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Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption

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The absorption of sound in seawater is considered as the sum of three contributions: those from pure water, magnesium sulfate, and boric acid. Contributions from other reactions are small and are not included. The pure water and magnesium sulfate contributions obtained from analyses of extensive oceanic measurements, including many in the Arctic, were discussed in Part I. In Part II, an analysis is made of all reported measurements in the low-frequency region (0.2–10 kHz) to evaluate the contribution of boric acid. This is done by subtracting the pure water and magnesium sulfate contributions determined in Part I from the total absorption to give a more accurate estimate of the boric acid contribution than previously obtained. The three contributions are then combined to form an equation with both a theoretical basis and a satisfactory empirical fit that will be useful to researchers and engineers in the field of underwater sound. The equation applies to all oceanic conditions and frequencies from 200 Hz to 1 MHz.

INTRODUCTION

The general equation for the absorption of sound in seawater gives the absorption as the sum of contributions from boric acid, magnesium sulfate, and pure water:

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_1^2 + f^2} + A_3 P_3 f^2, \qquad (1)$$

where f is the frequency of the sound, f_1 and f_2 are the relaxation frequencies of boric acid and magnesium sulfate, and P_1, P_2, and P_3 are nondimensional pressure correction factors.

The measurements and analyses reported earlier in Part I[1] resulted in more accurate equations for the pure water and magnesium sulfate contributions. Part II treats the boric acid contribution, which is important at frequencies below about 10 kHz.

Numerous low-frequency measurements of absorption have been made in various oceans using sound produced by explosives and transmitted along a sound channel. In analyzing these measurements, other investigators have generally treated the boric acid contribution as a relaxation process, but have usually accepted 1 kHz as the relaxation frequency regardless of the water properties. Our approach was to subtract the two components that were delineated in Part I from the total absorption to obtain a better measure of the boric acid portion. With three adjustable parameters available—the boric acid relaxation frequency, the absorption at that frequency, and a frequency-independent bias in α (such as a spreading loss error)—we made a three-variable least-squares fit to each set of data and obtained a relaxation frequency that varies with temperature and a proportionality factor that varies with pH.

In this paper, we first summarize the measurements reported by others for which the acoustic and environmental data were sufficiently documented to use in our analysis. We then analyze five selected sets whose frequencies bracketed the relaxation frequency to determine equations for the relaxation frequency and the absorption, and compare the boric acid equation thus derived with the remaining absorption measurements.

The paper concludes by combining the three contributions into a single equation and comparing it with the equations of other investigators. A one-page table of absorption versus frequency and temperature is included for the reader's convenience.

I. LOW-FREQUENCY MEASUREMENTS

A. Absorption anomaly

Measurements of low-frequency absorption in the 1950's showed higher values than expected from pure water and magnesium sulfate. Schulkin[2] proposed a nonchemical relaxation mechanism. A summary by Thorp[3] showed a preponderance of data that indicated an anomaly below 10 kHz.

In 1972 this anomaly was shown by Yeager *et al.*[4] to be caused mainly by a chemical relaxation of boric acid. Simmons,[5] using laboratory measurements, verified this and noted a variation between the Atlantic and Pacific Oceans. Mellen and Browning[6] reported that boron-induced absorption in the Pacific Ocean was about half that in the Atlantic. Further comparisons by Mellen and Browning[7] of the absorption and water properties in several widely spread locations showed that the absorption varied with pH.

At about the same time, Schulkin and Marsh[8] also examined the ocean variations reported by Simmons. They estimated the pH at the sound channel axis for each area, and also found a strong correlation between absorption and pH. Following Glotov's theory, they related the relaxation frequency of the boron absorption to the viscosity of the seawater as well as to the temperature and salinity, and published an equation for the boric acid contribution to absorption. Lovett,[9] using a Russian oceanographic atlas[10] to obtain pH values for the Atlantic, Indian, and Pacific Oceans, published a world contour map for predicting low-frequency absorption at the sound channel axis but gave no specific

temperature or salinity dependence.

The frequency range of the boric acid absorption and that of the $MgSO_4$ absorption overlap appreciably. At a temperature of 5 °C and a frequency of 3 kHz, for example, the effects are about equal; near the boric acid relaxation frequency of about 1 kHz, the $MgSO_4$ component is about 20% of the boric acid term. In this region, the study of the boric acid effect requires that the $MgSO_4$ component be accurately known. Contributions from other relaxations are small and have not been included in the analysis considering the accuracy of the available low-frequency data.

Numerous measurements of low-frequency absorption in all oceans during the past decade have provided field data for the studies just mentioned. Most of those measurements involved explosive sources and long-range transmission in a sound channel where cylindrical spreading could be assumed.

B. Review of ocean measurements

A review of the literature provided us with several absorption measurements that were performed in waters of known oceanographic properties. Five of these investiga-

TABLE I. Low-frequency absorption measurements used to derive equations.

