

Effect of dissolved NaCl, MgCl₂, and Na₂SO₄ in seawater on the optical attenuation in the region from 430 to 630 nm

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The split-pulse laser method is used to reinvestigate the optical attenuation of distilled water in the region from 430 to 630 nm. The studies are then extended to ionic solutions of NaCl, MgCl₂, and Na₂SO₄, these forming the major constituents of seawater. The effect of the concentration of these constituents on optical attenuation is investigated. Further, optical attenuation studies are carried out for the region from 430 to 630 nm for an aqueous solution prepared with all the major constituents in the same proportions as in natural seawater. These values are then compared with values obtained for natural seawater. The relative influence of dissolved salts and suspended particles on optical attenuation in seawater is discussed. The lowest attenuation is observed at ~450 nm for all solutions and is found to coincide with that for distilled water.

I. Introduction

Optical properties of seawater have become a subject of renewed interest in recent years. The motivation for such studies is the search for an optical window for underwater communications to complement ultrasonic transducer technology. Several authors have reported the optical properties of distilled water, clear natural water, and seawater. In 1963, Sullivan¹ reported the absorption coefficient $\alpha(\lambda)$ of distilled water, artificial seawater, and heavy water in the visible region. The experimental setup consisted of a single cell for which reflection corrections were required for the cell windows. This was followed by an exhaustive review by Irvine and Pollack² covering the available literature on the optical properties of water in the region from 0.7 to 200 μm . They tabulated the extinction coefficient $k(\lambda)$ and the Lambert absorption coefficient $\alpha(\lambda)$ collected from different papers. Zolotarev *et al.*³ have reported values for the optical constants of water throughout the 1–10⁶- μm spectral region. Hale and Querry⁴ again reviewed the subject and presented a fresh set of values of $n(\lambda)$ and $k(\lambda)$ of water in the region from 200 nm to 200 μm .

A major deviation from the conventional experiments began when Querry *et al.*⁵ reported the attenuation coefficient of deionized filtered water by the split-pulse laser method. A tunable dye laser was used as the source and reflection losses were corrected by a compensating cell. Hass and Davisson⁶ had also de-

termined the absorption coefficients of distilled water and deionized filtered water for wavelengths of 446 and 514.5 nm by the laser adiabatic calorimetric technique. Tam and Patel⁷ reported the absorption coefficients of distilled water by photoacoustic spectroscopy for the region from 446 to 695 nm. Later, Sz and Baker⁸ reported the attenuation of very clear natural water.

A close examination of the various experimental results reveal that discrepancies of a factor of 2 are common among reported values. The reasons for these discrepancies have also been discussed.^{5,7} The split-pulse laser method has the design advantage of eliminating many possible experimental errors. The photoacoustic method also eliminates many possible errors and has the added advantage of being more sensitive. However, the photoacoustic method cannot give information about the scattered light. In view of the several advantages, we adopted the split-pulse laser method for the present investigations to determine the total attenuation coefficients.

Even though there are reported results^{9–12} on transmission characteristics of light in seawater, a detailed study has been reported on the effect of dissolved constituents of seawater on optical attenuation. Since the dependence of optical attenuation on the concentration of dissolved constituents is a parameter of vital importance in the area of undersea laser communications, a careful and systematic study is undertaken in the region from 425 to 635 nm. It is hoped that these studies would also reveal the relative influence of suspended particles over dissolved constituents on the total attenuation by seawater. Above all, these studies are expected to give valuable information on the optical window in seawater and the influence of the constituents of seawater on that optical window.

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I. Experimental

The split-pulse laser method first used by Querry *et al.*⁵ was adopted for the present studies. A nitrogen laser pumped dye laser was used as the source. The lasers and the scanning system were built for this specific use. The dye laser operating at 10 pps gave pulses of ~ 3 -ns duration and 0.04-nm linewidth. A 500-cm sample cell and a 15-cm reference cell both of 5-cm internal diameter were used. The glass windows of these cells were identical in thickness and reflectivity. The mirrors were also of the same reflectivity, made by simultaneously coating aluminum on two optical flats. A semireflecting mirror was used as the beam splitter. Since the two pulses were not treated identically by the beam splitter, its nature was studied first by measuring the intensity ratio before using the cells, and this correction was applied to the final reading. A Hewlett-Packard PIN photodiode (5082-4207) was used as the detector. As the signals from the sample cell lag behind that from the reference cell by ~ 40 ns, it was possible to detect them separately by the photodiode. The signals were then fed to the two channels of a boxcar averager (EG&G PARC model 162). The ratio of the intensities of the pulses was obtained from the boxcar averager from which the attenuation coefficient $\alpha(\lambda)$ was calculated. All the measurements were carried out at $25 \pm 1^\circ\text{C}$. Measurements were taken for every 2.5 nm for the entire region from 430 to 635 nm. The average of ~ 1500 pulses was noted in each scan. Every value reported here is the average of five such scans. Our values for the 540–575-nm region are not sufficiently accurate due to the lack of suitable dyes and therefore they are not presented here.

