Observation of the Moon shadow with the ANTARES neutrino telescope

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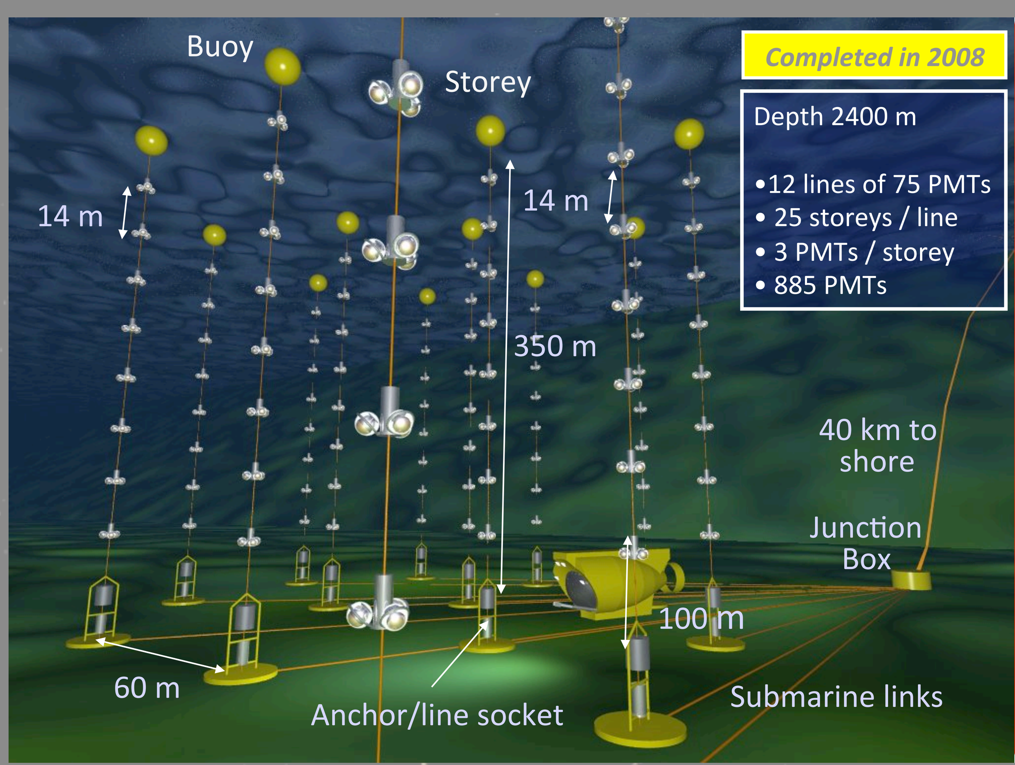
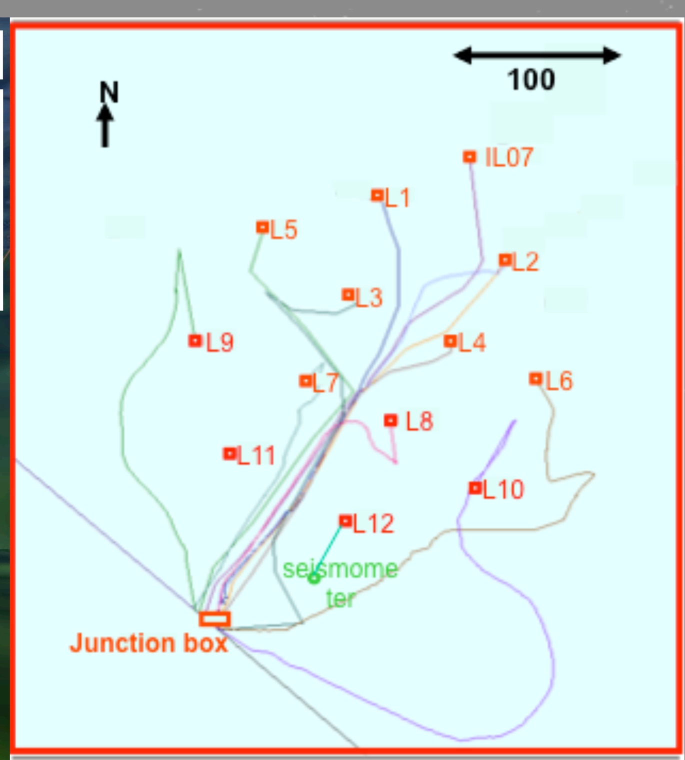
Introduction

ANTARES is currently the largest neutrino detector on the Northern Hemisphere. Operating since May 2008 in its full configuration, it aims at the detection of high-energy cosmic neutrinos. In the absence of an astrophysical neutrino standard candle, a possible way to measure the angular resolution and the pointing accuracy for a neutrino telescope is to look at the "Moon shadow" in the atmospheric muon flux. On their way to the Earth, primary cosmic rays may be hampered by the Moon. This effect will cause a lack of cosmic rays and thus a lack of atmospheric muons measured at Earth in the direction of the Moon. The detection of this deficit - the so called Moon shadow - and of its position in the sky provides a measurement of the detector angular resolution and of the detector absolute orientation. The technique, first discussed by Clark in 1957 [1], is commonly used to calibrate cosmic ray detectors. Recently it has been also adopted for the neutrino telescopes, such as IceCube [2] at the South Pole and ANTARES in the Mediterranean Sea. The analysis method and the present results of the observation of the Moon shadow with ANTARES will be presented and discussed.

