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RESULTS OF LIGHT ABSORPTION/ATTENUATION MEASUREMENTS IN FINNISH AND ESTONIAN LAKES IN SUMMER 1997

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Abstract. The values of the inherent optical properties – attenuation, absorption, and scattering – were measured with an underwater spectral absorption/attenuation meter ac-9 in 12 Finnish and Estonian lakes in summer 1997. The lakes selected for the study were quite different in their optical properties. Our results showed significant differences between the lakes as well as in a single lake during the summer. The difference of the attenuation coefficient between May and August in four lakes was from 60 to 80%. Also the spectral dependence of the scattering coefficient showed high variability. The wavelength dependence was greater in some more turbid lakes than in clear lakes, which is contradictory to previous results.

Key words: inherent optical properties, attenuation, absorption, scattering, optically active substances, optical properties of lakes.

INTRODUCTION

The first results of the light absorption/attenuation measurements in water made with an underwater absorption/attenuation meter ac-9 in summer 1997 in Finland and Estonia are presented here. These measurements are important in determining the ecological conditions of natural waters. The field work was performed within the project SUVI, which is a Finnish–Estonian joint project. SUVI started in 1994 and the cooperation, including extensive field measurements, has since then continued quite successfully. The light conditions in a number of Finnish and Estonian lakes that are especially relevant for remote sensing methods have been monitored every summer. In 1997 there were four periods in May, June, and August during which measurements were performed. The first period was in early May with measurements made in Finland right after the ice breakup. The second was in June with measurements in Estonia. During the last two periods in August measurements were performed in both countries. The 12 lakes under study belonged to different kinds of typical but variable Finnish and Estonian lakes. They represented both large and small oligotrophic, mesotrophic, hypertrophic, eutrophic, and humic lakes. Lake Lohjanjärvi was considered as the main lake, since it is reasonably large and the water quality varies from one site to another.

The optical and ecological parameters that were measured within this project include temperature, Secchi disk depth, total irradiance in air and water, spectral irradiance, absorption and attenuation of light in the water (since 1997), chlorophyll *a*, dissolved organic carbon, oxygen, and suspended matter. This paper concentrates on the results of the *in situ* measurements of the spectral beam attenuation coefficient (c_λ), the spectral absorption coefficient (a_λ), and the spectral scattering coefficient (b_λ) in the visible region of the solar spectrum. The studies of these inherent optical characteristics, which describe the optical properties of the aquatic environment, are also important in the development of new remote sensing methods in optical research.

DESCRIPTION OF THE ac-9 INSTRUMENT AND THE MEASUREMENTS

Light absorption/attenuation meter ac-9

The instrument ac-9 is a spectral absorption/attenuation meter that uses nine bandpass optical filters to spectrally discriminate the light from tungsten lamps (WET Labs Inc., 1995). The wavelengths used are 412, 440, 488, 510, 532, 555, 650, 676, and 715 nm. The meter is calibrated to provide a reading of 0.0 both for attenuation and absorption coefficients for each channel in clean fresh water. The instrument accuracy can be checked in the field using air calibration values provided by the manufacturer. The basic system components necessary to operate the ac-9 are shown in Fig. 1.

The ac-9 unit consists of two pressure housings separated by three stand-offs. The shorter of the two cylinders houses the light sources, filter wheel, and transmitter optics. The longer one houses the receiver optics and the control and acquisition electronics for the unit. The absorption and attenuation beam paths and flow tube assemblies are situated between the receiver and the transmitter

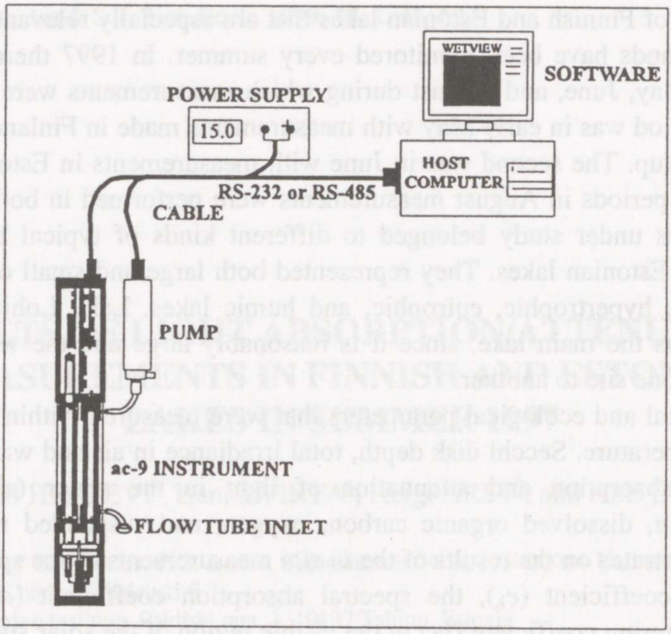


Fig. 1. System configuration of the ac-9 meter (WET Labs Inc., 1995).

housings. A pump that pumps the water through the flow tubes is mounted above the tubes on the upper pressure housing. The pump module is a compact unit consisting of a centrifugal pump head and a DC ball bearing motor contained in a titanium pressure housing. The ac-9 unit contains also a depth sensor.

Optics

The ac-9 meter performs simultaneous measurements of the water's light attenuation and absorption characteristics by incorporating a dual path optical configuration in one instrument. Each path contains its own source, optics, and detectors and the two paths share a common filter wheel and control and acquisition electronics. The beam performing the attenuation measurement is referred to as the *c beam* and the beam used to make the absorption measurement as the *a beam*.