II. Sample Preparation and Scheme of Study

In seawater, almost all the dissolved constituents are in the ionic state. Their proportions by mass are given in Table I.¹³ These proportions are reported to be constant throughout the ocean. In the sea, the variation of salinity is generally between 20 ppt (parts per thousand) and 35 ppt. Based on these figures, the salts and their concentrations are chosen for preparing the final solutions. To study the influence of the major constituents on optical attenuation, independent solutions of NaCl, MgCl₂, and Na₂SO₄ are investigated. A 0.25-M solution of NaCl (14.6 g/liter) will

contain sodium and chlorine of approximately the same order as is found in natural seawater. Therefore, 0.25-M solutions of the salts of NaCl, MgCl₂ · 6H₂O, and Na₂SO₄ were first studied for comparison. NaCl being the major constituent of seawater, it was studied for different concentrations, of which three results (10, 20, and 30 g/liter) are reported here. In the case of MgCl₂ · 6H₂O, a 0.25-M solution (50.83 g/liter) will contain a larger quantity of magnesium compared with that in natural seawater. Since magnesium is less abundant in seawater, the results of only two concentrations corresponding to the maximum and minimum in natural seawater (5 and 15 g/liter) are reported in this paper. The quantity of SO₄ in a 0.25-M solution of Na₂SO₄ (35 g/liter) is almost seven times that found in seawater. Therefore, the attenuation for a very low concentration (5 g/liter) is reported here. As there is no significant variation between the results for 5- and 25-g/liter solutions, studies on no other concentration are reported here.

Two samples of artificial seawater, both of 35-ppt salinity, are studied. The samples are prepared by adding the required salts in the proportions to match the ratios of these salts in natural seawater. The proportions by mass of the constituents of the two samples are shown in Table I. The first sample contained only the major constituents, while in the second sample minor constituents were also added, attempting to elucidate information on the influence of minor constituents on optical attenuation. Along with the above studies, two samples of natural seawater are also studied to make a comparison. The samples were collected from the Arabian Sea, one from 30 km to the west of Cochin (35.46-ppt salinity) and the other from 3 km to the west of Cochin (28.65-ppt salinity), both from a 10-m depth.

For the laboratory prepared samples, doubly distilled water and Analar grade salts were used for all the experiments. Other precautions to avoid dust particles and bubbles were taken to obtain consistent results.

IV. Results and Discussions

A. Distilled Water

The values of the attenuation coefficient of distilled water for different wavelengths are presented in Table II. Figure 1 plots attenuation coefficient against wavelength with similar plots reported by earlier workers.^{1,4,5,7} One important observation is that the present $\alpha(\lambda)$ values for all wavelengths below 540 nm are higher than those reported by Tam and Patel. The values of the attenuation coefficient depend on both absorption and scattering. The values reported by Tam and Patel contain only the absorption coefficient while the present values include molecular scattering also. Thus the relatively high values obtained here compared with the reported values of Tam and Patel are due to the scattering contribution. Above 580 nm, there is a sharp increase in the value of $\alpha(\lambda)$ and all the earlier reported values coincide in this region within

Table I. Percentage by Mass of the Constituents of Natural Sea Water and the Two Samples of Artificial Sea Water

Constituents	Natural sea water	Artificial sea water	
		Sample I	Sample II
Sodium (Na ⁺)	30.61	32.42	31.618
Magnesium (Mg ²⁺)	3.69	3.93	3.809
Calcium (Ca ²⁺)	1.16	—	0.036
Potassium (K ⁺)	1.10	—	1.139
Strontium (Sr ²⁺)	0.04	—	—
Chloride (Cl ⁻)	55.04	55.45	54.773
Sulfate (SO ₄ ²⁻)	7.68	8.19	7.935
Bicarbonate (HCO ₃ ⁻)	0.41	—	0.419
Bromide (Br ⁻)	0.19	—	0.193
Boric acid (H ₃ BO ₃)	0.07	—	0.078

