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Phase Functions of Light Scattering Measured in Waters of World Ocean and Lake Baykal

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Abstract — A set of twenty previously unpublished phase functions of light scattering measured *in situ* in waters of oceans, seas and lake Baykal is presented in the tabular form. In 18 cases these measurements were accompanied by the independent measurements of beam attenuation coefficient.

INTRODUCTION

Seawater phase functions of light scattering that are experimentally measured by Petzold became very popular among scientists involving in radiative transfer modeling in the ocean. The original work of Petzold [1] was published as a report and gives numerical values of fifteen phase functions with the values of absorption, scattering and backscattering coefficients. In about 30 years since Petzold's report there was no publications devoted to the seawater scattering phase functions.

In this presentation we propose additional twenty new experimental phase functions $p(\theta)$ or angular scattering coefficients (ASC) $\beta(\theta) = b\, p(\theta)$ measured during several oceanographic expeditions in various regions of World Ocean and Lake Baykal (here b is a total scattering coefficient, and θ is a scattering angle).

For the remote optical sensing of oceans and inland water basins it is very important to know relationships between backscattering and scattering coefficients. The practically useful relationship between these properties based on 20 new and 15 Petzold phase functions is proposed.

The visibility of underwater objects is determined by a modulation transfer function (MTF) that is dependent on parameters of scattering phase function. A full set of MTF parameters for these new phase functions is presented in accompanied paper (Ref. [2] of these Proceedings) and compared with the similar set computed using Petzold phase functions.

The light source in the angular nephelometer, used for measuring presented angular scattering coefficients, emitted non-polarized light. The detector also was non-sensitive to the polarization of measured light. The full set of technical parameters of the angular nephelometer is given in Tab. 1.

In situ measurements of presented phase functions were carried out at discrete depths. The time of phase function measurement was about 8 minute. In most cases we usually made three measurements and computed an average value. The signal from the submerged nephelometer was transmitted to the laboratory on the board of research vessel through the cable and was recorded to a digital tape.

Beam attenuation coefficient was measured with a separate laboratory nephelometer described in Ref. [3] that has an interference filter centered at 520 nm and has a precision of measurement about 10%.

The dates, depths and locations of measured 20 phase functions are given in Tab.2. The numerical values of these phase functions at 33 scattering angles and basic integral optical properties of water are presented in Tables 3-6.

Table 1. Angular nephelometer specifications [4].

Range of angular measurements	2° - 162.5°
Angular scanning step	5°
Angle of divergence of illuminating beam	1°
Visual angle of detector	1° 7’
Angle reading accuracy	0.2°
Accuracy of measurement of scattering light	12%
Wavelength of maximum sensitivity	520 nm
Half-width of sensitivity band	40 nm.
Maximum depth of submerging	200 m

Table 2. Date, location, and depth of measurements of angular scattering coefficient $\beta(\theta)$.

#	Date	z,m	Location	Coordinates
01	01/30/75	5	South Ocean	51° 55' S 20° 12' E
02	02/03/75	5	South Ocean	44° 01' S 19° 58' E
03	03/16/75	7	Indian Ocean	01° 31' N 49° 56' E
04	09/08/86	3	Atlantic	05° 00' N 31° 00' W
05	09/11/86	3	Atlantic	05° 30' N 29° 30' W
06	07/20/79	5	Lake Baykal	53° 22' N 108° 31' E
07	07/20/79	5	Lake Baykal	53° 34' N 108° 03' E
08	11/28/91	0	Black Sea	43° 50' N 34° 15' E
09	05/30/98	0	Aegean sea	39° 43' N 25° 45' E
10	05/25/98	0	Ionic Sea	35° 37' N 18° 16' E
11	10/03/92	0	Black Sea	45° 05' N 32° 24' E
12	10/11/92	0	Adriatic Sea	45° 23' N 13° 10' E
13	05/15/98	0	Gibraltar	35° 59.7' N 05° 26.9' W
14	05/13/98	0	Mediterranian	37° 20.1' N 03° 53.8' E
15	05/23/98	0	Mediterranian	37° 04.9' N 11° 30.6' E
16	05/27/98	0	Sea of Levant	35° 15.0' N 29° 15.0' E
17	05/15/98	0	Mediterranian	36° 17.1' N 07° 06.3' W
18	05/21/98	0	Mediterranian	36° 27.4' N 02° 02.2' W
19	05/21/98	0	Mediterranian	36° 42.8' N 00° 26.4' W
20	05/28/98	0	Mediterranian	35° 55.0' N 28° 05.0' E