Location and Investigator	Year	Sound Channel Axis Depth (m)	Max. Range (km)	Measurement f (kHz)	Measurement Total α (dB/km)	Boric Acid Excess $α^b$ (dB/km)	Adjusted to Give Eq. (7) f_1 $(αλ)_m$ $(10^{-5}$ Np)	Adjusted to Give Eq. (7) f_1 Total α (dB/km)	Calculated From Our Final Equation Total α (dB/km)	Calculated From Our Final Equation Adjusted α − Calculated α (dB/km)
NE Pacific[6] Chow and Turner[11]	1973	505	1400	0.160	0.0046 ± 0.0009	0.0044	0.42 ± 0.28	0.0016	0.0019	−0.0003
				0.250	0.0077 ± 0.0012	0.0071	0.54 ± 0.16	0.0047	0.0044	0.0003
				0.400	0.0131 ± 0.0016	0.0116	0.49 ± 0.09	0.0101	0.0104	−0.0003
(T=4.6°C, S=34.05‰,				0.630	0.0264 ± 0.0027	0.0226	0.56 ± 0.08	0.0234	0.0215	0.0019
pH=7.69[a], c=1476 m/s)				0.800	0.0328 ± 0.0033	0.0266	0.51 ± 0.07	0.0298	0.0299	−0.0001
Atlantic Thorp[3]	1962	1200	1800	0.354	0.0161 ± 0.0010	0.0150	0.90 ± 0.07	0.0135	0.0139	−0.0004
				0.446	0.0229 ± 0.0010	0.0211	0.92 ± 0.05	0.0203	0.0207	−0.0004
				0.562	0.0292 ± 0.0010	0.0264	0.82 ± 0.03	0.0266	0.0299	−0.0033
(T=5.0°C, S=35.0‰,				0.707	0.0398 ± 0.0010	0.0354	0.83 ± 0.03	0.0372	0.0415	−0.0043
pH=8.03, c=1490 m/s)				0.891	0.0550 ± 0.0010	0.0480	0.88 ± 0.02	0.0524	0.0555	−0.0031
				1.120	0.0638 ± 0.0025	0.0528	0.78 ± 0.04	0.0612	0.0711	−0.0099
				1.410	0.0789 ± 0.0037	0.0614	0.78 ± 0.05	0.0763	0.0882	−0.0119
				1.780	0.1129 ± 0.0120	0.0850	0.97 ± 0.14	0.1103	0.1076	0.0027
				2.240	0.1511 ± 0.0170	0.1070	1.13 ± 0.18	0.1485	0.1307	0.0178
				2.820	0.1826 ± 0.0200	0.1128	1.13 ± 0.20	0.1800	0.1614	0.0186
				3.540	0.1931 ± 0.0250	0.0832	0.79 ± 0.25	0.1905	0.2048	−0.0143
Mediterranean Sea Skretting and Leroy[12]	1966	800	32	0.500	0.0130 ± 0.0100	0.0111	1.72 ± 0.52	0.0350	0.0243	0.0107
				0.600	0.0170 ± 0.0080	0.0143	1.38 ± 1.30	0.0390	0.0332	0.0058
				0.800	0.0360 ± 0.0150	0.0313	1.30 ± 0.36	0.0580	0.0524	0.0056
				1.000	0.0570 ± 0.0160	0.0496	1.29 ± 0.29	0.0790	0.0719	0.0071
(T=13°C, S=38.0‰,				1.500	0.1150 ± 0.0200	0.0983	1.41 ± 0.23	0.1370	0.1155	0.0215
ph=8.15, c=1517 m/s)				2.000	0.1600 ± 0.0300	0.1304	1.45 ± 0.29	0.1820	0.1512	0.0308
				2.500	0.1950 ± 0.0300	0.1488	1.46 ± 0.26	0.2170	0.1822	0.0348
				3.000	0.2000 ± 0.0300	0.1335	1.24 ± 0.24	0.2220	0.2119	0.0101
				3.500	0.2600 ± 0.0300	0.1695	1.46 ± 0.23	0.2820	0.2423	0.0397
				4.000	0.3000 ± 0.0400	0.1818	1.51 ± 0.30	0.3220	0.2743	0.0477
				4.500	0.3400 ± 0.0400	0.1905	1.55 ± 0.29	0.3620	0.3088	0.0532
				5.000	0.4000 ± 0.0400	0.2155	1.71 ± 0.29	0.4220	0.3461	0.0759
				5.500	0.4200 ± 0.0300	0.1969	1.55 ± 0.21	0.4420	0.3865	0.0555
				6.000	0.4500 ± 0.0300	0.1847	1.46 ± 0.21	0.4720	0.4301	0.0419
				8.000	0.5800 ± 0.0400	0.1099	0.91 ± 0.28	0.6020	0.6382	−0.0362
Red Sea Browning[13]	1971	200	280	0.570	0.0360 ± 0.0022	0.0340	1.32 ± 0.12	0.0264	0.0246	0.0018
				0.720	0.0440 ± 0.0044	0.0408	1.12 ± 0.16	0.0344	0.0374	−0.0030
				0.890	0.0610 ± 0.0044	0.0562	1.17 ± 0.11	0.0514	0.0536	−0.0022
(T=22°C, S=40.5‰,				1.150	0.0920 ± 0.0044	0.0840	1.26 ± 0.07	0.0824	0.0802	0.0022
pH=8.18, c=1536 m/s)				1.400	0.1230 ± 0.0077	0.1111	1.32 ± 0.10	0.1134	0.1058	0.0076
				1.800	0.1530 ± 0.0077	0.1333	1.21 ± 0.08	0.1434	0.1445	−0.0011
				2.280	0.1910 ± 0.0109	0.1594	1.19 ± 0.09	0.1814	0.1856	−0.0042
				2.850	0.2340 ± 0.0131	0.1846	1.20 ± 0.09	0.2244	0.2284	−0.0040
				3.500	0.2900 ± 0.0241	0.2156	1.27 ± 0.15	0.2804	0.2727	0.0077
				5.600	0.4590 ± 0.0601	0.2686	1.39 ± 0.32	0.4494	0.4180	0.0314
				8.900	0.8420 ± 0.2406	0.3621	1.79 ± 1.22	0.8324	0.7214	0.1110
Gulf of Aden Browning[14]	1973	300	500	0.400	0.0350 ± 0.0040	0.0339	0.47 ± 0.31	0.0072	0.0080	−0.0008
				0.500	0.0400 ± 0.0040	0.0382	0.54 ± 0.21	0.0122	0.0121	0.0001
				0.630	0.0460 ± 0.0040	0.0432	0.54 ± 0.14	0.0182	0.0180	0.0002
(T=14.31°C, S=35.8‰,				0.790	0.0550 ± 0.0050	0.0506	0.57 ± 0.12	0.0272	0.0260	0.0012
pH=7.72, c=1510 m/s)				1.000	0.0690 ± 0.0050	0.0619	0.61 ± 0.07	0.0412	0.0369	0.0043
				1.300	0.0820 ± 0.0050	0.0700	0.56 ± 0.07	0.0542	0.0522	0.0020
				1.650	0.0980 ± 0.0060	0.0786	0.55 ± 0.06	0.0702	0.0691	0.0011
				2.000	0.1200 ± 0.0060	0.0915	0.60 ± 0.06	0.0922	0.0852	0.0070
				2.500	0.1530 ± 0.0070	0.1085	0.68 ± 0.06	0.1252	0.1081	0.0171
				3.200	0.1700 ± 0.0100	0.0972	0.53 ± 0.08	0.1422	0.1423	−0.0001
				4.000	0.1810 ± 0.0100	0.0673	0.29 ± 0.07	0.1532	0.1870	−0.0338
				5.000	0.2950 ± 0.0300	0.1175	0.63 ± 0.21	0.2672	0.2535	0.0137
				6.000	0.3720 ± 0.1000	0.1167	0.61 ± 0.69	0.3442	0.3329	0.0113

[a]All pH values have been corrected for temperature and pressure.
[b]Measured absorption less pure water and $MgSO_4$ contributions.

Location and Investigator	Year	Sound Channel Axis Depth (m)	Max. Range (km)	T (°C)	S (‰)	pH	Measured f (kHz)	Measured Total α (dB/km)	Calculated From Our Final Equation Total α (dB/km)	Measured α - Calculated α (dB/km)
NE Pacific Thorp[6] c=1479 m/s	1975	753	3000	4.25	34.1	7.67	0.120	0.0011	0.0010	0.0001
							0.150	0.0018	0.0016	0.0002
							0.200	0.0026	0.0028	-0.0002
							0.250	0.0035	0.0043	-0.0008
							0.300	0.0062	0.0061	0.0001
							0.400	0.0094	0.0101	-0.0007
Pacific Lovett[15] (ISAR) c=1481 m/s	1969	700	245	5.0	34.4	7.67	0.750	0.0221	0.0263	-0.0042
							1.500	0.0547	0.0594	-0.0047
							3.000	0.1470	0.1321	0.0149
Gulf of Alaska Lovett[15] c=1465 m/s	1971	75	270	4.0	33.1	7.72	1.500	0.0744	0.0644	0.0100
							2.500	0.1290	0.1132	0.0158
NE Pacific Morris[16] c=1476 m/s	1975	505	2900	4.60	34.1	7.69	0.050	0.0002	0.0002	0.0000
							0.080	0.0004	0.0005	-0.0001
							0.100	0.0007	0.0007	-0.0000
							0.125	0.0012	0.0012	0.0000
							0.160	0.0018	0.0019	-0.0001
							0.200	0.0028	0.0029	-0.0001
							0.250	0.0042	0.0044	-0.0002
							0.310	0.0068	0.0066	0.0002
							0.400	0.0092	0.0104	-0.0012
S. Pacific Kibblewhite and Denham[17] (Line PA) c=1488 m/s	1971	1250	1150	4.31	35.0	7.96	0.106	0.0007	0.0013	-0.0006
							0.212	0.0030	0.0049	-0.0019
							0.424	0.0083	0.0173	-0.0090
(Line PB1) c=1487 m/s	1971	1250	1700	4.07	35.0	7.90	0.106	0.0002	0.0012	-0.0010
							0.212	0.0032	0.0045	-0.0013
							0.424	0.0084	0.0158	-0.0074
(KIWI WEST)[6] c=1488 m/s	1974	1250	3000	4.31	35.0	7.96	0.029	0.0015	0.0001	0.0014
							0.060	0.0012	0.0004	0.0008
							0.120	0.0021	0.0016	0.0005
							0.250	0.0034	0.0067	-0.0033
							0.424	0.0079	0.0173	-0.0094
(TAS 1)[18] c=1489 m/s	1963	1300	900	4.35	35.0	7.87	0.450	0.0203	0.0165	0.0038
							0.900	0.0246	0.0440	-0.0194
S. Pacific Bannister et al.[19] (TAS 2, Northwest) c=1488 m/s	1975	1350	1800	3.92	35.0	7.87	0.125	0.0016	0.0015	0.0001
							0.250	0.0063	0.0059	0.0004
							0.500	0.0167	0.0197	-0.0030
(TAS 2, West) c=1484 m/s	1975	1100	2800	3.94	35.0	7.87	0.125	0.0012	0.0016	-0.0004
							0.250	0.0055	0.0059	-0.0004
			1600		•		0.500	0.0189	0.0198	-0.0009
Baffin Bay[a] Mellen et al.[20] c=1442 m/s	1972	100	400	-1.50	33.7	8.01	0.320	0.0170	0.0143	0.0027
							0.410	0.0198	0.0214	-0.0016
							0.500	0.0246	0.0288	-0.0042
							0.640	0.0393	0.0399	-0.0006
							1.000	0.0683	0.0643	0.0040
Bismarck Sea Mellen and Browning[21] c = 1546 m/s	1974	45	?	30	36	8.20	0.560	0.0700	0.0203	0.0497
							1.200	0.1000	0.0776	0.0224
							2.300	0.1900	0.1854	0.0046
							4.500	0.3600	0.3367	0.0233