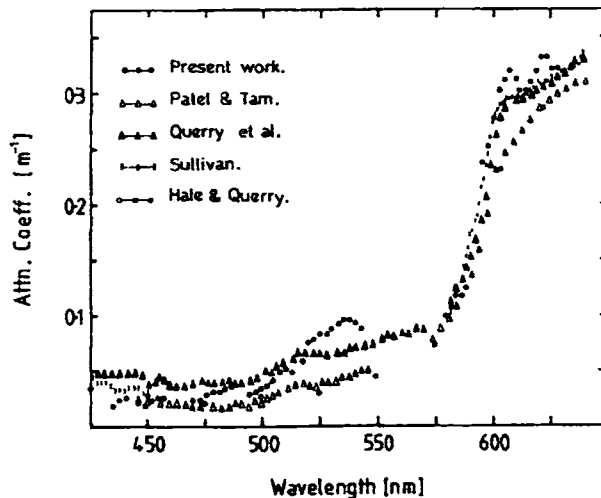


Fig. 1. Graphic comparison of the attenuation coefficient of distilled water obtained by the present investigation and some of the other reported results.

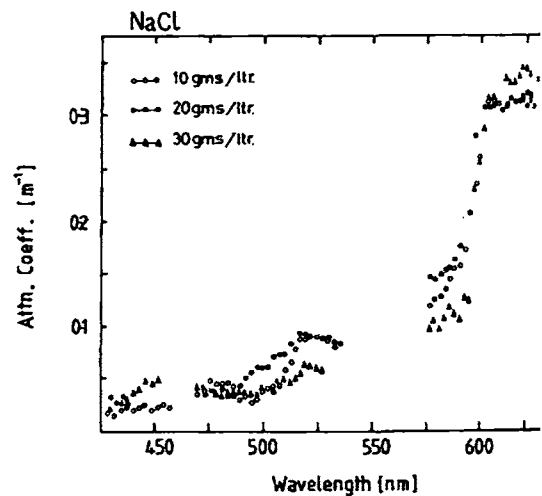


Fig. 2. Attenuation coefficient of NaCl solutions of three concentrations vs wavelength.

Table II. Attenuation Coefficients of Distilled Water for Different Wavelengths (in Units of 10^{-2} m^{-1})

Wavelength (nm)	Attenuation coefficient	Wavelength (nm)	Attenuation coefficient
434.9	1.8243	530.0	8.7396
437.6	2.2168	532.8	9.1854
440.5	2.5829	535.3	9.4161
442.2	3.1928	537.9	9.5843
446.2	2.0930	540.4	9.3734
449.1	1.8300	542.8	8.8541
451.8	2.2168	546.9	6.8053
454.8	2.4026		
457.0	2.4026	574.4	8.2680
		579.2	9.9630
470.0	2.3660	581.5	10.632
473.0	2.7899	584.0	11.727
479.0	2.9900	586.1	11.871
481.7	2.9900	588.2	12.383
484.2	3.1823	590.4	12.405
486.9	3.6060	592.8	12.746
489.6	3.9987	595.2	23.694
492.2	2.5438	597.5	25.148
494.8	2.7899	599.8	27.818
497.4	2.9877	602.3	30.227
500.0	3.1823	604.6	31.304
502.6	3.6062	606.9	31.921
505.1	3.9986	609.3	31.176
507.8	4.7057	611.5	30.262
510.4	4.8915	613.9	30.270
512.9	4.7293	616.2	31.068
515.5	4.1844	618.5	31.988
517.6	5.8697	620.8	33.148
520.1	7.4601	623.2	33.341
522.7	7.8373	625.5	32.213
525.2	8.1831	627.8	32.147
527.8	8.3434		

experimental limits. This clearly demonstrates absorption is very high in this region compared to scattering, and no sensitive change could be recorded. In our studies, the lowest attenuation coefficient was observed in the 435–480-nm region. This value is lower than the values reported by earlier workers. To obtain more reliable information on this minimum we scanned this region using two dyes: Coumarin 440 and coumarin 450 (Exciton Chemical Co.). Because of the very low attenuation coefficient value in this region the reported values are not so accurate as the values reported for other regions. However, there is no ambiguity in establishing the lowest attenuation in this region.

B. Sodium Chloride Solution

The attenuation for sodium chloride solutions of three different concentrations (10, 20, and 30 g/l) are shown in Fig. 2, and the values are given in Table III, e.g., 30 g/liter of NaCl solution will have 11.8% sodium which is more than the maximum value of sodium found in seawater. From the curves it can be seen that within these concentration levels, the attenuation is not much dependent on the concentration. The values are close to those for distilled water. There is no shift in the wavelength of the minimum attenuation.

