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Monitoring of the deep waters optical properties of Lake Baikal in 2024

B. Shaibonov[a*] **and E. Ryabov**[b] ***for the Baikal-GVD Collaboration***
(a complete list of authors can be found at the end of the proceedings)

a *https://orcid.org/0000-0003-2250-8502*

b *https://orcid.org/0000-0002-1894-526X*

E-mail: bair@jinr.ru, e_v_ryabov@mail.ru

We present the results of the one-year (03.2024-03.2025) monitoring of inherent optical properties (IOP) of Baikal deep waters in wavelength range of 400–620 nm within the effective volume of the deep underwater neutrino telescope Baikal-GVD, which were measured by a BAIKAL-5D Unit 2 at depth 1180 m. Measurements of the absorption spectrum, scattering length at three points of the spectrum (405nm, 460, 532nm) and small-angle dependence of the scattering function were carried out weekly. The results of measurements of the integral characteristics of the scattering function and the absorption and scattering coefficients in the 2024 expedition are also presented. Data on the angular and integral scattering characteristics made it possible to calculate corrections to compensate for the instrumental error in measuring the absorption and scattering coefficients. The obtained data allow us to estimate the range of changes in the absorption and scattering lengths over a sufficiently long period of time and to investigate the relationship between the processes of changes in absorption and scattering.

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[*]Speaker

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1. Introduction

The Baikal-GVD neutrino telescope project includes the creation of a continuous monitoring system for the inherent optical properties (IOP) of the aquatic environment: the absorption coefficient $a(\lambda)$ and the scattering coefficient $b(\lambda)$, as well as the scattering scattering function $\chi(\lambda, \gamma)$, where λ is the radiation wavelength and γ is the scattering angle [1] (sometimes, the inverse quantities are used: the absorption length $L_a(\lambda)=1/a(\lambda)$ and the scattering length $L_b(\lambda)=1/b(\lambda)$). Since 2020, in situ measurements of IOP have been carried out using "BAIKAL-5D" instruments developed at the Applied Physics Institute of ISU and provided long-term measurements of the IOP in the deep waters of Lake Baikal in the Baikal-GVD deployment area. In addition to regular measurements throughout the year at the instrumented depth of the Baikal-GVD, studies of the depth dependence of IOP are also carried out during winter expeditions.

2. Instruments for IOP measuring

The design of the "BAIKAL-5D" instrument is described in detail in [2-4]. The "BAIKAL-5D" devices provide measurements of absorption and scattering spectra in the range of 400-620 nm, registration of the small-angle dependence of the scattering function, and estimation of the forward and backward scattering ratio. The methods and algorithms used for measurements, as well as some results of IOP monitoring, are presented in [2-4]. It should be noted that earlier in [2, 4], we reported the measured values of the absorption coefficient a_{mes} and scattering coefficient b_{mes} in the deep waters of Lake Baikal. Reference [4] showed that to determine the true values of a and b from the absorption a_{mes} and scattering b_{mes} values measured by the "BAIKAL-5D" instrument, it is necessary to introduce corrections accounting for the incomplete collection of scattered light in the optical scheme of the instrument:

$$b(\lambda) = X(\lambda)\cdot b_{mes}(\lambda); \quad a = a_{mes} - \Delta a,\ \Delta a \approx 1{,}4\cdot b/(K+1) \qquad (1)$$

where K is the skewness coefficient of the scattering function, and $X(\lambda)$ is correction factor whoes calculated values for the optical scheme of the BAIKAL-5D devices and the average values of the IOP for 2021-2024 are: X(405nm)=1,72, X(470nm)=1,65, X(532nm)=1,6. The correction (1) $\Delta a/a$ for absorption is minimal in the red part of the spectrum and reaches a maximum value of 7% in the transparency window of Lake Baikal deep waters 480-500 nm.

Within the period between March 2024 and March 2025, regular measurements of the water's optical properties were carried out as follows:

- Depth 1180 m, BAIKAL-5D Unit 2: weekly measurement of scattering for three radiation wavelengths 405 nm, 460 nm, and 532 nm, as well as the absorption spectrum in the range of 400-620 nm. Under favorable conditions (absence of current) - measurement of the scattering function in the scattering angle range of $\gamma<30°$.
- Depth 1250 m, BAIKAL-5D Unit 1: absorption measurement for λ=450nm.
- Depth 1100 m, BAIKAL-5D Unit 3: weekly measurement of absorption and scattering spectra until 06/03/2024, after which connection with the device was lost.