Table 3. Natural logarithms of ASC $\beta(\theta)$ No. 01-05

Angle\#	01	02	03	04	05
2.00	2.3551	1.7334	1.1577	0.8584	0.2597
7.50	-1.5757	-1.4145	-2.1513	-3.9243	-3.9243
12.50	-2.8891	-2.3364	-3.3035	-4.7772	-4.7772
17.50	-3.4352	-3.1589	-3.8497	-5.3003	-5.3003
22.50	-4.3454	-3.8389	-4.5757	-5.7730	-5.7040
27.50	-4.6871	-4.2497	-5.1246	-6.2990	-6.1838
32.50	-5.2034	-4.9271	-5.6869	-6.5619	-6.5619
37.50	-5.4700	-5.0786	-6.2759	-6.9437	-6.9437
42.50	-6.4479	-5.7111	-6.3558	-7.2999	-7.1848
47.50	-6.8672	-6.1995	-6.9363	-7.5580	-7.6271
52.50	-7.1622	-6.5635	-7.2543	-7.8530	-7.8530
57.50	-7.5387	-6.8479	-7.4235	-8.0913	-8.0913
62.50	-7.8106	-7.2119	-7.7185	-8.4093	-8.2941
67.50	-8.1843	-7.3093	-7.6777	-8.4836	-8.4836
72.50	-8.3367	-7.5999	-7.9914	-8.6821	-8.6821
77.50	-8.5435	-7.8527	-8.3133	-8.7738	-8.7738
82.50	-8.6662	-7.8373	-8.4360	-9.0116	-9.0116
87.50	-8.7507	-8.1060	-8.2902	-9.0961	-9.0040
92.50	-8.7047	-8.3363	-8.5896	-9.1076	-9.0155
97.50	-8.7583	-8.2057	-8.6432	-9.0254	-9.0254
102.50	-8.8428	-8.2902	-8.7277	-9.0455	-9.0455
107.50	-8.7973	-8.2446	-8.7052	-9.0713	-8.9561
112.50	-8.6679	-8.3455	-8.8060	-8.9925	-8.9925
117.50	-8.8007	-8.3402	-8.5705	-8.8997	-8.8997
122.50	-8.6209	-8.2064	-8.5979	-8.8419	-8.8419
127.50	-8.4977	-8.1753	-8.5207	-8.7947	-8.7947
132.50	-8.3409	-8.2027	-8.4560	-8.6494	-8.7646
137.50	-8.2670	-8.1058	-8.4282	-8.6354	-8.5203
142.50	-8.0950	-7.9798	-8.4404	-8.5071	-8.5071
147.50	-8.0356	-7.8974	-8.3349	-8.4592	-8.4592
152.50	-8.0950	-7.9338	-8.7627	-8.3667	-8.3667
157.50	-7.7763	-7.6381	-8.4210	-8.2713	-8.2713
162.50	-7.6720	-7.5799	-8.3167	-8.2937	-8.2246
b, 1/m	0.4099	0.2993	0.1566	0.1059	0.0622
c, 1/m	0.5572	0.4029	0.2763	0.1612	0.1428
b_b 1/m	0.0032	0.0043	0.0028	0.0023	0.0023
B	0.0078	0.0143	0.0179	0.0213	0.0370
g	0.0213	0.0396	0.0228	0.0392	0.0278

