Optical properties in deep sea water at the site of the ANTARES detector

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Abstract: The ANTARES neutrino telescope is located at a depth of 2475 m in the Mediterranean Sea. Its main objective is the observation of extraterrestrial neutrinos. Relativistic charged leptons produced by neutrino interactions in and around the detector produce Cherenkov light in the sea water detected by a three dimensional grid of photomultiplier tubes. The propagation of Cherenkov light depends on the optical properties of the sea water and their understanding is crucial to reach the optimal performance of the detector. This paper presents the measurements made between 2008 and 2010 of the light velocity and attenuation length at the ANTARES site with a system of light sources (LEDs and laser) at different wavelengths (between 400 nm and 532 nm). The time variability of the optical properties are presented and the derived values are compared with theoretical predictions.

Keywords: Neutrino telescope, Optical Beacon system, Optical properties, Refractive index.

1 Introduction

The ANTARES neutrino telescope [1] is located at the bottom of the Mediterranean Sea at a depth of 2475 m, roughly 40 km offshore from Toulon in France. Sea water is used as the detection medium for the Cherenkov light emitted by relativistic charged particles resulting from interaction of neutrinos around or inside the detector. The particle direction is reconstructed from the arrival time of detected photons through the array of photomultiplier tubes (PMTs).

The measurement of the refractive index is performed with a pulsed light source shining through water and the time of light distributions of photons detected by PMTs at different distances from the source. The attenuation length is measured by the amount of light detected by these PMTs. The optical properties are measured at wavelengths between 400 nm and 532 nm and are compared with theoretical predictions.

A precise measurement of the optical properties minimizes the uncertainty on many physical results as seen in [2]. Moreover, the optical properties may change in time due to sea current. Several measurements of those presented in this paper have been performed in the past [3, 4, 5].

2 Experimental setup

The ANTARES detector consists of a three dimensional array of 885 PMTs arranged in twelve vertical approximately 450 m long lines. Along each line with a vertical separation of 14.5 m, PMTs are grouped in triplets and oriented with their axis pointing downward at an angle of 45° with respect to the the vertical line direction. The horizontal separation between lines is about 70 m.

The PMTs are sensitive to single photons in the wavelength range between 350 nm and 600 nm. They have a peak quantum efficiency of about 25% between 350 nm and 450 nm. The PMT measures the arrival time and charge amplitude of the detected photons.

The Optical Beacon system consists of a series of pulsed light sources distributed through the detector. The primary aim of the Optical Beacon system is the time calibration between the PMTs to reach the best angular resolution of the detector. In addition the Optical Beacon system can be also used to determine the optical properties of water.

There are four LED Beacons per line and one laser Beacon at the bottom of the central line. One LED Beacon contains 36 individual LEDs distributed over six vertical faces shaping an hexagonal cylinder. On each face, five LEDs point radially and one upwards. All the LEDs emit light at a nominal wavelength of 470 nm except two LEDs located on the lowest Beacon of line 12 which emit light at nominal wavelength of 400 nm.

The LEDs emit light with a maximum intensity of \(\sim 160 \text{ pJ}\) and a pulse width of \(\sim 4 \text{ ns (FWHM)}\). The laser is a more powerful device and emits shorter pulses than the LEDs. The laser emits pulses of light with a maximum intensity of \(\sim 1 \mu \text{J}\) and pulse width of \(\sim 0.8 \text{ ns (FWHM)}\) at a nominal wavelength of 532 nm. The LEDs and laser flash at
a frequency of 330 Hz. Further details about the Optical Beacon system can be found elsewhere [6, 7, 8].

The light spectrum of the three sources (two LEDs with nominal wavelengths of 470 nm and 400 nm and one laser with nominal wavelength of 532 nm) were measured using a high resolution calibrated spectrometer from Ocean Optics HR4000CG-UV-NIR. The spectrometer was cross-checked with the Green Nd-YAG laser (532 nm). The measured peak wavelengths of the LEDs in pulsed mode operation are 468.5 ± 14.4 nm and 403.1 ± 6.9 nm respectively.

3 Data acquisition and data analysis

In the special calibration data taken with Optical Beacon system, the emission time and the position of the isotropic light flash, as well as the arrival time and the position when the light reaches the PMTs are known. From the time and position difference between the PMTs the refractive index is measured, whereas the amount of light collected by these PMTs gives an information about the attenuation length.

3.1 Data acquisition

The various measurements of the water optical properties were taken from May 2008. Only data with stable background rates and below 100 kHz have been analyzed. The special calibration data duration takes only few minutes. One single upward looking LED of the lowest Optical Beacon in the line emits more than 10^5 light flashes towards the PMTs above. The photons are collected by the PMTs in the line. Figure 1 shows the arrival time distribution of photons for a LED Beacon illuminating a PMT located at 100 m.

3.2 Data analysis

Since the light path used in the analysis (few 100 m) has the same order as the scattering length the scattering has in some way to be taken in account. The arrival time distributions are fitted to a function which is the convolution of a gaussian distribution and an exponential distribution [9, 10]. The gaussian distribution models the transit time spread of the PMTs, the time width of the optical sources and the effect of the chromatic dispersion in water, while the exponential distribution models the scattering of photons in water. The fit function is given by

\[ f(t) = b + h \cdot e^{-\frac{t-\mu}{\sigma}} \cdot \text{Erfc} \left( \frac{1}{\sqrt{2}} \left( \frac{\sigma}{\tau} - \frac{t - \mu}{\sigma} \right) \right). \tag{1} \]

where \( t \) is the arrival time of the photons and the fit parameters are the background \( (b) \), the height of the fit function \( (h) \), the mean and width of the gaussian distribution \( (\mu, \sigma) \) and the exponential constant \( (\tau) \). The Erfc\((t)\) is the complementary error function distribution \( \text{Erfc}(t) = \frac{2}{\sqrt{\pi}} \int_{t}^{\infty} e^{-t'^2} dt' \). An example of such a fit is shown in the zoom of Figure 1. The fit is made in the range from -100 ns to the time of the most populated bin plus 20 ns. The arrival time at each PMT is given by the fitted mean value of the gaussian distribution. The fit is stable with respect to changes in the fit range and histogram binning.

