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Nuclear Instruments and Methods in Physics Research A 498 (2003) 231–239

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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

V. Balkanov[a], I. Belolaptikov[b], L. Bezrukov[a], N. Budnev[c], A. Capone[d,e], A. Chensky[c], I. Danilchenko[a], G. Domogatsky[a], Zh.-A. Dzhilkibaev[a], S. Fialkovsky[f], O. Gaponenko[a], O. Gress[c], T. Gress[c], R. Il'yasov[a], A. Klabukov[a], A. Klimov[g], S. Klimushin[a], K. Konischev[a], A. Koshechkin[a], Vy. Kuznetzov[a], L. Kuzmichev[h], V. Kulepov[f], B. Lubsandorzhiev[a], R. Masullo[d], E. Migneco[i,j], S. Mikheyev[a], M. Milenin[f], R. Mirgazov[c], N. Moseiko[h], E. Osipova[h], A. Panfilov[a], L. Pan'kov[c], Yu. Parfenov[c], A. Pavlov[c], M. Petruccetti[e], E. Pliskovsky[b], P. Pokhil[a], V. Poleschuk[a], E. Popova[h], V. Prosin[h], G. Riccobene[i,*], M. Rozanov[k], V. Rubtzov[c], Yu. Semeney[c], Ch. Spiering[l], O. Streicher[l], B. Tarashansky[c], R. Vasiljev[a], R. Wischnewski[l], I. Yashin[h], V. Zhukov[a]

[a] *Institute for Nuclear Research, 60th Anniversary prospect 7a, 117312 Moscow, Russia*
[b] *Joint Institute for Nuclear Research, Dubna, Russia*
[c] *Irkutsk State University, K. Marx street 3, 664003 Irkutsk, Russia*
[d] *Dipartimento di Fisica Universitá La Sapienza, P.le A. Moro 2, 00185 Rome, Italy*
[e] *INFN Sezione Roma-1, P.le A. Moro 2, 00185 Rome, Italy*
[f] *Nizhni Novgorod State Technical University, Nizhni Novgorod, Russia*
[g] *Kurchatov Institute, Moscow, Russia*
[h] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia*
[i] *Laboratori Nazionali del Sud INFN, Via S.Sofia 44, 95123 Catania, Italy*
[j] *Dipartimento di Fisica e Astronomia Universitá di Catania, Corso Italia 57, 95129 Catania, Italy*
[k] *St. Peterburg State Marine University, St. Peterburg, Russia*
[l] *DESY-Zeuthen, Zeuthen, Germany*

Received 5 September 2002; accepted 10 September 2002

Abstract

Measurements of optical properties in media enclosing Cherenkov 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 Cherenkov neutrino

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*Corresponding author. Tel.: +39-095-542271; fax: +39-095-714815.
E-mail address: riccobene@lns.infn.it (G. Riccobene).

doi:10.1016/S0168-9002(02)01789-8

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.

PACS: 95.55.Vj; 29.40.Ka; 92.10.Pt; 07.88.+y

Keywords: Absorption; AC9; Attenuation; Baikal; ASP-15; NEMO; Neutrino telescope

1. Introduction

After a long period of experimental work, large Cherenkov 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 Cherenkov light of secondary particles produced in neutrino interactions. Actually, the basic idea for this detection method goes back to the early 1960s [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 built the first deep underwater Cherenkov neutrino detector, which has been stepwise upgraded to its present stage, NT-200. The AMANDA Collaboration [4] has built a Cherenkov 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 [7] is performing an intensive R&D program aiming at the construction of a km^3 Cherenkov 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 Cherenkov neutrino telescopes, water acts not only as a target but also as radiator of Cherenkov 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 λ, 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 ϑ [9]. Another parameter commonly used in literature is the effective scattering coefficient $b^{\mathrm{eff}}(\lambda) = b(\lambda)(1 - \overline{\cos(\lambda, \vartheta)})$, where $\overline{\cos(\lambda, \vartheta)} = \int_0^\pi \cos(\vartheta)\beta(\lambda, \vartheta)\,\mathrm{d}\vartheta / \int_0^\pi \beta(\lambda, \vartheta)\,\mathrm{d}\vartheta$ is the average cosine of the phase scattering function at a given λ. The optical properties of natural water have to be measured 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 and 1200 m is adequate to operate a neutrino telescope. Put into operation on 6th April 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 and 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 section have been carried out during March–April 2001, from the ice camp above the neutrino telescope NT-200.

