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Informative Water Layer, Determined by Attenuation Depth, in Water Bodies of Different Turbidity

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Abstract – **By using values of vertical diffuse attenuation coefficient at certain visible wavelength (or its mean value for some spectral region) we can estimate the depth of informative to remote sensing water layer sometimes called penetration depth, but more often attenuation depth. This value is an important parameter because about ninety percent of the information detected by optical remote sensing instruments is related to the sea layer with this depth.**

1. INTRODUCTION

We compare some theoretical and numerically derived dependencies of diffuse attenuation coefficient on inherent optical properties of water mass and solar elevation with the in situ data measured by us in various seas and lakes and values of diffuse attenuation coefficient.

Comparison of modeled and experimental data is discussed and recommendations to improve effectiveness of in situ measurements and recommendations to increase effectiveness of processing remote sensing information to recover inherent optical properties and biological productivity of the upper water layer are proposed.

2. EXPERIMENTAL MEASUREMENTS

Using the values of vertical diffuse attenuation coefficient $K_d(\lambda)$ (or its mean value for some spectral region), here λ is a wavelength of light, we can estimate the depth of informative (for remote sensing) layer, called sometimes penetration depth, but more often attenuation depth, $z_K(\lambda)$. It is an important characteristic since 90% of the information detected by optical remote sensing instruments comes from above a depth where downward irradiance has fallen to a level which is $1/e = 0.36788$ less than its value just below the water surface. So, as it is known:

$$z_K(\lambda) = 1/K_d(\lambda). \qquad (1)$$

Through $K_d(\lambda)$ the attenuation depth depends on wavelength of light, on the inherent optical properties on the water body and on the angular distribution on downwelling solar irradiance (solar zenith angle, cloudiness). The variation range for oceans is easy to describe on the basis of K_d values for oceanic and coastal waters, given by Jerlov's water types [1]. The respective attenuation depths for wavelengths 400, 450, 500, 550, 600, 650 and 700 nm are shown in Table 1. It is known that Jerlov made his water classification a long time ago [1 - 3], but these data have not lost their value, describing adequately the variability range of the optical properties of the oceans. Consequently, in the sphere of interest have to be additionally the new data for marginal seas and lakes, not included into the Jerlov's classification. Some examples of the spectral distribution of the attenuation depth for three Estonian and four Finnish lakes are presented in Table 2 [4]. Here the necessary values of $K_d(\lambda)$ were determined from the profiles of downwelling irradiance in the water, measured by means of underwater spectrometer LI 1800UW and value of $z_K(\lambda)$ was computed by formula (1). In Fig. 1 also the results obtained for Estonian and Finnish lakes are presented, demonstrating the variability limits of $z_K(\lambda)$ for lakes under investigation ($K_d(\lambda)$ measurements were carried out altogether for 17 lakes in Estonia and Finland). In this figure the typical minimum (Lake Tuusulanjärvi, Aug.1995) and maximum (Lake Äntu Sinijärv, Aug.1995) spectra of $z_K(\lambda)$, and also comparison with $z_K(\lambda)$ of Jerlov's water types III, 5 and 9, are shown. Considering all these data it is obvious that the lake waters differ very much from open ocean and also from oceanic coastal waters. From all lakes, we investigated,

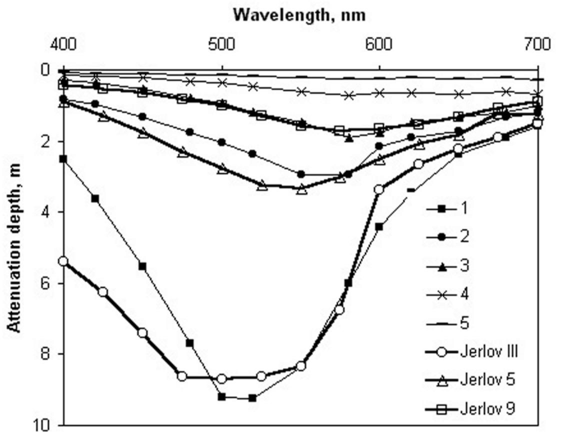

Fig.1. Spectral distribution of the attenuation depth z_K, computed from the values of diffuse attenuation coefficient K_d for the following lakes: 1. Äntu Sinijärv, Aug.1995; 2. Paukjärv, June 1997; 3. Päijänne, June 1995; 4. Uljaste, Aug.1995; 5. Tuusulanjörvi, Aug.1995. For comparison also the z_K spectra for Jerlov's water types III, 5 and 9 are shown.

