Simultaneous measurements of water optical properties by AC9 transmissometer and ASP-15 Inherent Optical Properties meter in Lake Baikal

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Abstract

Measurements of optical properties in media enclosing Čerenkov neutrino telescopes are important not only at the moment of the selection of an adequate site, but also for the continuous characterization of the medium as a function of time. Over the two last decades, the Baikal collaboration has been measuring the optical properties of the deep water in Lake Baikal (Siberia) where, since April 1998, the neutrino telescope NT-200 is in operation. Measurements have been made with custom devices. The NEMO Collaboration, aiming at the construction of a km$^3$ Čerenkov neutrino detector in the Mediterranean Sea, has developed an experimental setup for the measurement of oceanographic and optical properties of deep sea water. This setup is based on a commercial transmissometer. During a joint campaign of the two collaborations in March and April 2001, light absorption, scattering and attenuation in water have been measured. The results are compatible with previous ones reported by the Baikal Collaboration and show convincing agreement between the two experimental techniques.

Key words: absorption, AC9, attenuation, Baikal, ASP-15, NEMO, neutrino telescope

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1 Introduction

After a long period of experimental work, large Čerenkov detectors for high energy neutrinos are going to open a new observational window to the sky. Their main goal is to extend the volume of the explored Universe by neutrinos, to obtain a complementary view of astronomical objects and to learn about the origin of high energy cosmic rays. They are the successors of underground neutrino detectors which have turned out to be too small to detect the faint fluxes of neutrinos from cosmic accelerators.

The new detectors are large, expandable arrays of photomultipliers constructed in open water or ice. The photomultipliers span a three-dimensional coarse grid and map the Čerenkov light of secondary particles produced in neutrino interactions. Actually, the basic idea for this detection method goes back to the early 60’s (1). Pioneering attempts towards its realization have been made in the course of the DUMAND project (2). In 1993, the Baikal Collaboration (3) succeeded to build the first deep underwater Čerenkov neutrino detector, which has been stepwise upgraded to its present stage, NT-200. The AMANDA Collaboration (4) has built a Čerenkov detector in the South Pole ice. Other collaborations (ANTARES (5), NESTOR (6)) are constructing underwater neutrino detectors of similar size. Since a few years, the NEMO Collaboration
is performing an intensive R&D program aiming at the construction of a km$^3$ Čerenkov neutrino telescope in the Mediterranean Sea. Another cubic kilometer detector, IceCube (8) is planned at the South Pole. The cubic kilometer scale is set by various predictions on the extremely low fluxes of high energy neutrinos expected from astrophysical sources.

In underwater Čerenkov neutrino telescopes, water acts not only as a target but also as radiator of Čerenkov photons produced by relativistic charged particles. The detection volume, as well as the angular and energy resolutions strongly depend on the water transparency.

The transparency of water as a function of photon wavelength $\lambda$, is described by the so called inherent optical properties, like the coefficients for absorption $a(\lambda)$, for scattering $b(\lambda)$, for attenuation $c(\lambda) = a(\lambda) + b(\lambda)$, and by the phase scattering function $\beta(\lambda, \vartheta)$ (also referred to as volume scattering function) which represents, for a photon, the probability to be diffused at an angle $\vartheta$. Another parameter commonly used in literature is the effective scattering coefficient $b_{\text{eff}}(\lambda) = b(\lambda)(1 - \cos(\lambda, \vartheta))$, where $\cos(\lambda, \vartheta) = \int_0^\pi \cos(\vartheta) \beta(\lambda, \vartheta) d\vartheta / \int_0^\pi \beta(\lambda, \vartheta) d\vartheta$ is the average cosine of the phase scattering function at a given $\lambda$. The optical properties of natural water have to be measured \textit{in-situ} in order to allow an unbiased knowledge of light transmission properties in the medium.