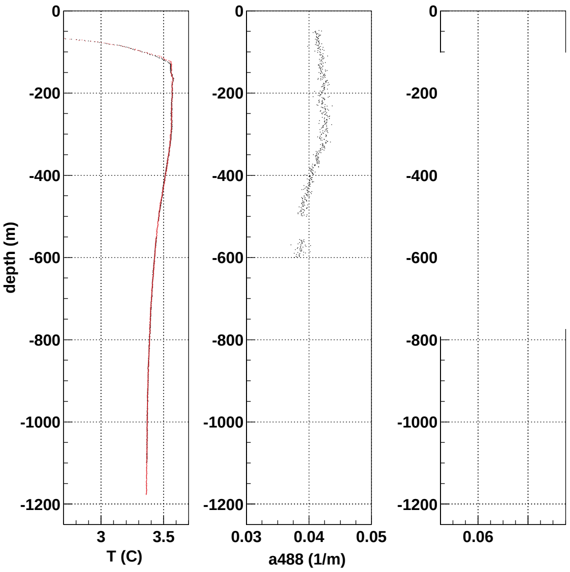
2. Instrumentation and data acquisition

2.1. *The AC9 transmissometer*

The AC9, manufactured by *WETLabs* [10], 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 $1.5 \times 10^{-3}\ \mathrm{m}^{-1}$ in a and c measurements [11].

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 ($50\ \mathrm{m} < \mathrm{depth} < 1100\ \mathrm{m}$), collecting about 10 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 Fig. 1 we show, as a function of depth, the water temperature together with the values for absorption and attenuation coefficient at $\lambda = 488$ 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 Fig. 2) has two receiving channels: one with a wide aperture to measure *a* and *b* and another one with a rotating mirror and a narrow angle collimator to measure the phase scattering function.

Two photomultipliers (type FEU-130) and 15 interference light filters are assembled in a cylindrical container. The filters wavelengths are ranged from 369 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 m 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 Refs. [12–14]. The principle of the *a* measurement with ASP-15 is described in Ref. [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

$$a = -\frac{\ln(E_1R_1^2/E_2R_2^2)}{R_1 - R_2}, \quad (1)$$

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 $R \leqslant a^{-1}$.

The scattering coefficient *b* is approximated [16] by

$$b = \ln(1 - E_s/E)/R, \quad (2)$$

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) and (2) and systematic errors is: $\Delta a(\lambda) \leqslant 5\%$ for $a \geqslant 0.02\ \text{m}^{-1}$ and $\Delta b(\lambda) \leqslant 10\%$ for $b \geqslant 0.02\ \text{m}^{-1}$. In all figures below, only statistical errors are shown for the ASP-15 data.

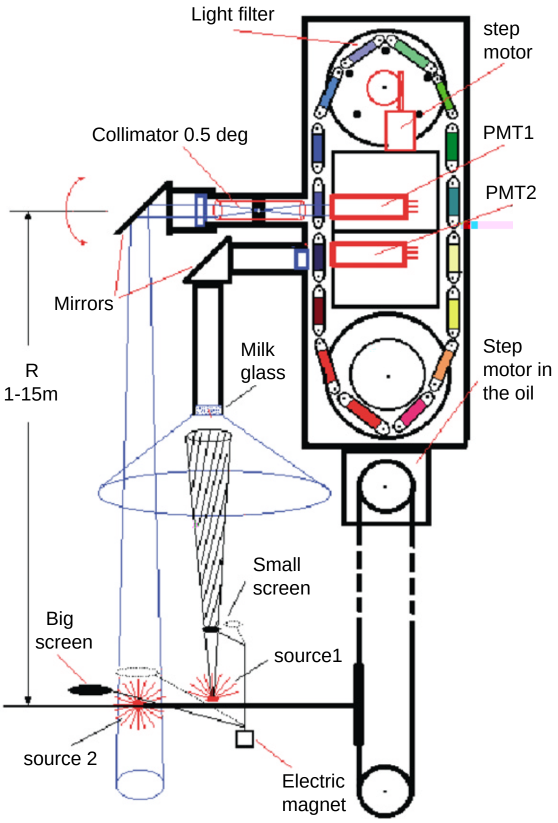


Fig. 2. The ASP-15 device for long-term monitoring of deep water inherent optical properties.