The c beam optics

The collimated light coming originally from a DC source passes through nine bandpass filters mounted upon a continuously rotating filter wheel, creating a narrow band spectral output. Once the light has passed through the filter wheel, the beam passes through a beam splitter creating a primary beam and a reflected beam. The reflected beam intensity is measured by a reference detector. Using a ratiometric scheme with the reference and signal detectors, the long term lamp drift is compensated. The primary beam then passes through a pressure window into the sample water volume. A flow tube encloses the water and light paths. The scattered light that hits the blackened surface of the flow tube is absorbed and does not contribute to the measurement of transmitted intensity. The light radiated through the flow path is therefore subject to both scattering and absorption by the water.

The a beam optics

The *a beam* and *c beam* optics are similar. The sample water volume is enclosed by a reflective flow tube. The light passing through the tube is absorbed both by the water itself and by various dissolved and suspended matter within the sample. Forward scattered light is reflected back into the water volume by the reflective tube. The light is then collected by a diffused large area detector at the far end of the flow tube.

Measurements

The ac-9 measurements were performed as depth profiles. Generally three profiles were measured at every station. The instrument was lowered at a steady speed from the boat to measure the *in situ* profiles of attenuation and absorption from surface to bottom. The ac-9 meter is relatively easy to use. It requires just a portable PC with connections (see Fig. 1) and a rope for lowering.

In addition basic laboratory measurements of the optically active substances from the water samples were made: concentration of chlorophyll *a* (Whatman glass microfibre filters, the Jettrey-Humphrey or Lorenzen method), concentration of suspended matter (dry weight after filtration of the water through cellulose acetate filters, pore diameter 0.45 μm), spectrometrical processing of the water samples (unfiltered and filtered water) to describe the beam attenuation coefficient spectra and to determine the optical influence of the yellow substance in the water in the PAR region (spectrophotometer Hitachi U1000).

The field measurements were performed during four periods: 5–8 May, 15–17 June, 5–8 August, and 11–15 August 1997. The experiment proceeded reasonably well, except for a few days in May when the wind was too strong and in June when it was raining. In May we were only able to measure during three days and on three lakes and in June only on two days and on two lakes. Altogether 29 measurement series in 12 lakes in southern Finland and Estonia were made. The lakes selected represent adequately different types of Finnish and Estonian lakes varying from very turbid eutrophic (Tuusulanjärvi) to clear oligotrophic lakes (Puujärvi). The dates of measurements at each station and some information on the lakes (Nõges & Nõges, 1998) are presented in Table 1.

Table 1. Investigated lakes

Lake	Type	Area, ha	Depth*, m	Station	Date	Secchi, m
FINLAND						
Enäjärvi	Eutrophic	500	3.4	P3	12 Aug	1
Keravanjärvi	Humic	100	2.2	P1	6 May	1.2
Lohjanjärvi	Eutro-mesotrophic	9 400	50	P2	7 May	0.7
					11 Aug	0.9
				P5	7 May	0.9
					11 Aug	1.75
				P6	7 May	1.1
					11 Aug	2.25
				P8	11 Aug	3.75
Puujärvi	Oligotrophic	700	21	P1	5 May	3
					12 Aug	6
				P2	5 May	3.3
Pääjärvi	Oligo-mesotrophic	1 300	85	P1	13 Aug	1.9
	Mesohumic			P5	13 Aug	
Tuusulanjärvi	Eutrophic		10		8 May	0.3
					14 Aug	0.5
Vesijärvi	Mesotrophic	11 100	41	P1	14 Aug	
				P5	15 Aug	3
ESTONIA						
Koorküla Valgjärv	Eutrophic	44.1	8.5	P1	17 Jun	3
	Oligotrophic			P1	7 Aug	4.75
Nohipalu Valgjärv	Oligotrophic	6.3	6.2	P1	6 Aug	4.5
Paukjärv				P1	15 Jun	5
Verevi	Hypertrophic	12.6	3.6	P1	6 Aug	2.5
Võrtsjärv	Eutrophic	27 000	2.8	P1	5 Aug	0.75

* In Finnish lakes the maximum depth and in Estonian lakes the mean depth.

RESULTS OF THE MEASUREMENTS OF LIGHT ATTENUATION AND ABSORPTION

Variation in different types of lakes

The physical, optical, and biological properties of the different types of lakes under study varied considerably, for example the Secchi disk depth varied between 0.3 (Lake Tuusulanjärvi) and 6 m (Lake Puujärvi). Data on the lakes and the measurements are presented in Table 1. The results of the measurements in Lake Vesijärvi were omitted from the analysis, because it does not represent any typical extreme lake type and the measuring stations in May and August were too different to enable a comparison between them.

The depth profiles of each measurement of attenuation, absorption, and scattering coefficients (*c*, *a*, and *b*, respectively) for each nine wavelengths were plotted and examined. In addition the averages of the surface layer (0–2 m) values of the respective parameters were calculated and plotted as spectra of wavelength. In the following these spectra will be examined and discussed in more detail. All values of the inherent optical properties presented in this paper are without the contributions from pure water.

Representative attenuation coefficients c_λ are plotted for all lakes, except Vesijärvi, in Fig. 2a. Based on these data and the corresponding Secchi disk depths (Z_s) the lakes were divided into two groups: clear and turbid ones. The turbid lakes in this study are those with $Z_s < 2$ m and c_λ at $\lambda = 412–440$ nm > 10 m^{-1}, like Keravanjärvi, Lohjanjärvi (P2), Tuusulanjärvi, Enäjärvi, and Võrtsjärv. The "clear" lakes with $Z_s \geq 2$ m are Puujärvi, Verevi, Paukjärv, Pääjärvi, Koorküla Valgjärv, and Nohipalu Valgjärv (Fig. 2b).

