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Discussion of sea water sound-speed determinations

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Available data on the speed of sound in sea water are examined to arrive at a basis for deriving simple equations suitable for most ocean areas. Extant laboratory data are compared. *In situ* measurements aboard deep submergence vehicles are presented, and convergence zone ranges discussed. Del Grosso and Mader [J. Acoust. Soc. Am. **52**, 961–974 (1972)] equations appear superior, after numerous intercomparisons, to serve as a foundation for generating simple sound-speed equations.

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INTRODUCTION

Historically, in 1938 Kuwahara[1] published an equation for salinity dependence and tables (computed with an abacus) giving sound-speed dependence on temperature, depth, latitude, and interaction effects. In 1951, more complete equations to fit Kuwahara's tables for all conditions were formulated by the author[2] to enable development of high-speed computations to rapidly reduce the backlog of oceanographic data. Laboratory measurements on sea water by Del Grosso[3] determined that values at atmospheric pressure were about 3m too low, which was later confirmed by Wilson.[4]

In 1960 Wilson[5,6] published two equations for sound speed as a function of temperature, salinity, and pressure, the first laboratory measurements of the pressure effect on sea water. Convergence zone propagation loss structure and range analyzed by Pedersen[7] indicated a better agreement when computed with Wilson instead of Kuwahara. General consensus concluded that Wilson's October equation be adopted for practical applications. Presently, vast amounts of data exist in which depth, temperature, salinity, and Wilson sound speed are tabulated.

Del Grosso and Mader[8] published more modern results in 1972, but this equation has not been universally adopted. Other candidate equations have been generated, mostly based on Wilson data, although some have combined Del Grosso and Mader atmospheric pressure data with Wilson's pressure dependence. In this paper, available experimental data are discussed.

I. LABORATORY MEASUREMENTS

A. Distilled water

Intercomparisons since 1964 between laboratory measurements at atmospheric pressure of various investigators and the Del Grosso and Mader sound-speed data displayed close agreement, and consequently an equation based on the latter was adopted for calibration of velocimeters by the author.[9] Recent outstanding work of Kroebel and Mahrt[10] agrees with Del Grosso and Mader[11] near 0 °C, but departs linearly to 0.06 m/s at 34 °C. Wilson versus Del Grosso differ from almost zero at 2 °C to as much as 1.7 m/s at 30 °C.

Fundamental first-order measurements of pressure and temperature effects on sound speed have been carried out for distilled water by Wilson[12] as well as Barlow and Yazgan[13] but not by Del Grosso. Wilson covered the range 0.906° to 91.269 °C from atmospheric (14.7 psi) to 14000 psi; Barlow and Yazgan covered 16.565° to 93.370 °C from atmospheric to 11603.2 psi. To intercompare pressure effects over an overlapping temperature range of interest, least-squares fits were computed for Wilson from 19.656° to 59.586 °C. Because of a suggestion[14] that Wilson's 10.203 °C measurement was really for 10.32, this value was excluded. Similarly, Barlow and Yazgan data were fitted from 16.565° to 60.590 °C; this 14-term LSF ($\sigma = 0.1115$ m/s) and the 12-term LSF for Wilson data ($\sigma = 0.0676$ m/s) were chosen for intercomparison. Results are plotted in Fig. 1. A definite pressure dependence for distilled water is obvious.

Second-order measurements were accomplished by Chen and Millero[15] with a Nusonics single-transducer sing-around velocimeter which had been calibrated with Wilson's[12] pressure versus temperature sound-speed data. After analysis they concluded that all pure-water data should be shifted by apparent errors at atmospheric values, agreeing (not surprisingly) with Wilson's pressure effect, and generated a new 19-term equation combining Wilson's pressure dependence and atmospheric data of Del Grosso and Mader.

B. Sea water

Definitive determinations at atmospheric pressure of sea water temperature dependence, which have been reported by Wilson[6] as well as Del Grosso and Mader,[8] differ significantly. Recent measurements by Kroebel and Mahrt[10] are in concurrence with Del Grosso and Mader and indicate Wilson's data are too high by 0.37 to 0.71 m/s.

Second-order measurements of sea water at atmospheric pressure were reported by Millero and Kubinski[16] who employed a Nusonics two-transducer velocimeter calibrated with a sound-speed equation for pure water developed by Kell[17] (similar to Del Grosso[9,11]). Kroebel and Mahrt demonstrate that differences between Del Grosso, and Millero and Kubinski can be as much as 0.21 m/s at 35 °C and depend on the pure-water data reference.