3. Measurement results

3.1 Measurements during the winter expedition 2024

In the 2024 winter expedition, the dependence of absorption and scattering on depth was investigated, and an estimate of the scattering function asymmetry coefficient *K* was made, whose previously measured and calculated values for the deep waters of Lake Baikal have been contradictory [5, 6]. Measurements were carried out in the depth range of 700-1250 m (with a total depth of 1358 m), corresponding to the depth of the Baikal-GVD optical modules. A new BAIKAL-5D Unit 4 was specifically manufactured for this purpose, and a method was developed to estimate the values of the scattering function asymmetry coefficient *K* [3]. Absorption and scattering measurements were carried out only for λ=450 nm (narrowband emission from the PL-450B laser diode), while blue (λ_{max}=468 nm) and green (λ_{max}=521 nm) LEDs with a bandwidth of $\Delta\lambda$≈20 nm were used in the *K* measurement procedure.

Table 1

Depth dependence of absorption, scattering, and asymmetry coefficient *K* of scattering function (measurements taken on 26-29 March 2024)

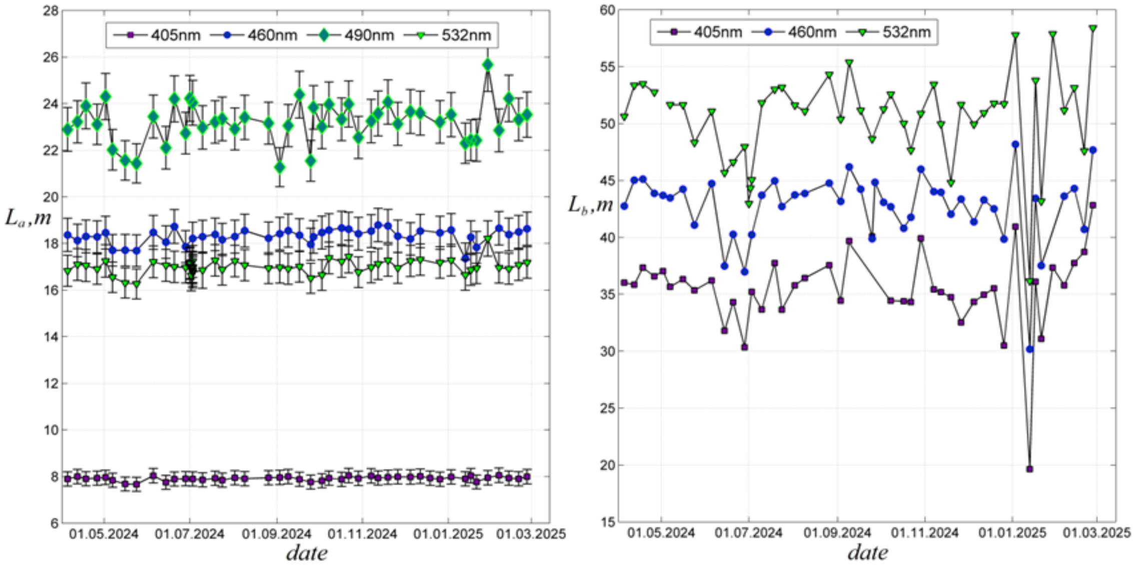
Depth, m	L_a(450nm), m	L_b(450nm), m	*K*(468 nm)	*K*(521nm)
700	15,7±0,5	37,2±2,0	8,9±0,5	13,1±0,9
800	16,3±0,6	35,0±1,7	9,5±0,6	13,0±0,7
900	16,5±0,5	36,8±1,5	9,5±0,5	12,9±0,8
1000	16,7±0,5	40,4±1,6	8,7±0,4	12,4±0,9
1100	16,9±0,6	41,4±1,7	8,5±0,5	12,5±1,0
1175	17,1±0,7	42,6±1,8	8,3±0,7	11,6±0,9
1250	15,8±0,7	37,8±1,8	9,2±0,6	13,0±1,1

The results of measurements presented in Table 1 indicate the presence of a weak minimum in absorption and scattering in the depth range of 1000-1175 m. The observed increase in absorption and scattering at greater and lesser depths is in good agreement with the vertical structure of water transparency in Lake Baikal [1]. In this case, the change in the absorption coefficient is about 9%, and the change in the scattering coefficient is about 19%, with the largest relative gap at depths of 1175-1250 m. The values of *K* obtained for the deep waters of Lake Baikal (Table 1) are close to the minimum values measured in the ocean [7] and are 2–10 times smaller than the values obtained for depths of 0-150 m [1, 6] in Lake Baikal. At the same time, the following patterns noted in [6] for the surface zone of Baikal and other natural waters can be observed:

- with increasing wavelength λ of visible light, *K* increases (for constant IOP of the medium);
- for λ=const, increasing scattering leads to an increase in *K* when the IOP of the water changes.