C. Magnesium Chloride Solution

Figure 3 shows the attenuation coefficient for three concentrations (5, 15, and 50.82 g/liter) of magnesium chloride ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) in water. The corresponding values are given in Table IV. The 15-g/liter solution of $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ contains 1.79 g of magnesium, which is almost equal to the maximum value of magnesium found in 1 liter of seawater. The curves show considerable dependence on concentration. As the concentration increases, the attenuation for the region below 540 nm also increases, whereas above 590 nm the attenuation is almost the same for all the solutions.

Table III. Attenuation Coefficients of NaCl Solutions for Different Wavelengths (in Units of 10^{-2} m^{-1})

Wavelength (nm)	10 g/liter	20 g/liter	30 g/liter	Wavelength (nm)	10 g/liter	20 g/liter	30 g/liter
429.4	1.7223	3.2136	2.2401	522.7	9.0282	9.0011	6.4735
432.0	1.5997	2.7571	2.8120	525.2	9.0040	9.0842	6.2574
434.9	2.0775	3.1980	3.0034	527.8	8.8712	8.6897	5.9707
437.7	2.3623	2.5820	3.2453	530.3	8.5771	8.7361	7.1998
440.5	2.0876	—	4.1204	532.8	8.3900	8.0774	9.7071
443.2	2.2440	—	4.1820	535.3	7.3706	8.1837	—
446.2	2.5033	—	4.8751	537.9	6.8434	—	—
449.2	1.9593	—	4.8222	540.4	5.7383	—	—
451.8	2.2029	—	5.0729	572.5	13.994	—	—
454.5	2.5822	—	—	574.4	13.185	—	—
456.9	2.2168	—	—	576.8	12.038	14.463	9.961
470.7	3.6062	—	4.3322	579.2	12.492	14.137	10.737
473.4	3.8660	3.4801	4.1044	581.5	12.861	14.677	10.091
476.2	4.7504	3.7324	3.7370	584.0	13.606	15.130	11.114
479.0	4.4714	4.2422	3.7370	586.1	14.533	15.618	12.004
481.7	4.5677	3.9941	3.7370	588.2	15.391	16.335	11.600
484.7	4.4714	3.2567	3.7370	590.4	15.682	17.514	10.881
486.9	4.1602	3.3259	3.7920	592.8	17.250	16.631	13.072
489.6	3.0900	4.3416	3.9977	595.2	20.864	—	12.746
492.2	3.2429	4.9380	3.4380	597.5	23.399	28.020	23.366
494.8	2.7557	5.3880	3.8702	599.8	26.099	31.211	25.771
497.4	3.0942	5.9172	3.8702	602.3	30.777	32.512	28.606
500.0	3.7061	5.9304	4.1225	604.6	31.326	30.438	31.449
502.6	4.0915	6.0136	4.1044	606.9	31.144	30.859	31.462
505.1	4.1450	6.9506	3.9258	609.3	30.893	28.915	30.827
507.8	4.3094	7.2331	4.6909	611.5	30.519	29.601	31.028
510.4	5.8713	7.2331	4.9370	613.9	31.116	30.810	33.610
512.9	6.5596	8.2650	5.0645	616.2	31.189	31.500	33.231
515.5	7.6689	9.7070	5.2261	618.5	31.266	30.987	33.184
517.6	8.7925	9.3083	5.8645	620.8	31.271	31.221	33.758
520.1	8.7769	8.9860	6.5782	623.2	31.872	31.221	34.248
				625.5	32.070	30.750	34.175
				627.8	31.170	31.672	33.733
				630.1	30.653	—	—
				632.6	33.305	—	—

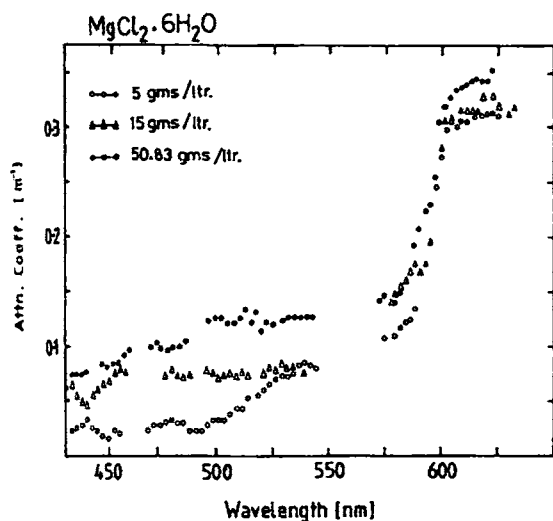


Fig. 3. Attenuation coefficient of $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ solutions of three concentrations vs wavelength.