Fundamental determinations of sound speed in sea

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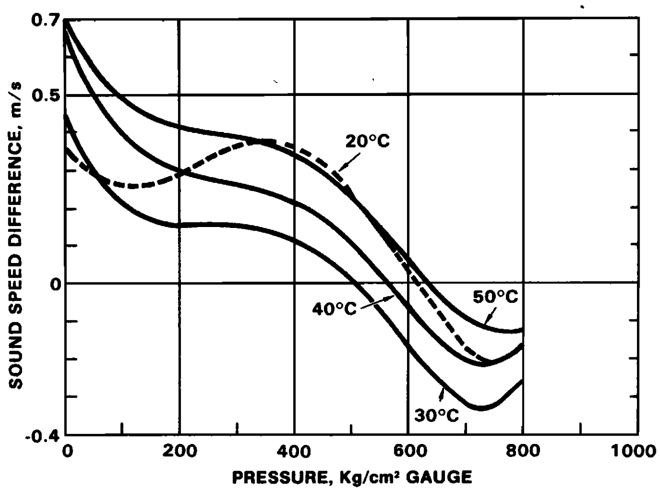

FIG. 1. Distilled water pressure effect, Wilson minus Barlow and Yazgan.

water as a function of pressure and temperature have been performed only by Wilson[5,6] and Del Grosso and Mader.[8]

Because some have suggested[18] that Wilson's October equation contains two different sets of data, the June equation was selected by the author for comparison with Table VI of Ref. 8. Here differences are between good sets of data within the common range of measurements; some are illustrated in Fig. 2 for 0° and 5 °C for salinities of 33, 34, 35, and 36 °/oo (parts per thousand). Obviously pressure gradients vary in a complicated manner because the trends in Figs. 1 and 2 are distinctly different.

Secondary measurements of Chen and Millero,[19] with a Nusonics single-transducer velocimeter (calibrated

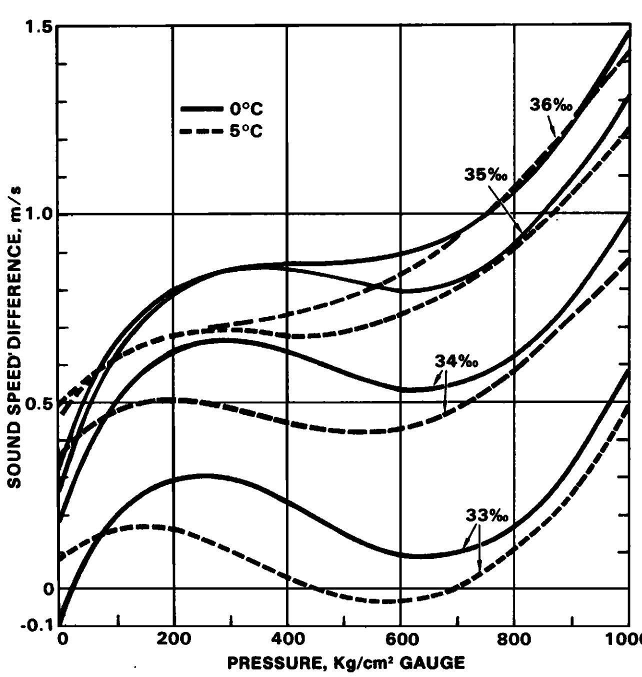

FIG. 2. Sea water pressure effect, Wilson minus Del Grosso and Mader.

relative to Wilson's pure-water pressure–temperature data) indicated a better agreement with Wilson than with Del Grosso and Mader for sea water under pressure. Chen and Millero present a 42-term expression for sound speed in sea water as a function of pressure, temperature, and salinity.

II. IN SITU MEASUREMENTS

Deep submergence vehicles were employed to simultaneously measure temperature, salinity, pressure, and sound speed. The object was to verify that *in situ* open ocean measurements would agree with predictions based on laboratory determinations with small sterile sea water specimens. Equipment mounted on the brow of DEEPSTAR–4000 (maximum certified depth 4000 ft or 1219 m) is displayed in Fig. 3. The NUS sing-around velocimeters were calibrated in distilled water immediately before and after each series of dives.[9] Del Grosso's distilled water sound speed was the standard. Small shifts were noted from calibration to calibration. A standard error for sound speed in the field was no less than 0.05 m/s.

