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WATERS

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## ABSTRACT

Measurements of the volume scattering function and other optical properties are presented for distilled water, Pacific coastal and offshore water, and lake water. The depth and time variability of Pacific water at one station is given and the effect of a wind storm on the optical properties of the lake water is demonstrated.

## INSTRUMENTATION

The scattering meter used in this work was originally described by Tyler and Richardson (1958). It has recently been critically tested for performance by comparing the results of measurements on prepared stable hydrosols by two independent methods, one of which employed the scattering meter, the other employed an optical integration method described by Tyler (1957). The results of these tests are reported elsewhere.

In order to maintain the accuracy of the data obtained with the scattering meter it has been necessary to maintain its calibration in several respects as follows:

1. *Angle calibration*—The scattering angle  $\theta$  is related to the output of a voltage divider circuit supplied by a highly stable power source. The phototube arm is geared directly to the potentiometer of the voltage divider which governs the position of the pen of a Brown synchronously driven strip-chart recorder. The performance of this circuit and power supply has been checked at the beginning of every series of measurements and can be post checked for each individual run if desired. The voltage divider has proved to be very precise. The indication of angle is accurate to  $\pm .25^\circ$  at  $180^\circ$ ,  $\pm .13^\circ$  at  $90^\circ$  and smaller fractions of an angle at  $0^\circ$ , the forward scattering direction. The error in the indication of angular

position is generally no larger than the error encountered in reading the data.

2. *Circuit calibration*—The output of the multiplier phototube circuit is designed to be proportional to the log of the light input to the phototube. The circuit used is not quite linear over its 5-log range. Data obtained with this circuit is read by means of a scale which is made by exposing the multiplier phototube to known steps in light

TABLE 1. Scattering properties of commercial "distilled" water samples. Bandwidth limited by a Wratten No. 57 filter

Sample	A	B
Total attenuation coefficient $\alpha/m$	.062	.047
Total scattering coefficient $s/m$	.00845	.00457
Absorption coefficient $a/m$	.0536	.0424
Forward scattering coefficient $f/m$	.00763	.00396
Backward scattering coefficient $b/m$	.00082	.000620
Ratio $f/s$	.900	.870
Volume scattering function $\sigma(\theta)$		
$\theta = 0^\circ$		
10		
20	.00648	.00316
30	.00223	.00107
40	.000941	.000520
50	.000473	.000294
60	.000271	.000191
70	.000181	.000128
80	.000140	.000096
90	.000117	.000083
100	.000110	.000079
110	.000118	.000082
120	.000126	.000092
130	.000134	.000102
140	.000139	.000112
150	.000146	.000119
160	.000171	.000141
170	.000193	.000161
180	.000201	.000169

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TABLE 2. *Scattering properties of Pacific Coastal and offshore water at the Stations shown in Figure 1. Bandwidth limited by a Wratten No. 57 filter*

Station number	1	2	3	4
Total attenuation coefficient $\alpha/m$	.736	.129	.118	.111
Total scattering coefficient $s/m$	.125	.01094	.01420	.0120
Absorption coefficient $a/m$	.611	.1181	.1038	.099
Forward scattering coefficient $f/m$	.119	.01010	.01321	.0110
Backward scattering coefficient $b/m$	.00630	.000847	.000982	.000984
Ratio $f/s$	.950	.925	.930	.915
Volume scattering function $\sigma(\theta)$				
$\theta = 0^\circ$				
10				
20	.1014	.00881	.01192	.00959
30	.0360	.00268	.00358	.00313
40	.0152	.00117	.00145	.00129
50	.00739	.000616	.000698	.000661
60	.00419	.000356	.000396	.000388
70	.00266	.000232	.000253	.000249
80	.00181	.000164	.000179	.000175
90	.00134	.000132	.000145	.000142
100	.00109	.000120	.000134	.000130
110	.000940	.000120	.000135	.000135
120	.000903	.000124	.000146	.000146
130	.000912	.000134	.000158	.000159
140	.000944	.000145	.000175	.000176
150	.001003	.000156	.000192	.000193
160	.001028	.000175	.000202	.000208
170	.001036	.000191	.000206	.000219
180	.001037	.000197	.000207	.000223

level, using the inverse square law to establish the steps. Scales of this kind have been made on the average of every two months

during the work, usually just before or just after a series of measurements.