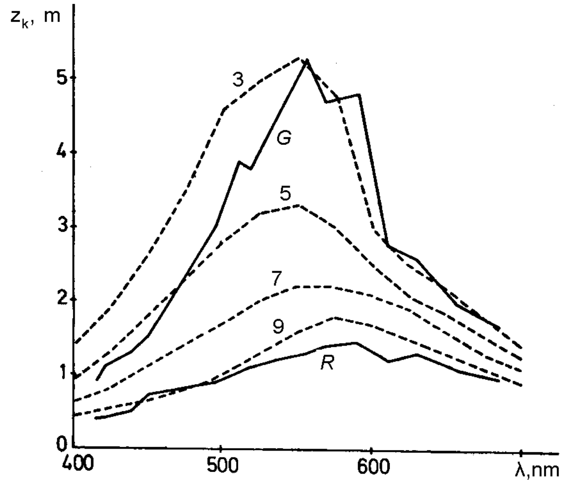

Fig.2. Spectral distribution of the attenuation depth z_K obtained for two regions of the Baltic Sea: Gotland Deep (G) and Gulf of Riga (R). For comparison the values of z_K calculated for Jerlov's coastal water types 3, 5, 7 and 9 are shown (dashed lines).

Lake Äntu Sinijärv is an exception, comparable with Jerlov's water type III (Fig.1). All the other lakes have smaller values of $z_K(\lambda)$ than Jerlov's water type 5 and many even smaller than Jerlov's *darkest* coastal water type 9. The most informative region is between 500 and 600 nm for lakes of medium transparency and beyond 600 nm for highly turbid lakes.

The Baltic Sea is a good example describing a marginal sea under strong human impact. The data about its attenuation depth show that z_K has here considerable spatial variability. Results published in [5], using measurement data by Kopelevich *et al.* [6] for absorption coefficients of light in the Baltic, give variation limits of z_K for open Baltic somewhere between Jerlov's water types II and 3, but for the Gulf of Riga between types 7 and 9. Later (in 1987) series of measurements were carried out in the Baltic [5, 7]: 1) between islands Hiiumaa and Saaremaa; and 2) near southern coast of the Gulf of Finland, in the Kunda Bay. The results, describing the spectral distribution of the attenuation depth in these areas are presented in Fig.2. We can see, that in the first case the Baltic waters lie between water types 3 and 5, but in the Kunda Bay even lower values of z_K than for type 9 were recorded.

In 1986–87 and 1991–93 the waters of the Pärnu Bay (Baltic Sea) were investigated [8, 9]. The values of attenuation depth for 1986-87 mostly exceeded those for 1991-93 and $z_K(\lambda)$ for the last

Table 1a. Attenuation depth $z_K(\lambda)$ (in m) computed with equation (1) using $K_d(\lambda)$ values given for Jerlov's water types [2]. The case of open ocean waters.

λ \ Type	I	IA	IB	II	III
400	35.7	26.3	19.6	10.4	5.40
450	52.6	38.5	27.8	14.7	7.41
500	37.0	31.2	23.8	14.3	8.70
550	15.9	14.9	13.9	11.2	8.33
600	4.25	4.17	4.08	3.85	3.39
650	2.78	2.70	2.67	2.50	2.25
700	1.79	1.75	1.72	1.64	1.52

Table 1b. Attenuation depth $z_K(\lambda)$ (in m) computed with equation (1) using $K_d(\lambda)$ values given for Jerlov's water types [2]. The case of coastal waters.

λ \ Type	1	3	5	7	9
400	1.96	1.28	0.91	0.62	0.53
450	4.00	2.56	1.78	1.12	0.62
500	5.88	3.45	2.78	1.72	1.01
550	8.33	5.26	3.33	2.17	1.59
600	3.33	3.03	2.50	2.08	1.67
650	2.22	2.17	1.85	1.59	1.32
700	1.54	1.41	1.25	1.09	0.91

Table 2. The values of the attenuation depth $z_K(\lambda)$ (in m) for some Estonian and Finnish lakes measured in the period 1995-97. The values of the Secchi disc depth z_{SD} (in m) are also shown.