[a]Measured values have been adjusted by -0.02 dB/km.

tions, each in a different ocean or sea, had a sufficient frequency spread to determine the relaxation frequency and were analyzed to develop an absorption equation. These measurements are summarized in Table I and described briefly in the following paragraphs. Other investigations
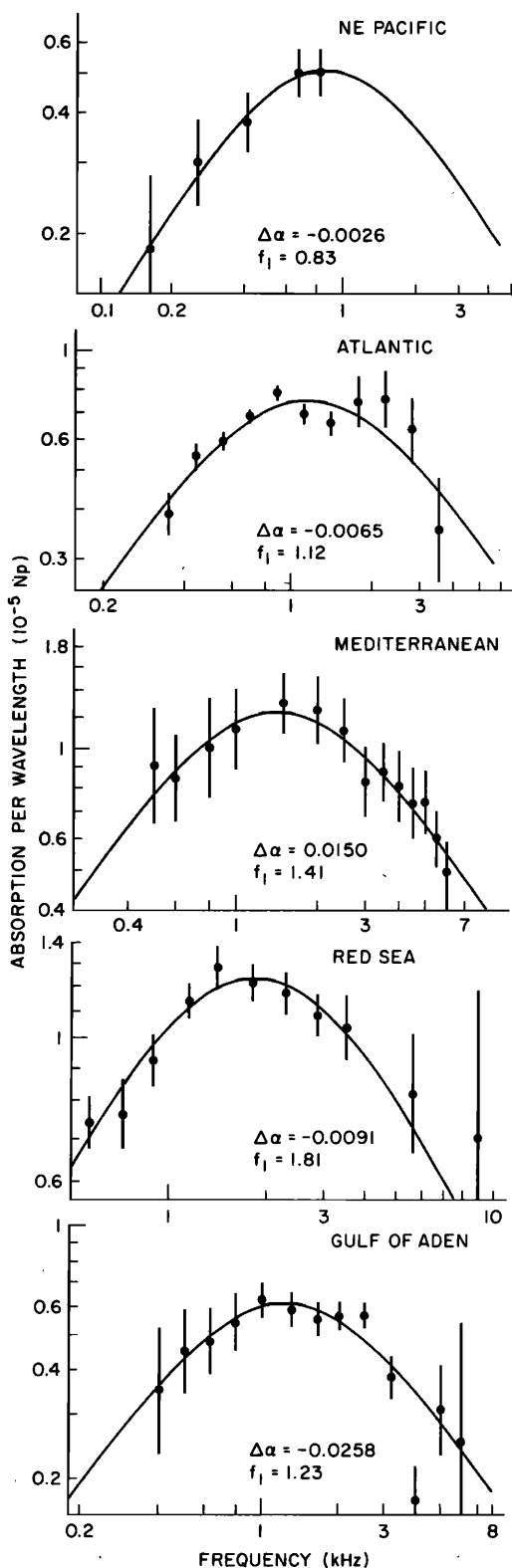

FIG. 1. Determination of the boric acid relaxation frequency for five water types. Each set of absorption measurements has been adjusted by $\Delta\alpha$ (in decibels/kilometer) to give the best fit to relaxation theory.

with limited frequency coverage are listed in Table II. In selecting these data, we avoided measurements that crossed ocean fronts and may have involved waters of different pH. The pH at the sound channel axis for each set of measurements was estimated from Lovett's contour diagram.[9] All the measurements reported involved explosive sources except for the cw transmissions of Lovett.[15]

1. Northeast Pacific Ocean

These measurements were made by the Canadian Defence Research Establishment Pacific (DREP) in 1973 during a joint project with U.S. laboratories. The data were presented by Mellen and Browning[6] and are especially valuable for studying pH dependence because of the low pH in the northeast Pacific. A scattering loss of 0.0033 dB/km was apparently present. Sufficient data were available to determine the relaxation frequency. More recently, another version of the data[11] became available which, when analyzed, gave similar results.

2. Atlantic Ocean

Thorp[3] reported measurements made in 1962 for which explosives were dropped from a ship and detonated every 9 km along a 900-km track extending southwest from Bermuda. Receivers were at the axis of the sound channel. In determining the absorption coefficient, Thorp assumed that cylindrical spreading started at about 40 km. The maximum range of useful measurements was 900 km for the lower frequencies, but dropped to 110 km for the highest frequency. However, Thorp disregarded the five highest frequencies and, instead, included a second set of lower-frequency measurements made the following year (1963). We found the higher frequencies to be helpful in determining the relaxation frequency. For the second set, at the lower frequencies, good documentation is not available. Although Thorp does not report the standard deviation of his absorption coeffi-
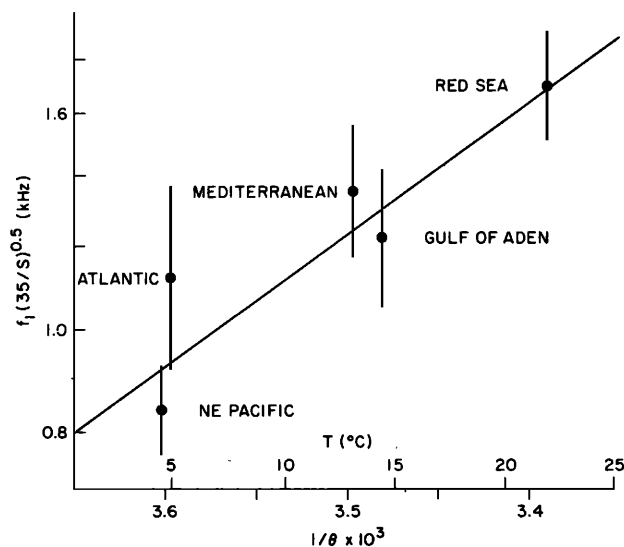
FIG. 2. Boric acid relaxation frequency f_1 determined from measurements in various oceans. θ is the absolute temperature $(T + 273)$. The best-fit line corresponds to Eq. (7).

TABLE III. Analysis of low-frequency absorption measurements.

Location	Adjusted For Best Fit			Adjusted to Give Same f_1 as Eq. (7)			Weighted Average[a]	Final Equation Parameters	
	$\Delta\alpha$ (dB/km)	f_1 (kHz)	$(\alpha\lambda)_m$ (10^{-5} Np)	$\Delta\alpha$ (dB/km)	f_1 (kHz)	$(\alpha\lambda)_m$ (10^{-5} Np)	$(\alpha\lambda)_m$ (10^{-5} Np)	f_1 (kHz)	$(\alpha\lambda)_m$ (10^{-5} Np)
NE Pacific	-0.0026	0.83 ± 0.08	0.52	-0.0030	0.90	0.52	0.52 ± 0.04	0.90	0.51
Atlantic	-0.0065	1.12 ± 0.22	0.78	-0.0026	0.93	0.85	0.86 ± 0.03	0.93	0.94
Mediterranean Sea	+0.0150	1.41 ± 0.20	1.25	+0.0215	1.29	1.36	1.31 ± 0.12	1.29	1.16
Red Sea	-0.0091	1.81 ± 0.22	1.24	-0.0096	1.81	1.24	1.24 ± 0.05	1.81	1.22
Gulf of Aden	-0.0258	1.23 ± 0.18	0.61	-0.0278	1.31	0.58	0.55 ± 0.04	1.31	0.54

[a]Average of the sets in Table I using a weighting of $1/\sigma$.

cient determinations, his plots of loss-versus-range gave us a good basis for estimation. The shortened range at the higher frequencies causes a considerable increase in the standard deviation of the calculated coefficient. Thorp presents results for both "refracted only data" and "all-path data." We have used only the refracted data, expecting a better fit to theory.

3. Mediterranean Sea

Skretting and Leroy[12] made transmission measurements in the western Mediterranean using explosive sources in June 1966 (trial 1). Similar measurements had been made in 1964 and 1965 and some were made later (trial 2) but we have sufficient information only on trial 1. Of all the low-frequency measurements examined, these are unique in that refraction upward from the deep was so uniform that spherical spreading was a close approximation. The shock wave data and the bubble pulse data gave nearly the same results, indicating that finite amplitude effects were negligible. We used the shock wave data which were scaled from Fig. 3 of Ref. 12. The frequencies bracketed the relaxation frequency, and the data were analyzed to determine a best fit to the relaxation equation. Our analysis required a correction of + 0.015 dB/km, which is in fair agreement with the correction of + 0.02 dB/km made by Skretting and Leroy to eliminate the negative attenuation at the lowest frequencies.

