ANTARES - Baikal-GVD Alerts Analysis

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Abstract

ANTARES and Baikal-GVD are both Cherenkov neutrino telescopes located in the Northern Hemisphere. As a consequence, their fields of view overlap allowing for a combined study of the sky (Fig: 1). Under a Memorandum of Understanding since December of 2018, Baikal-GVD received 31 alerts from ANTARES, and followed up a total of 25; and while no prompt coincidence was found, a cascade mode search showed some events falling within an angular distance of less than 5° around three of these alerts. The 4.5° median angular resolution of Baikal-GVD allows for the possibility of these events to be correlated, which makes them of extreme interest.

In this poster we present further evaluations focussing in addition on the ANTARES cascade dataset and the optimization of the search method with a novel Machine Learning Algorithm for background rejection compared to previous methods.

To navigate through the poster, read it left to right. Start with the boxes next to this for presentation of ANTARES and Baikal-GVD. Continue with the Baikal-GVD follow up results. And end with the optimization of the future analysis from the ANTARES side.

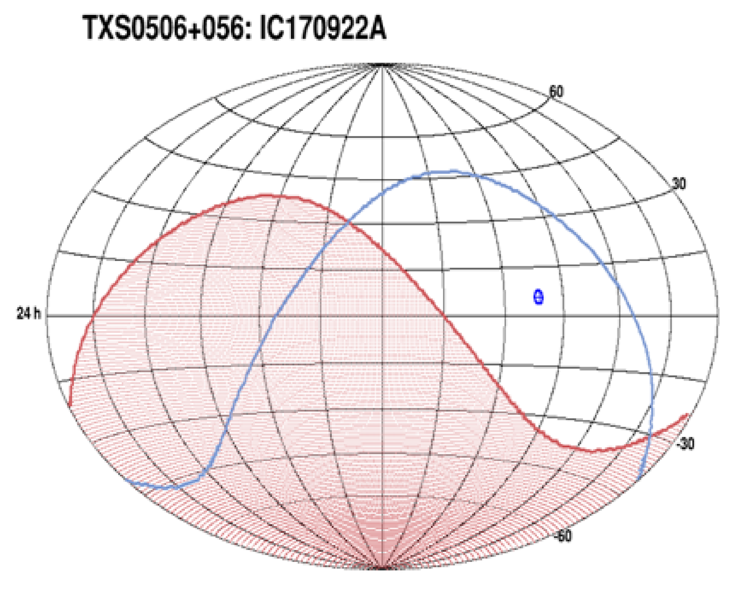

Fig. 1: Example of overlapping fov in time of known neutrino alert IC170922A. Red for GVD and blue for ANTARES.

ANTARES Alerts

ANTARES is located in the Mediterranean sea, 40 km offshore of the coast of Toulon, France [1]. It is optimized for the detection of up-going neutrinos coming across the earth. It is able of real-time processing with delays below 10 seconds between detection and alert emission, which combined with a median angular resolution of 0.5° for tracks (events induced by $\nu_\mu/\bar{\nu}_\mu$ interaction) makes it a powerful tool in multi-messenger astronomy. ANTARES sends alerts for doublets of neutrinos, neutrinos with $E > 1$ TeV and direction close to local galaxies (directional); and with high ($E > 7$ TeV) or very high energy ($E > 30$ TeV) neutrinos, HE and VHE respectively. The alerts of interest are listed below.

Alert A7: RA $= 151.1°$, $\delta = -27.3°$. Directional trigger.

Alert A15: RA $= 280.4°$, $\delta = 1.0°$. HE trigger.

Alert A16: RA $= 186.5°$, $\delta = -4.2°$. HE trigger.

Baikal-GVD

The deep underwater neutrino telescope Baikal-GVD is under construction in Lake Baikal [2]. It is built in individual clusters, separated 300 of each other. A cluster is composed of 288 optical modules divided in 8 strings. In season Apr 2018 - Feb 2019 three clusters where operational and were extended to five on Apr 2019. Currently seven cluster have been deployed. The data were evaluated for possibly correlated events with the alerts by ANTARES. Baikal-GVD data analysis is based on two developed reconstruction schemes using Cherenkov radiation, which is produced in the interaction of neutrinos with the water around the detector.