The small tail of delayed photons is due to the light scattering between LED and PMT. The zero time is defined by the illumination time of the LED. The flat distribution before and after the peak shows the detected optical background.
can be up to three PMTs at each distance). Due to the small wavelength range of the individual LEDs the light dispersion is minimized. By selecting only the PMTs of the same line as the emission of light the uncertainty on the PMT angular acceptance and the PMT positions are reduced. In this analysis, no correction of the PMT positions due to line movements have been applied. The minimal distance is set to eliminate the PMT which receives too much light and have an erroneous time estimation caused through the early photon effect (for explanation see [8]). The minimal distance for the fit range is defined as the distance where the average collected charge per hit (usually referred to as the amplitude) in the signal region is below 1.5 photo-electrons. The maximum distance is introduced due to avoid noise fluctuations. The signal has to be significantly larger than the average background (above seven sigmas). The slope of a linear fit through the measured points gives the inverse of the measured velocity of light in water ($v_m$). The measured refractive index is defined as

$$n = c/v_m$$

with $c = 3 \cdot 10^8 m/s$. The error of the refractive index given in Figure 2 is the error estimated by the linear fit.

As seen in Figure 1 the PMTs perform a time resolved measurement of the collected light. The amount of light detected depends on the attenuation length, whereas the shape of the arrival time distribution of the detected light is related to the photon path length distribution of the scattered photons. For the attenuation length measurement a similar selection criteria as in the refraction index measurement is used. An exponential fit to the collected charge as a function of the distance is shown in Figure 3 for two runs with sources with wavelength of 470 nm (tagged as Blue) and wavelength of 400 nm (tagged as UV). The attenuation length $L$ is obtained by

$$I \cdot R^2 \sim I_0 \cdot e^{-\frac{R}{L}}.$$  

where $I_0$ is the intensity at the source and $I$ the intensity detected by a PMT at a distance $R$.

4 Monte Carlo measurement

The Monte Carlo simulation takes into account the geometry of the detector and the optical properties of the water (refraction index, scattering length and absorption length). Monte Carlo generated time distributions with a large variety of optical properties has been used to analyze the time distributions and calculate the refraction index and also to check the stability of the analysis method. The analysis method was first validated with a Monte Carlo sample without scattering at three different refractive index. The variation of the absorption length between 30 m and 120 m has nearly no influence on the refraction index, with variation of the refraction index of less than 0.1%. A variation in the scattering length between 20 m and 50 m produces an uncertainty of 0.3% in the measurement of the refractive index.

5 Data measurement

Between May 2008 and March 2010 a total of 42 runs were taken with a nominal wavelength of 470 nm. 14 runs with a nominal wavelength of 400 nm and 13 runs with a nominal wavelength of 532 nm and have been analyzed according to the methods explained in section 3.2. The measured refraction of the 42 runs are shown in the Figure 4 and the mean value is evaluated by fitting the distribution with a gaussian. The fitted attenuation lengths for some of these runs as function of the data period are shown in Figure 5. The fitted values are reasonably stable with time. Since November 2010 runs with a modified Optical Beacon have been collected with light emission at six additional wavelengths with nominal peak values of 385, 400, 440, 460, 505 and 518 nm. First results are expected soon.
These measured refractive index with their systematic errors estimated in section 4 are shown in Figure 6. Also shown is the parametric formula of the refractive index. The refractive index at the ANTARES site depends on the wavelength, on the temperature, on the salinity of the water and on the pressure at the depth of the detector. The parametric formula for the phase refractive index of Quan and Fry [11], based on data from Austin and Halikas [12], is modified with appropriate pressure corrections as suggested in [3]. The phase refractive index for sea water as a function of wavelength, temperature \((T)\), salinity \((S)\) and pressure \((p)\) is given by

\[
n_p(340 < \lambda (\text{nm}) < 560, S(\%) = 3.844, \quad T(\degree \text{C}) = 13.2, 200 < p(\text{atm}) < 240) = 1.32292 + (1.32394 - 1.32292) \cdot \frac{p - 200}{240 - 200} + \frac{16.2561}{\lambda} - \frac{4382}{\lambda^2} + \frac{1.1455 \cdot 10^6}{\lambda^3},
\]

where \(\lambda\) is the wavelength of light.

The group refractive index \((n)\) [4] is related to its phase refractive index \((n_p)\) through

\[
n = \frac{n_p}{1 + \frac{\lambda}{n_p} \frac{dn_p}{d\lambda}}.
\]

The parametrization of the refractive indexes \(n\) and \(n_p\) is shown in Figure 6 for the given values of temperature, salinity and for a pressure between 200 atm and 240 atm. The measurements are in agreement with the parametrization of the group refractive index.

### 6 Conclusion

Pulsed light sources with wavelengths between 400 nm and 532 nm shining through sea water and the time of light distribution detected by the PMTs at distances between few tens and few hundred meters from the source have been used to measure the refraction index. Dedicated Monte Carlo simulation has been used to validate the analysis method and to evaluate the systematics. The data results are compatible with the parametrization of the group refractive index.

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