3.2 Time dependence of absorption and scattering

Continuous IOP monitoring over the period March 2024 – March 2025 was, for technical reasons, carried out only by the BAIKAL-5D Unit 2 (at 1180 m depth). This made it possible to extend the nearly uninterrupted series of IOP measurements at this depth to four years. The time dependence of the absorption length and scattering length is shown in Figure 1. Given an absorption length measurement uncertainty σ_{La}/L_a ≈4%, the difference between the maximum and minimum values of L_a is about 16%. A good correlation is observed in the variations of L_a for different wavelengths of light, both in the blue and in the yellow-green parts of the spectrum. No pronounced seasonal changes in absorption were observed.



a. *b.*

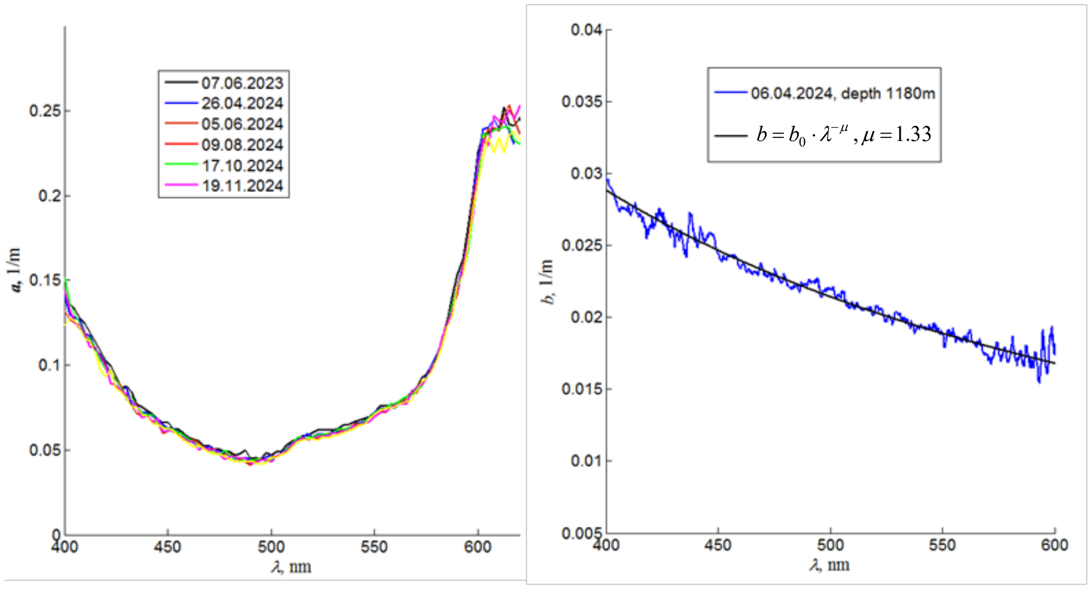
Figure 1. The time dependence of absorption (a) and scattering (b) lengths in 2024. Depth 1180m. σ_{Lb}≈10%.

In the case of scattering (Figure 1, b), the amplitude of variations is larger – on the order of 35% – not counting the recorded short-term maximum of scattering on 13 January 2025. There is also correlation in L_b for different wavelengths. A link between changes in absorption and scattering does exist, but it is weak and only intermittently evident.

3.3 Absorption and scattering spectra

The absorption spectra measured at 1180 m depth have a stable shape throughout the entire 2021–2024 observation period. The absorption minimum (L_a=24÷28 m) corresponds to the spectral range 485–495 nm; a clear bend of the spectrum is observed around 600 nm, determined by the absorption of pure water [8]. The changes in the absorption spectra (within ±9% during 2024) can be characterized as a vertical shift without a change in shape (Figure 2, a).

The scattering spectra decrease with wavelength (Figure 2, b). Using a hyperbolic fit for the scattering spectrum $b(\lambda)=b_0\cdot\lambda^{-\mu}$, one obtains μ=1,2÷1,45 for all spectra measured in 2024. Changes in the scattering spectra over this period consist of a vertical shift by about ±14%, with some change in slope corresponding to μ varying within the aforementioned range.



a. *b.*

Figure 2. Absorption spectra (a) and scattering spectrum (b). Depth 1180m. $\sigma_{a(\lambda)}\approx 8\%$. $\sigma_{b(\lambda)}\approx 12\%$.

The observable fluctuations in the absorption and scattering spectra (Figure 2) lie within the measurement error. This does not allow us to consider these fluctuations as elements of an internal structure of the spectrum, nor to assert the absence of such internal structure.

