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# Measurement of the group velocity of light in sea water at the ANTARES site

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A B S T R A C T

The group velocity of light has been measured at eight different wavelengths between 385 nm and 532 nm in the Mediterranean Sea at a depth of about 2.2 km with the ANTARES optical beacon systems. A parametrisation of the dependence of the refractive index on wavelength based on the salinity, pressure and temperature of the sea water at the ANTARES site is in good agreement with these measurements.



## 1. Introduction

The ANTARES neutrino telescope is located on the bottom of the Mediterranean Sea (42°50′ N, 6°10′ E) at a depth of 2475 m, roughly 40 km offshore from Toulon in France. The main objective of the experiment is the observation of neutrinos of cosmic origin in the southern hemisphere sky. Sea water is used as the detection medium of the Cherenkov light induced by relativistic charged particles resulting from the interaction of neutrinos. The particle trajectory is reconstructed from the measured arrival times of the detected photons. The detector consists of 885 photomultiplier tubes (PMTs) mounted on twelve vertical lines with a length of about 450 m. The horizontal separation between lines is about 70 m. Further details can be found elsewhere [1–3].

Charged particles traveling through sea water produce the emission of Cherenkov light whenever the velocity of the particle exceeds that of light in water. The Cherenkov photons are emitted at a characteristic angle, $\theta_c$, with respect to the particle direction. This angle is related to the index of refraction of the medium as $cos\ \theta_c = \frac{1}{\beta n_p}$. In this, $\beta$ is the velocity of the particle relative to the speed of light in vacuum. The index of refraction, $n_p$, corresponds to the ratio between the speed of light in vacuum and the phase velocity of light in water. The individual photons then travel through the water at the group velocity. Both the phase and the group velocity depend on the wavelength of the photons. This is usually referred to as chromatic dispersion. The group velocity is related to its phase velocity in the following way:

$$n_g = \frac{n_p}{1 + \frac{\lambda}{n_p}\frac{dn_p}{d\lambda}} \quad (1)$$

where $\lambda$ is the wavelength of light. The index of refraction, $n_g$, corresponds to the ratio between the speed of light in vacuum and the group velocity of light in water.

Since the PMTs cannot distinguish the photon wavelength, the variation of the photon emission angle and the group velocity due to chromatic dispersion cannot be accounted for on the individual photon level. Nevertheless, the average effect of the wavelength dependencies are accounted for in the algorithm used to reconstruct the particle trajectory [4,5].

A measurement of the group velocity of light has been made using the optical beacon system of ANTARES. This system consists of a set of pulsed light sources (LEDs and lasers) which are distributed throughout the detector and illuminate the PMTs with short duration flashes of light. The refractive index is deduced from the recorded time of flight distributions of photons at different distances from the sources for eight different wavelengths between 385 nm and 532 nm.

## 2. Experimental setup

The PMTs of ANTARES are sensitive to photons in the wavelength range between 300 nm and 600 nm. The maximum quantum efficiency is about 22% between 350 nm and 450 nm. The arrival time and integrated charge of the analogue pulse from the PMT are measured by the readout electronics [6]. The transit time spread of single photo-electrons of the PMT is around 3.5 ns (FWHM) [7].

The group velocity of light has been measured using the ANTARES optical beacon system. This system was primarily designed to perform time calibration *in situ* [7,8]. There are two types of optical beacons, the LED optical beacons and the laser beacons. There are four LED optical beacons distributed along each detector line and two laser beacons at the bottom of two central lines. The *in situ* measurement of the temperature and salinity is provided by some conductivity/temperature/depth sensors.[5]

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