

# Calibration of a Seawater Sound Velocimeter

Aaron D. Sweeney, C. David Chadwell, and John A. Hildebrand

**Abstract**—We calibrated a sound velocimeter to a precision of  $\pm 0.034$  m/s using Del Grosso's sound-speed equation for seawater at temperatures of 2, 7.2, 11.7, and 18 °C in a tank of seawater of salinity 33.95 at one atmosphere. The sound velocimeter measures the time-of-flight of a 4-MHz acoustic pulse over a 20-cm path by adjusting the carrier frequency within a 70-kHz band until the pulse and its echo are inphase. We used the adjustable carrier frequency to determine the internal timing characteristics of the sound velocimeter to nanosecond precision. Similarly, sound-speed measurements at four different temperatures determined the acoustic pathlength to micrometer precision. The velocimeter was deployed in the ocean from the surface to 4500 dbar alongside conductivity, temperature, and pressure sensors (CTD). We demonstrated agreement of  $\pm 0.05$  m/s (three parts in  $10^5$ ) with CTD-derived sound speed using Del Grosso's seawater equation from 500 to 4500 dbar after removing a bias and a trend.

**Index Terms**—Calibration, conductivity measurement, conductivity, temperature, and pressure sensors (CTD), least squares methods, marine technology, pressure effects, sound-speed measurements, sound velocimeter, temperature control, time measurement, underwater acoustic measurements, underwater acoustics.

## I. INTRODUCTION

**P**RECISE and accurate measurements of sound speed to  $\pm 0.015$  m/s (1 part in  $10^5$ ) are important for propagation studies probing ocean temperatures [1] and for geodetic surveys of ocean-bottom transponders [2]. Sound-speed errors of this size may contribute to a bias in estimated temperature of several millidegrees. Geodetic surveys of ocean-bottom transponders rely on centimeter-precision range estimates over 1 km paths, by measuring time-of-flight of an acoustic signal. The most direct measurement of sound speed is to time the flight of the acoustic signal through the seawater medium over a known fixed path. The first measurement of this type was made by Colladon and Sturm in 1827 in Lake Geneva by measuring the time it took for the sound of a bell struck underwater to traverse a known distance [3]. Modern applications can observe fine-scale variations in propagation by making sound-speed measurements over paths less than 1 m. Over such short paths, travel times must be known to a nanosecond and distances must be known to a micron to determine the sound speed to 1 part in  $10^5$ . Deploying instruments in the ocean that achieve this level of precision has

been problematic. However, under laboratory conditions, instruments with fixed and adjustable paths and with various techniques for measuring travel time, have approached measurement precisions of  $\pm 0.05$  m/s [4], [5].

Sound speed depends on temperature, salinity, and pressure. Instruments that measure these physical quantities are called conductivity, temperature, and depth sensors (CTDs). CTDs with the required precision are easily deployable in the ocean; the standard approach to measure sound speed is to observe temperature, pressure, and salinity, and calculate the sound speed from the laboratory-derived equation. In distilled water, the relationship between temperature and sound speed has been determined to a precision of  $\pm 0.015$  m/s [6]. In seawater, the relationship between sound speed and temperature, salinity, and pressure has been established with a precision of  $\pm 0.05$  m/s by Del Grosso [7] and  $\pm 0.19$  m/s by Chen and Millero [8]. To achieve  $\pm 0.05$  m/s precision in sound speed, the corresponding precision of  $\pm 0.001^\circ\text{C}$ ,  $\pm 1$  dbar, and  $\pm 0.01$  (PSS-78) are required for the measurement of temperature, pressure, and salinity, respectively. Throughout this paper, we have used the decibar as the unit of pressure (10 kPa=1 dbar, exactly), because of its close numerical equivalency to water depth expressed in meters.

