Observation of the cosmic ray shadow of the Sun with the ANTARES neutrino telescope

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The ANTARES neutrino telescope is operating in the Mediterranean Sea in its full configuration since 2008. On their journey to the Earth, cosmic rays (CRs) can be absorbed by celestial objects, like the Sun, leading to a deficit in atmospheric muons produced by CR interactions from the solid angle region covered by the Sun, the so-called Sun “shadow” effect. This phenomenon can be used to evaluate fundamental telescope characteristics: the detector angular resolution and pointing accuracy. This work describes the study of the Sun “shadow” effect using the ANTARES data collected between 2008 and 2017. The statistical significance of the Sun shadow observation is 3.7$\sigma$ and the estimated angular resolution value of the ANTARES telescope for downward-going muons is $0.59^\circ \pm 0.10^\circ$. This result is consistent with the expectations obtained from the Monte Carlo simulations and also with the estimation from the Moon "shadow" analysis of 2007-2016 years. No evidence of systematic pointing shift is found and the resulting pointing accuracy is in agreement with the expectations.
1. Introduction

In its 13 years of operation, the ANTARES neutrino telescope [1] has contributed to multiple searches for neutrinos from point sources, such as blazars, gamma ray bursts or fast radio bursts. Angular resolution and detector pointing are key parameters for this type of study since typically only a small number of signal events are searched for within a consistent background. The spatial correlation of the signals with the known position of the potential source allows the signal-to-background ratio to be drastically reduced. For this reason, a neutrino telescope needs the smallest possible angular resolution and the best possible absolute pointing. This type of detectors cannot use standard candles, such as electromagnetic telescopes, but can exploit the absorption of cosmic rays by celestial objects, such as the Moon or the Sun, to estimate their performance.

In this contribution, we will focus on the measurement of the so-called “Sun shadow” with the ANTARES detector. If cosmic rays on their way to the Earth intercept the Sun, they cannot pass through it. Thus, an observer on the Earth notices a deficit of cosmic rays in the direction of the Sun, so the Sun shadow can be used as a calibration source for a neutrino telescope.

Between 2006 and 2008, the 12 lines of the ANTARES detector were deployed 40 km off the coast of Toulon, France. Each detector line has 25 storeys and each storey houses three 10-inch Photo-Multiplier Tubes (PMTs) inside pressure-resistant glass spheres (the Optical Modules). Each line is 450 m long and the first storey is 100 m above the sea floor. The lines are connected to the shore by an electro-optical cable from the junction box to the shore station.

The neutrino detection mechanism is based on the interaction of neutrinos in the proximity of the detector producing charged particles. These particles have velocities higher than the speed of light in the water, resulting in the emission of Cherenkov light which can be detected by the PMTs of the telescope. By measuring the time and position of the signals (hits), the trajectory of the charged particle can be reconstructed (event) and thus the direction of origin of the neutrino.

Typically, upward-going events are studied, since downward-going events are dominated by the contribution of atmospheric muons, which is why the PMTs of the detector points downwards at an angle of 45°. However, in this study we will focus on the measurement of downward-going atmospheric muons, as we want to study the effect of the absorption of cosmic rays by the Sun.

The shadow of the Sun or the Moon has already been used by several cosmic ray detectors and the IceCube neutrino telescope to estimate the detector pointing performance [2], while the ANTARES collaboration has already presented a study of the Moon shadow and found a significance of 3.5 $\sigma$ by analysing a data sample corresponding to a livetime of 3128 days [3].