A. Temperature

The two Hewlett–Packard Dymec quartz temperature sensors consisted of two quartz crystal-controlled oscillators operating nominally at 28.2 MHz. A special (LC) cut was used with one crystal to gain a highly linear change of frequency with temperature of about 1000 Hz/°C. The other crystal was temperature insensitive (AT cut). Both crystals were mounted in a $\frac{1}{2}$-in.-diam aluminum can filled with helium for heat transfer. Output frequencies from the two oscillators were heterodyned to provide zero frequency output at 0 °C for one Dymec sensor and −2 °C for the other. Accuracies of 0.004 °C could be realized. Calibrations were conducted with the 1968 ITPS (International Temperature Practical Scale), converted to 1948 ITPS before computing Wilson or Del Grosso sound speeds. Standard reversing thermometers (calibrated with 1948 ITPS) were always utilized for backup.

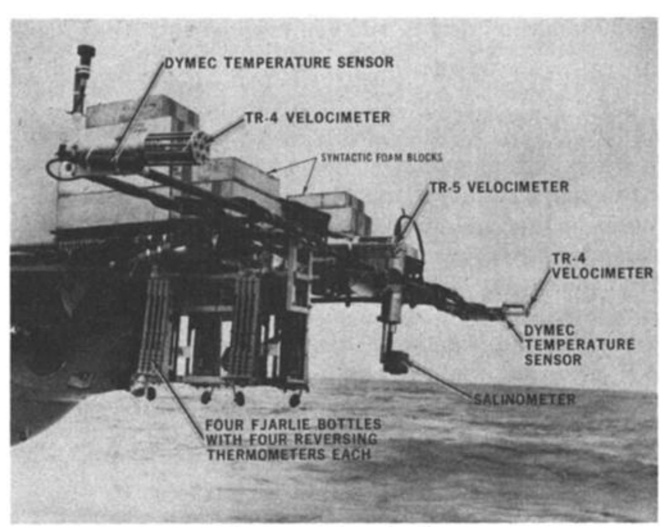

FIG. 3. Equipment mounted on brow of DEEPSTAR–4000.

B. Salinity

Salinities, measured via a Hytec Salinometer Model 6009, were determined by conductivity with a sea water coupled induction coil, and internally compensated for temperature and pressure to yield an output frequency proportional to salinity. Temperature was sensed by a platinum-wire thermometer, and pressure by a strain gauge—both an integral part of the salinometer unit. The salinometer calibration drifted somewhat between dives. Because salinity changed less than 1°/∞ between the surface and the sea floor at 1200 m, the assumption was that the salinometer would afford accurate values throughout the water column, if field-calibrated while suspended near the surface and at the bottom. Output frequencies were counted directly at these equilibrium positions and Fjarlie bottles trapped water samples. Later, salinities were ascertained in the laboratory with a conductivity method, and a simple least-squares fit produced the calibration of the day for each dive.

C. Depth/pressure

Depth, the most taken-for-granted variable, was subject to uncertainty because stable sensors for pressure measurements accurate to better than 1 part in 1000 were not available. Two Vibrotron pressure transducers (mounted aft of the DEEPSTAR brow) converted pressure to frequency by means of a taut vibrating wire attached to a pressure diaphragm. Despite shortcomings, temperature-compensated Vibrotrons proved more reliable than other methods. Output frequencies ranged from 9000 to 11 000 Hz. Vibrotrons with associated oscillators were calibrated at 0° and 20 °C with a deadweight tester for both increasing and decreasing pressures (ocean pressure gradients vary from 1.00 to 1.03 MPa per 100 m). Differences between corrected readings of protected and unprotected reversing thermometers enabled depth to be computed and compared with Vibrotron data, which sometimes differed by 3 m at 1000-m depths.

Because of weight constraints an upward-looking sonar, limited to moderate acoustic power, received surface echoes eventually masked by self-noise as depth increased. An upward-looking 23-kHz EDO echo sounder aboard DEEPSTAR–4000 failed to see the surface for depths greater than 800 m during any of the author's dives.

D. Procedure

Data were acquired with DEEPSTAR–4000 suspended 6 or 9 m below the surface. A period of 20 min was allowed for equilibrium and then a series of 10-s counts was logged for all sensors; afterwards one or two Fjarlie bottles were tripped to capture water samples before the dive commenced. As the vehicle descended verti-

TABLE I. Some *in situ* sound-speed data (m/s) obtained aboard DEEPSTAR–4000.