The optical characteristics of the lakes under study showed large variation (Fig. 2a and b). The attenuation coefficient, c_λ, varied between 2 and 28 at $\lambda = 412$ nm and it was strongly wavelength dependent. There were two lakes, Keravanjärvi (3) and Pääjärvi (6), in which the attenuation dependence on the wavelength was even stronger than in the others. These lakes are distinguished from the others by the spectral shape of c_λ. Lake Verevi (7) was to some extent similar (Fig. 2b). The reason for this can be found in Fig. 3, which displays spectra of the absorption coefficient, a_λ. The spectra of lakes 3, 6, and 7 decrease exponentially with increasing wavelength, due to large amounts of yellow substance (humic substances) in the water. Lakes Keravanjärvi and Pääjärvi are clearly humic brown water lakes, whereas lake Verevi is in addition strongly eutrophicated containing large amounts of chlorophyll *a* and suspended matter.

Figure 2b shows that the attenuation in Lake Verevi (7) is smaller in the violet and blue regions of the spectrum than in Lake Pääjärvi (6), but higher in the region 550–715 nm. This can be explained by the higher concentration of particles in the water of Verevi, as demonstrated by the higher scattering in Fig. 4b. A close look at the absorption spectra of the turbid lakes (Fig. 3a) reveals a small peak at the wavelength of 676 nm, which is due to the absorption of chlorophyll *a*.

In some lakes the attenuation of light is clearly dominated by absorption (Keravanjärvi (3), Pääjärvi (6)) and in some clearly by scattering by the particles in the water (Tuusulanjärvi (1), Võrtsjärv (2), Enäjärvi (5), Verevi (7)), especially so in the high end of the spectrum. Table 2 presents some values of water characteristics for the studied lakes. The measured characteristics are the averaged spectrometric attenuation coefficient for the range 412–715 nm ($c^*_{412–715}$), the Secchi disk depth (Z_s), and the concentrations of suspended matter (C_s), chlorophyll (C_{chl}), and yellow substance (C_y). It is clear that in Keravanjärvi and Pääjärvi yellow substance is the dominating factor for the attenuation (via absorption) and in Tuusulanjärvi and Võrtsjärv both chlorophyll and suspended matter are dominating and the C_s values are the highest. In Enäjärvi and Verevi the C_{chl} values are high affecting both the scattering and the absorption of light.

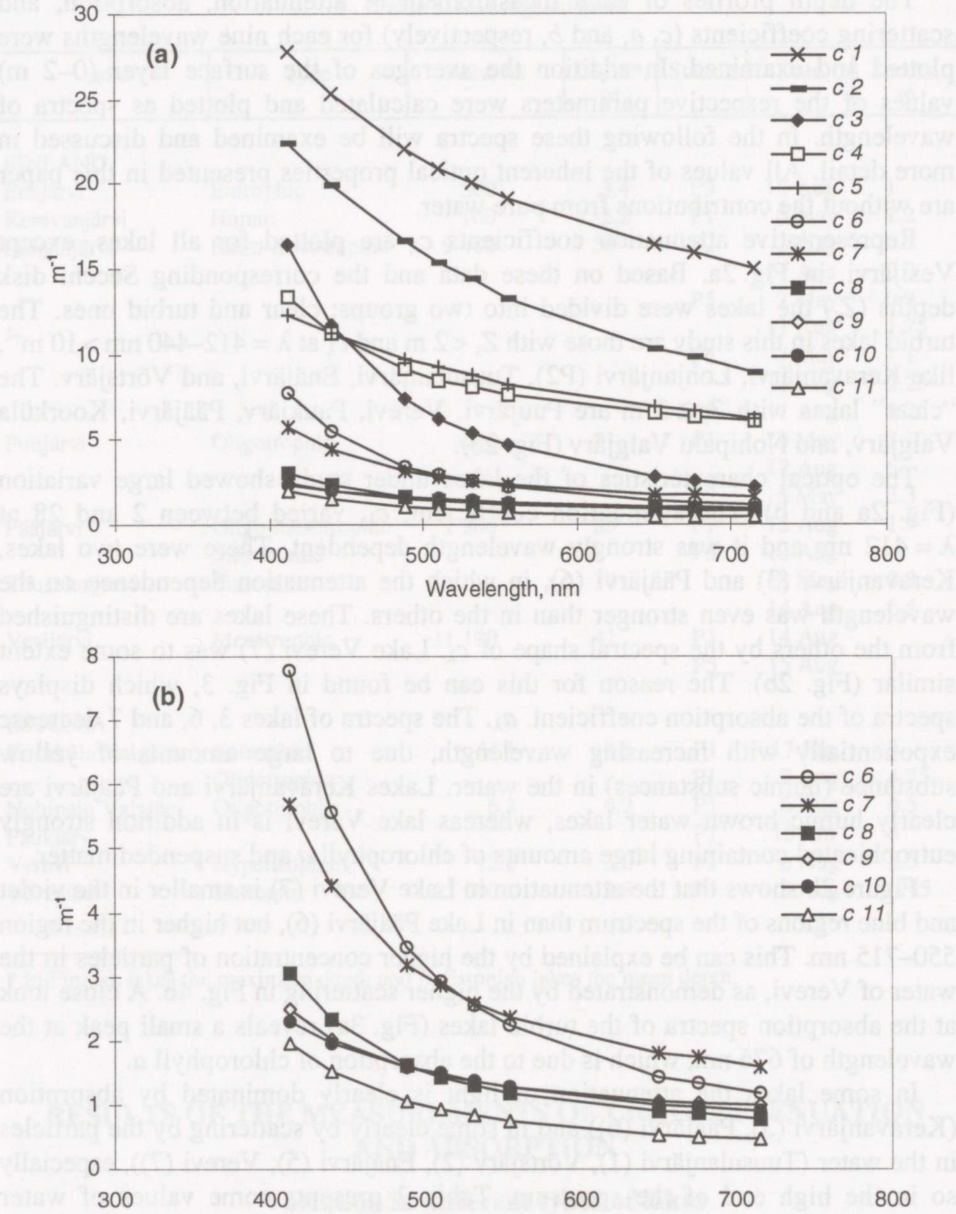


Fig. 2. Spectra of the attenuation coefficients in 11 investigated lakes (a) and in "clear" lakes with Secchi depth ≥ 2 m (b). The coefficient of pure water was subtracted. Lakes: 1, Tuusulanjärvi; 2, Võrtsjärv; 3, Keravanjärvi; 4, Lohjanjärvi (P2); 5, Enäjärvi; 6, Pääjärvi; 7, Verevi; 8, Nohipalu Valgjärv; 9, Koorküla Valgjärv; 10, Paukjärv; 11, Puujärvi.

