

Search for gamma-ray bursts with the ANTARES neutrino telescope

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Abstract. Satellites that are capable of detecting gamma-ray bursts can trigger the ANTARES neutrino telescope via the real-time gamma-ray bursts coordinates network. Thanks to the “all-data-to-shore” concept that is implemented in the data acquisition system of ANTARES, the sensitivity to neutrinos from gamma-ray bursts is significantly increased when a gamma-ray burst is detected by these satellites. The performance of the satellite-triggered data taking is shown, as well as the resulting gain in detection efficiency. Different search methods can be applied to the data taken in coincidence with gamma-ray bursts. For gamma-ray bursts above the ANTARES horizon, for which a neutrino signal is more difficult to find, an analysis method is applied to detect muons induced by the high-energy gamma rays from the source.

Keywords: gamma-ray bursts; neutrino telescope

I. INTRODUCTION

Several models predict the production of high-energy neutrinos by gamma-ray bursts (GRBs) [1]. The detection of these neutrinos would provide evidence for hadron acceleration by GRBs. Such an observation would lead to a better understanding of the extreme processes associated with these astrophysical phenomena. In particular, it would give insight into the creation and composition of relativistic jets.

One of the goals of the ANTARES neutrino telescope is to detect high-energy neutrinos from GRBs. The ANTARES telescope is situated in the Mediterranean Sea at a depth of about 2500 m. Neutrinos are detected through the detection of Cherenkov light induced by the charged lepton that emerges from a neutrino interaction in the vicinity of the detector. Measurements are focused mainly on muon-neutrinos, since the muon resulting from a neutrino interaction can travel a distance of up to several kilometres. Due to the transparency of the sea water (the absorption length is about 50 m), the faint Cherenkov light can be detected at relatively large distances from the muon track. A large volume of sea water is turned into a neutrino detector by deploying a 3-dimensional array of light sensors in the water. The instrumented volume of sea water in the ANTARES telescope amounts to about 50 million cubic metres. The track of the muon can be reconstructed from the measured arrival times of the Cherenkov photons at the photo-multiplier tubes. Since the muon and neutrino paths are approximately co-linear at high energies, the

direction of the neutrino, and thus its origin, can be determined.

The GRB Coordinates Network (GCN) [2] announces the occurrence of a GRB by distributing real-time alerts. The data acquisition system of the ANTARES detector is designed such that it can trigger in real time on these alerts. This increases the detection efficiency for neutrinos from GRBs significantly. The ANTARES detector is currently the only neutrino telescope that can trigger in real time on GRB alerts.

II. DATA TAKING WITH THE ANTARES DETECTOR

The ANTARES telescope is operated day and night. During operation, all signals from the photo-multiplier tubes are digitised, and the raw data (containing the charge and time information of detected Cherenkov photons) are sent to shore in a continuous data stream. This is known as the all-data-to-shore concept [3]. Although daylight does not penetrate to the depth of the ANTARES site, a ubiquitous background luminosity is present in the deep-sea due to the decay of radioactive isotopes (mainly ^{40}K) and to bioluminescence. This background luminosity produces a relatively high count rate of random signals in the detector (60–150 kHz per photo-multiplier tube). The total data rate is primarily determined by this background luminosity, and amounts to about 1 GB/s. On shore, the continuous data stream is divided over a farm of PCs. Each of these PCs has a sophisticated filter program running, which processes the data it receives in real time. This filter scans the full sky, and finds the correlated photons that are caused by a muon traversing the detector. It triggers at a threshold of 10 such photons, which translates to a high detection efficiency for muons, while preserving a high muon purity (better than 90%). At the average background rate, the total trigger rate is 5–10 Hz (depending on the trigger conditions). The data are effectively reduced by a factor of 10^4 .

III. SATELLITE TRIGGERED DATA TAKING

The data acquisition system of the ANTARES detector is linked with a socket connection to the GCN. The GCN network includes the Swift and Fermi satellites, both capable of detecting GRBs. When a GRB alert is received from the GCN, the standard data processing continues (described in section II), and in parallel to that the satellite triggered data taking is applied: all raw data covering a preset period (presently 2 minutes) are saved to disk for each GRB alert. There are about 1–2

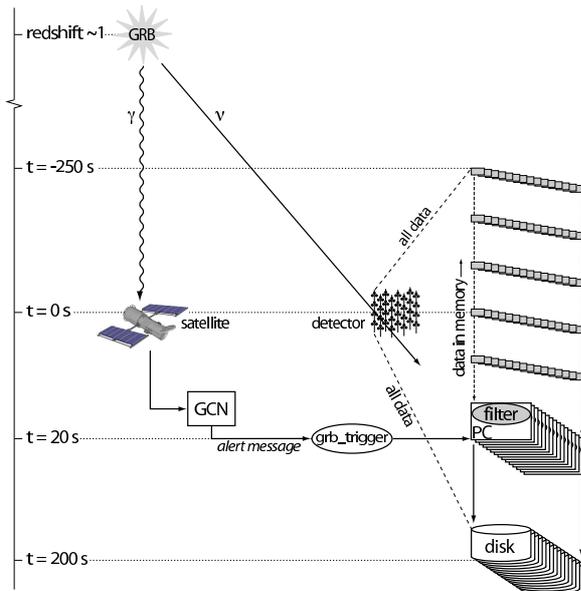


Fig. 1: Time line of the different events during a GRB. When an alert from the GCN is received by ANTARES (`grb_trigger` program), all raw data covering a few minutes are saved to disk, including all data in memory. Any neutrino signal from the GRB (before, during, and after the photon detection by the satellite) is stored on disk.