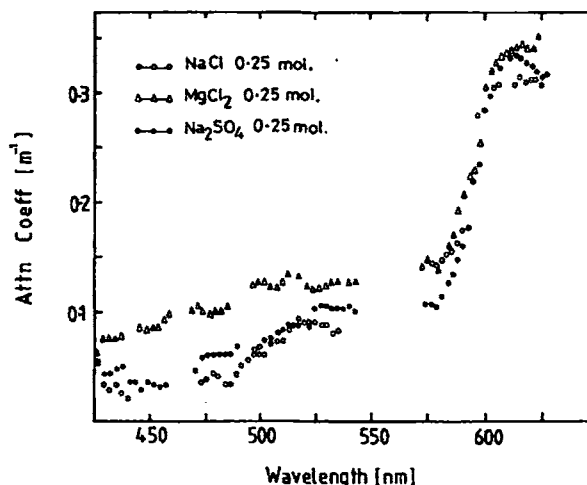


Fig. 4. Attenuation coefficient of Na_2SO_4 solutions of two concentrations vs wavelength.

Table IV. Attenuation Coefficients of Magnesium Chloride Solutions for Different Wavelengths (In Units of 10^{-2} m^{-1})

Wavelength (nm)	5 g/liter	15 g/liter	0.25 M	Wavelength (nm)	5 g/liter	15 g/liter	0.25 M
426.4	—	—	6.3618	525.2	7.0675	8.0752	12.1042
429.4	2.2169	6.4858	7.4519	527.8	7.1751	8.1564	12.3282
432.0	2.5792	5.5512	7.5431	530.3	7.3473	8.1564	12.6139
434.9	2.8077	5.0618	7.5709	532.8	7.6182	8.1564	12.6653
437.7	3.3172	4.7137	7.7528	535.3	8.1395	8.2340	12.7652
440.5	2.5638	5.7714	9.1564	537.9	8.3833	7.7941	12.8073
443.2	2.1800	6.2711	9.2643	540.4	8.1605	—	12.8452
446.2	1.6370	6.6418	8.4670	542.8	7.9382	—	12.6752
449.2	1.6085	6.8843	8.2024	572.5	—	—	14.1788
451.8	2.1766	7.7466	8.4813	574.4	10.7320	14.745	14.626
454.5	1.8961	7.7466	8.5145	576.8	9.930	14.266	14.165
456.9	—	7.6420	9.3227	579.2	10.968	14.893	14.057
459.7	—	—	9.6650	581.5	11.629	15.664	15.041
467.9	2.3660	—	—	584.0	12.280	16.157	15.936
470.7	2.7643	—	9.9902	586.1	12.436	16.942	17.022
473.4	2.7482	6.7461	10.6031	588.2	13.427	17.708	19.142
476.2	3.0882	7.4140	9.9018	590.4	—	16.901	20.710
479.0	3.1524	7.7673	9.6841	592.8	—	17.802	22.463
481.7	3.0427	7.5950	9.8924	595.2	—	19.815	23.048
484.2	2.9903	7.3148	10.0376	597.5	24.543	24.145	25.377
486.9	2.3032	7.5057	10.6000	599.8	27.267	28.199	30.491
489.6	2.2073	6.3422	—	602.3	29.723	30.665	31.897
492.2	2.3660	6.5211	—	604.6	30.527	31.116	32.705
494.8	2.7593	7.7561	—	606.9	30.121	29.925	33.378
497.4	3.1777	7.7673	12.5759	609.3	30.466	31.861	33.772
500.0	3.1941	7.3686	12.6781	611.5	30.547	31.643	33.982
502.6	3.1777	7.5751	12.7285	613.9	29.806	31.672	34.125
505.1	3.6637	7.6512	12.3590	616.2	30.987	31.609	34.568
507.8	4.3094	7.5595	12.3457	618.5	31.017	33.114	34.362
510.4	4.2532	7.7610	12.7751	620.8	31.156	32.360	34.365
512.9	5.2451	7.4784	13.5120	623.2	31.250	32.886	35.161
515.5	4.7480	—	12.3075	625.5	30.946	32.104	—
517.6	5.4688	—	13.2815	627.8	30.073	31.221	—
520.1	5.9171	7.8419	11.5916	630.1	—	31.221	—
522.7	6.6194	8.3099	12.1839	632.6	—	31.672	—

change in attenuation is predominant in the lower wavelength region. The region of minimum attenuation gets flatter at higher concentrations.