There remains an effort to develop portable sound velocimeters that measure sound speed directly to 1 part in  $10^5$ . Direct measurements may be more reliable in waters with chemical constituents significantly different from that used to derive the laboratory equations, e.g., the effluent of hydrothermal vents at midocean ridges. The desired instrument would calculate sound speed by measuring time to nanosecond level and pathlength to micron level. As yet, no approach to measuring pathlength at the micron level has been deployed on a portable instrument. Thus, an alternative is needed to establish a relationship between sound velocimeter observations and sound speed. To date, the only direct measurements of sound speed with required precision were collected by the devices used to derive the laboratory equations. Thus, one approach to establish the relationship would be to operate the portable instrument alongside the laboratory instrument. However, because of the difficulty in reconstructing the original laboratory instruments, a practical alternative has been to relate the portable sound velocimeter travel time to sound speed indirectly through the laboratory derived equations. This is done by recreating the bath conditions in which the original equations were derived, measuring temperature, pressure, and salinity to calculate the sound speed. The portable velocimeter is immersed in the bath and its observations are recorded as the temperature is varied to create a wide range of sound speeds. The relationship between the portable velocimeter observations and sound speed is subsequently derived. Because Del Grosso and Mader's equation of state for

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distilled water at one atmosphere is precise to  $\pm 0.015$  m/s and thought to be the most accurate of all state equations, the standard approach has been to calibrate the portable velocimeters in distilled water at one atmosphere over a wide range of sound speeds by varying the temperature [6], [9], [10].

Using this calibration approach, Mackenzie [9] established a precision of  $\pm 0.1$  m/s for a sing-around velocimeter, which used the repetition frequency of the transmit/receive cycle to measure the travel time. The precision of the sing-around technique suffered from interference of the transmitted pulse with secondary echoes from previous transmissions, so that the phase of the echo was not preserved. Boegeman *et al.* [11], improved the timing by preserving the phase of the echo by looking at the time-of-flight of a single pulse and first echo. Using an instrument based on this approach, McIntyre [12] performed a calibration that achieved a  $\pm 0.05$  m/s fit to Del Grosso and Mader's distilled water equation from 0 to 22 °C. Subsequently, Eaton and Dakin [10] developed an instrument using a time-of-flight approach to achieve a root-mean-squared (rms) misfit to Del Grosso and Mader's distilled water equation better than  $\pm 0.06$  m/s from 0 to 59 °C. However, all of these calibrations did not consider a more representative range of salinity and pressure encountered in the ocean.

To address this problem, Sweeney *et al.* [13] conducted an at-sea comparison, using the original Boegeman device calibrated by McIntyre. This entailed lowering an instrument package containing both the sound velocimeter and a CTD to a depth of 2 km. From the CTD measurements, the sound speed was calculated using Del Grosso's equation [7]. From the sound velocimeter observations, the sound speed was calculated with the relationship derived from the laboratory calibration in distilled water. The difference between the two instruments showed a sound-speed offset of 0.25 m/s and a trend with pressure of about 0.13 m/s per 1000 dbar, with an overall fit of  $\pm 0.07$  m/s. However, calibration of the sound velocimeter and comparison with at-sea CTD measurements using the same sound-speed equation is a more consistent approach, especially at the sea surface where one can reproduce similar conditions in the laboratory under controlled temperature and salinity.

In this paper, we calibrate the velocimeter in the laboratory in seawater and compare with CTD-derived sound speeds in the ocean at high pressure, in both instances using Del Grosso's equation. Del Grosso's equation was chosen to calculate the sound speed because of recent literature attesting to its greater accuracy over the Chen and Millero equation at high pressure [1], [15]. For this experiment, we constructed a second-generation instrument of the Boegeman *et al.* [11] design built using improved electronics and mechanical components to refine the timing and reduce the effect of temperature on the pathlength.

## II. DESCRIPTION OF DEVICE

The sound velocimeter measures the time of flight of a nominal 4-MHz pulse over a 20-cm pathlength through a small volume of seawater (Fig. 1). A voltage-controlled oscillator (VCO), a modified version of the standard Colpitts transistor oscillator, [16] generates a 3.94–4.01-MHz frequency that ensures operation near the resonance of the piezoelectric