4. Red Sea

Mellen et al.[13] summarized the results of absorption measurements in the Red Sea with a reference to a technical report for the details. The data were very valuable for this study because of the high temperature (22 °C).

5. Gulf of Aden

Mellen et al.[14] reported measurements of sound transmission using explosive sources over a 500-km track in the Gulf of Aden. The frequency range of 0.25 to 6.0 kHz was suitable for determining the relaxation frequency. During this process, we found that a correction of − 0.021 dB/km was required, which is in close agreement with the 0.02 dB/

kyd given by the investigators as the loss caused by scattering due to inhomogeneities in the sound speed.

II. BORIC ACID CONTRIBUTION
A. Equation for excess absorption due to boric acid

The excess sound absorption caused by boric acid is calculated from the first term of the absorption equation (1) and is referred to here as α_1.

$$\alpha_1 = A_1 P_1 f_1 f^2 / (f_1^2 + f^2), \tag{2}$$

where, as stated in Part I, $P_1 = 1$. The maximum product of the boric acid absorption and the wavelength $(\alpha\lambda)_m$, which occurs at $f = f_1$, appears to be a more fundamental constant than A_1, and is related to A_1 by the sound speed c. With conversion of units, the relation is given by

$$(\alpha\lambda)_m = cA_1/2(8686)10^3 \text{ Np}. \tag{3}$$

By replacing A_1 in Eq. (2) and multiplying by λ ($\lambda = c/f$), the absorption per wavelength can be expressed as

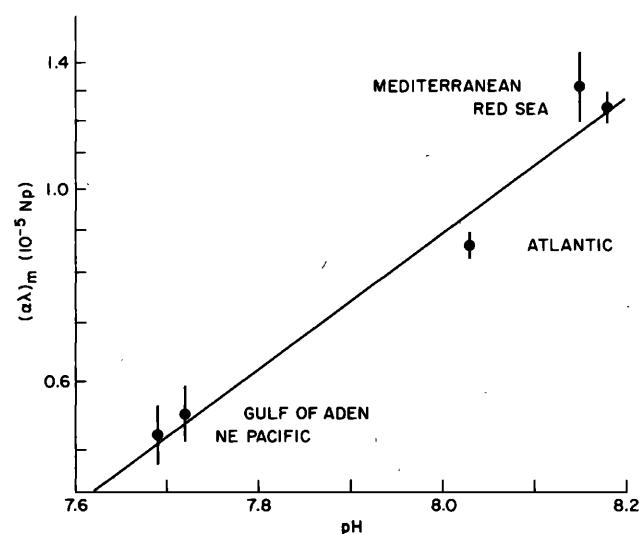$$\alpha_1\lambda = 2(\alpha\lambda)_m f_1 f / (f_1^2 + f^2) \text{ Np}. \tag{4}$$

FIG. 3. Boric acid excess absorption per wavelength $(\alpha\lambda)_m$ for waters with diverse pH. The best-fit line shown is given by Eq. (9).

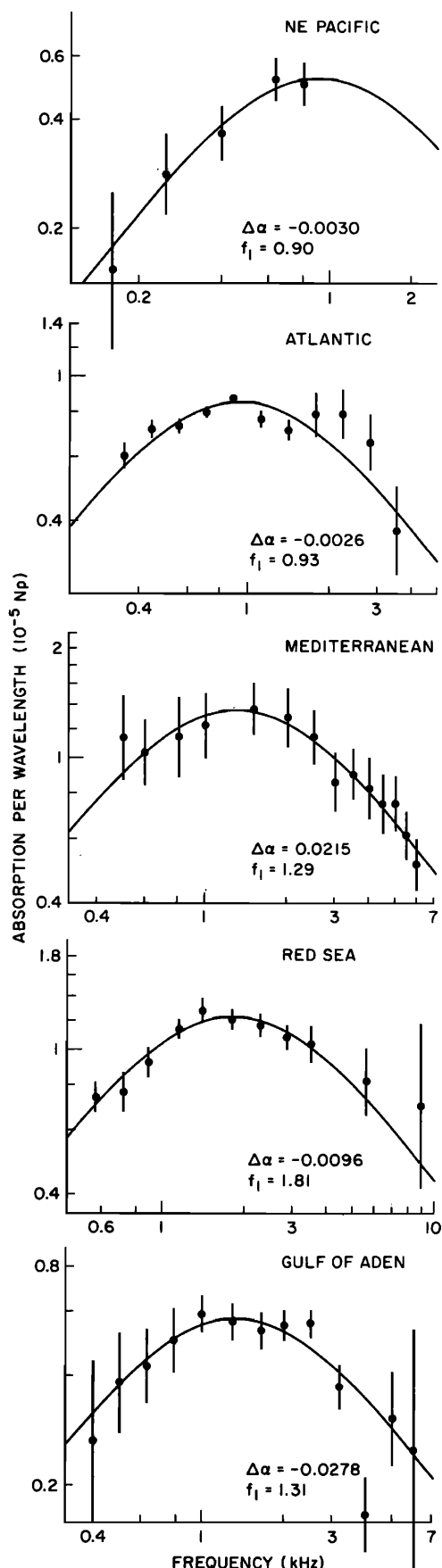R. E. Francois and G. R. Garrison: Sound absorption

FIG. 4. Comparison of our boric acid absorption equation with measured data that have been adjusted to give relaxation frequencies in agreement with Eq. (7). $\Delta\alpha$ is the adjustment in decibels/kilometer.

In most measurements reported in the literature, the investigator has calculated absorption assuming cylindrical spreading. In our analysis, we have included an adjustment $\Delta\alpha$ as described in Part I,[1] Sec. IV, to provide a better fit to the theoretical excess absorption equation. In essence, this corrects for any frequency-independent error such as a small deviation from the assumed spreading loss.

B. Theory of boric acid absorption

Glotov[22,23] examined the excess absorption due to the small concentrations of boric acid and its derivatives in ocean water, and related the relaxation frequency of the process to the association energy Δh by

$$f_1 = (F\theta/\eta)e^{-\Delta h/R\theta}, \tag{5}$$

where θ is the absolute temperature $(T + 273$, where $T \leqslant 20$ °C), η is the viscosity, R is the gas constant, and F is a constant.

Following the procedure of Schulkin and Marsh,[8] we combined Eq. (5) with Eq. (13) given for viscosity in Part I to obtain

$$f_1 = F/Ee^{-(\Delta h + \Delta u)/R\theta}, \tag{6}$$

where $\Delta h + \Delta u$ is the activation energy of the process. Their plot of $\ln f_1$ vs $1/\theta$ for the ocean data summarized by Simmons showed that the slope of the line giving the best (least-squares) fit required a negative Δh. Schulkin and Marsh pointed out that Δh could not be negative and set $\Delta h = 0$, which gave about as good a fit to the data.

The laboratory measurements of both Glotov[23] and Simmons[5] indicate that the boric acid relaxation frequency varies as the square root of the concentration. Considering that seawater has a very constant relative composition, the salinity S should be proportional to the boron concentration. A concentration dependence of $S^{0.5}$ is therefore assumed.

C. Analysis of low-frequency measurements

When analyzing low-frequency ocean measurements, the excess absorption due to boric acid is obtained by subtracting the values calculated for the $MgSO_4$ and pure water components from the measured absorption. If our results in Part I for the absorption due to $MgSO_4$ are correct, analyses in the past would be subject to error. The absorption calculated for $MgSO_4$ would be 5%–10% low if the Schulkin–Marsh equation[24] reported in 1962 was used and 20%–30% low if the Fisher–Simmons equation[25] was used. The use of our new equation for the $MgSO_4$ absorption should improve the accuracy of the remaining absorption allocated to boric acid.

We proceed in the next paragraphs to examine all suitable low-frequency data that we found in the literature, subtract the $MgSO_4$ and pure-water components calculated from our new equation, and examine the dependence of the remaining boric acid component on temperature and pH.

The five investigations listed in Table I permitted a reasonably accurate calculation of the relaxation frequency. Plots of the absorption per wavelength determined from the measured absorption are shown in Fig. 1 for the five sets.