GRB alerts per day, and half of them correspond to a real GRB.

The buffering of the data in the data filter processors is used to store the data up to about one minute before the actual alert. The amount of data that can be kept in memory depends on the background rate in the sea water, the number of data processing PCs, and the size of the RAM. These data not only cover the delay between the detection of the GRB by the satellite and the arrival time of the alert at the ANTARES site, but also include data collected by the ANTARES detector before the GRB occurred. These data therefore include a possible early neutrino signal that is observable before the gamma rays.

For each GRB that is detected by a satellite, and announced by the GCN, all raw data collected by the ANTARES detector in coincidence with the GRB are available on disk, as shown schematically in Fig. 1. The satellite triggered data taking period per GRB corresponds to a few times the typical duration of a GRB. As a result, any time-correlated neutrino signal from the GRB —before, during, and after the photon detection by the satellite— is stored on disk. Saving all raw data is only possible for transient sources like GRBs. It can not be done for continuous sources because of the high data output rate of the detector.

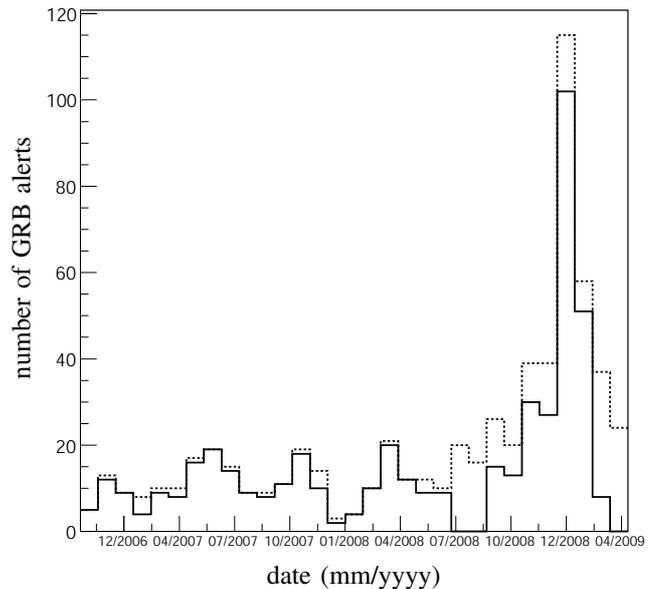


Fig. 2: The satellite triggered data taking of ANTARES since the implementation of the satellite triggered data taking system. The dashed line indicates the number of GRB alerts distributed by the GCN per month. The solid line indicates the number of GRB alerts for which the satellite triggered data taking was applied. In November 2008, the GCN started the distribution of alerts from the Fermi satellite. The relatively large amount of alerts received in January and February 2009 is due to the flaring activity of SGR 1550-5418.

IV. SATELLITE TRIGGERED DATA TAKING PERFORMANCE

The satellite triggered data taking for all GRB alerts distributed by the GCN is shown in Fig. 2. The satellite triggered data taking system became operational in autumn 2006. The dashed line shows the number of GRB alerts from the GCN per month as a function of time, and the solid line shows the number of satellite triggered data taking sessions that were realised. Although data taking with ANTARES is in principle continuous, inefficiencies can occur, for example, when a GRB alert is distributed during a calibration run, or due to power loss. As can be seen from Fig. 2, the typical efficiency of the satellite triggered data taking is about 90%.

The response time of the ANTARES satellite triggered data taking to the detection of the GRB by the satellite is shown in Fig. 3. The response time is defined as the time difference between the GRB time, as given in the GCN alert message, and the earliest datum in the unfiltered data set available on disk. This indicates the amount of overlap of the unfiltered data set with the observation period of the GRB by the satellite (the satellite triggered data taking lasts for a fixed period of time). At a response time of 0 seconds, the data in the unfiltered data set completely cover the period during which the GRB was

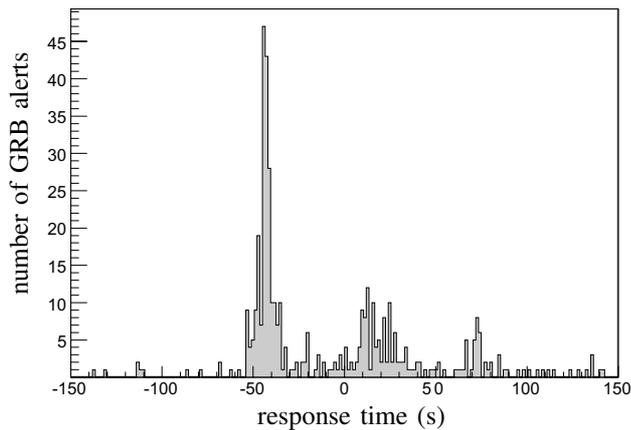


Fig. 3: Earliest datum in the unfiltered GRB data set relative to the detection time of the GRB by the satellite. At negative response times, the unfiltered data set includes data prior to the detection of the GRB by the satellite. Positive response times indicate a substantial delay between the detection of the GRB by the satellite, and the arrival time of the alert at the site.