D. Sodium Sulfate Solution

Table V gives the attenuation values for two concentrations of sodium sulfate (5 and 35.51 g/liter) which are plotted in Fig. 4. The figure shows that the attenuation is not much dependent on the concentration of Na_2SO_4 . There is no change for the region of minimum attenuation.

E. Equimolar Solutions

The attenuation coefficient for 0.25-M solutions of sodium chloride, magnesium chloride, and sodium sulfate are plotted in Fig. 5. The MgCl_2 solution shows higher attenuation for the region below 550 nm compared with the other two solutions. The higher value shown by Na_2SO_4 over that of NaCl is not significant when the concentration of SO_4^{2-} and Cl^- in seawater is taken into consideration (see Table I). Another important observation is that the shapes of the curves are almost same. There are no characteristic maxima and minima in the spectrum.

In water, these dissolved salts exist as ions. The ions are surrounded by a very high electric field. The electric field forces the neighboring water dipoles to orient its appropriate charged end toward the ion. Thus a cluster of sufficient size is formed whose dielectric properties are entirely different from the host medium. Such a cluster can act as a scattering center. The amount of light scattered depends on the scattering cross section which is related to the size of the clusters formed. The cluster size is a function of the ionic radius. The ionic radii of the above ions are $\text{Na}^+ = 0.95 \text{ \AA}$, $\text{Mg}^{2+} = 0.61 \text{ \AA}$, and $\text{Cl}^- = 1.81 \text{ \AA}$.

Thus the clusters formed by Cl^- ions are a larger than the other two. Therefore, chlorine ions scatter more light.

In equimolar solutions, there will be an equal number of solute molecules that split into ions. In MgCl_2 solution, there will be double the number of chlorine ions compared with an NaCl solution, resulting in higher scattering losses. The large attenuation shown by the MgCl_2 solution may be attributed to these scattering centers.

Table V. Attenuation Coefficients of Sodium Sulfate Solutions for Different Wavelengths (in Units of 10^{-2} m^{-1})

Wavelength (nm)	5 g/liter	0.25 M	Wavelength (nm)	5 g/liter	0.25 M
426.4	3.9986	5.3294	520.1	9.1977	8.6375
429.4	2.9102	4.3135	522.7	10.6893	8.7838
432.0	2.9311	4.1694	525.2	10.3446	10.3508
434.9	2.3136	4.7884	527.8	10.9391	10.3870
437.7	3.8756	5.0270	530.3	10.7404	10.3750
440.5	3.8432	3.5334	532.8	10.4589	10.2806
443.2	3.4397	3.4375	535.3	10.7547	10.3095
446.2	3.6768	2.8370	537.9	—	10.3394
449.2	3.7224	3.3949	540.4	—	10.3881
451.8	3.8702	3.1427	542.8	—	10.0977
454.5	3.8702	3.0060	572.5	12.4105	—
456.9	3.9986	3.3580	574.4	11.8833	10.7823
467.9	5.8684	—	576.8	13.2209	10.7317
470.7	5.1907	4.5058	579.2	13.1873	10.6093
473.4	5.7911	5.6408	581.5	14.4216	11.5223
476.2	5.6836	5.9398	584.0	14.9747	12.8000
479.0	5.5538	6.0143	586.1	15.4149	13.4062
481.7	6.7035	6.0463	588.2	15.5659	14.7683
484.2	6.5018	6.1169	590.4	15.5900	15.9146
486.9	5.8132	6.0036	592.8	16.2860	17.8312
489.6	—	6.7410	595.2	18.6732	22.0659
492.2	6.1971	5.0515	597.5	23.4709	23.4228
494.8	6.9277	5.2447	599.8	27.7182	28.5060
497.4	7.0322	6.5027	602.3	31.2888	29.7954
500.0	7.407	6.7104	604.6	31.5014	30.8008
502.6	7.8527	7.1511	606.9	31.5289	32.2829
505.1	7.9338	7.5631	609.3	30.0380	33.2932
507.8	8.4472	7.8939	611.5	29.5148	33.1828
510.4	8.9432	8.2821	613.9	30.0814	33.3973
512.9	9.0670	8.6567	616.2	30.6411	33.1976
515.5	8.7807	8.7841	618.5	30.830	32.7196
517.6	9.4596	8.7878	620.8	30.6656	32.4118
			623.2	29.7245	31.9759
			625.5	29.6274	31.5939
			627.8	28.8492	31.9033