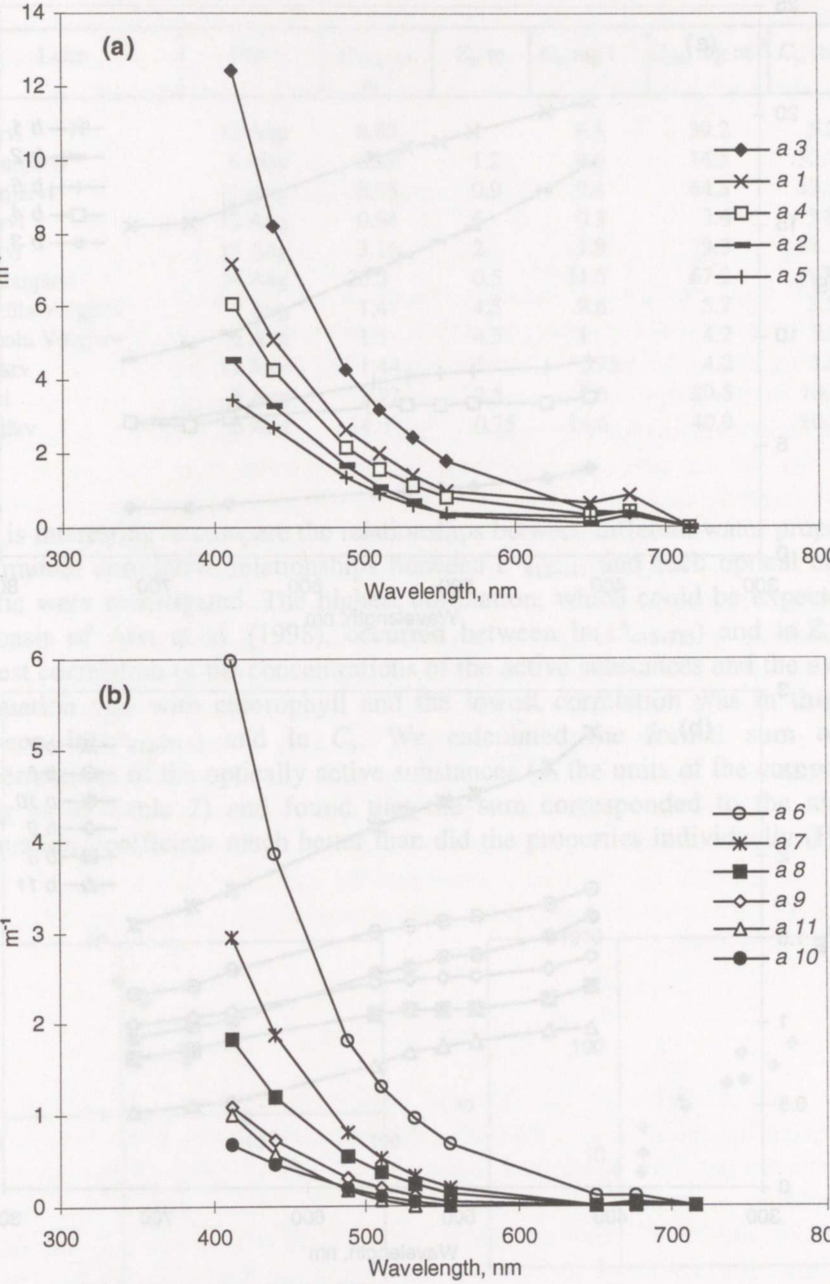


Fig. 3. Spectra of the absorption coefficients, *a*, in turbid (a) and "clear" lakes with Secchi depth ≥2 m (b). Refer to Fig. 2 for lakes.