2. Event selection criteria optimisation

The selection criteria optimisation is based on a Monte Carlo (MC) that features downward-going muon events which are generated with the MUPAGE code. A cylinder (can) surrounding the active volume of the detector, 650 m high, with a radius of 290 m, is considered in the simulation, where muons are generated according to parametric formulas that allow to calculate the flux and the angular distribution of underwater muon bundles [4]. The simulation includes all the steps of the muon detection: propagation of muons in the surroundings of the detector, the emission of Cherenkov light, the light propagation to the PMTs and the digitalisation of the signals [5].
The data of the ANTARES telescope are divided into time samples lasting several hours, called runs. For each of these runs, the environmental conditions and the detector configuration are recorded, so that the exact data acquisition conditions can be reproduced in the Monte Carlo simulation, the so-called run-by-run simulation [6].

The number of atmospheric muons is extremely large, so we typically choose to generate them with a reduced statistic, in our case $1/3$. However, in this analysis we can increase the statistic by using the additional zones approach. Instead of focusing only on the region of space where the Sun is at a given instant, one can add additional “artificial suns” by simply shifting the position of the Sun by certain time interval and eliminating the muons generated in these directions, as it is also done in the Monte Carlo for the real position of the Sun. By shifting the position of the Sun by 2 hours, 11 additional zones were obtained, so that the final statistics of our simulation is 4 times larger than in the data.

The optimisation of the selection criteria is performed exploiting two parameters: $\Lambda$, the quality of the reconstruction (based on likelihood optimisation of the reconstruction), and $\beta$, the angular uncertainty on the reconstructed track direction [7]. In order to exclude the region close to the horizon, where the muon statistic is lower due to muon longer path in Earth atmosphere, tracks with elevation below $15^\circ$ are excluded.

The hypothesis test approach is used to determine the selection criteria which maximise the sensitivity to the Sun shadow effect. The procedure is based on the production of two MC samples. In the first one no absorption of cosmic rays by the Sun is simulated (hypothesis $H_0$), while in the other one all muons coming from the direction of the Sun (radius = $0.26^\circ$) are eliminated from the simulation (hypothesis $H_1$), thus simulating the effect of the Sun shadow. The angular distribution of the events is now projected on a histogram as a function of the distance from the Sun centre (histogram bin size=0.4°). Each bin is normalised according to the corresponding area, resulting in an event density.

Assuming that the event population in each bin asymptotically follows a Gaussian probability distribution, two test statistic can be defined for the two different hypotheses ($H_0$ and $H_1$)

$$
\lambda_0 = \sum_{i=1}^{N_{bins}} \left( \frac{(n_i^0 - \mu_i)^2}{\sigma_{\mu,i}^2} - \frac{(n_i^0 - \nu_i)^2}{\sigma_{\nu,i}^2} \right),
$$

$$
\lambda_1 = \sum_{i=1}^{N_{bins}} \left( \frac{(n_i^1 - \mu_i)^2}{\sigma_{\mu,i}^2} - \frac{(n_i^1 - \nu_i)^2}{\sigma_{\nu,i}^2} \right),
$$

with $\mu_i$ ($\nu_i$) the expected number of events in the i-th bin under $H_1$ ($H_0$) hypothesis, $\sigma_{\mu,i}$ ($\sigma_{\nu,i}$) the error in the i-th bin under $H_1$ ($H_0$). The values of $n_i^1$ ($n_i^0$) are derived according to a Poisson distribution with expectation values equal to $\mu_i$ ($\nu_i$). The two test statistic $\lambda_0$ and $\lambda_1$ corresponds to $\chi^2$ differences.

The two test statistic are computed for $10^6$ pseudo-experiments for each set of selection criteria assumed and the one that maximise the sensitivity is selected. For reference, Fig. 1 shows the distribution of the two test statistic $\lambda_0$ and $\lambda_1$ for the best selection criteria ($\Lambda_{cut} = -5.9$ and $\beta_{cut} = 1.1^\circ$).

The significance is computed evaluating the p-value of the $\lambda_0$ distribution (null hypothesis, $H_0$) corresponding to the median of the $\lambda_1$ distribution, for which 50% of the pseudo-experiments under
the $H_1$ hypothesis (presence of the Sun shadow) are correctly identified. For the best selection criteria the p-value is equal to $7.4 \times 10^{-4}$, corresponding to a significance of $3.4\sigma$. Fig. 2 shows the dependance of the significance on the cuts applied on $\Lambda$ and $\beta$.

