expected trigger rate, after accounting for the duty cycle of the neutrino telescope. The image analysis of the 'prompt' images has not permitted yet to discover any transient sources associated to the selected high energy neutrinos, in particular no GRB afterglow. The analysis of the rest of the images to look for the light curve of a core collapse SNe is still ongoing.

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, ROTSE and ZADKO telescopes. This technique has been recently extended to the follow-up in X-ray with the Swift/XRT telescope to further improve the sensitivity to fast transient sources, like GRBs.

## 8 Acknowledgments

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**Table 2:** Magnitude limits in R-band ( $5\sigma$  threshold) for the neutrino alerts. The second column indicates the time delay between the first image and the neutrino detection. An estimate of the Galactic extinction is indicated.

Alert	Time delay (days)	Limiting magnitude (R mag)	Galactic extinction (R mag)
ANT100123	0.64	12.0	0.2
ANT100302	1.01	15.7	0.2
ANT100725	8.7e-4	14.5	0.3
ANT100922	4.7e-2	14.0	0.5
ANT101211	0.50	15.1	0.1
ANT110409	3.0e-3	18.1	6.7
ANT110529	5.2e-3	15.6	1.2
ANT110613	7.8e-4	17.0	2.3
ANT120730	2.4e-4	17.6	0.4
ANT120907	2.9e-4	16.9	0.2
ANT121010	2.8e-4	18.6	0.1
ANT121206	3.1 e-4	16.9	1.3

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