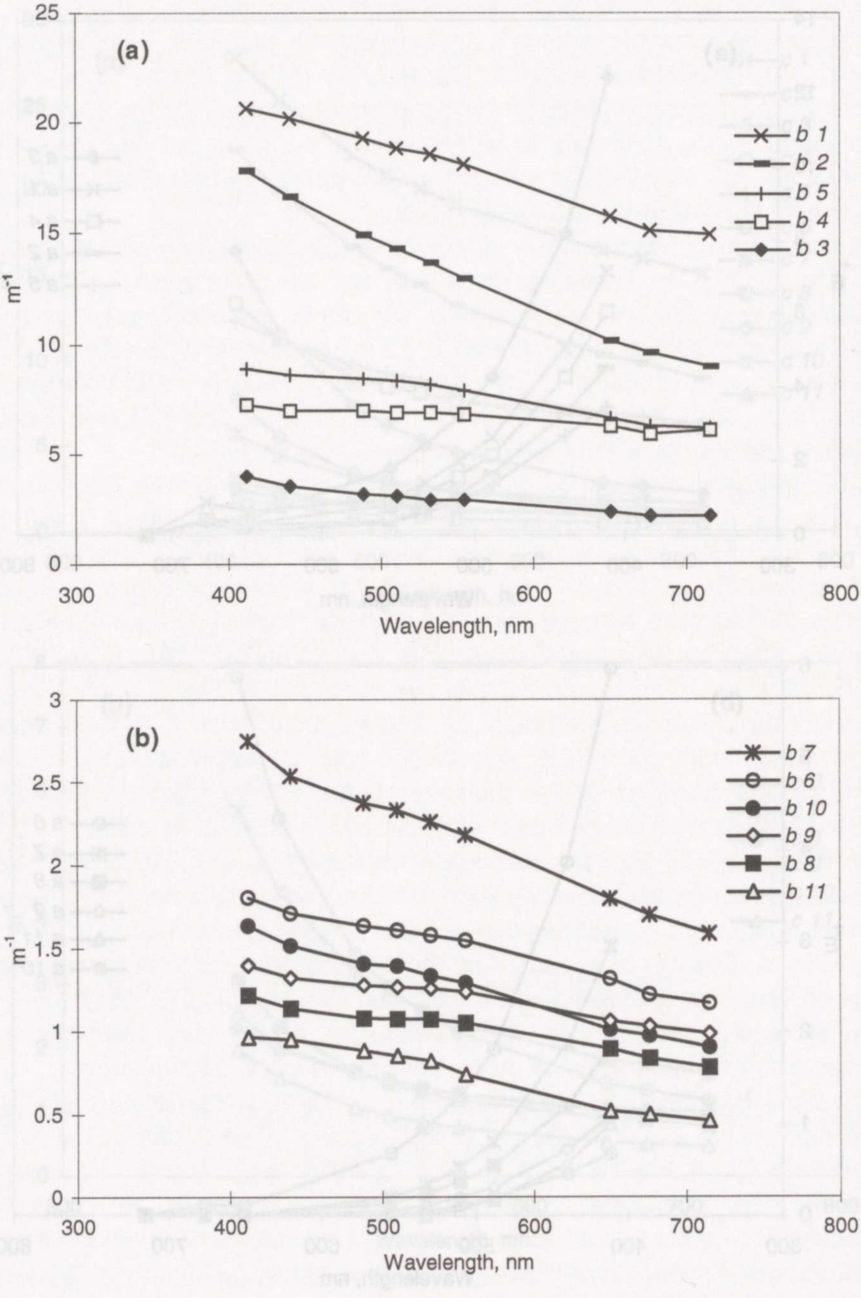


Fig. 4. Spectra of the scattering coefficients, *b*, in turbid (a) and "clear" lakes with Secchi depth ≥2 m (b). Refer to Fig. 2 for lakes.

Table 2. Some representative values of the measured optical quantities and components

Lake	Date	$c^*_{412-715}$, m^{-1}	Z_s, m	C_s, mg L^{-1}	C_{chl}, mg m^{-3}	C_y, mg L^{-1}
Enäjärvi	12 Aug	8.82	1	6.8	39.2	5.22
Keravanjärvi	6 May	6.59	1.2	0.6	14.5	32.15
Lohjanjärvi	11 Aug	8.55	0.9	9.4	64.5	13.56
Puujärvi	12 Aug	0.94	6	0.3	3.6	3.8
Pääjärvi	13 Aug	3.16	2	1.9	9.3	18.38
Tuusulanjärvi	14 Aug	20.3	0.5	31.5	67.2	11.2
Koorküla Valgjärv	7 Aug	1.47	4.5	9.6	5.7	3.3
Nohipalu Valgjärv	6 Aug	1.5	4.5	1	4.2	5.48
Paukjärv	15 June	1.44	5	1.75	4.2	1.22
Verevi	6 Aug	2.92	2.5	2.6	20.5	10.18
Võrtsjärv	5 Aug	14.6	0.75	14.6	40.9	10.53

It is interesting to compare the relationships between different water properties. The mutual correlative relationships between $c^*_{412-715}$ and each optical characteristic were investigated. The highest correlation, which could be expected on the basis of Arst et al. (1998), occurred between $\ln(c^*_{412-715})$ and $\ln Z_s$. The highest correlation of the concentrations of the active substances and the average attenuation was with chlorophyll and the lowest correlation was in this case between $\ln(c^*_{412-715})$ and $\ln C_y$. We calculated the formal sum of the concentrations of the optically active substances (S, the units of the components being as in Table 2) and found that the sum corresponded to the average attenuation coefficient much better than did the properties individually (Fig. 5).

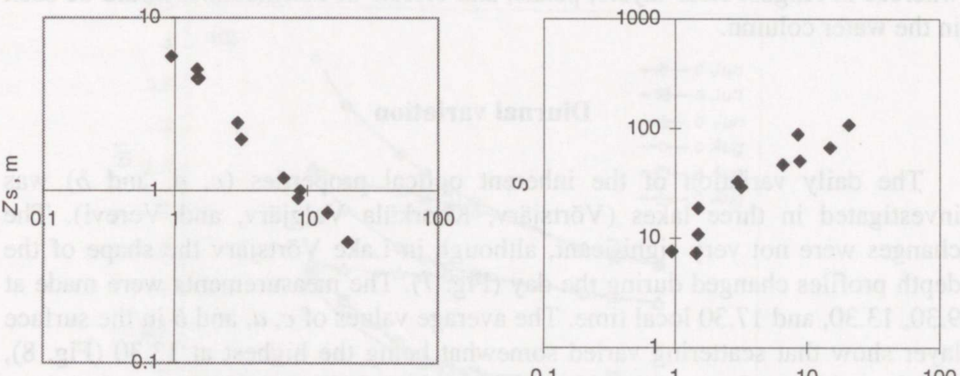


Fig. 5. Correlation $c^*_{412-715}$ vs. Z_s and $c^*_{412-715}$ vs. $S(C_{chl} + C_s + C_y)$.

