Multi-messenger programs in ANTARES: Status and prospects

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Abstract

With an instrumented volume of about 0.015 km^3, ANTARES is currently the largest neutrino telescope operating in the Northern Hemisphere. One of its main goals is the detection of high-energy neutrinos from (extra-)galactic astrophysical sources. Such observations would provide important clues about the processes at work in those sources, and possibly help solve the puzzle of ultra-high cosmic rays. In this context, ANTARES is developing several on- and off-line programs to improve its capabilities of revealing possible correlations (in space and time) of neutrinos with other cosmic messengers: photons (in different ranges of wavelengths), cosmic rays and gravitational waves.

Keywords: ANTARES, neutrinos, multi-messenger astronomy

1. Introduction and motivations

Astroparticle physics has entered an exciting period with the recent development of experimental techniques that have opened new windows of observation of the cosmic radiation in all its components: photons, cosmic rays, but also high-energy neutrinos and gravitational waves. In this context, it has been emphasized that not only a multi-wavelength but also a multi-messenger approach is suited for the study of astrophysical sources. Such strategies are being implemented, both at the on- and off-line levels, in most currently operating astroparticle detectors in order to extract the maximum amount of information from the data and to search for correlations between signals in different components of the cosmic radiation. This contribution presents a brief review of multi-messenger activities in the undersea neutrino telescope ANTARES.

This detector consists in a 3D array of photomultiplier tubes (PMTs) distributed on 12 lines anchored to the sea bed. It detects the Cherenkov radiation induced by charged leptons (mainly muons) originating from cosmic neutrino interactions with matter in the vicinity of the detector. The knowledge of the timing and amplitude of the light pulses recorded by the PMTs enables to reconstruct the trajectory of the muon and to estimate the arrival direction of the incident neutrino and its energy. The design and performance of the ANTARES detector are described elsewhere in these Proceedings [1]. Its instantaneous field of view is $\sim 2\pi$ sr for neutrino energies 100 GeV $\lesssim E_\nu \lesssim$ 100 TeV. Above this energy, the sky coverage is reduced because of neutrino absorption in the Earth; but it can be partially recovered by looking for horizontal and down-going neutrinos. ANTARES is expected to achieve an unprecedented angular resolution (about 0.3° for neutrinos above 10 TeV) as a result of the good optical properties of sea water, an important asset in the context of searches for astrophysical point sources.

2. Data acquisition and alert handling in ANTARES

The data acquisition system of ANTARES is based on the ”all-data-to-shore” concept[2]. The time and charge of all PMT signals (or “hits”) that pass a predefined threshold (typically 0.3 photoelectron) are digitized and sent to shore, where they are buffered into timeslices of 104 ms and processed on the fly by a PC farm. The data flow to the shore amounts to about 1 to 10 Gb/s; it is dominated by random hits ($\sim$ 60 – 150 kHz per PMT) due to the background light produced by the radioactive decay of ^{40}K and by bioluminescence. A filtering program is run on the PCs to select the physics events among the raw data and writes them to disk in ROOT format to be analyzed offline.

The filtering program allows to apply different physics triggers to the same data in parallel. Standard algorithms typically look for clusters of hits whose timing, position and amplitude are compatible with the emission of Cherenkov light by charged particles traversing the detector. They are able to select with a high level of efficiency the events potentially associated to muons that cross the detector. Triggers optimized for specific (astro)physics signals may also be implemented, such as the directional trigger used to track the Galactic Center. In normal background conditions, the global trigger rate of the experiment reaches 5 to 15 Hz, so that the rate of data written on disk amounts to about 0.3 Mb/s.

Apart from this standard data taking mode, ANTARES is also able to react to external alerts. In particular, satellites looking for GRBs and other bursting phenomena can currently trigger the detector in real time via the GCN (Gamma-Ray Burst Coordinate Network) alert system, as sketched in Figure 1. The GCN network includes e.g. the HETE, Integral, Swift and, since November 2008, Fermi satellites. The typical latency time of GCN alerts with respect to the GRB time is of the order of 10 seconds. When a GRB alert is received from the GCN, a spe-