Values for f_1, for $(\alpha\lambda)_m$, and for the adjustment $\Delta\alpha$, which was applied equally to all values, have been selected to give the best fit of $\alpha_1\lambda$ to the theoretical curve, Eq. (4).

The five relaxation frequencies determined in this manner have been plotted against temperature in Fig. 2, where logarithmic scales result in a straight line for Eq. (6). The line for Eq. (6) is the best fit to the five points, using a weighting of $1/\sigma$. This line corresponds to the equation

$$f_1 = 2.8(S/35)^{1/2}10^{(4-1245/\theta)} \text{ kHz}, \qquad (7)$$

and its slope is a measure of the activation energy for the process; i.e.,

$$\Delta h + \Delta u = 1245R \ln 10 = 5.7 \text{ kcal/mole}, \qquad (8)$$

where R is the general gas constant, $1.987 \text{ cal mole}^{-1} \text{deg}^{-1}$.

Since Δu, the activation energy of seawater viscosity, has been shown in Part I, Sec. V, to be 4.8 kcal/mole, we subtract this amount and obtain for the association energy
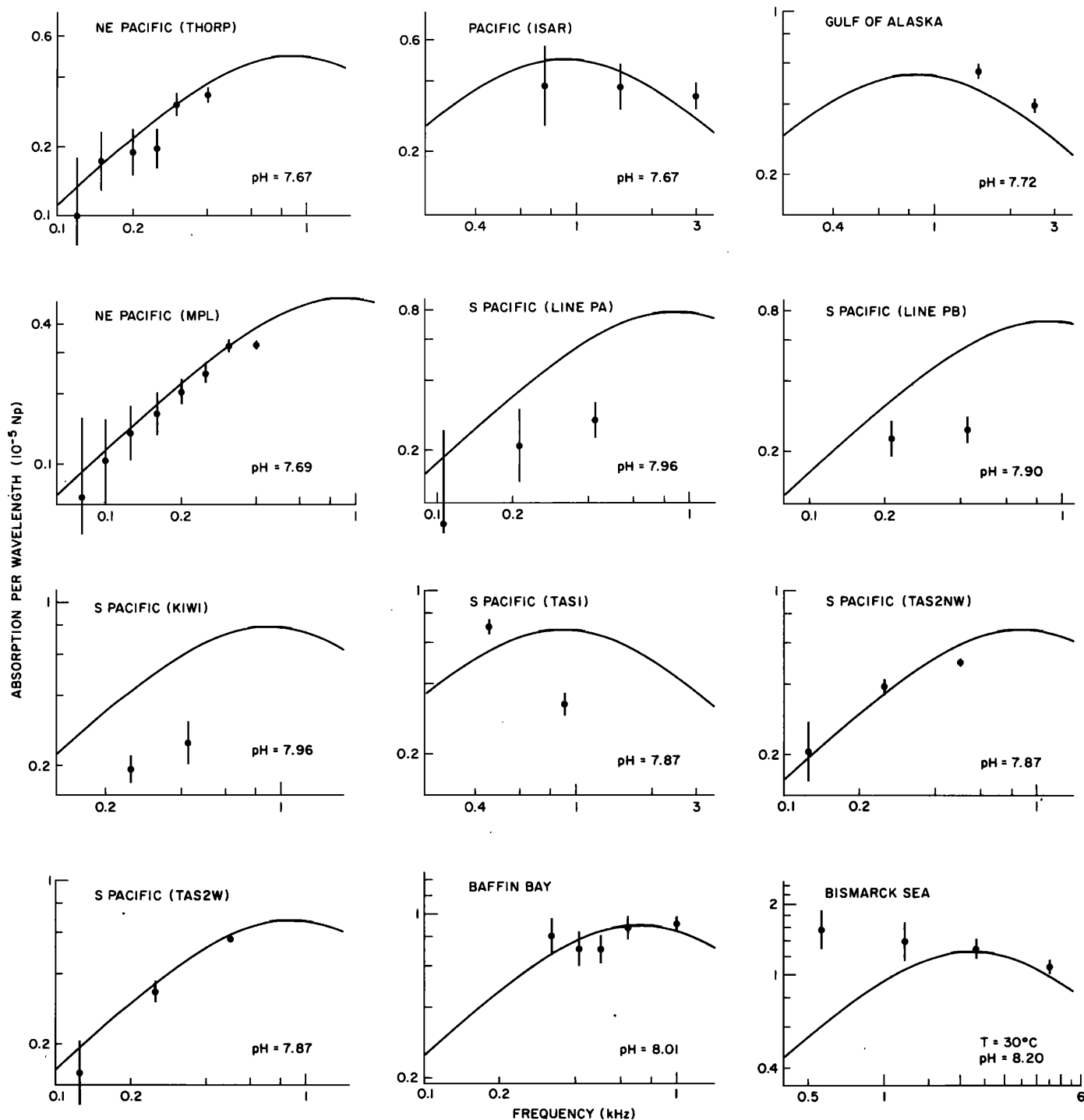
$$\Delta h = 0.9 \text{ kcal/mole},$$

FIG. 5. Comparison of our boric acid absorption equation with reported measurements of absorption that have an insufficient frequency spread for determining the relaxation frequency. The pH values given are our best estimate for the location and depth.
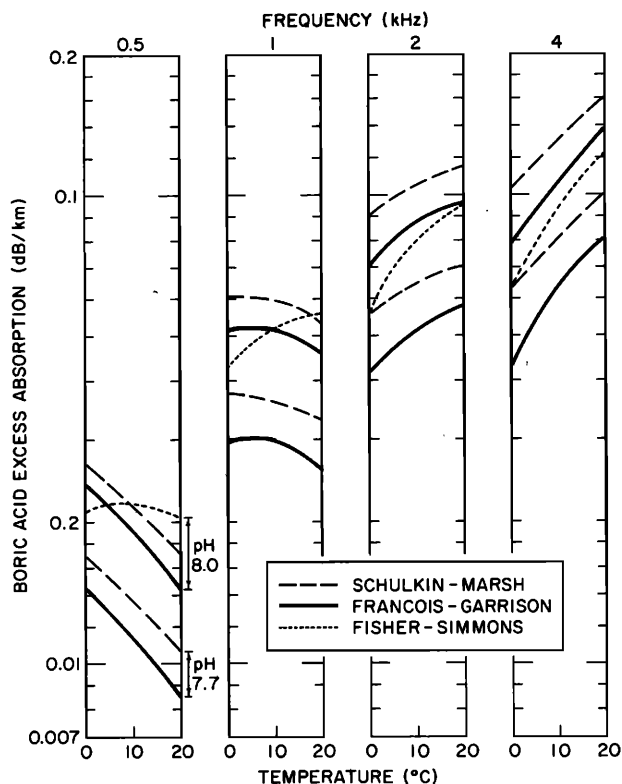
FIG. 6. Comparison of low-frequency absorption equations (for $S = 35\%o$ and two pH values).

$$Total\ Absorption = \begin{matrix} Boric \\ Acid \\ Contrib. \end{matrix} + \begin{matrix} MgSO_4 \\ Contrib. \end{matrix} + \begin{matrix} Pure \\ Water \\ Contrib. \end{matrix}$$

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \quad dB\ km^{-1}$$

for frequency f in kilohertz.

Boric Acid Contribution

$$A_1 = \frac{8.86}{c} \times 10^{(0.78\ pH\ -\ 5)} \qquad dB\ km^{-1}\ kHz^{-1}$$

$$P_1 = 1$$

$$f_1 = 2.8\ (S/35)^{0.5}\ 10^{(4\ -\ 1245/\theta)} \qquad kHz,$$

where c is the sound speed (m/s), given approximately by

$$c = 1412 + 3.21\ T + 1.19\ S + 0.0167\ D,$$

T is the temperature (°C), $\theta = 273 + T$, S is the salinity (‰), and D is the depth (m).