3.4 Evaluation of the scattering function at small angles

The BAIKAL-5D Unit 2 includes a system for measuring the scattering scattering function $\chi(\lambda,\gamma)$ at scattering angles $\gamma < 30°$ [3]. Measurements are only possible in the absence of water currents; therefore, in 2024 they were not conducted regularly. It should also be noted that the narrow-beam rotating emitter used as the light source in this system is highly susceptible to biofouling during prolonged operation. Therefore, the obtained values of $\chi(\lambda, \gamma < 30°)$ should be regarded as an estimate of the slope of the scattering function in the small-angle region. For this purpose, we approximate the measured scattering scattering function by $\chi(\lambda,\gamma)=A_0\cdot\exp(-s\cdot\gamma)$, where s is a parameter characterizing the increase rate of $\chi(\lambda,\gamma)$ with decreasing γ. In the 2024 measurements at 1180 m depth, the value of s was in the range 27–35 rad^{-1} for λ = 470 nm. We estimate the uncertainty for s at ~20%.

4. Comparison with results of other measurements

The absorption and scattering spectra measured in 2024 for the deep waters of Lake Baikal are in good agreement with the absorption and scattering spectra obtained by BAIKAL-5D Unit 1-3 at other time periods during 2021–2025. In earlier measurements (prior to 2010) of deep-water IOP in Lake Baikal using the ASP-15 device, similar average values of the absorption and scattering coefficients were obtained for discrete spectral points, differing only by a larger variation. Particularly noteworthy is the hypothesis that the deep waters of Lake Baikal become more transparent in years with maximum development of the algae genus *Aulacoseira (Melosira)* [1]. For example, an increase in absorption length by 30–40% was recorded in 2001 in comparative measurements with the ASP-15 and AC-9 instruments [9]. In 2020, the BAIKAL-5D Unit 1 also recorded high values of L_a(490nm)=32÷35 m in the second half of the year [10]. However, in the subsequent period of regular measurements (2021–2025), such high absorption values for the deep waters of Lake Baikal were not observed.

Comparing the absorption in deep Lake Baikal water with the light absorption (attenuation) in optically pure ocean waters at the sites of deep neutrino telescopes [11, 12] shows that the deep waters of Lake Baikal exhibit higher light absorption in the blue and UV regions of the spectrum. As a result, the absorption minimum is shifted from λ = 440–460 nm in the ocean [11] to λ = 485–495 nm in Lake Baikal, and the absolute value of a at the absorption minimum for Baikal deep water is approximately twice as high.

5. Conclusion

In 2024–2025, regular weekly monitoring of the hydro-optical characteristics of the deep water of Lake Baikal continued at the site of the Baikal neutrino telescope. The “BAIKAL-5D” instruments of our own design have demonstrated the ability to operate long-term (one year or more) without maintenance or adjustment. At the IOP monitoring point in the deep waters of Lake Baikal in 2024–2025, a relatively stable absorption spectrum was recorded with an absorption minimum corresponding to L_a=24÷28m at a wavelength of 485–495 nm. The scattering length for λ = 460 nm varied in the range 30–48 m, and a new short-term scattering maximum was recorded on 13 January 2025. The asymmetry coefficient of the scattering function, based on measurements in the 2024 winter expedition, is on the order of 10 in the transparency window of the deep water (700–1250 m) of Lake Baikal. The nature of the scattering function at small angles is sharply forward-directed.

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References

[1] *Baicalogy*: *in 2 books*.- Novosibirsk: Nauka, 2012.-Book 1.

[2] E. Ryabov et al, *Monitoring of optical properties of deep lake water, JINST* **16** C09001, https://doi.org/10.1088/1748-0221/16/09/C09001.

[3] A.D. Avrorin et al, *Instruments and methods for long-term monitoring of optical properties of deep waters of Lake Baikal,* Atmos. Ocean. Opt. 2025. V. 38, № 05. P. 367–375. DOI: 10.15372/AOO20250506.

[4] V.M. Aynutdinov et al*, Monitoring of optical properties of deep waters of Lake Baikal in 2021-2022,* in proceedings of ICRC2023 *PoS* ICRC2023 (2023) 977. DOI: 10.22323/1.444.0977.

[5] Tarashchanskii B.A., Kokhanenko G.P., Mirgazov R.R., Ryabov E.V., and Yagunov A.S.*, Monitoring of Optical Properties of Water near the Baikal Neutrino Telescope with the Use of a Submerged Device ASP-15: Methods and Results,* Atmospheric and Oceanic Optics, 2011, V. 24. No. 02. P. 188–197.