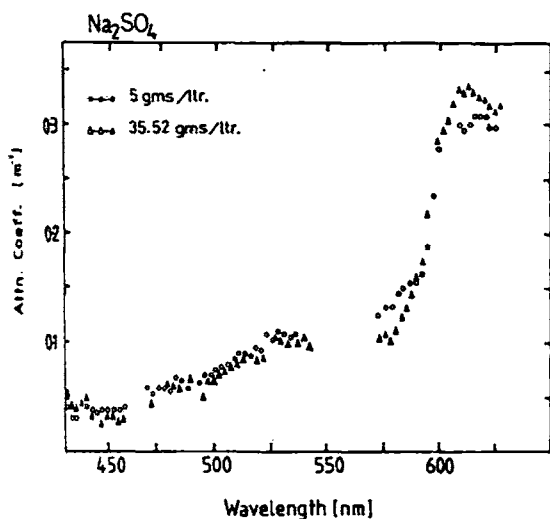


Fig. 5. Attenuation coefficient of 0.25-M solutions of NaCl , $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, and Na_2SO_4 vs wavelength.

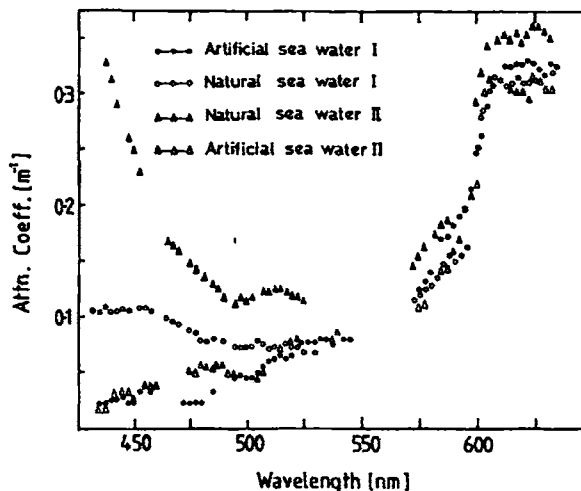


Fig. 6. Attenuation coefficient of two samples of artificial seawater and two samples of natural seawater.

Table VI. Attenuation Coefficients of Artificial Seawater and Natural Seawater (in Units of 10^{-2} m^{-1})

Wavelength (nm)	Artificial seawater I	Artificial seawater II	Natural seawater I	Natural seawater II	Wavelength (nm)	Artificial seawater I	Artificial seawater II	Natural seawater I	Natural seawater II
426.4	—	—	10.434	—	520.1	6.4353	8.0502	7.249	12.177
429.4	2.366	1.9398	10.504	32.753	522.7	6.2195	8.1146	7.180	11.688
432.0	2.2157	1.9957	10.674	33.018	525.2	7.6421	7.8204	6.845	11.745
434.9	2.4983	2.5137	10.578	31.595	527.8	7.7761	8.0263	7.211	11.099
437.7	2.4556	3.1714	10.456	29.143	530.3	7.7728	8.0233	6.667	—
					532.8	7.9004	8.1142	—	—
440.5	2.6486	3.1746	10.641	29.539	535.3	8.0250	8.1076	—	—
443.2	2.3104	3.1340	10.469	26.248	537.9	7.6216	8.3473	—	—
446.2	2.3660	2.7731	10.271	25.127	540.4	7.0158	9.0209	—	—
449.2	3.1823	3.5772	10.660	23.270	542.8	8.0376	—	—	—
451.8	3.9918	3.9725	10.846	23.270	545.2	8.0376	—	—	—
					572.5	—	—	11.604	14.634
454.5	3.1834	3.8379	10.598	24.390	574.4	12.5921	11.3321	11.957	15.901
456.9	2.3660	3.9986	—	25.065	576.8	13.3349	11.5179	12.506	16.298
459.7	—	—	10.109	—	579.2	14.0913	12.9242	12.712	16.298
462.3	—	—	9.687	17.052	581.5	13.9224	13.9224	13.379	17.438
465.0	—	—	9.476	16.777	584.0	16.9088	14.4391	14.645	18.441
467.9	—	—	9.367	16.351	586.1	17.2911	14.8608	15.517	18.667
470.7	2.1406	—	8.814	15.946					
473.4	2.1406	5.1869	8.657	14.920	588.2	18.2322	16.1852	15.004	—
476.2	2.1406	5.2522	8.462	14.557	590.4	19.0472	17.1942	15.428	—
479.0	2.3660	5.6415	7.784	13.451	592.8	19.6631	19.7962	16.164	—
					595.2	21.4880	21.1514	21.465	—
481.7	2.3660	5.5949	7.785	14.187	597.5	24.7274	22.2628	24.885	29.388
484.2	3.1823	5.6101	8.073	13.359	599.8	26.2044	28.1626	28.432	32.088
486.9	2.3660	5.7260	7.866	12.743	602.3	29.0429	30.4350	30.290	34.551
489.6	—	5.6855	7.772	12.031	604.6	30.8514	30.0490	31.406	36.488
492.2	—	4.9436	6.867	12.119	606.9	32.8532	31.5984	31.150	35.121
494.8	4.4857	5.0446	7.288	11.459	609.3	32.4821	30.7532	30.746	35.121
497.4	4.7293	4.6922	7.288	11.948					
500.0	4.4221	4.6922	7.180	11.874	611.5	32.5659	30.6277	30.968	34.973
502.6	4.4519	4.5670	7.339	11.919	613.9	32.6802	30.5726	31.573	35.448
505.1	5.0653	4.8356	7.718	10.603	616.2	32.6270	30.4785	30.991	34.811
					618.5	32.9568	29.6756	30.977	35.427
507.8	5.5013	5.3354	7.552	12.415	620.8	32.7983	31.4490	31.155	36.387
510.4	5.8969	5.9671	7.036	12.582	623.2	32.2350	31.4289	31.823	36.181
512.9	6.3704	7.3637	7.219	12.807	625.5	31.6772	30.8733	31.759	35.641
515.5	6.5794	7.4204	6.905	12.679	627.8	32.6344	30.6267	31.990	35.941
517.6	6.3667	7.5958	7.542	12.407	630.1	32.4824	—	—	—