$MgSO_4$ Contribution

$$A_2 = 21.44\ \frac{S}{c}\ (1 + 0.025\ T) \qquad dB\ km^{-1}\ kHz^{-1}$$

$$P_2 = 1 - 1.37 \times 10^{-4}\ D + 6.2 \times 10^{-9}\ D^2$$

$$f_2 = \frac{8.17 \times 10^{(8\ -\ 1990/\theta)}}{1 + 0.0018\ (S\ -\ 35)} \qquad kHz$$

Pure Water Contribution

For T ≤ 20°C,

$$A_3 = 4.937 \times 10^{-4} - 2.59 \times 10^{-5}\ T$$
$$+ 9.11 \times 10^{-7}\ T^2 - 1.50 \times 10^{-8}\ T^3 \qquad dB\ km^{-1}\ kHz^{-2}.$$

For T > 20°C,

$$A_3 = 3.964 \times 10^{-4} - 1.146 \times 10^{-5}\ T$$
$$+ 1.45 \times 10^{-7}\ T^2 - 6.5 \times 10^{-10}\ T^3 \qquad dB\ km^{-1}\ kHz^{-2}.$$

$$P_3 = 1 - 3.83 \times 10^{-5}\ D + 4.9 \times 10^{-10}\ D^2.$$

FIG. 7. Francois–Garrison equation for sound absorption in seawater.

which is nicely above 0 rather than negative as indicated by Mellen *et al.*[13]

The steepness of the line in Fig. 2 is determined primarily by the data point for the Red Sea. We calculated a higher relaxation frequency, 1.72 kHz compared with 1.50 kHz, for the Red Sea data than that presented by Mellen *et al.* using a three-relaxation model.[13] When we adjusted the same data by − 0.0026 dB/km to get the best fit to the relaxation equation, we obtained an even higher relaxation frequency, 1.81 kHz.

After selecting Eq. (7) as the equation for the relaxation frequency, we readjusted each set of data to the relaxation frequency calculated by this equation. The corresponding $(\alpha\lambda)_m$, which also varies with the adjustment, was then determined for each of the five locations. These manipulations are summarized in Table III. Using Eqs. (1)–(3) and the relaxation frequency obtained from Eq. (7), we calculated $(\alpha\lambda)_m$ in terms of the measured and adjusted absorption. After determining a value for $(\alpha\lambda)_m$ from each absorption measurement, we found the average and standard deviation for each set of data. These averages are shown in Table III and plotted in Fig. 3 against pH. The least-squares fit of an equation of the form given by Schulkin and Marsh[8] is

$$(\alpha\lambda)_m = 5.1 \times 10^{(0.78\ pH\ -\ 12)}\ Np. \qquad (9)$$

A_1 can be expressed in more practical units as

$$A_1 = [2(8686)(10^3)/c](\alpha\lambda)_m$$

$$= (8.86/c) \times 10^{(0.78\ pH\ -\ 5)}\ dB\ km^{-1}\ kHz^{-1}. \qquad (10)$$

With f_1 and $(\alpha\lambda)_m$ given by Eqs. (7) and (9), the boric

acid absorption can be computed using Eq. (4) for the conditions of the five sets of data in Table I. The values of f_1 and $(\alpha\lambda)_m$ for each set are tabulated in the final columns of Table III. Figure 4 shows the fit of our boric acid equation to the five sets of data. The $\Delta\alpha$ adjustment originally applied has been slightly altered so that the data are well fitted by the $\alpha_1\lambda$ curve corresponding to the relaxation frequency given by Eq. (7). In all five comparisons, our equation is a good representation of the data.

A similar comparison with the data listed in Table II, which had an insufficient frequency spread to determine the relaxation frequency, is presented in Fig. 5. No adjustments

TABLE IV. Absorption in seawater according to the Francois–Garrison equation (dB/km). The upper value for each frequency is for $S = 30\%_o$ and the lower for $S = 35\%_o$. Depth = 0 and pH = 8.