Lake:	NM	V	T	LP	KN	P	NV
$\lambda \backslash z_{SD}$	0.6	1.0	1.2	1.9	3.0	5.1	4.9
420	0.02	0.09	0.13	0.1	0.24	0.44	0.61
460	0.04	0.12	0.19	0.22	0.36	0.72	0.98
500	0.06	0.17	0.27	0.33	0.59	1.16	1.48
540	0.09	0.22	0.37	0.50	0.94	1.67	2.05
580	0.14	0.29	0.47	0.67	1.35	2.17	2.31
620	0.18	0.36	0.48	0.72	1.05	1.72	1.78
660	0.22	0.45	0.49	0.90	1.37	1.58	1.55
700	0.29	0.49	0.49	0.76	1.00	1.27	1.28

Legend, Lakes:

NM:	Nohipalu Mustjärv
V:	Valkeakotinen
T:	Tuusula
LP:	Lammi Pääjärvi
KN:	Kurtna Nõmmjärv
P:	Päijänne
NV:	Nohipalu Valgjärv
VJ:	Võrtsjärv

period often shows very low values, similar to highly turbid lakes Võrtsjärv and Tuusulanjärvi (see Tables 2 and 4).

If the water transparency is very low (Secchi disk depth is less than 2m), remote sensing measurements can yield information only on rather thin surface layer (down to 1 m) and on the state of water surface. Considering the spectral distribution of the attenuation depth it follows that for lakes and inland seas the most informative spectral region is often located beyond 500 nm and sometimes even beyond 580 nm. This have to be taken account choosing the wavelengths for color indices and other remote sensing characteristics.

Given above analysis on the variability of the attenuation depth (and corresponding values of diffuse attenuation coefficient) for different water bodies implies to the necessity to elaborate an optical classification for lakes and marginal seas, additionally to that for ocean and coastal waters.

As mentioned above, the diffuse attenuation coefficient depends on angular distribution on downwelling solar irradiance. The easiest way to estimate this dependence is to use Kirk's formulae, allowing to compute $K_d(\lambda)$ values if the absorption (a) and scattering (b) coefficients are known together with the data on the solar zenith angle and cloudiness. [10-13] have proposed the following equations:

Table 3. Comparison of the values of $K_d(\lambda)$ computed by equation (2). and by two-stream model [5, 14] for four values of solar zenith angle j_0 (a and b are the absorption and scattering coefficients).

λ, nm		420	500	620	690	765
a, 1/m		0.40	0.08	0.27	0.53	2.40
b, 1/m		0.185	0.182	0.181	0.181	0.180
$j_0 =$ 0°	Eq.	0.43	0.10	0.29	0.55	2.42
	M	0.41	0.09	0.28	0.54	2.44
$j_0 =$ 48°	Eq.	0.51	0.11	0.34	0.66	2.91
	M	0.51	0.11	0.36	0.67	2.93
$j_0 =$ 60°	Eq.	0.55	0.12	0.37	0.72	3.18
	M	0.56	0.13	0.40	0.74	3.23
$j_0 =$ 80°	Eq.	0.62	0.13	0.42	0.80	3.58
	M	0.55	0.12	0.39	0.76	3.37

$$K_d(z_m) = \frac{\sqrt{a^2 + \left(0.473\cos j_0 - 0.218\right)ab}}{\cos j_0}, \qquad (2)$$

$$\overline{K}_d = \frac{\sqrt{a^2 + \left(0.425\cos j_0 - 0.190\right)ab}}{\cos j_0}, \qquad (3)$$

where z_m is the midpoint of euphotic zone (the depth, where the downward irradiance has fallen to the 10% of its surface value), $\overline{K}_d$ is the average value of K_d for monochromatic light through the euphotic zone, j_0 is the angle of photons in the direct solar beam to the vertical just below the sea surface. For the light coming from a standard overcast sky (equivalent to a cardioidal radiance distribution) the respective equations are:

$$K_d(z_m) = 1.168\sqrt{a^2 + 0.168\,ab}, \qquad (4)$$

$$\overline{K}_d = 1.168\sqrt{a^2 + 0.162\,ab}. \qquad (5)$$

3. DISCUSSION

The question is whether equations (2) and (3) are applicable for natural illumination conditions (direct plus diffuse solar radiation). In Kirk's opinion [15] they work best for sunny days with fairly high solar altitude. The suitability of Kirk's formulae have been also estimated in [5], where the results obtained using (2) have been compared with those by a two-flow

Table 4. Dependence of the attenuation depth (z_K, in m) on solar zenith angle j_0, estimated by Kirk's formula (3).