The Baikal collaboration has been investigating the fresh water deep in Lake Baikal since 1980. The inherent optical properties have been measured with a series of specially designed devices. It was shown that the water transparency at depths between 900 m and 1200 m is adequate to operate a neutrino telescope. Put into operation at April 6$^{th}$, 1998, the neutrino telescope NT-200 incorporates a long-term monitoring system which performs continuous measurements of the water parameters. This information serves as input for Monte-Carlo simulations of the detector response to atmospheric muons which represent a well-known calibration source for neutrino telescopes. The muon fluxes measured with NT-200 are in very good agreement with simulation results. This fact confirms that the custom-made devices and the methods to extract the relevant information on optical parameters yield reliable results.

The NEMO collaboration has been investigating oceanographic and optical properties of several deep sea marine sites close to the Italian coast, with the aim to select the optimal site for the construction of a km$^3$ detector in the Mediterranean Sea. Absorption and attenuation coefficients for light in the wavelength region between 412÷715 nm (11) have been measured with a set-up based on commercial devices.

Optical measurements in deep water are extremely difficult, and possible systematic errors related to these measurements suggest careful cross checks of
results by complementary methods. For these reasons, during March - April 2001, the NEMO and Baikal Collaborations have started a joint campaign to measure the optical properties of deep water in Lake Baikal using two different devices. One set-up is based on the transmissometer AC9, operated by the NEMO group, the other device, ASP-15 (Absorption, Scattering and Phase function meter), was developed and operated by the Baikal Collaboration. The cross check of experimental results has been crucial for both devices, since both have an excellent sensitivity in measuring water optical properties, however, they can be affected by different sources of systematic errors which could deteriorate the absolute accuracy. The measurements reported in the following sections have been carried out during March - April 2001, from the ice camp above the neutrino telescope NT-200.

2 Instrumentation and data acquisition

2.1 The AC9 transmissometer

The AC9, manufactured by WETLabs, is a transmissometer capable to measure absorption and attenuation coefficients at nine different wavelengths in the range 412–715 nm. Using an accurate calibration procedure, the NEMO collaboration has achieved an accuracy of about $1.5 \cdot 10^{-3}$ m$^{-1}$ in $a$ and $c$ measurements.

During the measurements in Lake Baikal, the AC9 device and a CTD (a probe that measures water conductivity, temperature and pressure) were operated through an electro-mechanical cable. With this set-up we have obtained two vertical profiles of the water column ($50 \text{ m} < \text{ depth } < 1100 \text{ m}$), collecting about ten data-sets per meter of depth. Each data-set consists of a measurement of temperature and optical properties, $a(\lambda)$ and $c(\lambda)$, over the nine wavelengths.

In figure 1 we show, as a function of depth, the water temperature together with the values for absorption and attenuation coefficient at $\lambda = 488 \text{ nm}$ measured during the first and the second deployment in Lake Baikal (for discussion see section 3).

2.2 ASP-15 - an instrument for long-term monitoring of the inherent optical properties of deep water

The ASP-15 device (see figure 2) has two receiving channels: one with a wide aperture to measure $a$ and $b$ and another one with a rotating mirror and a
Fig. 1. Profiles of water temperature and water optical properties (absorption and attenuation coefficients: $a(488)$ and $c(488)$), as functions of depth, obtained by two measurements (red and black dots) with the AC9-CTD set-up in Lake Baikal during March 2001. The NT-200 telescope is located between 1100 m and 1170 m depth.

Two photomultipliers (type FEU-130) and 15 interference light filters are assembled in a cylindrical container. The filters wavelengths are ranged from 369 nm to 691 nm. Both photomultipliers operate in photon counting mode. Two isotropic point-like light sources and two screens are assembled on a frame, which can be moved by a stepping motor over distances ranging from 0.4 to 15 meters with respect to the milk glass window. Measurements were carried out separately for each source and controlled via cable by a computer on shore or at the ice camp. The device is described in detail in [12; 13; 14]. The principle of the measurement with ASP-15 is described in [15]. We measure the dependence of the luminosity $E$ on the distance $R$ between source and receiver with each of the 15 light filters and approximate the absorption coefficient by

$$a = -\frac{\ln(E_1 \cdot R_1^2 / E_2 \cdot R_2^2)}{R_1 - R_2},$$

where $E_1$ and $E_2$ are the luminosity at distances $R_1$ and $R_2$, respectively. Monte-Carlo simulations [15] have shown that for an isotropic or a Lambertian (cosine) light source in water, the difference between approximation (1) (which is an exact definition of $a$ in a case of a medium without scattering and isotropic point like source) and the exact value of $a$ is less than 1%, provided a strongly anisotropic phase scattering function, low scattering and $R \leq a^{-1}$.