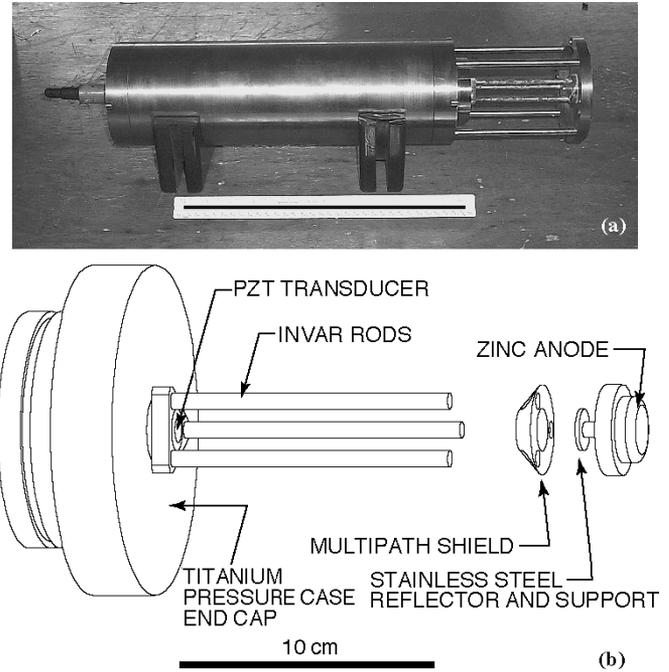


Fig. 1. (a) Photograph of sound velocimeter showing titanium pressure case and transducer assembly, or sound head, purchased from Applied Microsystems, Ltd. Black scale bar is 30.5 cm. (b) Exploded view of the sound head, including the PZT transducer (2-mm-thick, 9.52-mm-diameter) and a stainless steel reflector (1.5-mm-thick) and standoff (6-mm-dia., 8.9-mm-long) held in place by three Invar rods (6.4-mm-dia., 110-mm-long). The combination of Invar and stainless steel is designed to reduce the effective coefficient of thermal expansion of the sound path to  $5.5 \times 10^{-9}$  per °C [10]. The conical mask was used to eliminate multipath effects. The two-way pathlength was approximately 20 cm. Black scale bar is 10 cm.

transducer (PZT 850). Applying 128 cycles of the continuous sine wave output of the VCO to the transducer generates an acoustic pulse of approximately  $32 \mu\text{s}$  duration. The pulse travels through the water, is reflected off a perpendicular plate, and is received at the same transducer with a round trip travel time of approximately  $140 \mu\text{s}$ . The pulse length ensures that the signal reaches a constant amplitude. A pulse repetition of approximately 1 ms (4096 VCO cycles) ensures that the echoes decay before the next transmit pulse. Fig. 2 shows a block diagram relating the VCO to the sound path.

The time of flight of the pulse ( $t$ ) is measured from the product of the VCO period ( $P$ ) and the number of VCO cycles (called the lane  $n$ ) between the transmitted pulse and the received echo

$$t = nP = \frac{n}{f} \quad (1)$$

where  $f$  is the VCO frequency. The velocimeter uses a temperature-compensated 10-MHz counter to determine the VCO frequency to a resolution of 3 Hz. The VCO frequency is adjusted to make the lane a whole number [11], [14]. When this condition is met, the transmitted pulse and received echo are in-phase. The absolute number of cycles is not known since it depends on the unknown pathlength. In addition, there are possible electronic delays present in the instrument. Because the time of flight is about  $140 \mu\text{s}$  and the VCO frequency is adjustable over a 70-kHz span, the lane can take on up to ten distinct values