Table 4. Natural logarithms of ASC $\beta(\theta)$ No. 06-10

Angle\#	06	07	08	09	10
2.00	1.9406	1.2959	2.2169	1.2959	0.7663
7.50	-0.4244	-1.0000	-1.1842	-2.6118	-3.2105
12.50	-1.5766	-2.0831	-2.1062	-3.6487	-3.2701
17.50	-2.4221	-3.0208	-2.8366	-4.3560	-4.5402
22.50	-2.8948	-3.4474	-3.6086	-4.9899	-5.1513
27.50	-3.6049	-3.9503	-4.3187	-5.4007	-5.5852
32.50	-3.9370	-4.6047	-4.7429	-5.8248	-6.0784
37.50	-4.6641	-5.1477	-5.0556	-6.3217	-6.4139
42.50	-4.6749	-5.5729	-5.4578	-6.4940	-6.7473
47.50	-5.6008	-5.9692	-5.6699	-6.9361	-7.2126
52.50	-5.9648	-6.2642	-5.8727	-7.1392	-7.4615
57.50	-6.2722	-6.6176	-6.2953	-7.4003	-7.6766
62.50	-6.4981	-6.9817	-6.6133	-7.6262	-7.7415
67.50	-6.8258	-7.0100	-6.8028	-7.7005	-7.8619
72.50	-7.1624	-7.3927	-7.0703	-7.9681	-8.2677
77.50	-7.2771	-7.6225	-7.3001	-8.0830	-8.2442
82.50	-7.4228	-7.6071	-7.5840	-8.2287	-8.4590
87.50	-7.4152	-7.8297	-7.7606	-8.3823	-8.4514
92.50	-7.6685	-7.8297	-7.9448	-8.4169	-8.4859
97.50	-7.7452	-7.7452	-7.9755	-8.2978	-8.5281
102.50	-7.7606	-8.1290	-8.0139	-8.5090	-8.9234
107.50	-7.7150	-7.9683	-8.1756	-8.5783	-8.9930
112.50	-7.7698	-8.1152	-8.1152	-8.6561	-8.7254
117.50	-7.8336	-8.0869	-8.1790	-8.5817	-8.8122
122.50	-7.8380	-8.0683	-8.1373	-8.6897	-8.8509
127.50	-7.7378	-7.8299	-8.0602	-8.6474	-8.8085
132.50	-7.6731	-7.8343	-8.0876	-8.5018	-8.7784
137.50	-7.6453	-7.7144	-8.1058	-8.6584	-8.6584
142.50	-7.6114	-7.5423	-7.9108	-8.5553	-8.6704
147.50	-7.5290	-7.6671	-8.0356	-8.4728	-8.6342
152.50	-7.4502	-7.5423	-7.8877	-8.3941	-8.4634
157.50	-7.0395	-7.4539	-7.7763	-8.1445	-8.2829
162.50	-7.0273	-7.2805	-7.8332	-8.0171	-8.1095
b, 1/m	0.5181	0.2901	0.4674	0.1681	0.1151
c, 1/m	0.6263	0.4352	0.5849	0.2372	0.1681
b_b 1/m	0.0071	0.0059	0.0047	0.0030	0.0026
B	0.0137	0.0204	0.0101	0.0179	0.0222
g	0.0615	0.0392	0.0386	0.0416	0.0461

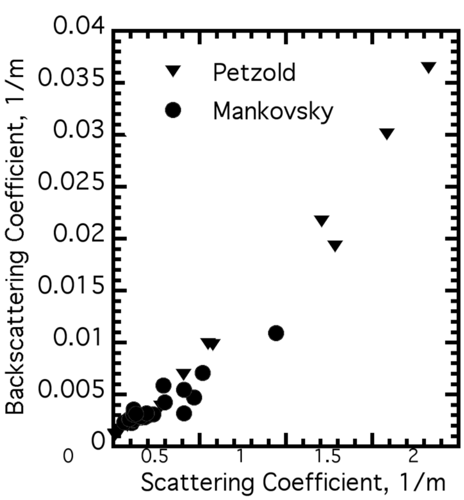

Figure 1. Dependence of backscattering coefficient b_b of sea and lake waters on beam scattering coefficient b.

Here b is a scattering coefficient, c is a beam attenuation coefficient, b_b is a backscattering coefficient, $B = b_b / b$ is a probability of backscattering [5], and $g = b_b / (c - b + b_b)$ is a Gordon's parameter that determines remote sensing and diffuse reflection coefficients. The values of b were estimated by integrating values of angular scattering coefficient $\beta(\theta)$. We used parabolic approximation to smaller angles using values of $\log \beta(\theta)$ at 2, 7.5, and 12.5 degrees. Extrapolation to larger than 162.5 degrees was: $\beta(\theta > 162.5°) = \beta(162.5°)$. The values of beam attenuation coefficient c for two phase functions No. 12 and 16 were not measured.

