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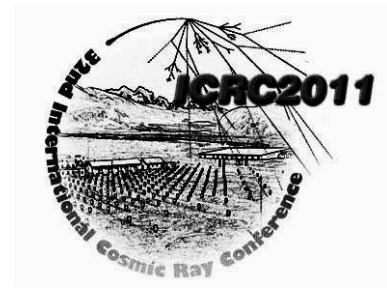
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ANTARES sensitivity to steady cosmic gamma ray sources

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Abstract: Amongst the atmospheric muons recorded by neutrino telescopes are muons produced by the interaction of cosmic gamma rays with the Earth's atmosphere. Although they are not numerous, it has been suggested that such muons could be distinguished by neutrino telescopes from the isotropic background by correlating their direction with known sources of gamma rays.

The ANTARES neutrino telescope is taking data at the bottom of the Mediterranean Sea in its full configuration since May 2008. Its expected sensitivity to steady gamma ray sources is discussed, as well as the gamma ray induced neutrino contamination of cosmic neutrino signals. It is shown that the expected signal from steady gamma ray sources is well below the ANTARES detection ability, and that gamma rays are a negligible source of atmospheric neutrinos background.

Keywords: TeV gamma rays, ANTARES, neutrino telescope

1 Introduction

A large number of astrophysical sources are known to emit photons above the TeV range. When interacting with the Earth's atmosphere, such photons will produce electromagnetic air showers which may contain high energy muons. Their detection by neutrino telescopes has long been proposed and investigated theoretically (see e.g. references in Ref. [1]). Although its location more than 2000m depth in the Mediterranean Sea is supposed to suppress most of atmospheric muons, which are considered as background for cosmic neutrino searches, some of these gamma ray induced muons may reach the ANTARES neutrino telescope. Its configuration being optimized for the detection of up-going muons [2], their detection is however challenging.

Even though it may not be competitive with atmospheric Čerenkov telescopes and extended air shower arrays, the ability of ANTARES to detect gamma rays and correlate them to their source could be used as a calibration tool and would be an independant way to check the absolute pointing of the detector.

The following is an update of preliminary results presented earlier [1]. In particular, more accurate software is used. Most notably, the treatment of muon pair production from photons has been corrected in the CORSIKA program [3], and the treatment of light dispersion in water as well as the trigger simulation have been improved in the ANTARES simulation tools.

2 Monte-Carlo simulation

Three Monte-Carlo productions of gamma rays have been generated in three contiguous energy ranges, following an E^{-1} flux : 2.5×10^9 photons between 1 and 100 TeV, 2.5×10^8 photons between 100 and 1000 TeV and 5×10^7 photons between 1 and 10 PeV. Interactions in the atmosphere are processed with the CORSIKA program (version 6.960) [4], which makes use of the EGS4 code system for the electromagnetic interactions [5], and the selected hadronic model is QGSJET [6]. Sources are considered as fixed in the sky, with an azimuth angle of 0° (North) and a zenith angle of 20 or 60° (downward vertical particles having a zenith angle of 0°).

The propagation of muons in water is performed by a dedicated program which makes use of the GEANT3 program for the emission of secondary particles [7] and MUSIC tables for the propagation of particles itself [8], and which generate Čerenkov photons using photon tables previously generated.

Optical background is added using standard medium quality real data, and hits on the detector are selected using a standard trigger strategy [2].

Muon tracks are reconstructed using a standard likelihood-based reconstruction algorithm relying on the minimization of hit time residuals [9]. A cut is performed on the reconstruction quality estimator so that most events with an angular resolution better than 2° are selected while most of badly reconstructed events are rejected.

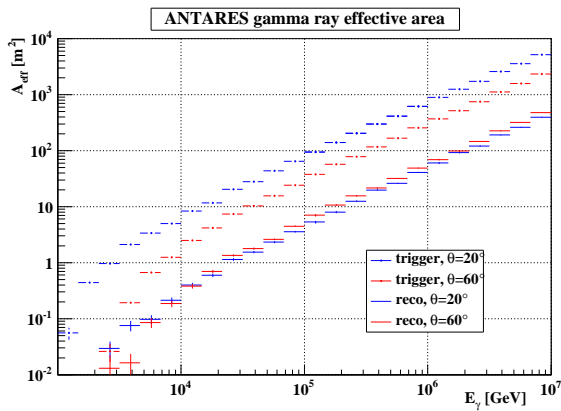


Figure 1: ANTARES gamma ray effective area at trigger and reconstruction level, for two zenith angles.