3. Results

3.1. Light absorption in Lake Baikal

In this section, we discuss the results of light absorption measurements performed with both devices AC9 and ASP-15. In Table 1 and Fig. 3 we present, respectively, the absorption coefficients and absorption lengths ($L_a(\lambda) = 1/a(\lambda)$) as a function of wavelength. ASP-15 data have been taken at a depth of 200 m, the AC9 values are the

Table 1
Absorption coefficients measured during two deployments of AC9 (28 March) and during one deployment of ASP-15 (28 March) at a depth of 200 m

λ (nm)	AC9 1 a (m^{-1})	AC9 2 a (m^{-1})	ASP-15 28/03 a (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	

AC9 data are averaged over the depth interval 180–220 m.

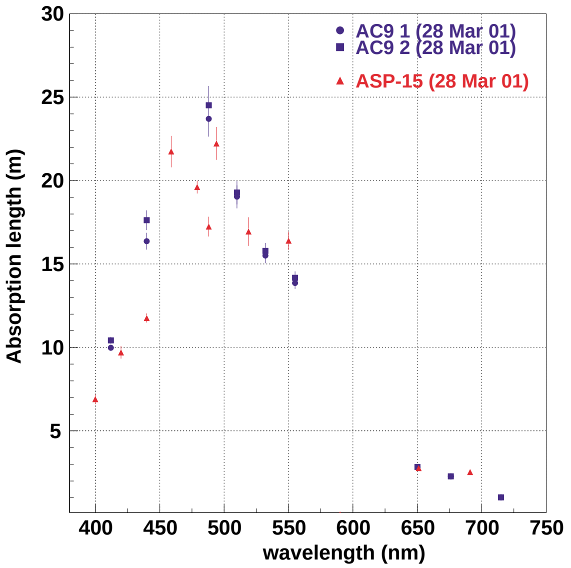


Fig. 3. Absorption length measured with ASP-15 at a depth of 200 m. AC9 data are averaged over the depth interval 180–220 m.

average of data collected at depths between 180 and 220 m.

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

The two sets of AC9 data were collected with about 10 h 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 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 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 Refs. [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 [15–17].

The obvious differences between optical properties at 1000 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 ~ 400 m (see Fig. 1). Above the solar radiation boundary depth the water column shows a time dependent behavior, strongly influenced by

Table 2
Absorption coefficients measured during two deployments of the AC9 (28 March) and during three deployments of ASP-15 (23 March, 4 and 8 April) in Lake Baikal at 1000 m depth

λ (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			

AC9 data are averaged over the depth interval 980–1020 m.

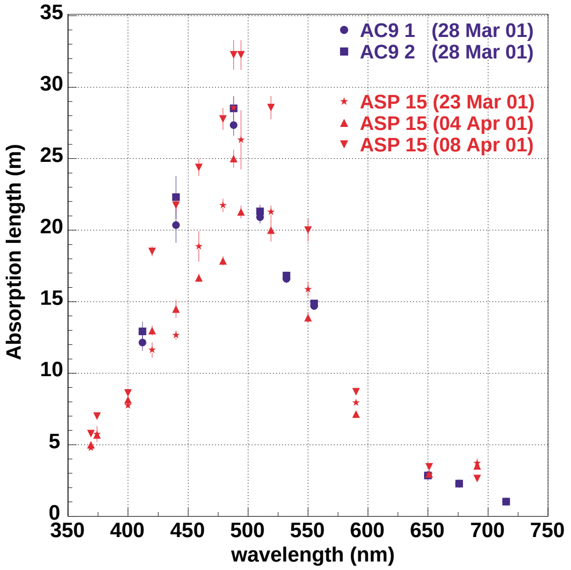


Fig. 4. Absorption length measured with ASP-15 at 1000 m depth. AC9 data are averaged over the depth interval 980–1020 m.

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 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

Table 3
Mean attenuation coefficients measured during two deployments of the AC9 (28 March) at depths between 180 and 220 m

λ (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 (28 March) at depths between 980 and 1020 m

λ (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

Table 5
Scattering coefficients measured with ASP-15 at a depth of 200 m (27 March)

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 (4 and 8 April)

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

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 and 1000 m with AC9.

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

Figs. 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 and 2 and $c(\lambda)$ from Tables 3 and 4).