Figure 1 displays dependence of backscattering coefficient b_b on scattering coefficient b for both Petzold and our new phase functions. The following linear relationship, derived from the data shown in Fig. 1,

$$b_b = 0.0009 + 0.015b, \qquad r^2 = 0.95, \qquad (1)$$

Table 5. Natural logarithms of ASC $\beta(\theta)$ No. 11-15.

Angle\#	11	12	13	14	15
2.00	2.7930	2.0792	1.3420	1.5262	0.6282
7.50	-0.3776	-1.3677	-2.2895	-1.8750	-3.3487
12.50	-1.3700	-2.2450	-3.4876	-2.9120	-4.0633
17.50	-1.8697	-2.7907	-4.2641	-3.6424	-4.7706
22.50	-2.4569	-3.7233	-4.8059	-4.2993	-5.2434
27.50	-3.1684	-4.4118	-5.4009	-5.0555	-5.7924
32.50	-3.6841	-4.8815	-5.7329	-5.5487	-6.1935
37.50	-4.0433	-5.3328	-6.3219	-5.9535	-6.5982
42.50	-4.2137	-5.6644	-6.6091	-6.3098	-6.8855
47.50	-4.5637	-6.0604	-7.0744	-6.6599	-7.2125
52.50	-5.0680	-6.3344	-7.2083	-7.0011	-7.4616
57.50	-5.2131	-6.6176	-7.4004	-7.2393	-7.6768
62.50	-5.5999	-6.9354	-7.6263	-7.5112	-7.7415
67.50	-5.9499	-7.1012	-7.7007	-7.7007	-8.0001
72.50	-6.3805	-7.5087	-7.9683	-7.8301	-8.2676
77.50	-6.4703	-7.4834	-7.9449	-7.9449	-8.4054
82.50	-6.8249	-7.6077	-8.2288	-8.0676	-8.3900
87.50	-6.9078	-7.7137	-8.2212	-8.2212	-8.4514
92.50	-7.0689	-7.8748	-8.4169	-8.4169	-8.4860
97.50	-7.1012	-7.9071	-8.2979	-8.2979	-8.5282
102.50	-7.1380	-7.9439	-8.5090	-8.5090	-8.5090
107.50	-7.3475	-7.9923	-8.5785	-8.4173	-8.6475
112.50	-7.2393	-8.0452	-8.7254	-8.6563	-8.6563
117.50	-7.1887	-7.9946	-8.5819	-8.5819	-8.7431
122.50	-7.2854	-7.7459	-8.5287	-8.5287	-8.6899
127.50	-7.3936	-7.8541	-8.5093	-8.5093	-8.6474
132.50	-7.3268	-7.8334	-8.7783	-8.5020	-8.6401
137.50	-7.2762	-7.8518	-8.6584	-8.4973	-8.6584
142.50	-7.2670	-7.7275	-8.8317	-8.4402	-8.5554
147.50	-7.1841	-7.7597	-8.7493	-8.4730	-8.6342
152.50	-7.1288	-7.8656	-8.4634	-8.4634	-8.5555
157.50	-6.8778	-7.7989	-8.5591	-8.2828	-8.6972
162.50	-6.9584	-7.6262	-8.2936	-8.1094	-8.4087
b, 1/m	0.9418	0.4099	0.1796	0.2303	0.0921
c, 1/m	1.1052	-	0.2072	0.2671	0.1151
b_b 1/m	0.0110	0.0055	0.0028	0.0031	0.0026
B	0.0116	0.0133	0.0158	0.0135	0.0287
g	0.0628	-	0.0930	0.0777	0.1028

Table 6. Natural logarithms of ASC $\beta(\theta)$ No. 16-20.