F. Artificial Seawater

Figure 6 shows the attenuation of two samples of artificial seawater both of 35-ppt salinity. Sample I contained only the major constituents while sample II contained the major and minor constituents (Table I). The attenuation curves of these samples overlap. It is therefore safe to conclude that the presence of minor dissolved constituents such as Ca^{2+} , K^+ , HCO_3^- , B^- , and H_3BO_3 does not influence the attenuation. The attenuation coefficient values of these two samples are given in Table VI.

G. Natural Seawater

The attenuation for two samples of natural seawater of 35.46- and 28.65-ppt salinities are also plotted in Fig. 6 along with those for artificial seawater. There is a wide variation between these curves. The values for natural seawater are higher than those for artificial seawater especially below 520 nm. The dissolved constituents of both natural and artificial seawater being almost the same, the difference in attenuation is attributed to the presence of suspended particles in natural seawater.

Among the natural seawater samples, sample II, collected 3 km off the coast, showed very high attenuation in the blue region compared with sample I, collected 12 km off the coast. It has already been established that this large variation cannot be due to salinity and we can safely attribute it to the suspended particles. It is safe to conclude that the suspended particles would have a factor of considerable influence in the coastal belt while the factor will be much lower as we proceed to the interior regions. More systematic investigations on the particle size and its influence are not within the scope of present investigations. However, broad conclusions on the influence of suspended particles presented earlier are justified.

V. Conclusions

The absolute values of the attenuation coefficients of distilled water are determined and are compared with some of the existing results in the literature. The general agreement between these values. The attenuation minimum is identified to be in the 435-440 nm region.

A detailed and systematic study on the dependence

of optical attenuation on the dissolved constituents of seawater shows that such dependence is not significant. The variations in the concentrations of NaCl and Na₂SO₄ do not have any significant effect on the attenuation. But the change in concentration of MgCl₂ produces notable changes in attenuation, but within the concentration levels applicable to seawater, this effect is not significant. Thus it is concluded that the effect of dissolved constituents on optical attenuation is insignificant. The studies on two samples of artificial seawater unambiguously show that the presence of minor dissolved constituents does not have any influence on attenuation.

The attenuation coefficient values of natural seawater when compared with artificial seawater are quite high. These high values may be because of the presence of suspended particles that act as scattering centers. It may also be broadly concluded that the scattering from suspended particles is less in the deep sea compared to the shore. The region of minimum attenuation is not affected by the presence of dissolved constituents. But in natural seawater, because of the presence of suspended particles, the minimum attenuation region shifted from blue to green (490–530 nm).

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Peter A. Schulz of MIT Lincoln Laboratory at the 1987 OSA Annual Meeting. Photo: F. S. Harris, Jr.