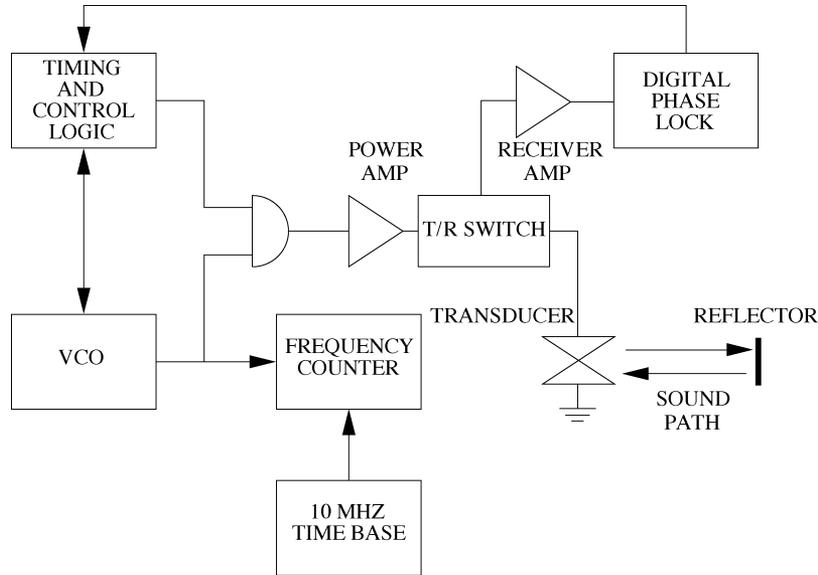


Fig. 2. Block diagram of sound velocimeter electronics and sound path. The carrier frequency of the pulse generated at the PZT transducer is defined by a VCO. The pulse travels through the water, reflects, and is received by the same transducer. The device determines the integral number of cycles of the free-running VCO between the transmitted pulse and received echo, and adjusts the frequency of the VCO and transmitted pulse until the received echo and VCO are in phase. The VCO frequency is precisely measured by a 10-MHz oscillator. The travel time is the number of cycles of the VCO between the outgoing and incoming pulses divided by the VCO frequency.

at the same sound speed. This feature is exploited to overdetermine the sound speed in the laboratory calibration discussed in the next section.

The velocimeter sound speed  $SV_V$  is calculated from the lane ( $n$ ), frequency ( $f$ ), pathlength ( $L_0$ ), and temperature ( $T$ ) using

$$SV_V = \frac{L_0(1 + \alpha T)}{\frac{n}{f}} \quad (2)$$

where  $\alpha$  is the effective coefficient of thermal expansion of the sound path,  $5.5 \times 10^{-9}$  per  $^{\circ}\text{C}$ , specified by the manufacturer. The prototype sound velocimeter used by McIntyre [12] and Sweeney *et al.* [13] consisted of stainless steel supports along the sound path, resulting in a coefficient of thermal expansion of  $1.5 \times 10^{-5}$  per  $^{\circ}\text{C}$ . The new instrument uses a combination of Invar and stainless steel manufactured by Applied Microsystems, Ltd., Sydney, BC, Canada, that reduces the sensitivity of the pathlength to temperature by over three orders of magnitude. The dimensions and opposing arrangement (Fig. 1) of the Invar rods and the stainless steel reflector and support were selected so that their expansions would nearly cancel [10].

The sound speed derived from (2) is an idealized form that neglects possible systematic effects in the lane, frequency, and pathlength. To account for these possibilities, additional terms were introduced in the travel time as follows:

$$SV_V = \frac{L_0(1 + \alpha T)}{\frac{n + a_0}{f + \Delta f} + a_1 + a_2 f} \quad (3)$$

including a lane offset  $a_0$ , a constant time delay  $a_1$ , and a linear frequency-dependent term  $a_2$ . Mackenzie [9] described a similar constant offset term in his calibration of sing-around velocimeters. The frequency of the 10-MHz oscillator used for counting the VCO cycles has not been independently measured.

If it is not exactly 10 MHz, this will alter the calculated VCO frequency  $f$  by the value  $\Delta f$ . However, recall that we also do not measure the pathlength, and a change in pathlength may appear to be equivalent to  $\Delta f$ . The  $\Delta f$  term is shown here for completeness, but it is not retained in the final form of the equation, as it can be absorbed into the selected value for pathlength  $L_0$ .

### III. LABORATORY CALIBRATION AT ATMOSPHERIC PRESSURE

The acoustic pathlength and travel time delays are determined by a laboratory calibration in seawater of salinity 33.95 (practical salinity scale of 1978) [17] at one atmosphere and at temperatures of 2, 7.2, 11.7, and 18  $^{\circ}\text{C}$ , corresponding to sound speeds of 1456.67, 1478.03, 1494.80, and 1514.71 m/s, respectively. Because our thermometers are calibrated against the International Temperature Scale of 1990 (ITS-90), [18] we use a modified form of Del Grosso's equation [7], [19]. The equation is precise to 0.05 m/s (about three parts in  $10^5$ ).