3 ANTARES effective area

Dividing the number of surviving events by the incident flux, one can compute the effective area of the detector as a function of the incident particle energy, which expresses the detector efficiency. Figure 1 shows the effective area of the ANTARES telescope to gamma rays at standard trigger level, which represents all remaining events after applying the standard trigger strategy, and at the reconstruction level, representing all reconstructed events surviving the reconstruction quality cut, for both simulated zenith angles.

Although almost three times lower at trigger level, the effective area for a 60° zenith angle exceeds the effective area for a 20° zenith angle at reconstruction level. The reason for this is comes from the granularity of the detector, which is more important in the horizontal plane than in the vertical dimension : lines are separated by about 60 m, while storeys on a line are separated from 14.5 m. Consequently, although muons are less numerous to reach the detector at 60° because of the increased distance to travel in water, their Čerenkov light is detected by more lines than at 20°. Their direction can thus be reconstructed more efficiently. This affects particularly the determination of the azimuth angle.

4 ANTARES sensitivity

The expected number of events for a few sources of interest, assuming a 100 % visibility over one year and a fixed position in the sky, is presented in Table 1. The sources are selected both for their visibility from ANTARES (Table 2) and for their strong flux. The case of a fictional source with a very powerful flux ($dN/dE = 1000E^{-2} \text{ m}^{-2}\text{s}^{-1}$) is also considered. The higher bound extrapolates gamma ray fluxes up to 10 PeV and is thus quite unlikely since the validity of flux parametrizations is limited to a few tens of TeV at best and since interactions of ultra-high energy photons with photons from the extragalactic background light

source	N_{trig}	N_{reco}
Crab	4-15	0.1-0.3
	<i>0.6-2.6</i>	<i>0.1-0.4</i>
1ES 1959+650	0.5-25	0.01-0.5
	<i>0.1-6</i>	<i>0.01-0.8</i>
Mkn 421	1-25	0.01-1
	<i>0.1-2</i>	<i>0.01-1</i>
Mkn 501	1-100	0.03-10
	<i>1-50</i>	<i>0.03-15</i>
fictional	820-1860	22-68
	<i>226-660</i>	<i>29-92</i>

Table 1: Expected number of gamma ray events seen by ANTARES at trigger level (N_{trig}) and after reconstruction (N_{reco} , with a cut on the reconstruction quality and reconstructed within 2° from source), for one year assuming a 100 % visibility, for a 20° zenith angle (straight font) and a 60° zenith angle (italic). The lower bound assumes a cut-off at 100 TeV while the upper bound assumes events as energetic as 10 PeV.

(EBL) limit their range to galactical distances. The lower bound is more realistic and does not extrapolate above 100 TeV.

source	visibility	$\langle\theta\rangle$
Crab	62 %	51.7°
1ES 1959+650	100 %	49.7°
Mkn 501	78 %	49.4°
Mkn 421	76 %	49.2°

Table 2: Actual visibility and mean zenith angle of selected sources from the ANTARES down-going muons field of view.

These results show that it is unlikely for ANTARES to detect steady gamma ray sources : in the same optical background conditions, the number of reconstructed tracks surviving the selection cuts within 2° from source in a sample from actual data extrapolated to one year is about 53800 (17900) for a zenith angle of 20° (60°), which is still far above the expected number of events detected from the fictional powerful source. Reducing the observation cone does not improves the signal over background ratio enough to compensate the loss of signal it induces.

Results are reported in Figure 2 as the power law flux normalization needed to obtain a 3 or 5 standard deviations sensitivity (after selection of events) as a function of the spectral index. Also shown is the area covering Crab flux parametrizations and the position of the fictional powerful source. It follows that ANTARES would need a source more than three orders of magnitude larger than the Crab or alternatively a powerful source with an extremely hard spectrum to obtain a reasonable sensitivity, again assuming a 100 % visibility and a fixed position in the sky. Sources providing such characteristics are very unlikely to exist since similar features have yet never been measured even for short strong outbursts [10].

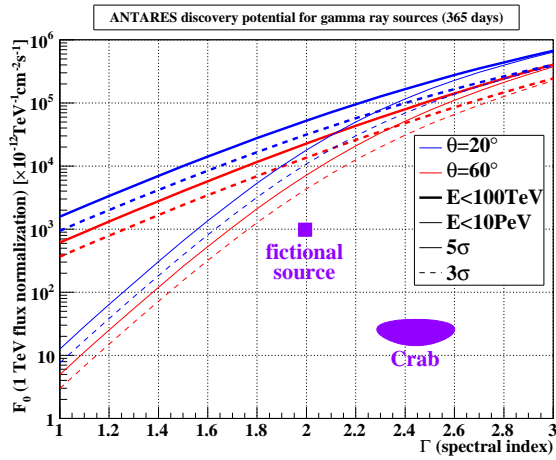


Figure 2: ANTARES one year sensitivity to steady gamma ray sources, as a function of flux normalization and spectral index assuming a power law spectrum.