Dive number	171	172	173		478	479
Near-surface (suspended)						
Temperature, °C	17.87[a]	17.06[a]	17.19[a]		19.483	18.460
Salinity, °/∞	33.456	33.502	33.560		33.676	33.661
Pressure, kg/cm^2	1.95	1.95	1.95		1.65	1.65
Del Grosso VI	1513.87	1511.41	1511.86		1518.63	1515.70
Wilson, Oct.	1514.52	1512.07	1512.53		1519.26	1516.35
Wilson minus Del Grosso	0.65	0.66	0.67		0.63	0.65
Velocimeter: TR–3B	1513.81	1511.47	1511.95	TR–4 #17	~~1518.68~~	~~1515.96~~
TR–4 #17	1513.79	1511.37	1511.72	TR–4 #559	1518.62	1515.82
				TR–5 #603	1518.41	1515.80
Average	1513.80	1511.42	1511.84		1518.52	1515.81
Av. minus Del Grosso	–0.07	+0.01	–0.02		–0.11	+0.11
Bottomed (about 1200 m)						
Temperature, °C	3.52[a]	3.51[a]	3.49[a]		3.703	4.077
Salinity, °/∞	34.520	34.510	34.508		34.513	34.484
Pressure, kg/cm^2	124.46	126.77	126.90		112.33	120.84
Del Grosso VI	1483.56	1483.88	1483.81		1482.38	1485.28
Wilson, Oct.	1484.05	1484.36	1484.30		1482.85	1485.76
Wilson minus Del Grosso	+0.49	+0.48	+0.49		+0.47	+0.48
Velocimeter: TR–3B	1483.57	1483.93	1483.88	TR–4 #17	~~1481.21~~	~~1483.63~~
TR–4 #17	1483.56	1483.82	1483.90	TR–4 #559	1482.63	1485.20
				TR–5 #603	1482.36	1484.93
Average	1483.56	1483.88	1483.89		1482.49	1485.06
Av. minus Del Grosso	0.00	0.00	+0.08		+0.11	–0.22
Near-surface minus bottom						
Velocimeter average	30.24	27.54	27.95		36.03	30.75
Del Grosso VI	30.31	27.53	28.05		36.25	30.42
Wilson, Oct.	30.47	27.71	28.23		36.41	30.59

[a]1948 ITPS.

TABLE II. Sound-speed gradients near the bottom, measured aboard DEEPSTAR-4000.

Tethered 30.5 m above bottom			
TR–4 17, m/s	1483.468		
Del Grosso VI, m/s	1483.411		
Wilson, Oct., m/s	1483.894		
Pressure, kg/cm^2	121.66	Differences, m/s	
Temperature, $°C_{68}$	3.588		
Salinity °/°°	34.526	TR–4 #17	0.316
		Del Grosso VI	0.313
Bottomed		Wilson, Oct.	0.317
TR–4 17, m/s	1483.784		
Del Grosso VI, m/s	1483.724		
Wilson, Oct., m/s	1484.211		
Pressure, kg/cm^2	124.80		
Temperature, $°C_{68}$	3.540		
Salinity, °/°°	34.534		

cally to ensure that the sensors sampled undisturbed water, data were recorded on a 7-channel tape recorder throughout the water column. On the bottom the procedure was the same as for near-surface data collection.

Data for the five dives represented in Table I are the most complete and have been partially reported[20]; values depicted are the best reconciliation among the sensors, and sound speed is presented to two decimal places but only the first place is reliable. Small computed pressure corrections were applied, but ideally, velocimeters should also be calibrated under pressure when a standard has been accepted. Each instrument may indeed manifest individual idiosyncrasies. Attention is called to values for the TR–4 #17 on dives 478 and 479 which are crossed out. This instrument, which appeared to behave normally at sea, yielded reasonable values near the surface but not at depth, failed to sing-around when later placed in distilled water for calibration, but would sing-around in tap water because of conductivity. Examination revealed that most of the outer electrode plating on the receiving crystal was destroyed. Grounding problems were encountered on this series of dives. Because of drifting, frequent calibrations were required to assure dependable data. Examination of Table I manifests a decided advantage for Del Grosso and Mader for the overall sound-speed gradient over the limited range of 1200 m.

Table II tabulates some special data for the gradient over 30.5 m above the bottom. For this dive the TR–4 was operating optimally. While bottomed at about 1200 m, a small weight was released to allow DEEPSTAR to rise until restrained 30.5 m above the seafloor by a light line attached to the jettisoned weight. After sufficient data were acquired, a small explosive was detonated to release the tether line and begin ascent.