An 80-gallon plastic-coated tank filled with deionized water created a temperature controlled bath, within which we used a smaller stainless steel tank to contain a seawater bath (Fig. 3). A platinum resistance thermometer was placed in the inner tank as close as possible to the velocimeter sound head. A heater/cooler feedback loop regulated the bath temperature measured by this thermometer to  $\pm 0.0001$   $^{\circ}\text{C}$ . The bath was stirred continuously to eliminate temperature gradients. The seawater used in the bath was taken from the end of Scripps Pier in La Jolla, CA, and filtered with a  $2\text{-}\mu\text{m}$  filter before use. The bath water was sampled periodically to determine its salinity. The conductivity ratio between standard seawater and the bath water sample at the same temperature was measured with a salinometer, enabling salinity determination to 0.001. A flow shield of monk's cloth was placed over the sound head to reduce turbulence. The velocimeter was oriented horizontally about 0.3 m below the water surface, so the instrument was calibrated at 1.03 atm.

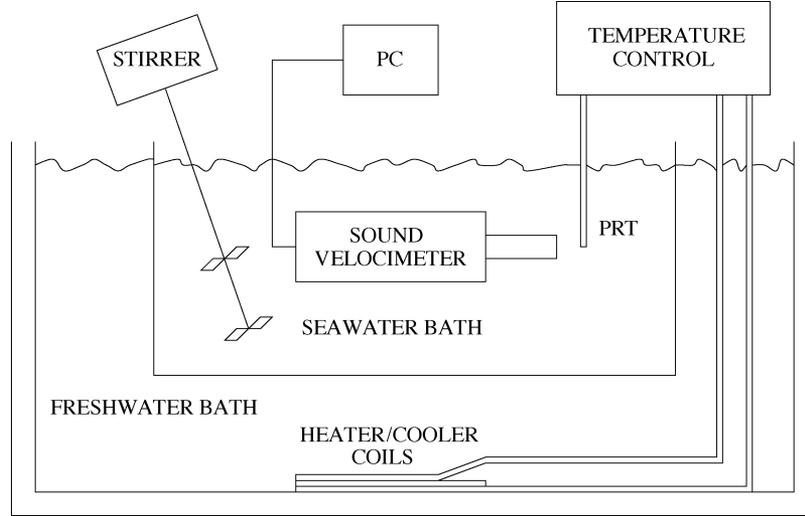


Fig. 3. Calibration tank. The sound velocimeter was calibrated in a seawater bath (salinity 33.95) at controlled temperature (2, 7.2, 11.7, and 18 °C) and atmospheric pressure.

The velocimeter electronics and sound head, initially at room temperature, were allowed to equilibrate with the bath overnight. Starting at a bath temperature of 18 °C, the velocimeter was cycled through each of its 10 lanes. At each lane, the frequency was recorded at 10 samples/s, for 30 s. Then the instrument and seawater bath were cooled to 11.7 °C by adding ice to the outer freshwater bath. The velocimeter frequency was permitted to stabilize within 6 Hz at a fixed lane before the instrument was cycled again through each lane and a new set of frequencies recorded. Additional measurements were collected at 7.2 and 2 °C.

Each of the four bath temperatures corresponds to a different sound speed. At each sound speed, nine to ten measurements of velocimeter travel time were collected by cycling through each lane and recording the frequency. The frequency changed by approximately 70 kHz from 3.94 to 4.01 MHz. Because dispersion is small over this frequency span, the travel time is essentially frequency-independent [20], [21]. For a single observed sound speed, the travel times calculated from each lane and frequency pair should be equal. This condition is expressed mathematically as

$$F_{1,i,j}(f_{i,j}, \mathbf{x}) = t_{i,j} - t_{i,j+1} = 0 \quad (4)$$

where  $t_{i,j}$  is the travel time of the  $j$ th frequency at the  $i$ th observation of sound speed and  $\mathbf{x}$  is the vector of unknown model parameters ( $L_0$ ,  $a_0$ ,  $a_1$ , and  $a_2$ ). These equations are applied to the frequencies to enforce travel time equality at a common sound speed. The lane does not have a random error, as it is always a whole number. In the model, it is not considered to be an observation. To make the velocimeter sound speed agree with the Del Grosso value  $SV_{DG}$  we apply the additional condition equations

$$F_{2,i}(\mathbf{l}_i, \mathbf{x}) = SV_{V,i} - SV_{DG,i} = 0 \quad (5)$$

where  $\mathbf{l}_i$  is the  $i$ th vector of observations ( $SV_{DG}$  and  $f$ ). This is applied to a single pair of sound speed and frequency to make the

velocimeter sound speed match the Del Grosso value. The total number of observations of sound speed and frequency is 43.