![Figure 2](image)

**Figure 2:** Expected significance of the Sun shadow effect based on pseudo-experiment approach, as a function of cut on $\Lambda$ and $\beta$ ($\Lambda_{\text{cut}}$ and $\beta_{\text{cut}}$). The red point represents the best selection criteria ($\Lambda_{\text{cut}} = -5.9$ and $\beta_{\text{cut}} = 1.1^\circ$). The expected significance for the selected set of cut values is $3.4\sigma$.

3. Analysis of the 2008-2017 data sample

The ANTARES data sample, corresponding to 2925 days of livetime collected in 10 years (2008-2017), counts $2.6 \times 10^6$ events reconstructed as downward-going muons with the standard ANTARES reconstruction chain. After the application of the selection criteria described in the
previous section $6.5 \times 10^5$ events survived. As previously described, the events are projected on a histogram as a function of the distance from the Sun centre (histogram bin size=0.4°) obtaining Fig. 3.

The data distribution is fitted with the function

$$f(\delta) = \frac{dN}{d\Omega} = k(1 - \frac{R_{\text{Sun}}^2}{2\sigma_{\text{res}}^2}e^{-\frac{\delta^2}{2\sigma_{\text{res}}^2}}),$$

where $\Omega$ is the solid angle of the concentric ring around the Sun centre, $k$ is the average muon event density in the $H_0$ hypothesis (fitted value $k = 2086 \pm 3$), $R_{\text{Sun}}$ is the average angular radius of the Sun (0.26°) and $\sigma_{\text{res}}$ is the width of the Gaussian dip (fitted value $\sigma_{\text{res}} = 0.59° \pm 0.10°$). The number of absorbed events in the Sun shadow dip is $N_{\text{abs}} = k\pi R_{\text{Sun}}^2 = 443 \pm 1$.

The influence of the finite-size radius of the Sun in the estimation of the detector resolution is estimated through dedicated pseudo-experiments. The discrepancies obtained between the assumed detector angular resolutions and the fitted values of the Gaussian width are negligible with respect to the statistical uncertainty (below 10% for the assumed angular resolution values above 0.35°) [8].

In the hypothesis of no shadowing effect ($H_0$), the data distribution in Fig. 3 would follow the profile of Eq. 3,

$$\frac{dN}{d\Omega} = k;$$

the Sun shadow significance can be estimated fitting the event density according the two different hypotheses defining the test statistic $-\lambda = x^2_0 - x^2_1$. For the 2008-2017 sample the significance of the shadowing effect is 3.7.$\sigma$. Unfortunately the data sample is not sufficient to study how the significance depends on the activity of the Sun.
The measurement of the Sun shadow allows also an estimation of the detector pointing performance. For this purpose the data sample is projected on a 2D-histogram as a function of 

\[ x = (\alpha_\mu - \alpha_{\text{Sun}}) \times \cos(h_\mu) \] 
\[ y = h_\mu - h_{\text{Sun}} \] 

where \( \alpha_\mu, \alpha_{\text{Sun}} \) are the azimuthal coordinates and \( h_\mu, h_{\text{Sun}} \) are the elevation angles of the reconstructed track and the Sun, respectively. The bin size is \( 0.4^\circ \times 0.4^\circ \) spanning the range \([-10^\circ, 10^\circ]\).