Fig. 6 shows good agreement between results obtained with AC9 and ASP-15 at 1000 m depth. At 200 m depth (Fig. 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 distribution of biologically active substances, a strong variation of optical parameters within 1 day appears to be realistic.

At last we show in Figs. 7 and 8 the values of the attenuation lengths ($L_c(\lambda) = 1/c(\lambda)$) obtained at depths of 200 and 1000 m. The values of $c(\lambda)$ for

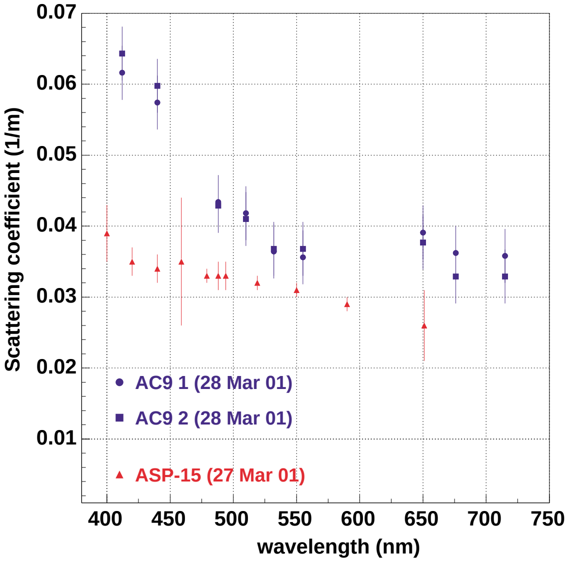


Fig. 5. Scattering coefficients estimated from AC9 data and measured with ASP-15 at a depth of 200 m.

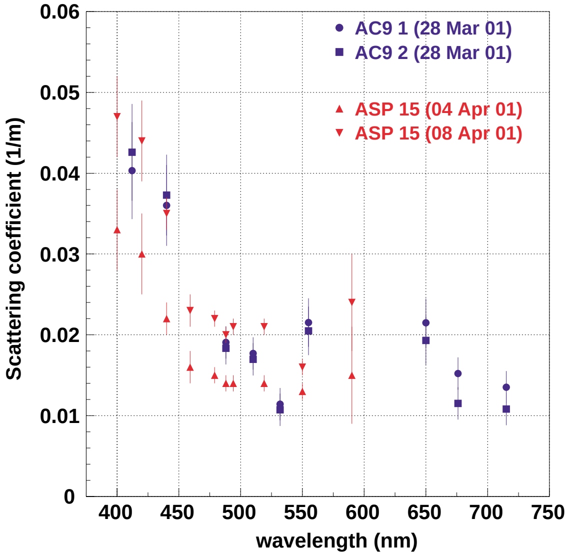


Fig. 6. Scattering coefficients estimated from AC9 data and measured with ASP-15 at a depth of 1000 m.

ASP-15 are obtained adding the absorption and scattering coefficients reported in Tables 1, 2, 5 and 6, while for AC9 they are measured directly (see Tables 3 and 4). To evaluate the ASP-15 results at 200 m depth we have used the absorption data measured on 28 March and the scattering

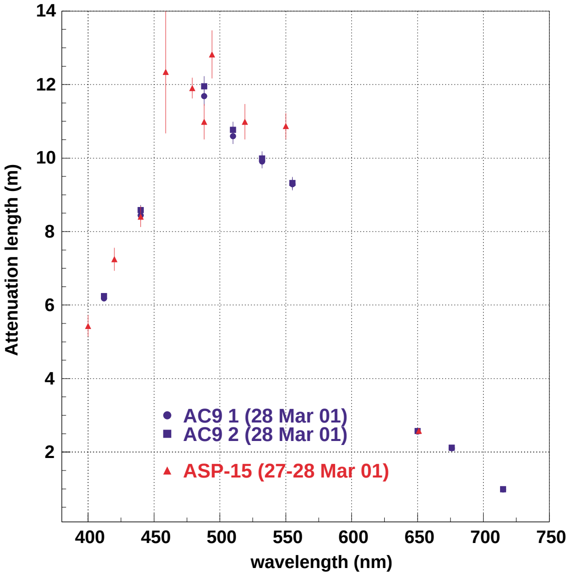


Fig. 7. Attenuation length measured with AC9 (28 March) and ASP-15 at 200 m depth. The values of $c(\lambda)$ for ASP-15 are the sum of the values of $a(\lambda)$ measured on 28 March and the values of $b(\lambda)$ measured on 27 March.