The circuit has been found to vary  $\pm 2.5\%$

TABLE 3. *Variability in the optical properties of coastal water at Station 4. Data taken in November 1960. Bandwidth limited by a Wratten No. 57 filter*

Depth (m)	$\alpha$ (per m)	$s$ (per m)	$a$ (per m)	$f/s$	Time	Tide (ft)
20	.218	.0205	.197	.935	1850	
10	.162	.0176	.144	.940	1910	
1	.148	.0156	.132	.928	1925	4.4
20	.183	.0200	.163	.940	2200	
10	.153	.0173	.136	.935	2213	
1	.161	.0186	.142	.935	2225	
20	.148	.0189	.129	.935	0100	
10	.132	.0167	.115	.935	0110	
1	.111	.0120	.099	.917	0123	1.1
20	.139	.0151	.124	.929	0405	
10	.133	.0131	.120	.944	0420	
1	.133	.0130	.120	.944	0430	
Averages						
20m	.172	.0186	.153	.934		
10m	.145	.0161	.129	.938		
1m	.138	.0148	.123	.931		
Overall	.152	.01653	.1343	.9347		
Variability	$\pm 35\%$	$\pm 25\%$	$\pm 35\%$	$\pm 1.5\%$		

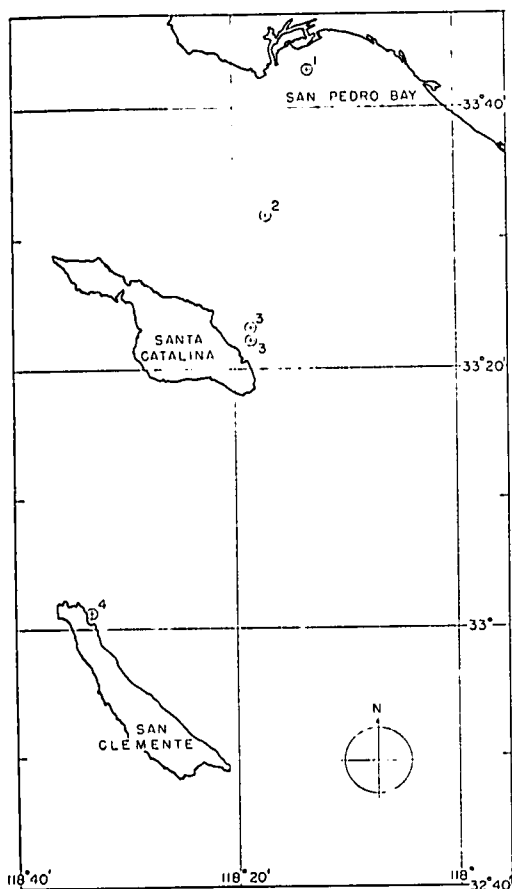


FIG. 1. Chart showing location of coastal and offshore stations where the volume scattering function has been measured.

at high light levels,  $\pm 10\%$  at the extreme low light levels.

3. *Volume calibration*—The sample volume has been determined by a method very similar to that described by Pritchard and Elliott (1960). Since the volume is defined by optical and mechanical components, which do not change their characteristics as readily as electrical components, a volume calibration, made near the beginning of these measurements in 1959, was used throughout. The volume calibration consisted of 59 determinations of the sample volume at 15 different angular settings. Maximum uncertainty in the determination of the sample volume is  $\pm 12\%$ .

4. *Irradiance input calibration*—Irradi-

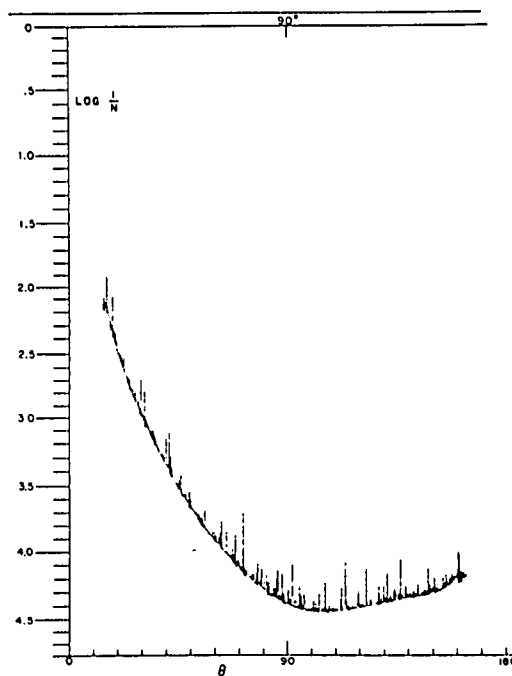


FIG. 2. Data record from a depth of 20 m at Station 4, showing bioluminescent flashing superimposed on the scattering data. This record is uncorrected for changes in the sample volume.