Angle\#	16	17	18	19	20
2.00	0.8815	1.0887	0.8354	1.3420	0.9506
7.50	-3.2565	-2.1974	-2.7730	-1.8750	-2.5658
12.50	-4.1554	-3.3495	-3.7640	-3.4186	-3.8100
17.50	-4.6555	-4.0108	-4.4483	-4.1029	-4.3562
22.50	-5.3585	-4.5296	-4.8749	-4.6907	-4.8749
27.50	-5.4930	-5.0555	-5.4930	-5.4930	-5.4009
32.50	-6.0783	-5.6408	-5.9402	-5.8250	-5.7329
37.50	-6.4140	-5.9535	-6.4831	-6.1837	-6.1837
42.50	-6.8855	-6.4940	-6.6091	-6.4940	-6.4940
47.50	-7.0744	-6.5218	-7.0744	-6.9362	-6.7981
52.50	-7.3004	-7.1392	-7.1392	-7.2083	-7.1392
57.50	-7.5616	-7.1472	-7.2393	-7.1472	-7.2393
62.50	-7.6263	-7.1888	-7.5112	-7.3500	-7.5112
67.50	-7.8619	-7.3093	-7.5856	-7.4705	-7.7007
72.50	-8.1064	-7.6689	-7.8301	-7.6689	-7.8301
77.50	-8.2442	-7.8067	-8.0830	-8.0830	-8.0830
82.50	-8.3900	-7.9295	-8.2288	-8.2288	-8.3900
87.50	-8.3824	-8.0600	-8.3824	-8.3824	-8.3824
92.50	-8.4169	-8.2557	-8.2557	-8.2557	-8.2557
97.50	-8.4591	-8.4591	-8.2979	-8.1367	-8.4591
102.50	-8.5090	-8.5781	-8.1867	-8.5090	-8.5090
107.50	-8.5785	-8.6475	-8.5785	-8.5785	-8.5785
112.50	-8.7254	-8.6563	-8.4951	-8.3339	-8.4951
117.50	-8.5819	-8.5819	-8.2826	-8.4207	-8.7431
122.50	-8.5287	-8.5287	-8.2524	-8.5287	-8.5287
127.50	-8.5093	-8.6474	-8.2099	-8.6474	-8.5093
132.50	-8.6401	-8.6401	-8.5020	-8.5020	-8.6401
137.50	-8.6584	-8.6584	-8.4973	-8.4973	-8.6584
142.50	-8.4402	-8.4402	-8.4402	-8.5554	-8.5554
147.50	-8.3118	-8.3118	-8.4730	-8.6342	-8.4730
152.50	-8.2561	-8.4634	-8.3943	-8.5555	-8.3943
157.50	-8.1446	-8.6972	-7.8913	-8.2828	-8.0065
162.50	-7.8791	-8.2936	-8.1785	-8.1785	-7.7640
b, 1/m	0.1151	0.1589	0.1174	0.1911	0.1313
c, 1/m	-	0.2164	0.1566	0.2233	0.1520
b_b, 1/m	0.0062	0.0029	0.0036	0.0032	0.0032
B	0.0270	0.0182	0.0303	0.0168	0.0242
g	-	0.0478	0.0833	0.0903	0.1327

connects backscattering coefficient with scattering coefficient. This relationship is valid for the values of b in the range of: $b_w(520) \le b \le 2\,\mathrm{m}^{-1}$, where $b_w(520) \approx 0.0019$ is a scattering coefficient for pure water at 520 nm.

CONCLUSION

Presented here 20 new phase functions of light scattering by natural water with corresponding integral inherent optical properties compliment earlier Petzold phase functions [1] for the case of open ocean, sea, and clear lake waters.

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REFERENCES

[1] T. J. Petzold, Volume Scattering Functions for Selected Ocean Waters, SIO Ref. 72-78, Scripps Institute of Oceanography, Visibility Laboratory, San Diego, CA, 1972, 79 p.

[2] V. I. Haltrin, and V. I. Mankovsky, "Analytical representation of experimental light scattering phase functions measured in seas, oceans and lake Baykal," – in these *Proceedings*.

[3] V. I. Mankovsky, and M. N. Kaigorodov, "Laboratory auto-collimated transmissometer with variable base," pp. 91-92 in *Automatizaton of Scientific Investigations of Seas and Oceans*, (Marine Hydrophysical Institute Ukrainian Academy of sciences, Sevastopol, 1980), in Russian.

[4] V. I. Mankovsky (*a.k.a* V. I. Man'kovsky), "Marine pulse-time nephelometer," pp.81-89 in *The Probes for Scientific Investigations and Automatic Systems*, (Naukova Dumka, Kiev, Ukraine, 1981), in Russian.

[5] V. I. Haltrin, "Theoretical and empirical phase functions for Monte Carlo calculations of light scattering in seawater," in *Proceedings of the Fourth International Conference Remote Sensing for Marine and Coastal Environments*, I, pp. 509-518, (Envir. Res. Inst. of Michigan, Ann Arbor, MI, 1997).