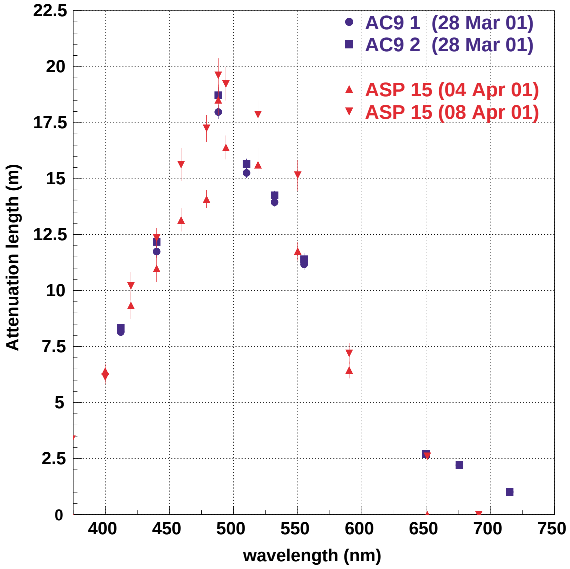


Fig. 8. Attenuation length measured with AC9 (28 March) and ASP-15 at 1000 m depth. The values $c(\lambda)$ for ASP-15 are the sum of $a(\lambda)$ and the values of $b(\lambda)$ measured during two runs on 4 and 8 April.

data measured on 27 March. Fig. 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. The depth profile of the absorption coefficient measured by AC9 (see Fig. 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.

Acknowledgements

This work was supported by the Russian Ministry of Industry, Science and Technology (contract 102-11(00)-p), the Russian Ministry of Education, the German Ministry of Education and Research, Russian Fund of Basic Research (Grants 99-02-1837a, 01-02-31013 and 00-15-96794), the Russian Federal Program *Integration*, the Program *Universities of Russia* and UNESCO Chair of Water Researches. We thank the NEMO Collaboration for the factive support to this work.

References

[1] M.A. Markov, I.M. Zheleznykh, Nucl. Phys. 27 (1961) 385.
[2] DUMAND web page available at `www.phys.washington.edu/~dumand`.
[3] I.A. Belolaptikov, et al., Astroparticle Phys. 7 (1997) 263.
[4] E. Andres, et al., Astroparticle Phys. 13 (2000) 1.
[5] ANTARES proposal astro-ph/9907432, available at `antares.in2p3.fr`.
[6] L.K. Resvanis, Proceedings of the Third NESTOR Workshop, Pylos, 1993.
[7] A. Capone, et al., Proceedings of the XXVI ICRC HE 6.3.05, 1999, webpage available at `nemoweb.lns.infn.it`.
[8] C. Spiering, Nucl. Phys. B 91 (Proc. Suppl.) (2001) 445 astro-ph/0012532.
[9] C.D. Mobley, Light and Water, Academic Press, San Diego, CA, 1994.
[10] WETLabs, AC9 manual, `www.wetlabs.com`.
[11] A. Capone, et al., Nucl. Instr. and Meth. A 487 (2002) 423.
[12] B.A. Tarashansky, O.N. Gaponenko, V.I. Dobrynin, Izv. Atmos. Oceanic Opt. 7 (1–12) (1994) 819.
[13] B.A. Tarashansky, R.R. Mirgazov, K.A. Pocheikin, Atmos. Oceanic. Opt. 8 (5) (1995) 771.
[14] O.N. Gaponenko, R.R. Mirgazov, B.A. Tarashansky, Izv. Atmos. Oceanic Opt. 9 (8) (1994) 677.
[15] L.B. Bezrukov, et al., Okeanologiya 30 (6) (1990) 1022.
[16] N.M. Budnev, R.R. Mirgasov, A.V. Rzhetshizki, B.A. Tarashansky, Proceedings of the Workshop on Simulation and Analysis Method for Large Neutrino Telescopes, Zeuthen, 1998, pp. 165–173.
[17] I.A. Belolaptikov, et al., Appl. Opt. 33 (1999) 6818.
[18] L.B. Bezrukov, et al., Izv. Atmos. Oceanic Phys. 34 (1) (1998) 85.
[19] I.A. Belolaptikov, et al., Izv. Atmos. Oceanic Phys. 34 (1) (1998) 78.