5 Uncertainties

This study suffers many sources of systematic uncertainties. Given the low sensitivity of ANTARES to gamma ray induced muons, the various contributions are not computed in a quantitative way. Many of the systematics have a negligible effect on the simulation. This is for instance the case of the Earth magnetic field, the LPM effect [11] or the preshower effect [12].

Important systematics are mainly due to the simulation of interactions in the atmosphere. Charm photoproduction cross-section remaining unknown at very high energy, it is not included in CORSIKA. It is small but increases with the energy and may not be negligible above a few tens of TeV [13]. Furthermore, the charm carries a large fraction of the incident photon energy and has thus a high probability to reach the detector, which makes this contribution difficult to estimate. The lack of charm production is hence an important flaw of this simulation. The hadronic model also introduces important uncertainties. Switching the hadronic model to VENUS [14] can increase the number of muons with an energy higher than 500 GeV at sea level by about 10% and the number of events producing such muons by 7%. Finally, the photoproduction cross-section used in CORSIKA is quite conservative, and the muon yield might be increased by about 10% by other realistic scenarios [15]. According to these effects, the present simulation may be thought as pessimistic.

On the other hand, the description of the sea water optical properties used for the light simulation in water is not the most accurate and overestimates the number of detected Čerenkov photons and hence the number of reconstructed muons. The number of detected muons could be increased by as much as 20% with regard to reality. The geometry of the detector also affects the detection of events : the az-

imuth angles for which several detector lines are aligned are favoured, and the number of reconstructed events may be increased by a factor of two in the extreme cases.

Furthermore, a neutrino telescope is sensitive to variable sources of uncertainties. The muon yield itself depends on atmospheric variations : the higher the pressure and temperature, the lower the muon yield, by a few percents. This affects both signal and muon background. The sea water optical properties and most of all the optical background due to radioactive decays (mostly ^{40}K) and bioluminescence are also strong sources of variability. The present simulation is valid for standard conditions of optical background qualified for data analysis, but small degradation or improvement of these conditions may have an effect as large as 20% on the number of reconstructed tracks. Finally, the accuracy of the software used for the simulation of light propagation and detection has been greatly improved since versions used in this simulation.

Last but not least, in order to ensure statistical consistency of the simulation, the source zenith angle is fixed. In reality ANTARES sensitivity to gamma ray sources is obviously affected by their motion in the sky.

6 Discussion

Although this simulation suffers large uncertainties, it is unlikely that the results would vary by an order of magnitude or more. It is thus clear from this study that steady gamma ray sources are out of reach of the ANTARES neutrino telescope under the conditions discussed here.

This analysis makes use of standard triggers and reconstruction algorithms, optimized for detection of upgoing neutrinos. Dedicated strategies and background discrimination methods would have to be developed to improve significantly the sensitivity : directional trigger, use of the muon-poor electromagnetic showers characteristic, muon pair discrimination. . .

In addition, the present study assumes that the gamma ray source flux at very high energy can be parametrized by a power law (possibly with an exponential cutoff). A significant deviation of this assumption at higher energies would have a strong impact on the presented results.

7 Gamma-induced neutrino background

Gamma rays interacting with the atmosphere may also produce neutrinos. These so-called atmospheric neutrinos form an irreducible background for neutrino telescopes, since there is no way to distinguish them from cosmic neutrinos. Furthermore, such atmospheric neutrinos are localized from the direction of gamma ray sources, which are cosmic neutrino emitter candidates.

The present study is the opportunity to estimate the number of upgoing atmospheric neutrinos polluting the signal from the direction of a gamma ray source. This is simply done

by multiplying ANTARES neutrino effective area [16] by the gamma ray induced neutrino flux at sea level.

It is found that the expected number of reconstructed events is smaller by several orders of magnitude than the expected cosmic neutrino signal for all simulated sources. The contamination induced by steady gamma ray sources to a potential source of neutrino can thus be considered as negligible.

8 Conclusions

It has been demonstrated through a complete Monte-Carlo simulation that the observation and identification of very high energy gamma rays from steady sources is out of reach of the ANTARES neutrino telescope with its standard trigger and reconstruction strategies. It is also clear from this study that the gamma ray flux of such sources will not interfere with the identification of a possible neutrino sources.

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