The scattering coefficient $b$ is approximated [16] by
$b = \ln\left(1 - \frac{E_s}{E}\right)/R$, \hspace{1cm} (2)

where $E_s$ and $E$ are the luminosity at distance $R$ from the screened and unscreened source, respectively.

Our estimation of the total uncertainties due to approximations (1,2) and systematic errors is: $\Delta a(\lambda) \leq 5\%$ for $a \geq 0.02 \text{ m}^{-1}$ and $\Delta b(\lambda) \leq 10 \%$ for $b \geq 0.02 \text{ m}^{-1}$. In all figures below, only statistical errors are shown for the \textit{ASP-15} data.

3 Results

3.1 Light absorption in Lake Baikal

In this section we discuss the results of light absorption measurements performed with both devices \textit{AC9} and \textit{ASP-15}. In table 1 and figure 3 we present respectively the absorption coefficients and absorption lengths ($L_a(\lambda) = 1/a(\lambda)$) as a function of wavelength. \textit{ASP-15} data have been taken at a depth of 200 m, the \textit{AC9} values are the average of data collected at depths between 180 m and 220 m.
Table 1
Absorption coefficients measured during two deployments of AC9 (March 28th) and during one deployment of ASP-15 (March 28th) at a depth of 200 m. AC9 data are averaged over the depth interval 180÷220 m.

| $\lambda$ (nm) | AC9 1 (m$^{-1}$) | AC9 2 (m$^{-1}$) | ASP-15 28/03 (m$^{-1}$) |
|---------------|-----------------|-----------------|------------------------|
| 369           |                 |                 | 0.212±0.026            |
| 374           |                 |                 | 0.264±0.006            |
| 400           |                 |                 | 0.145±0.006            |
| 412           | 0.100±0.003     | 0.096±0.003     |                        |
| 420           |                 |                 | 0.103±0.004            |
| 440           | 0.061±0.002     | 0.057±0.002     | 0.085±0.002            |
| 459           |                 |                 | 0.046±0.002            |
| 479           |                 |                 | 0.051±0.001            |
| 488           | 0.042±0.001     | 0.041±0.001     | 0.058±0.002            |
| 494           |                 |                 | 0.045±0.002            |
| 510           | 0.052±0.001     | 0.052±0.001     |                        |
| 519           |                 |                 | 0.059±0.003            |
| 532           | 0.064±0.001     | 0.063±0.001     |                        |
| 550           |                 |                 | 0.061±0.002            |
| 555           | 0.072±0.001     | 0.070±0.001     |                        |
| 650           | 0.352±0.001     | 0.351±0.001     |                        |
| 651           |                 |                 | 0.361±0.006            |
| 676           | 0.439±0.001     | 0.439±0.001     |                        |
| 691           |                 |                 | 0.395±0.012            |
| 715           | 0.979±0.001     | 0.979±0.001     |                        |

Table 2 and figure 4 show the results obtained for absorption coefficients and absorption lengths at a depth of 1000 m (ASP-15) and for depths between 980 m and 1020 m (AC9).

The two sets of AC9 data were collected with about ten hours time difference. Each measurement was preceded by an accurate cleaning of the instrument optics and by a calibration. The agreement between the results obtained from the two data sets confirms the reliability of the calibration procedure.

The agreement of the results obtained by means of AC9 and ASP-15 at 1000
Fig. 3. Absorption length measured with *ASP-15* at a depth of 200 m. *AC9* data are averaged over the depth interval 180–220 m.