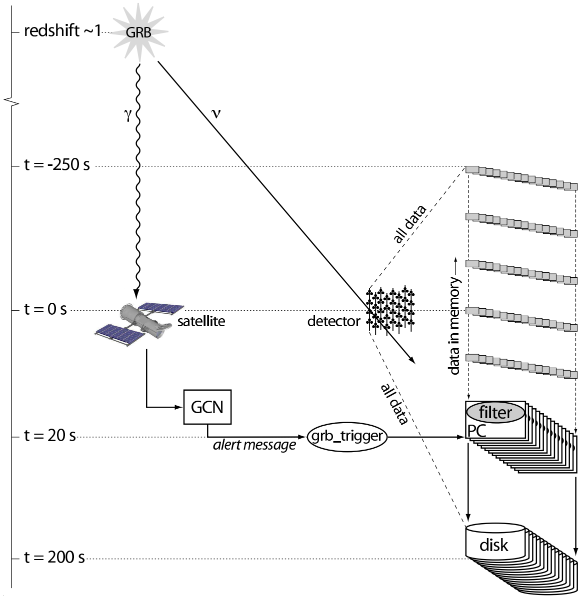

Figure 1: Time line of the different events during a GRB. The observation of the burst by a satellite triggers a GCN alert. At the moment this alert is received by ANTARES, all raw data covering a few minutes are saved to disk, including the buffered data in memory. Any neutrino signal from the GRB (before, during, and after the photon detection by the satellite) is then stored on disk.

cific data taking mode is activated in parallel with the standard one. All raw data covering a preset period (typically a few minutes, depending on the background rate, the number of PCs in the farm and the RAM available) are saved to disk and kept for offline analysis without any filtering[3]. Data buffering in the filter processors makes it possible to store the data up to about one minute before the actual GCN alert. As can be seen from Figure 3, it includes in most cases data collected by ANTARES before the GRB occurred, which can be used to search for an early neutrino signal that would occur before the gamma rays.

The time distribution of GRB alerts processed by ANTARES since its connection to the GCN network is shown in Figure 2. The efficiency of the triggered data taking mode is about 90%, for a total of more than 15 Tb of raw data recorded on disk. No alert was processed during July and August 2008 as the detector was not operating due to a cable failure. The global increase in the number of alerts since November 2008 reflects the arrival of Fermi on the GCN network. The particularly large amount of alerts received in January and February 2009 is due to the bursts of the Soft Gamma-ray Repeater SGR 1550-5418, a galactic source with a soft gamma-ray flaring activity. Such a high rate of alerts (more than 100 in one month) however generates a data flow which is difficult to handle for the ANTARES online acquisition system, so that the decision can be taken to stop the acquisition in alert-triggered mode for some time once it is established that most alerts come from the same source.

Another feature recently implemented in ANTARES is the possibility to trigger an external detector on the basis of "golden" neutrino events selected by a fast, online reconstruction procedure. These events can be neutrino doublets coincident in time and space or single neutrinos of very high energy. This

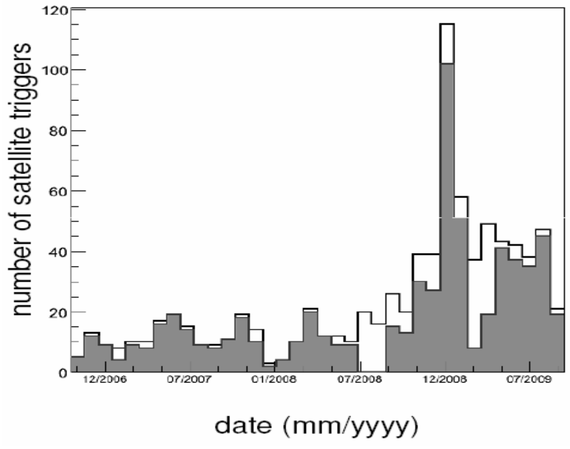

Figure 2: Time distribution of the GRB alerts in ANTARES since the implementation of the satellite-triggered data taking system. The empty histogram shows the number of alerts distributed by the GCN, while the shaded histogram indicates the number of alerts for which the satellite triggered data taking was applied. In November 2008, the GCN started the distribution of alerts from the Fermi satellite.

method was first proposed in [4]; the follow-up of interesting neutrino events possibly correlated to astrophysical transients can be done with fast-repositioning telescopes operating in different wavelength domains, from optical to X-rays and gamma-rays. Alerts are currently sent by ANTARES to the TAROT telescope in the framework of the TAToO project, described elsewhere in these proceedings [5]. The online reconstruction allows a very short latency ($<$ 1s) for the alert sending while maintaining a reasonable pointing accuracy ($\sim$ 1°), which is compatible with the field of view of TAROT. Due to the repositioning time of the telescope, the first optical image can typically be obtained after a few seconds; successive sets of images can then be recorded minutes, hours and/or days after the alert. This is designed to follow the time profile of different transient sources (such as GRB afterglows or core-collapse supernovae) on appropriate time scales.

3. Multi-messenger studies

The capabilities of the ANTARES data acquisition system discussed hereabove make it well suited for the search of astrophysical sources - and transients in particular. In addition to the searches for steady point sources in the standard physics data, specific strategies are being developed to look for neutrinos with timing and /or directional correlations with potential sources of gamma-rays (in connection with the GCN alerts), ultra-high energy cosmic rays (such as CenA) and gravitational waves.