Freq. (kHz)	Temperature (°C)															
	-1.8	-1.5	-1	0	2	4	6	8	10	12	14	16	18	20	25	30
0.4	0.021	0.021	0.020	0.020	0.019	0.018	0.017	0.016	0.015	0.014	0.013	0.013	0.012	0.011	0.010	0.008
0.4	0.020	0.020	0.020	0.019	0.018	0.017	0.016	0.015	0.015	0.014	0.013	0.012	0.011	0.011	0.009	0.008
0.6	0.036	0.036	0.036	0.035	0.034	0.033	0.032	0.031	0.030	0.028	0.027	0.026	0.025	0.023	0.020	0.018
0.6	0.036	0.036	0.036	0.035	0.034	0.033	0.032	0.030	0.029	0.028	0.026	0.025	0.024	0.022	0.019	0.017
0.8	0.050	0.050	0.049	0.049	0.049	0.048	0.047	0.046	0.045	0.044	0.042	0.041	0.039	0.038	0.033	0.030
0.8	0.051	0.051	0.051	0.051	0.050	0.049	0.048	0.046	0.045	0.043	0.042	0.040	0.038	0.036	0.032	0.028
1	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.060	0.059	0.058	0.057	0.056	0.054	0.052	0.048	0.043
1	0.064	0.064	0.064	0.064	0.064	0.063	0.062	0.061	0.060	0.059	0.057	0.055	0.054	0.052	0.047	0.042
2	0.111	0.111	0.111	0.111	0.112	0.112	0.113	0.114	0.114	0.115	0.116	0.117	0.117	0.117	0.116	0.113
2	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.123	0.123	0.123	0.123	0.123	0.122	0.119	0.115
4	0.256	0.254	0.252	0.248	0.240	0.233	0.227	0.223	0.219	0.216	0.214	0.212	0.212	0.211	0.213	0.215
4	0.291	0.290	0.287	0.282	0.272	0.264	0.256	0.250	0.245	0.241	0.237	0.235	0.233	0.232	0.231	0.231
6	0.485	0.481	0.475	0.463	0.440	0.420	0.401	0.384	0.369	0.356	0.345	0.335	0.327	0.321	0.309	0.304
6	0.558	0.553	0.546	0.532	0.505	0.481	0.459	0.438	0.420	0.405	0.391	0.379	0.368	0.360	0.344	0.335
8	0.794	0.788	0.777	0.755	0.714	0.675	0.638	0.605	0.575	0.547	0.522	0.500	0.481	0.464	0.430	0.409
8	0.918	0.910	0.897	0.872	0.824	0.778	0.735	0.696	0.660	0.627	0.597	0.571	0.547	0.526	0.485	0.457
10	1.18	1.17	1.15	1.12	1.06	0.995	0.938	0.884	0.835	0.789	0.747	0.709	0.675	0.644	0.581	0.536
10	1.36	1.35	1.33	1.29	1.22	1.15	1.08	1.02	0.963	0.909	0.859	0.815	0.774	0.737	0.661	0.606
12	1.62	1.61	1.59	1.55	1.46	1.38	1.30	1.22	1.15	1.08	1.02	0.962	0.910	0.863	0.764	0.689
12	1.88	1.86	1.84	1.79	1.69	1.59	1.50	1.41	1.33	1.25	1.18	1.11	1.05	0.992	0.874	0.784
14	2.12	2.10	2.08	2.03	1.92	1.82	1.71	1.61	1.51	1.42	1.34	1.26	1.19	1.12	0.978	0.867
14	2.45	2.43	2.41	2.35	2.23	2.10	1.98	1.86	1.75	1.65	1.55	1.45	1.37	1.29	1.12	0.992
16	2.65	2.64	2.61	2.55	2.43	2.30	2.17	2.05	1.93	1.81	1.70	1.60	1.50	1.41	1.22	1.07
16	3.07	3.05	3.02	2.96	2.82	2.67	2.52	2.37	2.23	2.10	1.97	1.85	1.74	1.63	1.41	1.23
18	3.22	3.20	3.18	3.12	2.98	2.84	2.69	2.53	2.39	2.24	2.11	1.98	1.86	1.74	1.50	1.30
18	3.73	3.71	3.68	3.61	3.46	3.29	3.11	2.94	2.77	2.60	2.44	2.29	2.15	2.02	1.73	1.50
20	3.81	3.79	3.76	3.70	3.57	3.41	3.24	3.06	2.89	2.72	2.55	2.40	2.25	2.11	1.81	1.56
20	4.40	4.39	4.36	4.29	4.13	3.95	3.75	3.55	3.35	3.15	2.96	2.78	2.61	2.44	2.09	1.80
30	6.78	6.79	6.80	6.81	6.75	6.62	6.43	6.19	5.92	5.63	5.33	5.03	4.74	4.45	3.80	3.24
30	7.81	7.82	7.84	7.85	7.80	7.66	7.45	7.18	6.87	6.53	6.19	5.84	5.50	5.17	4.40	3.75
40	9.45	9.50	9.59	9.74	9.94	10.0	9.95	9.78	9.52	9.19	8.81	8.40	7.97	7.53	6.48	5.53
40	10.8	10.9	11.0	11.2	11.4	11.5	11.5	11.3	11.0	10.7	10.2	9.75	9.25	8.75	7.52	6.42
50	11.7	11.8	12.0	12.3	12.8	13.2	13.4	13.4	13.3	13.1	12.7	12.3	11.8	11.2	9.77	8.39
50	13.3	13.4	13.6	14.0	14.7	15.1	15.4	15.5	15.4	15.1	14.7	14.2	13.6	13.0	11.3	9.74
60	13.6	13.7	13.9	14.4	15.3	16.0	16.5	16.9	17.1	17.0	16.8	16.4	15.9	15.3	13.6	11.8
60	15.4	15.6	15.8	16.4	17.4	18.3	19.0	19.5	19.7	19.6	19.4	19.0	18.4	17.7	15.7	13.7
70	15.2	15.4	15.7	16.3	17.4	18.5	19.4	20.1	20.6	20.8	20.8	20.6	20.2	19.6	17.7	15.6
70	17.2	17.4	17.7	18.4	19.8	21.1	22.2	23.1	23.7	24.0	24.0	23.8	23.4	22.7	20.6	18.1
80	16.7	16.9	17.3	17.9	19.3	20.6	21.9	23.0	23.8	24.4	24.7	24.8	24.5	24.1	22.2	19.8
80	18.8	19.0	19.4	20.2	21.9	23.5	25.0	26.3	27.3	28.1	28.5	28.6	28.4	27.9	25.8	23.0
90	18.2	18.4	18.7	19.5	21.0	22.6	24.1	25.5	26.8	27.7	28.4	28.8	28.8	28.6	26.9	24.3
90	20.3	20.6	21.0	21.9	23.7	25.6	27.4	29.2	30.6	31.8	32.7	33.2	33.3	33.0	31.2	28.2
100	19.6	19.8	20.2	21.0	22.6	24.4	26.1	27.9	29.4	30.8	31.9	32.6	33.0	33.0	31.7	29.1
100	21.8	22.1	22.5	23.4	25.4	27.5	29.7	31.7	33.6	35.3	36.6	37.5	38.0	38.1	36.7	33.7
120	22.6	22.8	23.1	23.9	25.7	27.6	29.8	32.0	34.2	36.2	38.0	39.6	40.7	41.4	41.3	39.1
120	24.8	25.1	25.5	26.5	28.6	31.0	33.6	36.2	38.8	41.3	43.5	45.3	46.7	47.6	47.7	45.2
140	25.8	25.9	26.3	27.0	28.7	30.8	33.1	35.6	38.2	40.9	43.4	45.6	47.6	49.1	50.7	49.4
140	28.1	28.3	28.7	29.6	31.8	34.3	37.1	40.1	43.2	46.4	49.4	52.1	54.5	56.3	58.4	57.1
160	29.3	29.4	29.7	30.3	31.9	33.9	36.3	39.0	41.9	45.0	48.1	51.0	53.7	56.0	59.6	59.7
160	31.6	31.8	32.2	33.0	35.0	37.5	40.4	43.7	47.2	50.9	54.5	58.0	61.3	64.0	68.5	68.8
180	33.1	33.2	33.4	33.9	35.3	37.2	39.5	42.3	45.4	48.8	52.3	55.8	59.2	62.2	67.9	69.7
180	35.5	35.6	35.9	36.6	38.4	40.8	43.7	47.1	50.9	54.9	59.1	63.3	67.3	70.9	77.8	80.2
200	37.4	37.4	37.5	37.8	38.9	40.6	42.9	45.6	48.8	52.4	56.3	60.2	64.1	67.8	75.5	79.3
200	39.8	39.9	40.1	40.6	42.1	44.3	47.2	50.6	54.4	58.7	63.3	68.0	72.7	77.1	86.4	91.1
250	49.8	49.7	49.5	49.2	49.4	50.3	52.0	54.5	57.6	61.3	65.6	70.2	75.1	80.1	92.1	101
250	52.2	52.1	52.0	52.0	52.6	54.1	56.4	59.6	63.4	68.0	73.1	78.7	84.5	90.4	105	116
300	64.9	64.5	63.9	63.0	61.8	61.7	62.6	64.4	67.2	70.7	75.0	79.8	85.2	90.9	106	120
300	67.3	67.0	66.5	65.8	65.1	65.6	67.1	69.6	73.1	77.5	82.7	88.6	95.1	102	120	137
350	82.6	81.9	80.9	79.1	76.5	75.1	74.9	75.9	77.9	81.0	85.0	89.8	95.3	101	119	136
350	85.0	84.4	83.5	81.9	79.8	79.0	79.4	81.1	84.0	87.9	92.9	98.8	105	113	133	154
400	103	102	100	97.7	93.3	90.4	88.9	88.8	90.0	92.4	95.9	100	106	112	130	151
400	105	105	103	100	96.6	94.3	93.4	94.1	96.1	99.4	104	110	116	124	146	170
450	126	125	123	119	112	108	105	103	104	105	108	112	117	123	142	164
450	129	127	125	122	116	112	109	109	110	112	116	121	128	135	158	185
500	152	150	147	142	133	127	122	119	118	119	121	124	129	135	154	177
500	154	153	150	145	137	131	127	125	125	126	129	134	140	147	170	198
600	212	209	205	197	183	171	163	157	153	151	151	153	156	160	178	203
600	214	212	207	199	186	175	167	162	159	158	160	162	167	173	195	225
700	282	279	272	261	240	224	211	201	194	189	187	186	187	190	205	229
700	285	281	275	264	244	228	215	206	200	196	195	196	198	203	222	252
800	364	359	350	335	307	284	266	251	240	232	227	224	223	224	235	257
800	366	361	353	338	311	288	271	257	247	240	235	234	234	236	252	280
900	456	450	439	419	383	353	329	309	293	281	273	267	263	262	269	288
900	459	452	442	422	386	357	333	314	299	289	281	277	275	274	286	311
1000	560	551	538	513	468	430	398	373	352	336	324	315	308	304	306	321
1000	562	554	540	515	471	434	403	378	359	344	332	325	319	316	323	344

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have been applied. Some of the data at frequencies below 200 Hz have been omitted because the attenuation was excessively high. Mellen and Browning[6] relate this phenomenon to an oceanic scattering process which sometimes becomes evident when the boric acid absorption is very low. Measurements at frequencies below 200 Hz have been summarized by Kibblewhite and Hampton[26] in an effort to show a regional dependence for the excess attenuation at low frequencies. They state that this anomalous contribution, which they also attribute to various scattering processes, is constant with frequency and varies with latitude, from 0.004 dB/km in polar waters to as low as 0.0002 dB/km in the tropics.

The South Pacific data (lines PA, PB, and KIWI in Fig. 5) would fit our equation if $pH = 7.6$, which is about minimum for the Pacific Ocean, instead of nearly 7.9 as shown. This would require that low pH values extend 20° farther south than outlined by Lovett[9] and would be in appreciable disagreement with his information[10] about pH in the Pacific.

A visual comparison between the values given by our equation, by the Schulkin–Marsh equation,[8] and by the Fisher–Simmons equation,[25] is presented in Fig. 6, which shows the variation of absorption with temperature and pH. The values given by our equation tend to fall between the others. The need for an equation with temperature and pH dependence is clear.
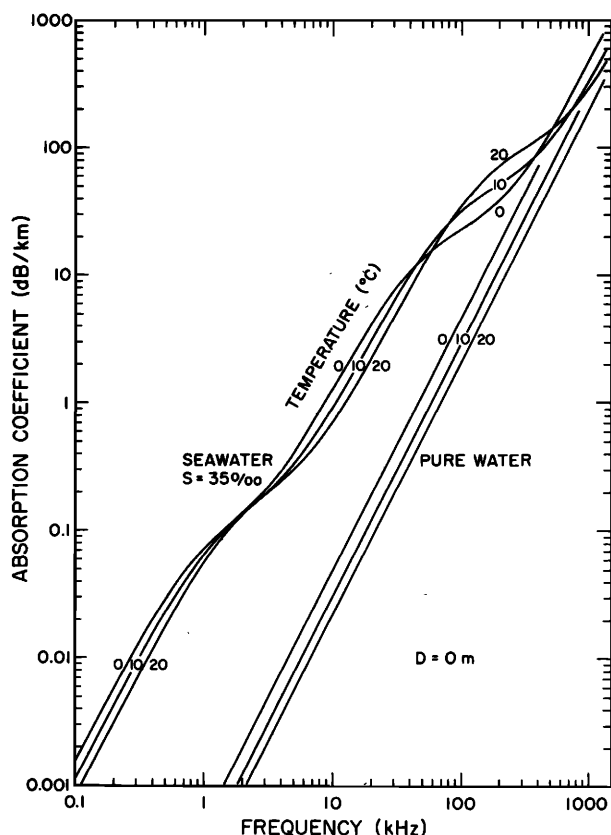
III. RECOMMENDED ABSORPTION EQUATION

In summary of both Part I and this paper, we present the equations shown in Fig. 7 for predicting the absorption of sound in seawater.