A least-squares fit of the condition equations to all of the data yields the values of the unknown parameters. The linearization of the above condition equations is [22]

$$\mathbf{A}\mathbf{v} + \mathbf{B}\Delta = -\mathbf{F}(\mathbf{l}, \mathbf{x}) \quad (6)$$

where

$$\mathbf{A} = \frac{\partial \mathbf{F}}{\partial \mathbf{l}} \quad \text{and} \quad \mathbf{B} = \frac{\partial \mathbf{F}}{\partial \mathbf{x}} \quad (7)$$

and both types of condition equations are included in  $\mathbf{F}(\mathbf{l}, \mathbf{x})$ . The vector of observations is  $\mathbf{l}$ . The observational residuals are  $\mathbf{v}$ , and the corrections to the model parameters are  $\Delta$ . The function to be minimized in a least-squares sense is

$$\phi' = \mathbf{v}^T (\mathbf{A}\Sigma_{\mathbf{ll}}\mathbf{A}^T)^{-1} \mathbf{v} - 2\mathbf{k}^T (\mathbf{A}\mathbf{v} + \mathbf{B}\Delta + \mathbf{F}) \quad (8)$$

where the covariance matrix for the observations is  $\Sigma_{\mathbf{ll}}$ . The first term in (8) is just the weighted sum of the squared residuals. The second term incorporates the corrections to the model parameters by the use of Lagrange multipliers  $\mathbf{k}$ . The solution that satisfies the least-squares criterion in this case is

$$\hat{\mathbf{x}} = \mathbf{x}_0 + \Delta \quad (9)$$

where  $\mathbf{x}_0$  is the initial guess for the unknowns, and the model parameter corrections are

$$\Delta = - \left[ \mathbf{B}^T (\mathbf{A}\Sigma_{\mathbf{ll}}\mathbf{A}^T)^{-1} \mathbf{B} \right]^{-1} \mathbf{B}^T (\mathbf{A}\Sigma_{\mathbf{ll}}\mathbf{A}^T)^{-1} \mathbf{F}. \quad (10)$$

The estimated variance of  $\hat{\mathbf{x}}$  is

$$\Sigma_{\hat{\mathbf{x}}\hat{\mathbf{x}}} = \hat{\sigma}_0^2 \left[ \mathbf{B}^T (\mathbf{A}\Sigma_{\mathbf{ll}}\mathbf{A}^T)^{-1} \mathbf{B} \right]^{-1} \quad (11)$$

where  $\hat{\sigma}_0^2$  is the reduced chi-squared statistic

$$\hat{\sigma}_0^2 = \frac{\mathbf{v}^T (\mathbf{A}\Sigma_{\mathbf{ll}}\mathbf{A}^T)^{-1} \mathbf{v}}{\text{d.f.}} \quad (12)$$

TABLE I  
MODELING RESULTS

Model #	$\frac{L_0}{\sigma_{L_0}}$	$\frac{a_0}{\sigma_{a_0}}$	$\frac{a_1}{\sigma_{a_1}}$	$\frac{a_2}{\sigma_{a_2}}$	$\sigma_0$	RMS <sub>1</sub> [ns]	RMS <sub>2</sub> [m/s]	$\sigma_{SV_V}$ [m/s]
1	4300	-	-	-	13.4	1.6	0.120	0.340
2	7600	51	-	-	1.7	0.2	0.200	0.042
3	780	77	-7	-	1.1	0.2	0.034	0.038
4	850	-2.7	2.8	-3.1	1.0	0.2	0.035	0.035

The number of degrees of freedom **d.f.** is the difference between the number of observations (43) and the minimum number of observations required to uniquely determine the unknowns ( $2 \times$  number of unknowns). The solution is iterated until  $\Delta$  divided by the square root of the estimated variance of  $\hat{\mathbf{x}}$  is less than  $10^{-3}$  for all model parameters.