Lake:	VJ, Aug. 1997			P, May 1995		
λ,nm	400	550	700	400	550	700
a	8.1	2.0	1.1	2.98	0.41	0.69
b	13.6	10.2	8.2	0.5	0.42	0.39
0°	0.105	0.337	0.542	0.329	2.19	1.362
40°	0.095	0.315	0.512	0.289	1.96	1.208
60°	0.085	0.293	0.483	0.252	1.737	1.061
70°	0.080	0.283	0.470	0.235	1.636	0.995

[5, 14, 16] irradiance models (see Table 3). As we could see, the differences are small up to solar zenith angle j_0 = 60° and even for j_0 = 80° they do not exceed 12 %.

Some results, describing the dependence of attenuation depth on solar zenith angle, are presented in Table 4. The values of z_K are computed by equation (1), using the values of K_d given by equation (3). The spectral absorption and scattering coefficients for lakes Võrtsjärv and Päijänne are estimated from beam attenuation coefficient spectra by means of method, described in [17]. These data show that differences between $z_K(0°)$ and $z_K(70°)$ vary from 14% to 33%. Consequently, the variations of K_d recorded by repeated measurements in some water body or in different lakes can be caused not only by differences in inherent optical properties of water, but also by different light conditions during the measurements.

4. CONCLUSION

Using the values of vertical diffuse attenuation coefficient at certain visible wavelength (or its mean value for some spectral region) we can estimate the depth of informative to remote sensing water layer sometimes called penetration depth, but more often attenuation depth. This value is an important parameter because about ninety percent of the information detected by optical remote sensing instruments is related to the sea layer with this depth.

Comparison of theoretical and numerically derived dependencies of diffuse attenuation coefficient on inherent optical properties of water mass and solar elevation with the in situ data measured by us in various seas and lakes and values of diffuse attenuation coefficient showed the applicability of the equations used here.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] N. G. Jerlov, 1976. *Marine Optics*, Elsevier Oceanography Series 14, Amsterdam: Elsevier Pub. Co. - 321 p.

[2] N. G. Jerlov, 1964. "Optical classification of ocean water." – In: *Physical Aspects of Light in the Sea*. Univ. Hawaii Press, Honolulu, Hawaii, 45-49

[3] N. G. Jerlov, 1968. *Optical Oceanography*, Elsevier Oceanography, Amsterdam, 194 p. (First Edition)

[4] H. Arst, T. Kutser, S. Mäekivi, A. Reinart, A. Blanco-Sequeiros, J. Virta, and P. Nõges, 1996. "Optical investigation of Estonian and Finnish lakes." – *Lakes and Reservoirs: Research and Management*, **2**, 187-198.

[5] H. Arst, D. Pozdnyakov, and A. Rosenstein, 1990. *Optical Remote Sensing in Oceanology*, Tallinn, Valgus Press, 444 p. (in Russian).

[6] O. V. Kopelevich, S. I. Russanov, N. M. Nosenko 1974. "Absorption of light in the sea." – In: *Hydrophysical and Hydrooptical Investigations in the Atlantic and Pacific Oceans*, Moscow, Nauka, 208-234 (in Russian).

[7] L. Laesson,T. Lukk, H. Arst, K. Purga, and H. Ohvril, 1988. Experimental and numerical studies on the attenuation of the solar radiation and small-angle-scattering of light in the Baltic. Waters. – In: *Proc.16th Conf. Baltic Oceanographers*, Kiel, **2**, 641-647.

[8] H. Arst, T. Kutser, L. Laesson, and T. Lukk 1993. Optical measurements in Pärnu Bay. – *Proc. Estonian Acad. Sci., Ecology*, **3**, No 1, 27-37.

[9] H. Arst, and T. Kutser, 1994. Data processing and interpretation of sea radiance factor measurements. – *Polar Research*, **13**, 3-12.

[10] D. M. Phillips, and J. T. O. Kirk, 1984. Study of the spectral variation of absorption and scattering in some Australian coastal waters. – *Austr. J. Marine Res.,* **35**, 635-644.

[11] J. T. O. Kirk, 1984. Attenuation of solar radiation in scattering-absorbing waters: a simplified procedure for its calculation. – *Appl. Optics,* **23**, Marine optics 1, 3737-3739.

[12] J. T. O. Kirk, 1984, Dependence of relationship between inherent and apparent optical properties of water on solar altitude. – *Limnol. Oceanogr.*, **29**, No 2, 350-356.