The boric acid contribution has been determined from measurements in waters with salinities of 34‰–41‰, temperatures of − 2° to 22 °C, and depths to 1500 m. The equation may not hold below 200 Hz, where the boric acid contribution may be exceeded by a scattering loss.

Table IV presents our results for ocean temperatures of − 1.8° to 30 °C, frequencies of 0.4 to 1000 kHz, and salinities of 30‰ and 35‰. The values are estimated to be accurate to within 5% in the range of parameters covered by the APL–UW measurements and to within about 10% outside our frequency range.

The absorption equation is plotted for three temperatures in Fig. 8, which shows the effect of the two relaxation phenomena. A three-dimensional plot for a family of absorption curves is shown in Fig. 9 to illustrate the changes in the relaxation phenomena with temperature.

Comparisons of our absorption equation with the 1962 Schulkin–Marsh equation (which has been augmented by the low-frequency boric acid equation prepared by Schulkin and Marsh in 1977) and with the Fisher–Simmons equation are given in Fig. 10. Above 10 kHz the agreement with the Fisher–Simmons equation is much better than with the Schulkin–Marsh equation, with a maximum difference of about 20%. Below 1 kHz, in warm waters, the agreement with the Schulkin–Marsh equation is the better.

Considering that our absorption equation is probably accurate to within 5%, we note large areas in the frequency-temperature domain where the disagreement with the other equations is significant. Our equations represent an improvement of 10%–20% in absorption prediction over most

FIG. 8. Seawater absorption at three temperatures (°C) for frequencies of 100 Hz to 1 MHz as given by our absorption equation (for $S = 35‰$ and $pH = 8$). Lines for pure water absorption have been added.
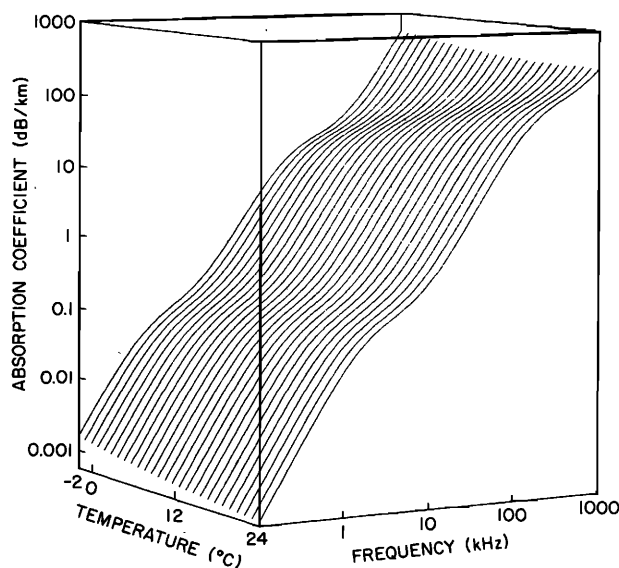

FIG. 9. Three-dimensional diagram of seawater absorption versus frequency and temperature. The effect of the boric acid and magnesium sulfate relaxation frequencies is apparent.
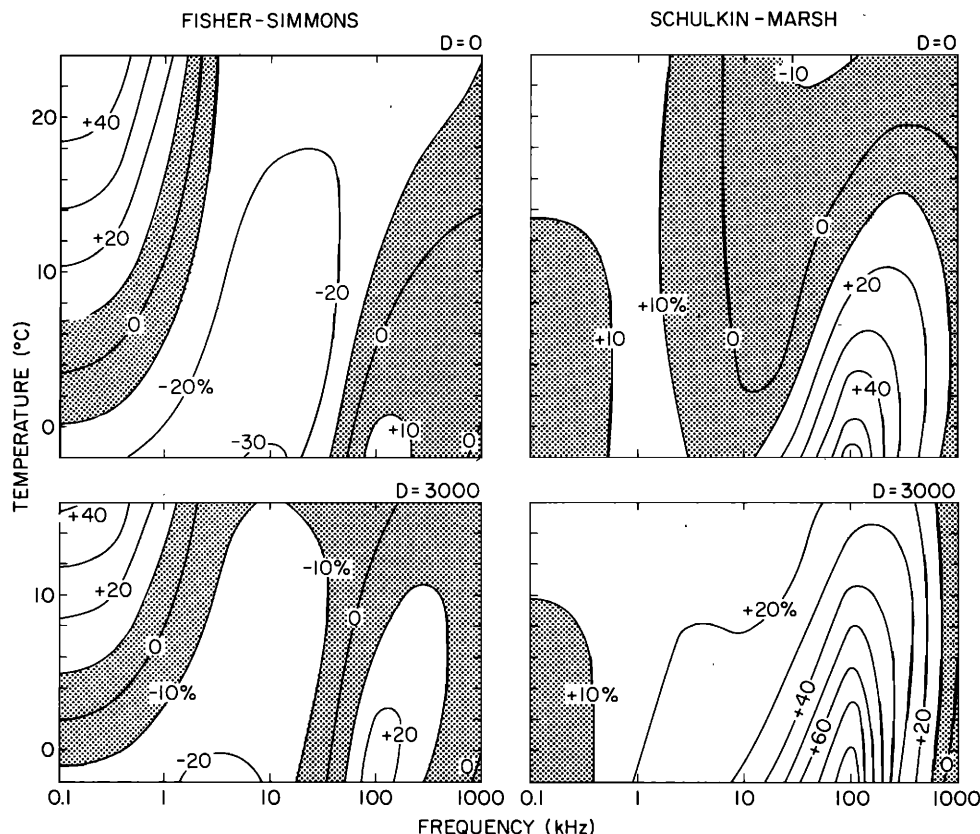
FIG. 10. Absorption predicted by the Fisher–Simmons and Schulkin–Marsh equations compared with our equation, for $S = 35\%_o$ and $pH = 8$, at depths of 0 and 3000 m. The shaded areas indicate a difference of less than 10%.

ocean conditions and over the acoustic frequencies of interest.

IV. SUMMARY

Low-frequency measurements of absorption reported in the literature that were conducted at widespread locations and over long ranges were reviewed. The $MgSO_4$ and pure water components, now given more accurately by the equations we developed in Part I, were subtracted to obtain a better estimate of the excess absorption due to boric acid. The dependence of the boric acid relaxation frequency on temperature and the change in the absorption from ocean to ocean as a result of pH differences were determined.

Combining our results for boric acid with the results for pure water and $MgSO_4$ developed in Part I, we have compiled an equation to predict absorption in natural seawater in the frequency range of 200 Hz to 1 MHz and to depths of 5000 m. In general, our predicted absorption lies near or between the Schulkin–Marsh and the Fisher–Simmons predictions, which differ by 30%–50% in some areas. Our equation, the result of an extensive review of field measurements and fitting of data to relaxation theories, is sufficiently accurate to improve absorption prediction in these areas.

Future absorption measurements would be more valuable if investigators obtained a better record of the environment along the transmission path. The sound intensity measurements and the environmental properties should be reported in detail so that others can analyze the data using their preferred methods. One problem at low frequencies is that properties along the axis of the sound channel are often

used in the calculations, even though the nonsymmetry of the channel results in much of the transmission being off axis. The pH measurement is very important and should always be included in the environmental data set. Ideally, measurements of absorption should be performed over a frequency range that brackets one of the relaxation frequencies so that, when the data are fitted to relaxation theory, errors in the assumed spreading loss will become evident. Such refinements may lead to more accurate results and a better fit to theory. Some of the large discrepancies we observed, however, indicate that absorption may be affected by some seawater property or component that has not been included in the analysis.

ACKNOWLEDGMENTS

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