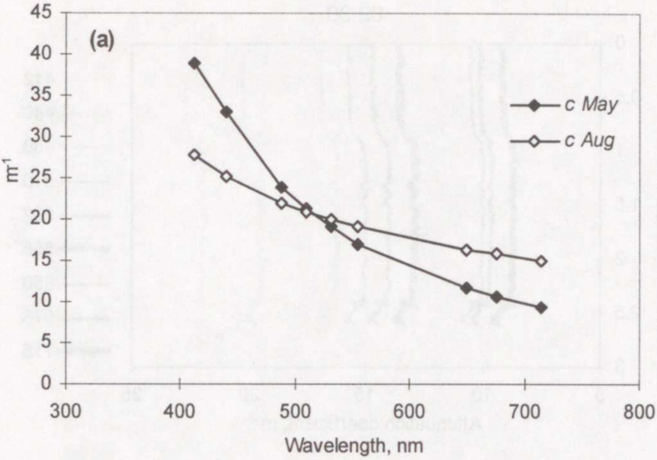
This means that if we know the $c^*_{412-715}$ values (ac-9) it is possible to deduce one of C_s, C_{chl}, or C_y if the other two are known. Generally the laboratory measurements of $c^*_{400-700}$ were significantly smaller (20%) than the corresponding field measurements of $c^*_{412-715}$. The reason for this is not yet known.

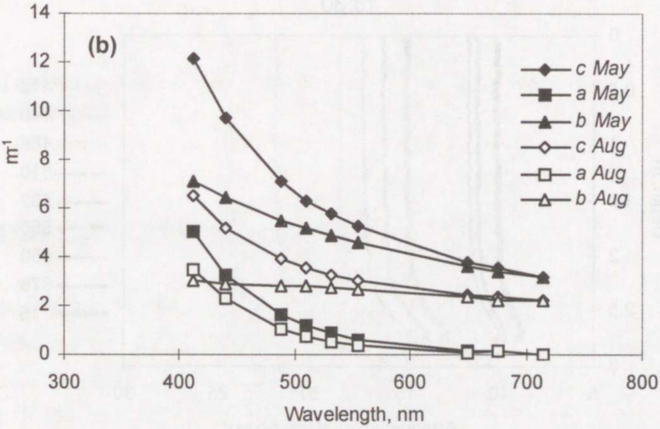
Variation during the summer

We investigated four lakes in two time periods during the summer and observed quite significant variation. Figure 6 shows the three lakes with the greatest variation. The measurement times were early May in Finland, mid-June in Estonia, and mid-August in both countries. In Lake Tuusulanjärvi (Fig. 6a) the changes in the shape of the attenuation coefficient spectrum were less wavelength dependent during the summer. This indicates more yellow substance in May after the ice melt and more particles in the water (both suspended matter and chlorophyll) in August. The collected concentration data of these substances verified this. In Lake Lohjanjärvi (Fig. 6b) the changes were similar, but not so big. In May the shapes of the attenuation and absorption spectra were more exponential indicating amounts of yellow substance in the water. The fact that the scattering is clearly bigger in May (especially at the lower wavelengths) is not easily explained since according to the concentration data only the C_y value is bigger in May. In Koorküla Valgjärv (Fig. 6c) there were clearly more scatterers in the water in June than in August. The data show higher chlorophyll concentration in June. The values of absorption were about the same indicating that the amount of yellow substance was quite stable during the summer. Generally in these lakes the water in the upper layers was clearly more turbid in May–June (mostly C_y) than in August and no stratification occurred in May, whereas in August clear layers, peaks, and effects of thermoclines could be seen in the water column.

Diurnal variation

The daily variation of the inherent optical properties (c, a, and b) was investigated in three lakes (Võrtsjärv, Koorküla Valgjärv, and Verevi). The changes were not very significant, although in Lake Võrtsjärv the shape of the depth profiles changed during the day (Fig. 7). The measurements were made at 9.30, 13.30, and 17.30 local time. The average values of c, a, and b in the surface layer show that scattering varied somewhat being the highest at 13.30 (Fig. 8), which could have been caused by a higher chlorophyll concentration at that time. These changes were small, however, and the change in the shape of the profiles was more interesting. The explanation can be that the chlorophyll concentration was the highest at 13.30 and chlorophyll reached down to 2 m before ascending again and diminishing in concentration.





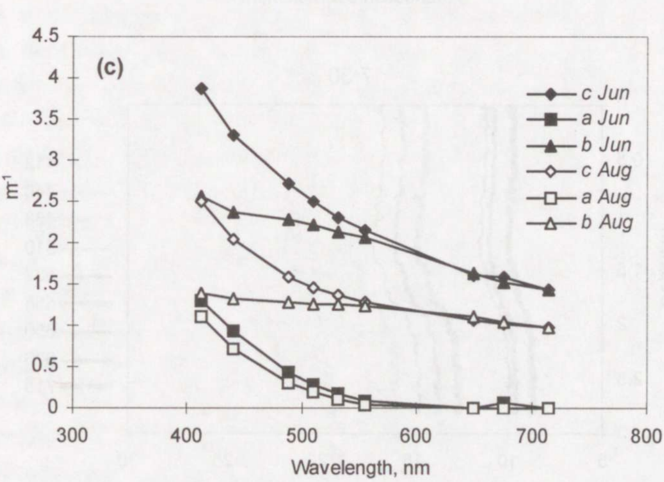


Fig. 6. Change of the inherent properties during summer in lakes Tuusulanjärvi (a), Lohjanjärvi (b), and Koorküla Valgjärv (c).