Charged Current interactions of $\nu_{e,\tau}/\bar{\nu}_{e,\tau}$ and Neutral Current interactions of any flavoured neutrino might emit electrons and hadrons, creating *electromagnetic or hadronic cascades*. Hence, these events are usually called **cascade events**. Baikal-GVD's accuracy for cascade direction reconstruction is about 4.5° (median value), and for energy it is about 30%.

Follow up of ANTARES neutrino alerts: 5° cone radius ± 1 day

Follow-up frame:

1. Search for events per cluster in different time windows of ±500 sec, ±1 hour and ±1 day around alerts inside a 5° cone radius.
2. Search for coincidence on two or more clusters within 6 μs for the first ±10 seconds and, in an extended interval, for the next ±1 hour around the trigger.

As result, for three ANTARES alerts, cascades were found in time/space coincidence by different clusters among the 5 operational ones. For alert A7, *three cascades* were found at arrival times of -3.1 hours, -23.2 hours and +21.7 hours from the alert time. *Two cascades* arrived -36 minutes and +20.3 hours relative to alert A15. For alert A16, *another two* were found at -14.5 and -18.6 hours to the alert.

The expected number of background events per cluster and day inside the 5° cone are 0.021, 0.054 and 0.045 for A7, A15 and A16 respectively. They are computed with scrambled data from season 2018-2019 (3 clusters). Notice that for alert A16, an additional ANTARES track was found (see Figure 4).

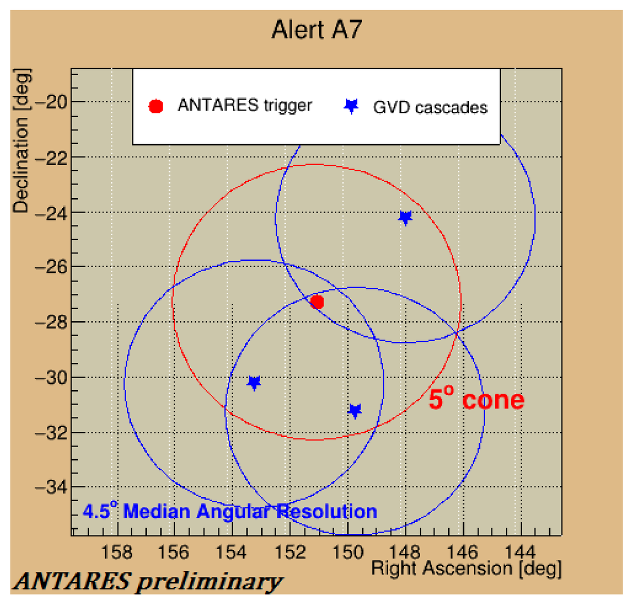

Fig. 2: Alert A7: A triplet of cascades was reconstructed around the ANTARES trigger in ±1 day time.

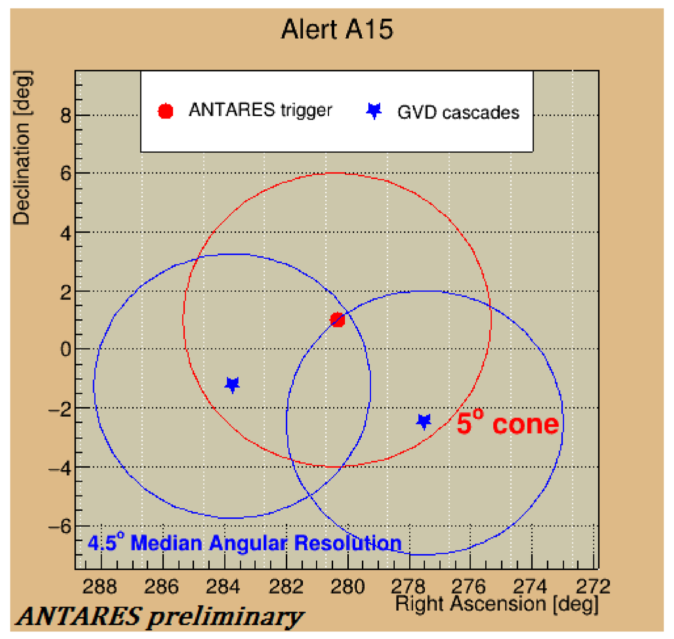

Fig. 3: Alert A15: Two cascades were reconstructed around the ANTARES trigger in ±1 day time.