Fig. 4. Absorption length measured with *ASP-15* at 1000 m depth. *AC9* data are averaged over the depth interval 980–1020 m.

m depth is rather good: in spite of the fact that the two instruments are based on different methodologies and have different sources of systematic errors, the central values are compatible. This result proves the validity of both
Table 2
Absorption coefficients measured during two deployments of the AC9 (March 28\textsuperscript{th}) and during three deployments of ASP-15 (March 23\textsuperscript{rd}, April 4\textsuperscript{th} and April 8\textsuperscript{th}) in Lake Baikal at 1000 m depth. AC9 data are averaged over the depth interval 980÷1020 m.

| $\lambda$ (nm) | AC9 1 $a$ (m$^{-1}$) | AC9 2 $a$ (m$^{-1}$) | ASP-15 23/03 $a$ (m$^{-1}$) | ASP-15 04/04 $a$ (m$^{-1}$) | ASP-15 08/04 $a$ (m$^{-1}$) |
|----------------|---------------------|---------------------|-----------------------------|-----------------------------|-----------------------------|
| 369            | 0.209±0.007         | 0.200±0.004         | 0.173±0.006                 |                             |                             |
| 374            | 0.174±0.017         | 0.176±0.004         | 0.143±0.004                 |                             |                             |
| 400            | 0.129±0.003         | 0.123±0.003         | 0.116±0.003                 |                             |                             |
| 412            | 0.082±0.003         | 0.077±0.003         |                             |                             |                             |
| 420            | 0.086±0.004         | 0.077±0.002         | 0.054±0.001                 |                             |                             |
| 440            | 0.049±0.002         | 0.045±0.002         | 0.079±0.002                 | 0.069±0.003                 | 0.046±0.001                 |
| 459            | 0.053±0.003         | 0.060±0.001         | 0.041±0.001                 |                             |                             |
| 479            | 0.046±0.001         | 0.056±0.001         | 0.036±0.001                 |                             |                             |
| 488            | 0.037±0.001         | 0.035±0.001         | 0.035±0.001                 | 0.040±0.001                 | 0.031±0.001                 |
| 494            | 0.038±0.003         | 0.047±0.001         | 0.031±0.001                 |                             |                             |
| 510            | 0.048±0.0015        | 0.047±0.001         |                             |                             |                             |
| 519            | 0.047±0.001         | 0.050±0.002         | 0.035±0.001                 |                             |                             |
| 532            | 0.060±0.001         | 0.059±0.001         |                             |                             |                             |
| 550            | 0.063±0.002         | 0.072±0.002         | 0.050±0.002                 |                             |                             |
| 555            | 0.068±0.001         | 0.067±0.001         |                             |                             |                             |
| 590            | 0.126±0.003         | 0.140±0.003         | 0.115±0.003                 |                             |                             |
| 650            | 0.351±0.001         | 0.351±0.001         |                             |                             |                             |
| 651            | 0.343±0.003         | 0.338±0.008         | 0.290±0.006                 |                             |                             |
| 676            | 0.439±0.001         | 0.439±0.001         |                             |                             |                             |
| 691            | 0.269±0.023         | 0.284±0.008         | 0.379±0.021                 |                             |                             |
| 715            | 0.984±0.001         | 0.984±0.001         |                             |                             |                             |

Measurement techniques.

The spread between data collected with AC9 and ASP-15 at 200 m depth can be attributed to local changes in optical and hydro-physical properties of the water column, extensively discussed by the Baikal Collaboration in [18; 19]. The two data samples have been collected at two sites with about 100 m distance.
At a depth of 200 m, the maximum value of the absorption length is located in the blue-green region, at $\lambda \sim 490$ nm. The average of the measured values are $L_a = 24.1 \pm 0.5$ m for $AC9$ ($\lambda = 488$ nm) and $L_a = 22.2 \pm 1.0$ m for $ASP-15$ ($\lambda = 494$ nm).

For the data samples collected at 1000 m depth, the maximum values of the absorption lengths are also observed at $\lambda \sim 490$ nm. Their mean values are: $L_a = 27.9 \pm 0.7$ m for $AC9$ ($\lambda = 488$ nm) and $L_a = 28.3 \pm 1.5$ m for $ASP-15$ ($\lambda = 488$ nm). These values do not contradict previous measurements of the Baikal Collaboration [13, 16, 17].