III. CONVERGENCE ZONE MEASUREMENTS

A. Range determinations

Measured sound levels at convergence zones demonstrate that sound is received in the "so-called" shadow zone and caustics are not sharply defined. In fact, as the zone is approached, sound levels increase before the range of the predicted first caustic and reach a first maximum at a greater range. These facts, well-known for 25 years, are reasonably explained by recent theory.[21] A practical definition of the range to a convergence zone can be the distance where the propagation loss first drops to −95 dB as the zone is approached, or as the range to the first sound level maximum. The definition in Ref. 14 is unspecified and requires clarification.

Ranges to convergence zones generally are computed with Wilson's October equation and measured travel time differences between simultaneous radio and acoustic signals. Because acoustic signals are detected in the presence of noise, travel time accuracy of 0.05 s (75 m) is seldom attainable to the start of a zone. Archival deep data are usually spliced onto *in situ* sound-speed data at some distance below the surface. For depths less than 3000 m under certain conditions, archival data may be in error due to Rosby[22] or planetary (baroclinic) waves that may cause periodic oscillations of sound-speed profiles to depths of 3000 m and must be considered for long range computations based on spliced profiles. Wavelengths may be over 200 nmi with a period more than 100 days.

Sound-speed profiles near the surface at both ends of the propagation path are necessary. Several bathythermographs (BTs) are required to establish means and probable errors. For accurate ranges to, and propagation loss in convergence zones, effects of probable errors must be accounted for.

Other factors that must be considered for precise computations for low angle caustics include effects of the ocean surface on reflected paths and the actual depths of the source and receivers in a heaving sea. Generally the heavy source hangs directly below the stern and participates in the vertical motion of the ship, which causes part of the observed pulse-to-pulse fluctuation.

Receivers normally are suspended below a buoy streamed away from the receiving ship, usually adrift to reduce noise. The wind may blow the ship from $\frac{1}{2}$ to 3 kn, resulting in a receiving hydrophone being shallower than its nominal depth, which at 30 m may in reality be 25 m or shallower. For a 3° ray the error in range would thus be 95 m.

B. Earth curvature effects

Most computations are published assuming a flat earth. For comparisons with observed convergence zone range data, a correction for the curvature of the earth is essential. Generally this may be accomplished by adjusting the real sound-speed profile and then computing as for a plane earth. A procedure for this adjustment is given by Watson[23] based on Pryce.[24] Computed ranges for an ellipsoidal earth are significantly less than for a plane earth with an unadjusted profile. Reference 14 does not specify if earth curvature was considered.

C. Convergence zone data

Acoustically determined convergence zone ranges attributed to Anderson by Lovett[14] are referenced as criteria to decide that pressure effects of both Wilson, and Del Grosso and Mader are incorrect. No convergence zone propagation loss versus range data are given in either of Lovett's Anderson references. The paradox of why Del Grosso and Mader exhibit a pressure discrepancy may be that Anderson's unpublished convergence zone data are not sufficiently accurate. These and other pertinent data should be fully published and subjected to the same relentless error analyses that both Wilson and Del Grosso have long endured.

IV. CONCLUSIONS

Based on laboratory measurements, conclusions include: (1) the Del Grosso and Mader equation is superior to Wilson's at atmospheric pressure and (2) evidence is inconclusive as to the better equation under high pressures, but Wilson's pressure dependence agrees with neither Barlow and Yazgan nor Del Grosso and Mader (Figs. 1 and 2). For sea water, definitive independent fundamental measurements are required for temperature, salinity, and pressure effects to choose between Wilson, Del Grosso, or others.

In situ data tend to confirm that laboratory measurements by Del Grosso and Mader on small samples, agree with open sea water values to depths of 1200 m. It must be emphasized that at-sea measurements are difficult because four independent variables must be accurately determined under nonideal conditions.

Convergence zone data should be reported in detail. Until convergence zone ranges have been studied thoroughly, it is premature to assume that Del Grosso and Mader offer incorrect pressure dependence or that the merged equation of Ref. 14 is more correct. Measurements, if merited after error analysis, should be conducted in diverse geographic regions under carefully controlled conditions.

After numerous intercomparisons, Del Grosso and Mader equations were chosen to serve as a foundation for generating simple sound-speed equations.[25]

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