First, in the \( H_0 \) hypothesis (no shadowing effect), the background distribution is assumed as

\[ p_2(x, y; k) = k_0 + k_1 x + k_2 x^2 + k_3 y + k_4 y^2, \quad (4) \]

while, in the \( H_1 \) hypothesis (presence of the shadowing effect), the data distribution is approximated with a function obtained by subtracting from \( p_2(x, y; k) \) a two-dimensional Gaussian function:

\[ G(x, y; A_{\text{sh}}, x_s, y_s) = \frac{A_{\text{sh}}}{2\pi \sigma_{\text{res}}^2} e^{-\frac{(x-x_s)^2+(y-y_s)^2}{2\sigma_{\text{res}}^2}}, \quad (5) \]

where \( A_{\text{sh}} \) is the amplitude of the deficit caused by the shadowing effect (free parameter), \((x_s, y_s)\) is the assumed position of the Sun. The width of the Gaussian function is assumed equal in both \( x \) and \( y \) direction (\( \sigma_{\text{res}} = 0.59^\circ \)).

The procedure applied foresees the assumption of different Sun shadow centre positions spanning the whole region of interest with a step size of \( 0.1^\circ \). The nominal Sun position is \( O \equiv (0^\circ, 0^\circ) \).

Then the test statistic \( \lambda(x_s, y_s) \) is computed as

\[ \lambda(x_s, y_s) = \chi^2_{H_1}(x_s, y_s) - \chi^2_{H_0}, \quad (6) \]

where \( \chi^2_{H_0} \) is the \( \chi^2 \) value obtained from the fit with Eq. (4), which is a constant value for all the bins of the histogram, and \( \chi^2_{H_1}(x_s, y_s) \) is the \( \chi^2 \) value obtained from the fit with the function used to describe hypothesis \( H_1 \), \( p_2(x, y; k) - G(x, y; A_{\text{sh}}, x_s, y_s) \).

The result is provided in Fig. 4 where the values of the test statistic \( \lambda(x_s, y_s) \) as a function of the assumed Sun position is shown. The minimum value is \( \lambda_{\text{min}} = -13.7 \) in the position \( \lambda(x_s, y_s) = (0.2^\circ, 0^\circ) \). The values of \( \lambda(x_s, y_s) \) and \( A_{\text{sh}} \) for the nominal Sun position are \( \lambda_O = -13.1 \) and \( A_O = 54\pm15 \). As the \( -\lambda \) follows the distribution of a \( \chi^2 \) with one degree of freedom, the significance to reject the no-Sun hypothesis can be computed (p-value= \( 3.1 \times 10^{-4}, \) significance=3.6σ).

The test statistic \( \lambda(x_s, y_s) \) behaves as a bi-dimensional profile-likelihood, with \( A_{\text{sh}} \) treated as the nuisance parameter and the interval corresponding to a desired confidence level (CL) is obtained for \( \lambda(x_s, y_s) \leq \lambda_{\text{cut}} = \lambda_{\text{min}} + Q \), where \( Q \) is the quantile for the joint estimation of two parameters (Fig. 5).

4. Conclusions

This contribution presented the study of the Sun shadowing effect in 2008-2017 ANTARES data sample (2925 days of livetime). The two strategies applied in this analysis achieved compatible results showing a significance of the phenomenon equal to 3.7σ using the one-dimensional approach. Besides the ANTARES detector is designed to maximise the angular resolution for upward-going track (PMTs are pointing 45°
Figure 4: The distribution of the test statistic $\lambda(x_s, y_s)$. The minimum value $\lambda_{\text{min}} = -13.7$ is found at $(0.2^\circ, 0^\circ)$ point (white dot).

Figure 5: Contours corresponding to different confidence levels (red: 68.27%; yellow: 95.45%; green: 99.73%). The white dot indicates $(0.2^\circ, 0^\circ)$ point for which a minimum value of $\lambda_{\text{min}} = -13.7$ is obtained.
below the horizon), this study demonstrated that the ANTARES angular resolution for downward-going muons is $0.59^\circ \pm 0.10^\circ$. This results is compatible with the previous Moon shadow analysis ($0.73^\circ \pm 0.14^\circ$) [3].

The pointing performance study did not evidence any significant deviation from the expectations, confirming the results of the Moon shadow study [3].

References


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