The obvious differences between optical properties at 1000 m and 200 m are due to the different characteristics of Lake Baikal waters below and above the boundary depth of solar radiation penetration, which is located at a depth of about $\sim 400$ m (see figure 1). Above the solar radiation boundary depth the water column shows a time dependent behavior, strongly influenced by biological activity. Below the solar radiation boundary depth, where the water column is more stable and the biological activity is reduced, the water transparency increases (about 25% increase of $L_a$ at blue wavelengths). The best water transparency is measured between 900 m and 1150 m, covering the vertical extension of the NT-200 telescope. Below the absorption length decreases, probably due to the water streamed along the very steep slope of the lake bed.

3.2 Light attenuation and scattering in Lake Baikal

While $ASP-15$ is designed to measure directly the absorption, $a(\lambda)$, and scattering, $b(\lambda)$, coefficients the $AC9$ measures the absorption, $a(\lambda)$, and attenuation, $c(\lambda)$ coefficients. In the latter case the scattering coefficient can be obtained as the difference between absorption and attenuation coefficients ($b(\lambda) = c(\lambda) - a(\lambda)$) and compared to the results from the direct measurements with $ASP-15$.

In tables 3 and 4 we present the attenuation coefficients measured at depths of about 200 m and 1000 m with $AC9$.

Tables 5 and 6 show the values of the scattering coefficients measured with $ASP-15$ at depths of 200 m and 1000 m, respectively.

Figures 5 and 6 show the comparison between the scattering coefficients, $b(\lambda)$, measured directly by $ASP-15$ (tables 5 and 6) and evaluated from the absorption and attenuation coefficients measured by $AC9$: ($a(\lambda)$ from tables 1,2 and $c(\lambda)$ from tables 3,4).
Table 3
Mean attenuation coefficients measured during two deployments of the AC9 (March 28th) at depths between 180 m and 220 m

| $\lambda$ (nm) | $AC9$ 1 ($c$ (m$^{-1}$)) | $AC9$ 2 ($c$ (m$^{-1}$)) |
|---------------|--------------------------|--------------------------|
| 412           | 0.162±0.002              | 0.160±0.002              |
| 440           | 0.118±0.002              | 0.116±0.002              |
| 488           | 0.086±0.001              | 0.084±0.001              |
| 510           | 0.094±0.001              | 0.093±0.001              |
| 532           | 0.101±0.001              | 0.100±0.001              |
| 555           | 0.108±0.001              | 0.107±0.001              |
| 650           | 0.391±0.002              | 0.389±0.002              |
| 676           | 0.476±0.002              | 0.472±0.002              |
| 715           | 1.015±0.001              | 1.012±0.001              |

Table 4
Mean attenuation coefficients measured during two deployments of the AC9 (March 28th) at depths between 980 m and 1020 m.

| $\lambda$ (nm) | $AC9$ 1 ($c$ (m$^{-1}$)) | $AC9$ 2 ($c$ (m$^{-1}$)) |
|---------------|--------------------------|--------------------------|
| 412           | 0.123±0.002              | 0.120±0.002              |
| 440           | 0.085±0.002              | 0.082±0.002              |
| 488           | 0.056±0.001              | 0.053±0.001              |
| 510           | 0.065±0.001              | 0.064±0.001              |
| 532           | 0.072±0.001              | 0.070±0.001              |
| 555           | 0.090±0.001              | 0.088±0.001              |
| 650           | 0.373±0.002              | 0.370±0.002              |
| 676           | 0.455±0.002              | 0.451±0.002              |
| 715           | 0.997±0.001              | 0.995±0.001              |

Figure 6 shows good agreement between results obtained with AC9 and ASP-15 at 1000 m depth. At 200 m depth (figure 5) there are discrepancies which confirm the different optical properties of the water layers measured by AC9 and ASP-15, already indicated by the results of the absorption measurements at the same depth (see section 3.1).