The search for transient events associated to a GCN alert (typically generated by a GRB or a SGR flare) can be conducted both on the standard physics data set and on the raw data stored in coincidence with the alerts. The standard analysis is based on filtered data and the reconstruction of the muon trajectory on the basis of a five-parameter fit. It uses the absolute time of the alert to define an "on-time" window; the selection parameters

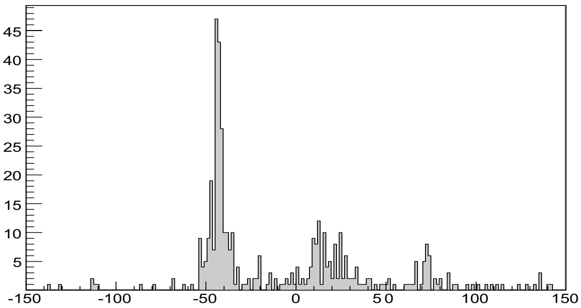

Figure 3: Earliest datum in the unfiltered GRB data set relative to the detection time of the GRB by the satellite. Negative response times mean that the unfiltered data set includes data prior to the detection of the GRB by the satellite. Positive response times are related to the latency time of the satellites, which delays the arrival time of the alert at the ANTARES site.

are tuned in a blind way on data from the off-time region. The alternative method is based on the unfiltered data saved on disk after a GRB alert; it takes into account the position of the GRB on the sky, which is also provided by the GCN. To ensure the blindness of the analysis, random fake alerts are generated and included in the raw data sample. Since these data are recorded without any filtering, the knowledge of the direction of the signal enables to apply looser selection criteria resulting in a lower detection threshold and a significantly higher efficiency [3]. It has also been proposed to detect the muons created in the atmosphere by the interaction of TeV gamma-rays originating from GRBs or other astrophysical sources. Such analyses focus on down-going events and look for a global excess of the muon flux in a direction correlated with the position of the source (and within a given time window, if the source is transient) [6].

For ultra-high energy cosmic rays no time-correlation is expected with neutrino events. Nevertheless, spatial correlations can be searched for in the direction of potential common sources (such as Cen A). Another method consists in cross-correlating the HEN events detected by ANTARES with the highest-energy events recorded by the Pierre Auger Observatory (which are expected to have undergone limited deflection) [7].

Finally, coincident searches of neutrinos and gravitational waves (GW) are also performed. The network of GW detectors formed by the LIGO [8] and Virgo [9] interferometers can determine the direction/time of GW bursts in connection with neutrino events observed in ANTARES. Requiring the consistency between both, totally independent, detection channels shall enable new searches for cosmic events arriving from potential common sources, among which putative “hidden sources“ such as the failed or choked GRBs, which are completely opaque to photons and hadrons [10]. The VIRGO/LIGO network started a data-taking phase mid-2009; it monitors a good fraction of the sky in common with ANTARES, as can be seen from Figure 4. Joint searches are ongoing within a dedicated ”GWHEN“ working group: preliminary investigations indicate that, even if the constituent observatories provide several triggers a day, the false alarm rate for the combined detector network can be maintained at a very low level, $\sim 1/(600 \text{ yr})$.

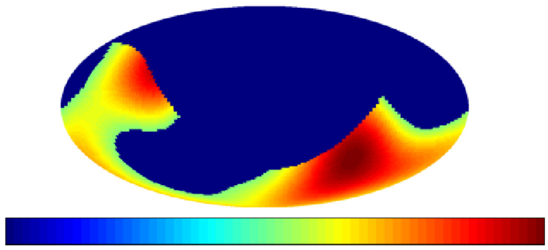

Figure 4: Instantaneous common sky coverage for VIRGO + LIGO + ANTARES in geocentric coordinates. This map shows the combined antenna pattern for the gravitational wave detector network (above half-maximum), with the simplifying assumption that ANTARES has 100% visibility in its antipodal hemisphere and 0% elsewhere. The colour scale is from 0% (left, blue) to 100% (right, red)[11]. The overlap of visibility maps is about 4 sr (~ 30% of the sky).

4. Conclusions and perspectives

Through the on- and off-line multi-messenger programs described hereabove, the ANTARES detector not only enhances its own capabilities as a neutrino telescope, but also contributes to the global effort of understanding the most violent phenomena in our Universe. In addition to offline searches for spatiotemporal correlations with other cosmic messengers (photons, cosmic rays and gravitational waves), ANTARES has the capability to handle external alerts in real time and to trigger follow-up observations with the small latency time required for the study of transient sources. The possibility to store a few minutes of raw data in coincidence with a GCN alert also brings new opportunities for offline analysis. This could be extended in the future to handle alerts involving other messengers, such as gravitational waves. Finally, the extension of the follow-up programs to other instruments in different ranges of wavelengths would undoubtely contribute to the development of the astrophysical potential of ANTARES.

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