The propagated uncertainty in the sound speed calculated with (3),  $\sigma_{SV_V}$ , depends on the uncertainty in the observed frequency  $\sigma_f$ , and the covariance matrix of the estimated parameters  $\Sigma_{\hat{\mathbf{x}}\hat{\mathbf{x}}}$

$$\sigma_{SV_V}^2 = \sigma_f^2 \left( \frac{\partial SV_V}{\partial f} \right)^2 + \left( \frac{\partial SV_V}{\partial \mathbf{x}} \right) \Sigma_{\hat{\mathbf{x}}\hat{\mathbf{x}}} \left( \frac{\partial SV_V}{\partial \mathbf{x}} \right)^T. \quad (13)$$

To determine the most appropriate model, we began with the simplest model, with the pathlength as the only unknown. The rms misfit of the model to the data was evaluated, the reduced chi-squared statistic was computed, and the propagated uncertainty in the velocimeter sound speed was determined (Table I). The rms misfit was divided into contributions from the travel time condition [(4), rms<sub>1</sub>] and the sound-speed condition [(5), rms<sub>2</sub>]. A reduced chi-squared statistic close to 1 meant that the model matched the observations to within the expected error. The observation uncertainties used in  $\Sigma_{\mathbf{11}}$  were  $\pm 0.05$  m/s for the Del Grosso sound speed  $\sigma_{SV_V}$  and  $\pm 10$  Hz for the frequency  $\sigma_f$ . Additional unknowns were added to the model until rms<sub>1</sub>, rms<sub>2</sub>, and  $\sigma_{SV_V}$  stopped changing significantly. Based on these criteria, Model #3, which included  $L_0$ ,  $a_0$ , and  $a_1$ , resulted in a rms misfit of 0.034 m/s in sound speed and a propagated uncertainty  $\sigma_{SV_V}$  of 0.038 m/s, and was chosen as the best calibration equation. The best fit values of  $L_0$ ,  $a_0$ , and  $a_1$  are given in Table II. The inclusion of  $a_0$  is appropriate because, as mentioned above, the lane is not known absolutely before the fit. There may be unknown time delays, hence  $a_1$  is also included. It must be noted that because there is no independent means of determining the absolute travel time, there is a high degree of correlation between  $L_0$  and  $a_1$ . With these values of  $a_0$  and  $a_1$  at a given sound speed, the travel times calculated from the 10 lane and frequency pairs agree to 1 ns compared to 9 ns without applying  $a_0$  and  $a_1$ . This satisfies our goal of one nanosecond precision in travel time measurement. The new instrument requires only a time bias versus a fourth order term in frequency required by the prototype demonstrating improved behavior of the timing electronics [13].

#### IV. HIGH PRESSURE TEST AT SEA

In June 1998, we carried out a high-pressure sea test of the sound velocimeter 200 km southwest of Hawaii ( $19^\circ 20.52' N$ ,  $159^\circ 5.70' W$ , depth=4500 m). The sound velocimeter sound

TABLE II  
BEST-FIT PARAMETERS FOR THE CALIBRATION EQUATION

	value	uncertainty	correlation coefficients		
$L_0$ [m]	0.19990	0.00026	1	0.001	0.998
$a_0$ [cycles]	3.55	0.05		1	-0.065
$a_1$ [ $\mu$ sec]	-1.28	0.17			1
$a_2$ [ $\mu$ sec/Hz]	defined to be 0				

head and the CTD sensors were mounted on a frame approximately 30 cm apart, to ensure that the two instruments were sampling the same water. A water sampling bottle was mounted adjacent to the two devices to collect salinity samples as a check on the CTD conductivities. The bottle could be tripped by a remote-controlled release, once per lowering, so the exact time and depth of each sample could be precisely known. The package was lowered on a wire at a rate of 30 m/min to a depth of 4425 m, and brought back to the surface while collecting both CTD and sound velocimeter data. The CTD data were collected at a rate of 1 sample/s, and the velocimeter data were collected at a rate of 10 samples/s.