The ANTARES Telescope

ANTARES operates by detecting Cherenkov light emitted by high energy secondary muons that result from neutrino interactions inside or near the instrumented volume. The Cherenkov light is detected using an array of photomultiplier tubes (PMTs), housed in pressure resistant glass spheres called Optical Modules (OMs). The OMs are placed in triplets along a total of twelve detector lines, which are anchored to the sea bed at a depth of 2475 meters. Each detector line contains 25 floors of triplets, spaced 14.5 meters apart. The 12 lines are placed approximately 60 meters apart [3]. The arrival time and intensity of the Cherenkov light on the OMs are digitized into 'hits' and transmitted to shore, where events containing muons are separated from the optical backgrounds due to natural radioactive decays and bioluminescence, and stored on disk. From the timing and position information of the hits, the muon direction and position are reconstructed using a multi-stage fitting procedure, which maximizes the likelihood of the observed hit times as a function of the muon direction and position [4].



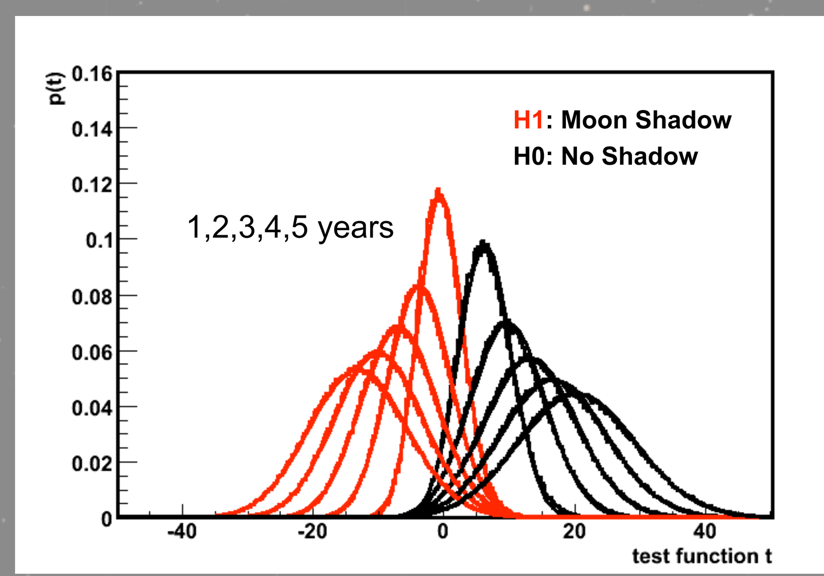


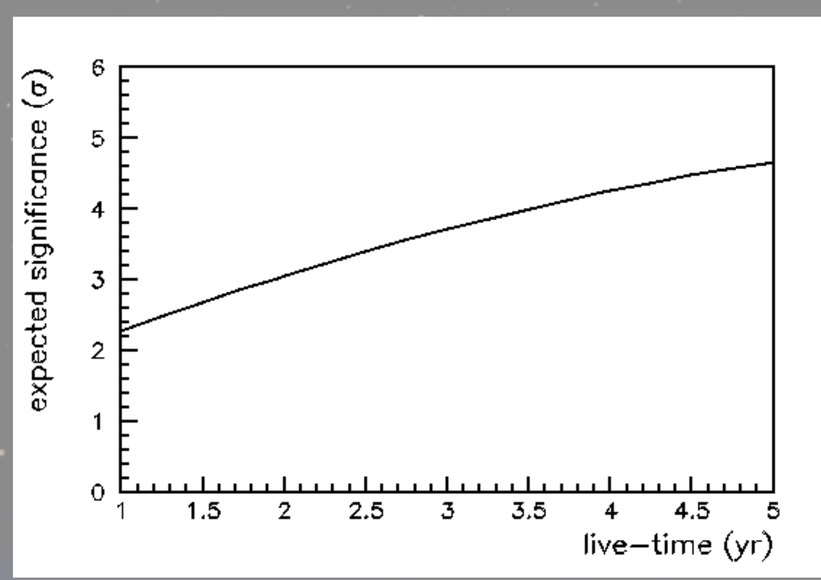
While designed to observe up-going neutrinos, it also records many signals of down-going muons produced by the interaction of high energy cosmic rays in the atmosphere. Although atmospheric muons represent a background for astrophysical neutrinos, they may be used to calibrate and check the detector performance, as in the analysis presented here. The data, analysed in this work, were collected between Jan 31st, 2007 and Dec 31th 2010. During this time, the construction of the ANTARES detector was still in progress. The detector consisted of 5 lines for most of 2007 and it reached the 12 lines full configuration in May 2008. The total live time presented in this analysis is 814 days.