ance input has been determined from measurements on the beam itself using the instrument's own multiplier phototube in order to cancel out optical and circuit gain factors. The calibration procedure has been repeated 5 times during the course of this work and, in between these calibrations, the irradiance input has been controlled by regulation and control of the lamp voltage to  $\frac{1}{4}\%$ . The accuracy of the irradiance input calibration is estimated to be  $\pm 10\%$ .

The sources of inaccuracy in these measurements do not characteristically vary during short periods of time. Thus, values of the volume scattering function in a single determination can be expected to describe accurately the shape of the curve but there is a high degree of probability that the values reported will collectively be too high, or too low, by 10%. Similarly there is a high degree of probability that data taken during one month will be inconsistent with data taken during another month by  $\pm 10\%$ .

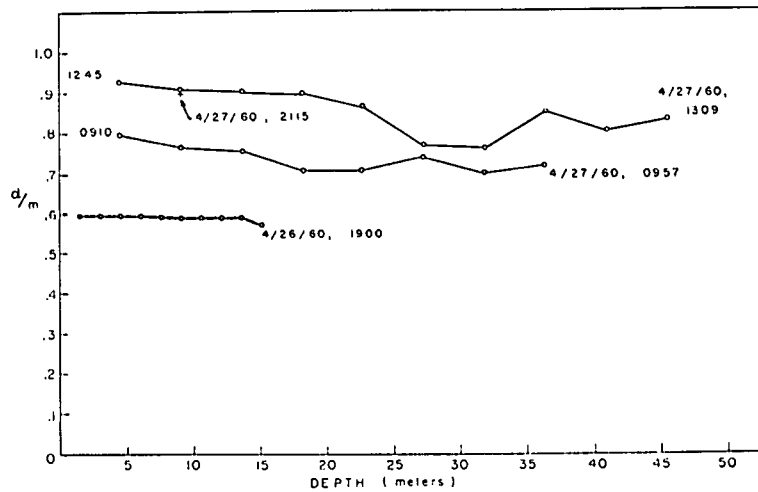


FIG. 3. Showing the variation of  $\alpha$  with depth at Lake Pend Oreille on a calm day (April 26, 1960) and at various times during the following day, which was very windy. Bandwidth limited by a Wratten No. 45 filter.

Because of the circuitry employed the lake and ocean data presented here have been obtained at night and the distilled water data has been obtained in a darkened tank.

#### RESULTS

Table 1 gives the volume scattering function and other optical data for two samples

which were purchased as distilled water. Neither sample is regarded as being distilled in the strict sense of the word. The two samples do, however, provide a convenient base for comparison. The filter used has its maximum transmittance at about  $522\text{ m}\mu$  and has a halfband width of about  $80\text{ m}\mu$ . Sample B compares favorably

TABLE 4. Variability in the optical properties of coastal water at Station 4. Data taken in January, 1961. Bandwidth limited by a Wratten No. 57 filter

Depth (m)	$\alpha$ (per m)	$s$ (per m)	$a$ (per m)	$f/s$	Time	Tide (ft)
20	.153	.0154	.138	.938	0230	
10	.162	.0149	.147	.935	0245	1.4
1	.159	.0123	.147	.935	0255	
20	.176	.0157	.160	.943	1920	
10	.186	.0163	.170	.945	1935	
1	.170	.0131	.157	.939	1945	
20	.165	.0154	.150	.936	2210	
10	.152	.0141	.138	.943	2230	4.6
1	.139	.0108	.128	.924	2240	
20	.167	.0157	.151	.937	0100	
10	.162	.0166	.145	.935	0110	
1	.162	.0143	.148	.930	0125	
					0850	6.9
					1558	-1.7
Averages						
20m	.165	.0156	.150	.939		
10m	.166	.0155	.150	.940		
1m	.158	.0126	.145	.932		
Overall	.163	.0146	.148	.937		
Variability	$\pm 10\%$	$\pm 20\%$	$\pm 11\%$	$\pm 1.1\%$		