detected by the satellite. For positive response times, the delay between the detection of the GRB by the satellite and the arrival time of the alert at the ANTARES site plays a role. As a result, the unfiltered data saved on disk do not fully cover the period during which the GRB was detected by the satellite. For negative response times, the buffering of the data filtering PCs becomes apparent: the unfiltered data set on disk includes data that were recorded before the GRB was detected by the satellite, and could include an early neutrino signal.

V. GRB DATA ANALYSES

The GRB data analysis can be done in two alternative ways. The standard way is based on real-time filtered data and reconstruction of the muon trajectory. The reconstruction is based on a five parameter fit, including the two direction angles [4].

The alternative method is based on the unfiltered data saved on disk after a GRB alert. This analysis takes into account the position of the GRB on the sky, which is also provided by the GCN. Since these data do not need to be processed in real time, a much lower detection threshold can be applied than is done for the standard data filtering. In the GRB analysis with unfiltered data, at least 6 time-position correlated photons are required, compatible with a muon travelling in the same direction as a neutrino from the GRB. In this way, the analysis method is only sensitive to a physics signal from a specific GRB. The position of the GRB on the sky is also used to constrain the direction angles in the fit. The same fit is repeated using many alternative directions, covering the opposite hemisphere and the downward hemisphere. A cut on the likelihood ratio between the result of the first fit and the best result of all fits using the alternative directions is applied in

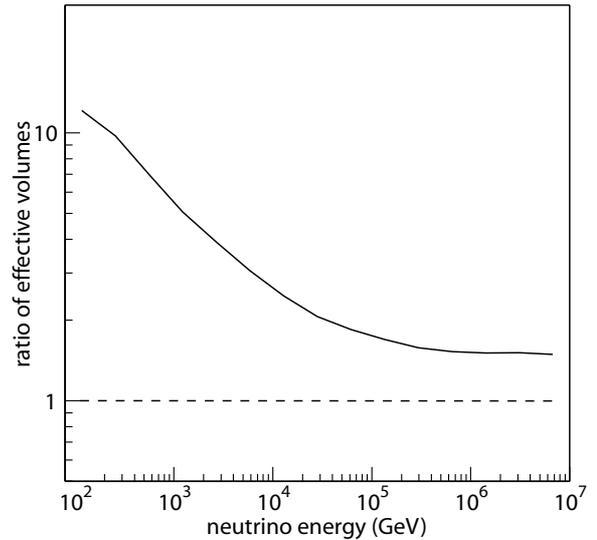


Fig. 4: The gain in detection efficiency for GRBs as a function of neutrino energy (simulation). The solid line shows the result obtained with the satellite triggered data taking, in combination with the analysis method that uses the position of the GRB, relative to the result obtained with the standard data taking and standard analysis method (dashed line).

order to select neutrinos coming from the GRB. The whole analysis is thus reduced to a simple counting experiment. In addition, the remaining background is low due to the short duration of the GRB. The gain in detection efficiency over the standard method is shown in Fig. 4. This result is obtained using a simulation of the detector response to muons, originating from neutrinos from a specific GRB. The gain is expressed as the ratio of effective volumes (the volume in which a neutrino interaction produces a detectable muon), and is shown relative to the result obtained with the standard data taking and standard analysis method, using the same simulated data. The increased detection efficiency that is obtained with the unfiltered GRB data is due to the lower detection threshold. A higher threshold is required in the standard data taking method in order to process the data in real time, which leads to an unavoidable detection inefficiency.

For GRBs above the ANTARES horizon, for which a neutrino signal is more difficult to find, an analysis method is applied to detect muons induced by high-energy gamma rays from the source. The detection principle is presented in reference [5]. A similar gain in detection efficiency can be expected when applying a specialised analysis to the unfiltered data saved on disk after a GCN alert.

VI. CONCLUSIONS

The unique features of the ANTARES data acquisition system, in combination with the real-time distribution of GRB alerts by the GCN, make it possible to trigger in real time on GRB alerts. The ANTARES detector

also has the possibility to buffer a large amount of data, resulting in very fast, and even negative, response times to GRB alerts. It is foreseen that the future, much larger, neutrino telescope KM3NeT [6] will be designed such that it can trigger on GRB alerts in the same way. These satellite triggered data lead to a significant increase in the sensitivity to neutrinos from GRBs. Therefore the availability of networks like the GCN are very important for neutrino telescopes. It is, however, imperative that the GRB alerts are distributed within a few tens of seconds in order to maximise the discovery potential for the detection of neutrinos from GRBs.

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