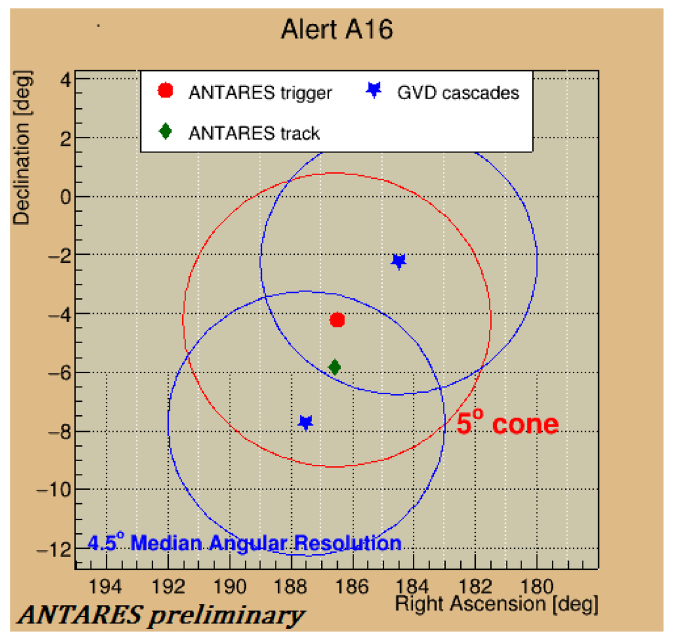

Fig. 4: Alert A16: Two cascades were reconstructed around the ANTARES trigger in ±1 day time. An additional track was found in ANTARES data 9 hours and 15 minutes after the alert within 2 degrees.

[1]Check F. Versari's poster on *Atmospheric Electron Neutrinos with ANTARES*!! (ID: 376)

Optimization of the ANTARES follow-up with cascades

ANTARES is looking for additional cascades events for these three alerts with associated GVD events in the same time window

An optimization process has been started to select a set of cuts so that a single detected event yields a 3σ significance detection The cuts are aiming to distinguish cascades from tracks and background. One of the reconstruction algorithms used in ANTARES uses a random decision forest (RDF) to separate cascades from atmospheric muons and is commonly used to remove the bulk of the muon background. By now a new **boosted decision tree (BDT) has been trained especially for the separation of muons from cascades originating from atmospheric neutrino** interactions. In the current study both the RDF and BDT score are evaluated and compared for the optimization.

In Figure 5 both distributions can be seen for alert A7. In terms of background rejection, the **BDT can achieve a muon background free sample** with a strict enough cut, which is subjected to statistical fluctuations in the tail of the distribution. However, a significant part of the astrophysical neutrino distribution (green) is left out of the resulting event sample after such a cut. On the contrary, the **RDF** can not achieve such purities but it **keeps in comparison more astrophysical events even for strict cut values**.

Then, as a second step, the likelihood ratio L_μ, which uses basic reconstruction information, is used to distinguish muons from neutrinos and further push the background inside the region of interest (RoI) below the desired value ($\sim 2.7 \cdot 10^{-3}$). **Results on the optimization are shown below** and are obtained from Figure 6 (notice that, again, only alert A7 is shown as an example).

UPGOING SKY	First Cut	*RoI radius*	L_μ cut
Alert A7	BDT> -0.06	11°	> -8
Alert A15	BDT> -0.06	14°	> -18
Alert A16	BDT> -0.06	11°	> -18

In conclusion, both cut quantities show similar signal efficiencies, the BDT performing slightly better. In terms of the down going-sky, the optimization of the cuts is still underway. Since background levels are higher than for the up-going sky, extra cuts will need to be considered, which makes the optimization harder. At present, we are not able to say if there are any cascade events around these alerts. Nevertheless, finalization of the cut selection and unblinding for all 3 alerts is imminent.