TABLE 5. Volume scattering function for Lake Pend Oreille before and after a high wind. Bandwidth limited by a Wratten No. 45 filter

Sample date	April 26	April 27
Total attenuation coefficient $\alpha/m$	.589	.909
Total scattering coefficient $s/m$	.258	.585
Absorption coefficient $a/m$	.331	.324
Forward scattering coefficient $f/m$	.248	.559
Backward scattering coefficient $b/m$	.00976	.0256
Ratio $f/s$	.960	.955
Volume scattering function $\sigma(\theta)$		
$\theta = 0^\circ$		
10		
20	.222	.470
30	.0715	.166
40	.0291	.0758
50	.0137	.0380
60	.00712	.0206
70	.00416	.0121
80	.00271	.00780
90	.00198	.00559
100	.00162	.00448
110	.00147	.00394
120	.00143	.00379
130	.00145	.00372
140	.00149	.00371
150	.00156	.00383
160	.00163	.00396
170	.00168	.00406
180	.00170	.00410

with the distilled water described by Hulburt (1945). The ratio of  $f/s$  for distilled water is lower than it is for the lake and ocean samples. This would be expected as a consequence of predominately smaller particle size in the cleaner water. The minimum value of the volume scattering function occurs at  $100^\circ$  in both samples.

Table 2 gives the volume scattering function and other data for coastal and off-shore water in the Los Angeles—San Diego area. Station locations are shown in Figure 1. Station 1 is in the outfall area of a sewage disposal plant. The water at Station 1 was full of phosphorescent microorganisms. However, the relative motion between the scattering meter and the water was very slow at this station and phosphorescence was not seen during the measurements. It is unlikely that the relative motion between instrument and water caused enough phosphorescence to affect the measurement.

Stations 2, 3, and 4 were outside the

TABLE 6. Variability in the optical properties of Lake Pend Oreille as a function of depth before and during a high wind. Bandwidth limited by a Wratten No. 45 filter

Depth (m)	$\alpha$ (per m)	$s$ (per m)	$a$ (per m)	$f/s$	Date
4.6	.594	.236	.348	96.4	
9.2	.589	.258	.331	96.6	April 26, 1960
13.8	.589	.245	.344	96.1	
9.2	.909	.585	.324	95.5	
18.2	.897	.559	.338	95.2	April 27, 1960
24.7	.865	.585	.280	95.7	

sewage outfall area but were full of flashing bioluminescent organisms. A typical record from Station 4 at 20-m depth is shown in Figure 2. Relative motion between instrument and the water was fairly rapid at Station 4 and the organisms could be seen flashing as they bumped into the various parts of the scattering meter. The same Wratten No. 57 filter was used in these measurements. Note that the angular position of the minimum value of the volume scattering function varies from  $100^\circ$  to  $120^\circ$  in these data.

Tables 3 and 4 show the principle features of the time and depth variability of the water at Station 4—again using the Wratten No. 57 filter. In Table 3 the water appears to become more absorbing and more scattering with depth and exhibits a high degree of variability. In Table 4, the water is much less variable with time and depth. The ratio of  $f/s$  is substantially constant for both days and for all depths and times, indicating that the particle shape is not varying significantly.

Table 5 gives the volume scattering function for lake water at the southern end of Lake Pend Oreille, Idaho, just before (April 26) and after (April 27) a strong north wind. These data were taken with a Wratten No. 45 filter which has a peak transmittance at  $480 m\mu$  and a half bandwidth of about  $60 m\mu$ . Minimum scattering here occurs at  $120^\circ$  and  $140^\circ$  and the ratio  $f/s$  is the highest reported.

There has been an obvious increase in scattering following the high wind. The changes in  $\alpha$  are followed in a little more detail in Figure 3 which shows  $\alpha$  as a func-

tion of depth on April 26 at 1900 and for two periods during April 28 with one check point taken at 2115. The slopes of the two curves for the 28th suggest that wave action along the shores is introducing scattering material into the surface water which is being carried away from shore by the wind and mixed by wave action. Disturbing of bottom sediments at the station seems unlikely because of the 750 ft of depth.

Table 4 gives additional data on the variability of the lake water with depth on these two days.

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