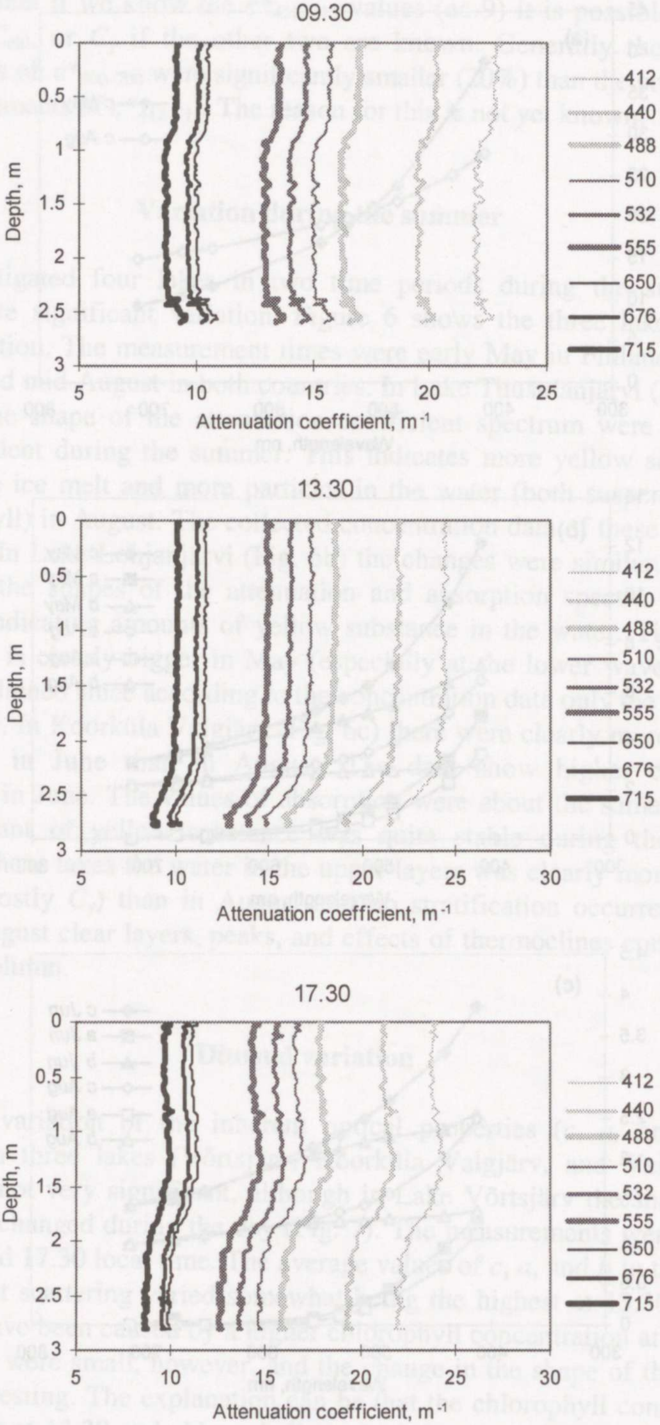


Fig. 7. Diurnal variation of the attenuation profile in Lake Võrtsjärv.

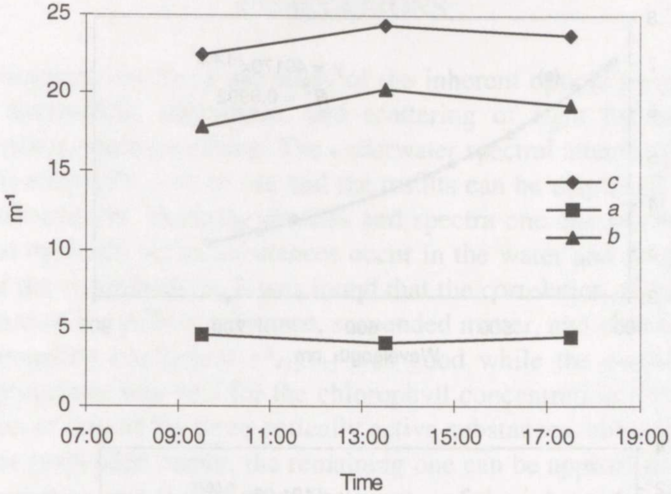


Fig. 8. Diurnal variation of the averages of absorption, scattering, and attenuation at the wavelength 412 nm in Lake Võrtsjärv.

SPECTRAL DISTRIBUTION OF THE SCATTERING COEFFICIENT

Data provided by the ac-9 allow us to describe the dependence of the scattering coefficient, b, on wavelength. According to results of different authors the spectral distribution of b is influenced by the turbidity of the water (Halturin et al., 1983; Kopelevich, 1983; Jerlov, 1974; Phillips & Kirk, 1984; Arst et al., 1997). The data presented in these papers show that the dependence of b on wavelength becomes weaker with increasing water turbidity. Modelling this dependence by the power law $b(\lambda) = b(\lambda_0)\cdot(\lambda_0/\lambda)^n$, where λ is wavelength, yields the value of n for the clearest ocean water of about 1.22 (Halturin et al., 1983). According to Jerlov (1974) and Phillips & Kirk (1984) the value of n is almost zero for the Baltic Sea and for Australian coastal waters. In the paper by Arst et al. (1997) the value $n \sim 0.6$ is used. Two examples of the spectral distribution of b, measured with ac-9, are presented in Fig. 9. The values of n for the investigated Finnish and Estonian lakes are shown in Table 3. These results lead to interesting conclusions, which are difficult to explain: (1) contradictory to the common opinion, the value of n for turbid lakes often exceeds that for clear lakes; (2) the values of n, determined in May–June are in most cases 2–3 times greater than those obtained for the same lakes in August; (3) the values of n are greater than expected, varying from 0.34 to 1.51, mostly exceeding 0.6. These results and the spectra suggest that the scattering coefficient is more wavelength dependent than expected. Can it be that the wavelength dependence is affected by the type of the scatterer?