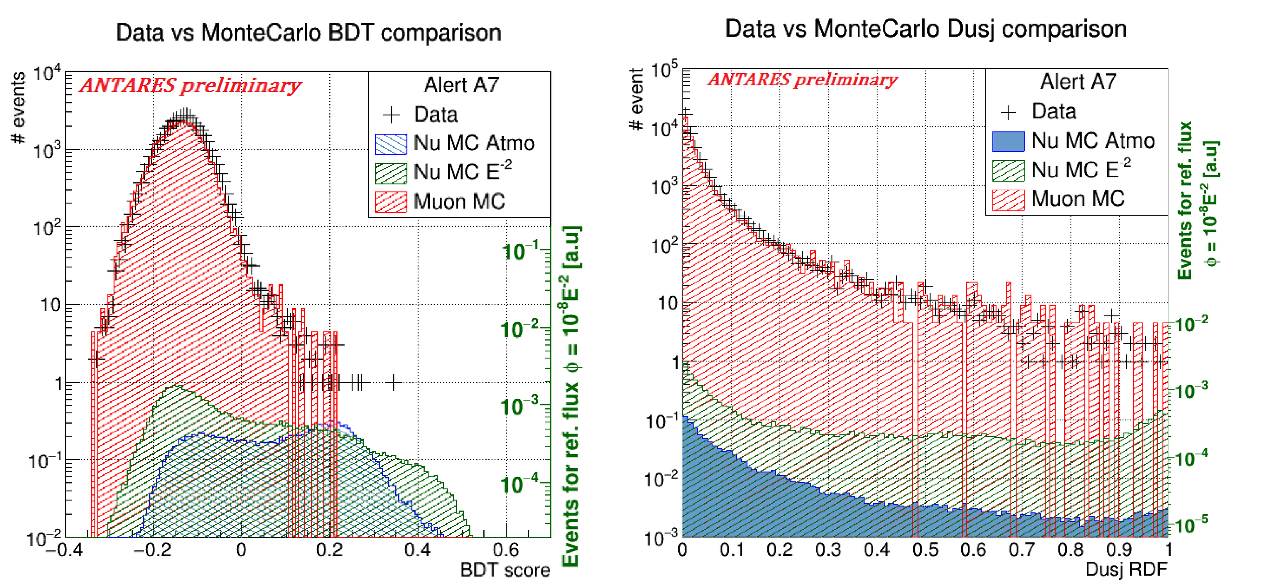

Fig. 5: Distribution for the output variables of the new BDT (left) and RDF (right) for data, MC generated atmospheric neutrino and muon background, and MC signal.

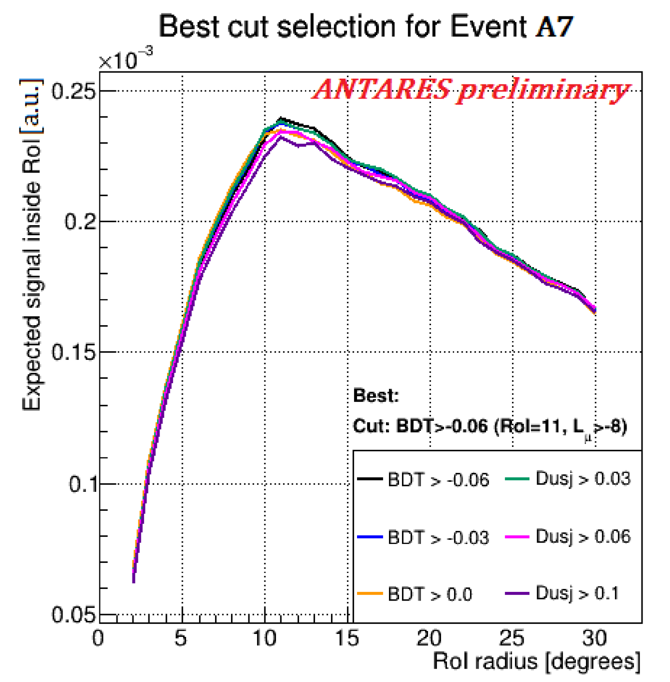

Fig. 6: Expected signal inside the region of interest for many values of the radius around alert A7.

References:

[1] Ageron, M., et al. "ANTARES: the first undersea neutrino telescope." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 656.1 (2011): 11-38.

[2] Avrorin, A. D., et al. "The Baikal-GVD neutrino telescope: First results of multi-messenger studies." arXiv preprint arXiv:1908.05450 (2019).

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