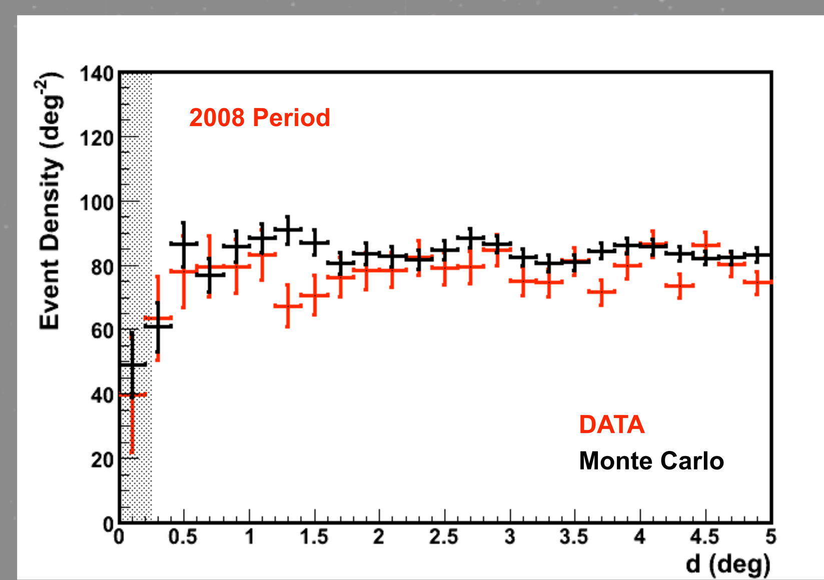
Monte Carlo simulations

A detailed simulation of the shadow effect was carried out using a modified version of Corsika vrs.6.2 [5,6], where we implemented the generation of the Moon position. More than 10^{10} air showers induced by primary nuclei with energies ranging from 1 to 10^5 TeV/nucleon and zenith angles between 0° and 85° were generated using QGSJET.01 [7] for the description of hadronic interactions and propagated to the sea level. Muons reaching the sea level with energies larger than 500 GeV are propagated through sea water to the detector with the MUSIC package [8]. The events are weighted according to the NSU model [9]. The detector response is then simulated taking into account the local environmental parameters as the light transmission and the optical noise recorded during the data acquisition.

The Monte Carlo simulation was used to optimize the data analysis procedure. The probability to observe the shadow effect is inferred from a hypotheses test in which the hypotheses no shadow visible H0 and shadow visible H1 are examined. The test statistic t(x) (for a measurement x) is defined as the χ^2 of the of the two hypotheses. The probability density functions were simulated for the two hypotheses (see plot on the right for the 12 line configuration) and used to compute the expected significance (see below). The event density as a function of the angular distance *d* from the Moon is also plotted for the 2008 period in order to check the Monte Carlo – data agreement. The difference of number of events is within systematic errors.







Data analysis and present results

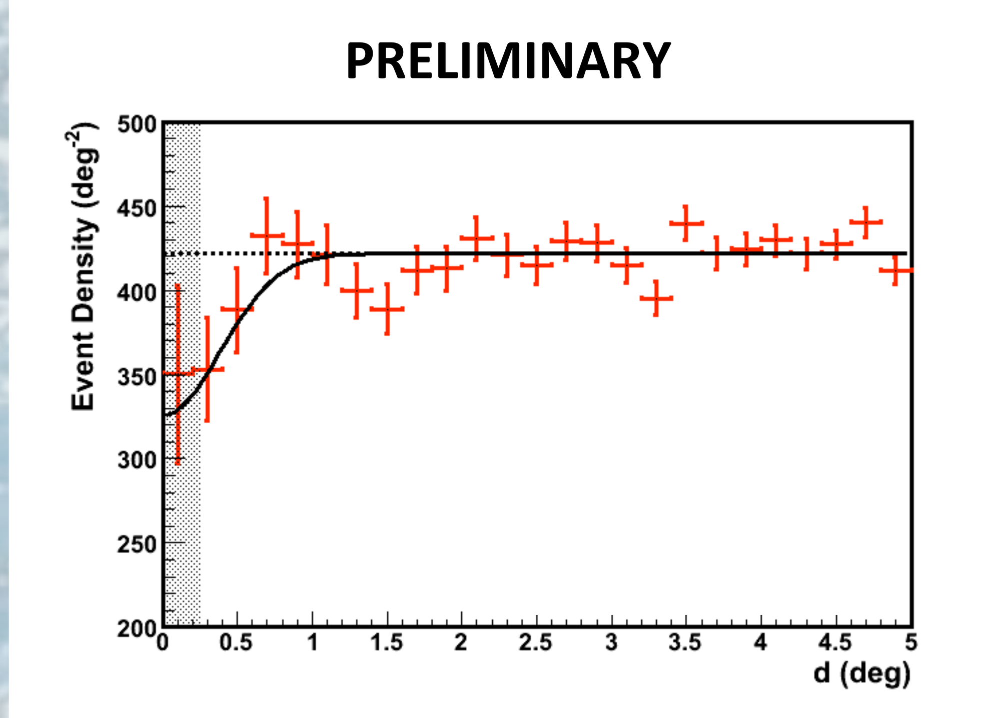
After the reconstruction, the muon tracks are selected applying the following event selection criteria: the track must be reconstructed as down-going and detected when the Moon is above the Horizon. Besides, the uncertainty on the reconstructed muon track direction obtained from the fit is required to be ≤1° and value of the log-likelihood function of the fitted muon track must be must greater than a value optimized through the Monte Carlo simulations.