[6] V.I. Mankovskiy. *Spectral variability of light scattering phase function in Lake Baikal waters*, Atmos. Ocean. Opt. 2022. V. 35, N 35. P. 868–870. DOI: 10.15372/AOO20221010.

[7] V.I. Mankovskiy, *Extreme indicatrices of light scattering by sea water,* Marine hydrophysical research. 1973. N. 3. P. 100.

[8] Pope R.M., Fry E.S., *Absorption spectrum (380–700 nm) of pure water,* Appl. Opt. 1997. V. 36, N 33. P. 8710–8722. DOI: 10.1364/AO.36.008710.

[9] Balkanov et al,*(* NEMO & Baikal Collaborations)) *Simultaneous measurements of water optical properties by AC-9 transmissometer and ASP-15 inherent optical properties in Lake Baikal.* //Nucl. Instrum. Meth. 2003. V. A298. P.231-239. e-Print Archive: astro-ph/0207553.

[10] E.V. Rjabov, B. Tarashansky, *Monitoring of optical properties of deep lake water*, in proceedings of ICRC2021 *PoS* (ICRC2023) 1034. DOI: 10.22323/1.395.1034.

[11] G.Riccobene et al*, Deep seawater inherent optical properties in the Southern Ionian Sea*, Astropart. Phys. 2007. V.27, Is.1. P 1-14. DOI:10.1016/j.astropartphys.2006.08.006.

[12] N. Bailly et al, *Two-year optical site characterization for the Pacific Ocean Neutrino Experiment (P-ONE) in the Cascadia Basin*, Eur. Phys. J. C. 2021. V.81, №12. P. 1071. DOI:10.1140/epjc/s10052-021-09872-5.

Full Authors List: Baikal-GVD Collaboration

V.A. Allakhverdyan[1], A.D. Avrorin[2], A.V. Avrorin[2], V.M. Aynutdinov[2], I.A. Belolaptikov[1], Z.Beňušová[3,4], E.A. Bondarev[2], I.V. Borina[1], N.M. Budnev[5], V.A. Chadymov[13], A.S. Chepurnov[6], V.Y. Dik[1,7], A.N. Dmitriyeva[8], G.V. Domogatsky[2], A.A. Doroshenko[2], R. Dvornický[3,4], A.N. Dyachok[5], Zh.-A.M. Dzhilkibaev[2], E. Eckerová[3,4], T.V. Elzhov[1], V.N. Fomin[13], A.R. Gafarov[5], K.V. Golubkov[2], T.I. Gress[5], K.G. Kebkal[9], V.K. Kebkal[9], I.V. Kharuk[2], S.S. Khokhlov[8], E.V. Khramov[1], M.M. Kolbin[1], S.O. Koligaev[12], K.V. Konischev[1], A.V. Korobchenko[1], A.P. Koshechkin[2], V.A. Kozhin[6], M.V. Kruglov[1], V.F. Kulepov[10], A.A. Kulikov[5], Y.E. Lemeshev[5], M.V. Lisitsin[8], S.V. Lovtsov[5], R.R. Mirgazov[5], D.V. Naumov[1], A.S. Nikolaev[6], I.A. Perevalova[5], A.A. Petrukhin[8], D.P. Petukhov[2], E.N. Pliskovsky[1], M.I. Rozanov[11], E.V. Ryabov[5], G.B. Safronov[2], B.A. Shaybonov[1], V.Y. Shishkin[6], E.V. Shirokov[6], F. Šimkovic[3,4], A.E. Sirenko[1], A.V. Skurikhin[6], A.G. Solovjev[1], M.N. Sorokovikov[1], I. Štekl[4], A.P. Stromakov[2], O.V. Suvorova[2], V.A. Tabolenko[5], V.I. Tretyak[1], B.B. Ulzutuev[1], Y.V. Yablokova[1], D.N. Zaborov[2], S.I. Zavyalov[1] and D.Y. Zvezdov[1]

[1] Joint Institute for Nuclear Research, Dubna, Russia, 141980
[2] Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia, 117312
[3] Comenius University, Bratislava, Slovakia, 81499
[4] Czech Technical University in Prague, Prague, Czech Republic, 11000
[5] Irkutsk State University, Irkutsk, Russia, 664003
[6] Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia, 119991
[7] Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan, 050032
[8] National Research Nuclear University MEPHI, Moscow, Russia, 115409
[9] LATENA, St. Petersburg, Russia, 199106
[10] Nizhny Novgorod State Technical University, Nizhny Novgorod, Russia, 603950
[11] St. Petersburg State Marine Technical University, St. Petersburg, Russia, 190008
[12] INFRAD, Dubna, Russia, 141980 13Independent researcher