[13] J. T. O. Kirk, 1989. “The assessment and prediction of optical water quality.” – *Australian Water and Wastewater Assoc. 13th Fed. Convention,* Canberra 6-10 March, 1989, Barton, 504-507.

[14] H. Arst, and G. Arst 1983. Model computations of reflected solar radiation from wind-ruffled sea. – In: *Investigations of the variability of optical properties of the Baltic Sea*, Tallinn, Valgus, 1983, 177-202 (in Russian).

[15] J. T. O. Kirk, private communication

[16] V. I. Haltrin, “Self-consistent approach to the solution of the light transfer problem for irradiances in marine waters with arbitrary turbidity, depth and surface illumination,” *Appl. Optics*, **37**, 3773-3784 (1998).

[17] H. Arst, S. Mäekivi, T. Lukk, and A Herlevi, 1997. “Calculating irradiance penetration into water bodies from the measured beam attenuation coefficient.” – *Limnol. Oceanogr.*, **42**(**2**), 379-385.

[18] V. I. Haltrin, “Chlorophyll-based model of seawater optical properties,” *Appl. Optics*, **38**, 6826-6832 (1999).

[19] V. I. Haltrin,"Empirical algorithms to restore a complete set of inherent optical properties of seawater using any two of these properties,” *Canadian Journal of Remote Sensing*, **26**, 440-445, (2000).

[20] Haltrin, “Apparent optical properties of the sea illuminated by Sun and sky: case of the optically deep sea,” *Appl. Optics*, **37**, 8336-8340, (1998b).

[21] V. I. Haltrin, and V. I. Mankovsky, “Analytical Representation of Experimental Light Scattering Phase Functions Measured in Seas, Oceans and Lake Baykal,” - *2002 IEEE International Geoscience and Remote Sensing Symposium and the 24th Canadian Symposium on Remote Sensing Proceedings on CD ROM*, June 24-28, 2002, Toronto, Canada, Library of Congress Number: 2002 105858, Paper # I1E09_1287.

[22] V. I. Mankovsky, and V. I. Haltrin, “Phase Functions of Light Scattering Measured in Waters of World Ocean and Lake Baykal,” - *2002 IEEE International Geoscience and Remote Sensing Symposium and the 24th Canadian Symposium on Remote Sensing Proceedings on CD ROM*, June 24-28, 2002, Toronto, Canada, Library of Congress Number: 2002 105858, Paper # I2E09_1759.

[23] H. Arst, and V. I. Haltrin, “Components of Remote Rensing Reflectance of Northern Baltic Natural Water Basins,” - pp. 1-8, paper No. 00032 in *Proceedings of the Seventh International Conference on Remote Sensing for Marine and Coastal Environments*, 20-22 May, 2002, Miami, Florida, USA, ISSN 1066-3711, Published by: Veridan, P.O. Box 134008, Ann Arbor, MI 48113-4008, USA, 2002.

[24] V. I. Haltrin, D. R. Johnson, and V. A. Urdenko, “Connection Between Light Field Parameters and Optical Properties of Seawater,” pp. 123-132, in *Ocean Optics: Remote Sensing and Underwater Imaging, Proceedings of SPIE*, Vol. 4488, Robert J. Frouin, and Gary D. Gilbert, Editors, Bellingham, WA, USA, 2002.

[25] V. I. Haltrin, R. A. Arnone, and V. A. Urdenko, “Effective Wavelength as a Universal Parameter of Hyperspectral Light Radiance Upwelling from the Sea,” pp.133-142, in *Ocean Optics: Remote Sensing and Underwater Imaging, Proceedings of SPIE*, Vol. 4488, Robert J. Frouin, and Gary D. Gilbert, Editors, Bellingham, WA, USA, 2002.

[26] V. I. Haltrin, “Empirical algorithms to restore a complete set of inherent optical properties of seawater,” in: *Proceedings of the Fourth International Airborne Remote Sensing Conference and Exhibition/21st Canadian Symposium on Remote Sensing*, Published by ERIM International, Inc., Ann Arbor, MI, USA (1999), pp. II-770-777.

[27] V. I. Haltrin, “An algorithm to restore spectral signatures of all inherent optical properties of seawater using a value of one property at one wavelength,” in: *Proceedings of the Fourth International Airborne Remote Sensing Conference and Exhibition/21st Canadian Symposium on Remote Sensing*, Published by ERIM International, Inc., Ann Arbor, MI, USA (1999), pp. I-680-687.