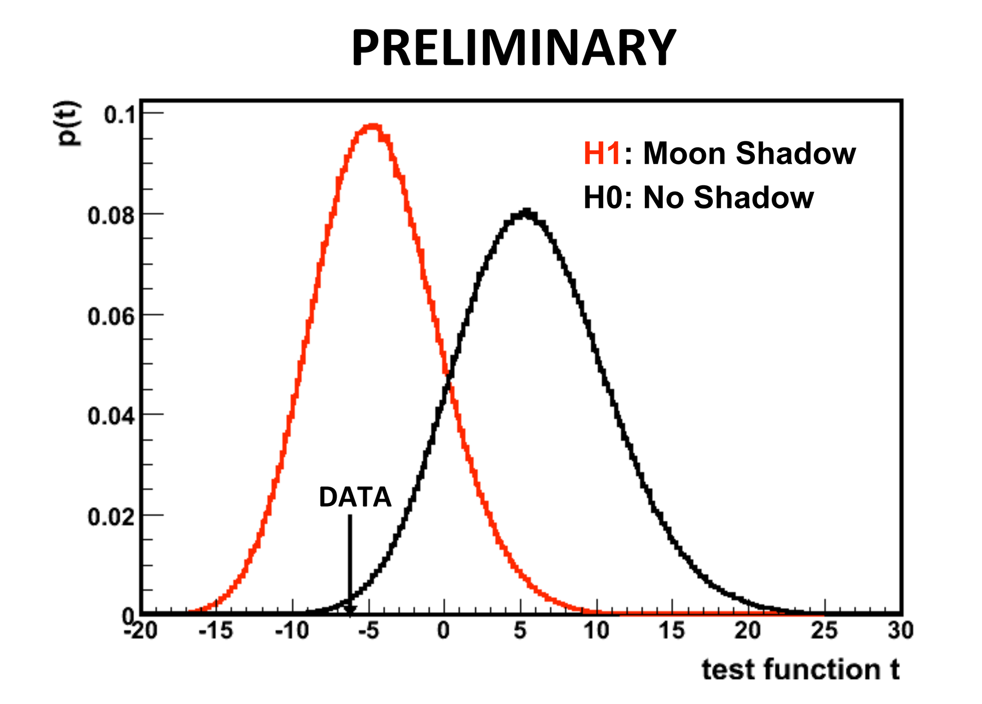
The event density of muons surviving the selection is plotted versus the distance *d* from the Moon and fitted with the following function:

$$\frac{dn}{dd^2} = k\left(1 - \frac{R^2_{Moon}}{2A^2} e^{-\frac{d^2}{2A^2}}\right)$$

where *n* in the number of reconstructed muons as a function of *d* and R_{moon}=0.26° is the Moon angular radius. The free parameters of the fit are *k* and *A*: *k* represents the flat event density (i.e. in the absence of the Moon) and *A* is related to the detector angular resolution. From the fit we find an *A*=0.4°±0.1° with *k*=307±2 deg^{-2}.

The value of the test function for the analyzed data set is -6.2, which represents a significance of 2.8σ consistently with the expected one.





Systematic studies are still ongoing to improve the events selection (track quality, number of lines, error estimate, etc.). Besides, these data have been processed using the standard track reconstruction algorithm of ANTARES. As this algorithm is optimized for up-going tracks of cosmic origin, an algorithm dedicated to the reconstruction of down-going atmospheric muons would improve the results presented in this poster.

References:

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