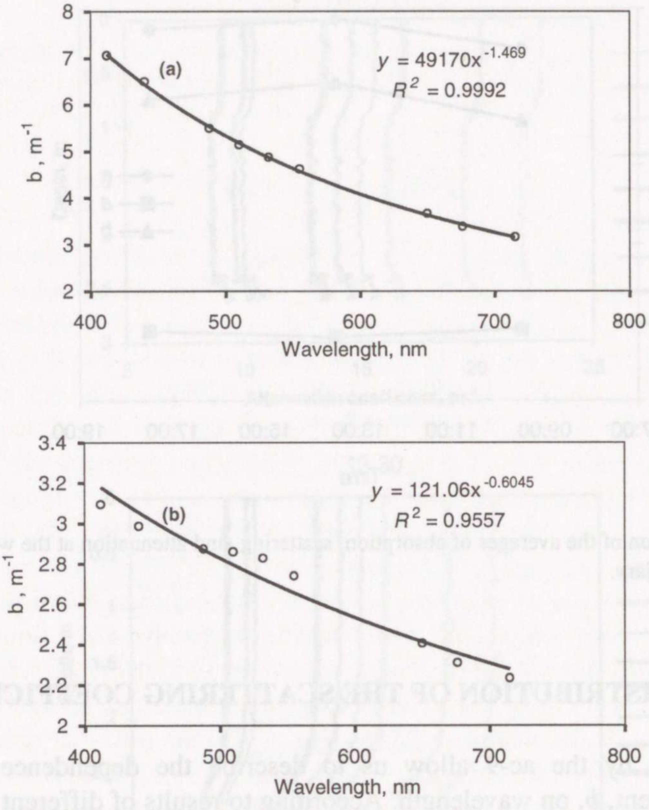


Fig. 9. The wavelength dependence of the scattering coefficient, *b*, in Lake Lohjanjärvi: (a) 07.07.1997, (b) 11.08.1997.

Table 3. Values of *n* calculated from the power law $b(\lambda) = b(\lambda_0)\cdot(\lambda_0/\lambda)^n$

Lake	Station	May–June	August
Lohjanjärvi	P2	1.40	0.34
Lohjanjärvi	P5	1.44	0.65
Lohjanjärvi	P6	1.51	0.52
Lohjanjärvi	P8	–	0.53
Puujärvi	P1	0.80	0.81
Puujärvi	P2	1.06	–
Pääjärvi	P5	–	0.79
Vesijärvi	P5	–	0.35
Enäjärvi	P3	–	0.71
Keravanjärvi	P1	1.06	–
Nohipalu Valgjärv	P1	–	0.72
Koorküla Valgjärv	P1	1.08	0.54
Paukjärv		0.81	–
Verevi	P1	–	1.04
Võrtsjärv	P1–P3	–	1.24
Tuusulanjärvi		(2.43)	0.61

– No measurements made.

CONCLUSIONS

The preliminary results of our study of the inherent optical properties of the water, i.e. attenuation, absorption, and scattering of light by dissolved and suspended matter, seem promising. The underwater spectral attenuation/absorption meter ac-9 is relatively easy to use and the results can be displayed immediately after the measurement. From the profiles and spectra one can predict quite well what kind of optically active substances occur in the water and what the overall condition of the water body is. It was found that the correlation of the sum of the concentrations of the yellow substance, suspended matter, and chlorophyll vs. the average attenuation coefficient $c^*_{412-715}$ was good while the correlation of the individual properties was best for the chlorophyll concentration. If we know the concentration of two of the three optically active substances, chlorophyll, yellow substance, or suspended matter, the remaining one can be approximated from the average attenuation and the shape of the spectra of the inherent properties helps solve this question further. The variation of the water properties during the summer was also quite significant with the attenuation at $\lambda = 412$ nm varying from May to August between 39 and 27 m^{-1} in the turbid eutrophic Lake Tuusulanjärvi and from 12 to 6.5 m^{-1} in the eutro-mesotrophic Lake Lohjanjärvi. An interesting result against the previous knowledge was that the wavelength dependence of the scattering coefficient, *b*, was in many cases greater in more turbid lakes than in clearer lakes. Also the value of *n* in the model of wavelength dependence, $b = b_0(\lambda_0/\lambda)^n$ was greater than expected, varying from 0.34 to 1.51. Further studies are required to explain these results and more field expeditions have been planned to learn more about the usability and reliability of the ac-9 instrument.

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VEEALUSE VALGUSE NEELDUMIS- JA NÕRGENEMISMÕÕTJA ac-9 ABIL SOOME JA EESTI JÄRVEDES 1997. AASTA SUVEL TEHTUD MÕÕTMISTE TULEMUSED

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Valguse neeldumis- ja nõrgenemismõõtja ac-9 abil mõõdeti 1997. aasta suvel vee primaarseid optilisi karakteristikuid (nõrgenemis-, neeldumis- ja hajumiskoefitsiente) 12 Soome ja Eesti järves. Uuritavad järved olid valitud sooviga kajastada erinevaid optilisi veetüüpe. Tulemusena saadud koefitsientide väärtused demonstreerivad ilmekalt järvede optiliste omaduste mitmekesisust ning enamikel juhtudel ka muutust suve jooksul. Neljas uuritavas järves erinesid valguse nõrgenemiskoefitsiendid, mõõdetud mais ja augustis, koguni 60–80%. Hajumiskoefitsiendi spektraalne muutlikkus oli suurem kui oodatud, eelkõige just häguste järvede puhul. Tihti oli see muutlikkus hägustes järvedes suurem kui selgeveelistes järvedes, kuid see pole kooskõlas teiste autorite saadud tulemustega.