Given the strong water currents at shallow depth and inhomogeneous distribu-
Table 5
Scattering coefficients measured with ASP-15 at a depth of 200 m (March 27th).

| λ (nm) | ASP-15 27/03 b (m⁻¹) |
|--------|----------------------|
| 400    | 0.039±0.004          |
| 420    | 0.035±0.002          |
| 440    | 0.034±0.002          |
| 459    | 0.035±0.009          |
| 479    | 0.033±0.001          |
| 488    | 0.033±0.002          |
| 494    | 0.033±0.002          |
| 519    | 0.032±0.001          |
| 550    | 0.031±0.001          |
| 590    | 0.029±0.001          |
| 651    | 0.026±0.005          |

Table 6
Scattering coefficients measured with ASP-15 at a depth of 1000 m (April 04th and April 08th).

| λ (nm) | ASP-15 04/04 b (m⁻¹) | ASP-15 08/04 b (m⁻¹) |
|--------|----------------------|----------------------|
| 369    | 0.145±0.005          |
| 374    | 0.155±0.005          |
| 400    | 0.033±0.005          | 0.047±0.005          |
| 420    | 0.030±0.005          | 0.044±0.005          |
| 440    | 0.022±0.002          | 0.035±0.002          |
| 459    | 0.016±0.002          | 0.023±0.002          |
| 479    | 0.015±0.001          | 0.022±0.001          |
| 488    | 0.014±0.001          | 0.020±0.001          |
| 494    | 0.014±0.001          | 0.021±0.001          |
| 519    | 0.014±0.001          | 0.021±0.001          |
| 550    | 0.013±0.001          | 0.016±0.001          |
| 590    | 0.015±0.006          | 0.024±0.006          |
| 651    | 0.095±0.006          |
Fig. 5. Scattering coefficients estimated from AC9 data and measured with ASP-15 at a depth of 200 m.

Fig. 6. Scattering coefficients estimated from AC9 data and measured with ASP-15 at a depth of 1000 m.

...of biologically active substances, a strong variation of optical parameters within one day appears to be realistic.
At last we show in figures 7 and 8 the values of the attenuation lengths \((L_c(\lambda) = 1/c(\lambda))\) obtained at depths of 200 m and 1000 m. The values of \(c(\lambda)\) for ASP-15 are obtained adding the absorption and scattering coefficients reported in tables 1,2,5,6, while for AC9 they are measured directly (see tables 3,4). To evaluate the ASP-15 results at 200 m depth we have used the absorption data measured in March 28\(^{th}\) and the scattering data measured on March 27\(^{th}\). Figure 8 shows good agreement between results from AC9 and ASP-15. Similarly to the absorption coefficient, the attenuation coefficient has its smallest value in the region of \(\lambda \sim 490\) nm for both depths.

### 4 Conclusion

Measurements of the optical water properties in Lake Baikal confirm that the NT-200 telescope is located at optimal depth, where light absorption and attenuation processes are the smallest. Data have been collected with two instruments, which use different measurement principles and have different sources of systematic errors. Data show that, at a depth of 1000 m, the highest transparency is observed for \(\lambda = 488\) nm. The measured values for absorption length \(L_a\), scattering length \(L_b\) and attenuation length \(L_c\) at 1000 m depth are: \(L_a(488) = 27.9 \pm 0.7\) m, \(L_c(488) = 18.3 \pm 0.3\) m as measured with AC9 and \(L_a(488) = 28.3 \pm 1.0\) m, \(L_b(488) = 58.8 \pm 3.5\) m as measured with ASP-15.
Fig. 8. Attenuation length measured with AC9 (March 28th) and ASP-15 at 1000 m depth. The values \( c(\lambda) \) for ASP-15 are the sum of \( a(\lambda) \) and the values of \( b(\lambda) \) measured during two runs on April 4th and on April 8th.

The depth profile of the absorption coefficient measured by AC9 (see figure 1) shows the effect of biologically active substances and mineral particulate suspended in water. This effect is very conspicuous in the depth range 0 ÷ 400 m (above the boundary depth of penetration of solar radiation), and starts to be visible again for depth higher than 1150 m, near the lake bed. The obtained results demonstrate that the systematic errors are rather small for both instruments and validate the use of both devices to characterize in situ the inherent optical properties of underwater sites.

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