We used a CTD composed of a high-precision Paroscientific Digiquartz Sensor, a platinum resistance thermometer (PRT), and an FSI inductive-type conductivity sensor. The pressure sensor was calibrated with a dead weight tester to a precision of 0.1 dbar over the range 10–6900 dbar absolute. The dead weight tester is accurate to 0.01% of the pressure reading. The PRT was calibrated to a precision better than 0.001 °C, over the range 0 to 30 °C, using a laboratory device accurate to 0.0003 °C. The manufacturer of the conductivity sensor indicated a precision of 0.02 mmho/cm (about 0.02 salinity). It was calibrated *in situ* with water samples taken at pressures relative to the sea surface of 523, 1021, 1730, and 2540 dbar, corresponding to salinities ranging from 34.123 to 34.653  $\pm 0.001$ . From each water sample, two glass bottles were rinsed, filled, sealed, and taken back to land for analysis. The accuracy of the salinometer salinity was about 0.001. The salinities contained in the two glass bottles at each depth agreed to 0.001, except for two at 4195 dbar, which disagreed by 0.03. This calls into question how well the glass bottles were rinsed before filling with the water from 4195 dbar. For this reason, the salinity at 4195 dbar was not used in the calibration, but it is still included in Fig. 4 for comparison. The salinity computed from the CTD measurements agreed with the water samples to 0.02 between 523 and 2540 dbar, and to 0.09 at 4195 dbar. Because a salinity calibration point is lacking at the sea surface, our discussion is limited to pressures greater than 523 dbar. Fig. 4 shows the temperature, salinity, and sound speed derived from these CTD measurements.

The laboratory calibration coefficients [(3) and Table II] were used to calculate the velocimeter sound speed. The sound speed calculated from the Del Grosso equation was subtracted from the velocimeter sound speed for comparison (Fig. 5). Deviations increased nearly linearly from 0.1 m/s near 500 dbar to 1 m/s near 4500 dbar. To accommodate the discrepancy at pressures greater than 500 dbar, two terms were added to (3), an offset  $SV_{V0}$ , and a linear trend  $\partial SV_V / \partial P$

$$SV_V = \frac{L_0(1 + \alpha T)}{\frac{n+a_0}{f} + a_1 + a_2 f} - \frac{\partial SV_V}{\partial P} P - SV_{V0}. \quad (14)$$

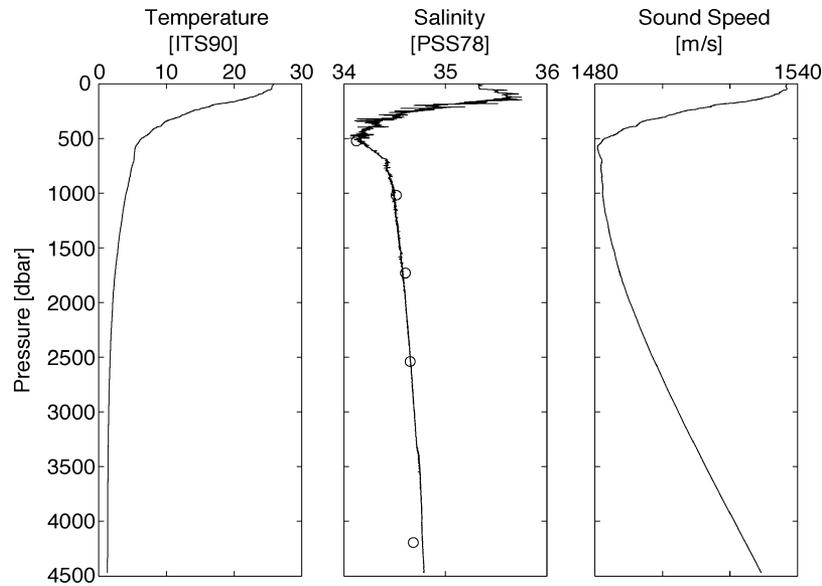


Fig. 4. Single upcast with the CTD showing the measured temperature, calculated salinity, and calculated sound speed based on Del Grosso's equation [7], [19]. The CTD was oriented with its sensors pointing toward the direction of travel. The circles denote water samples taken during later casts.

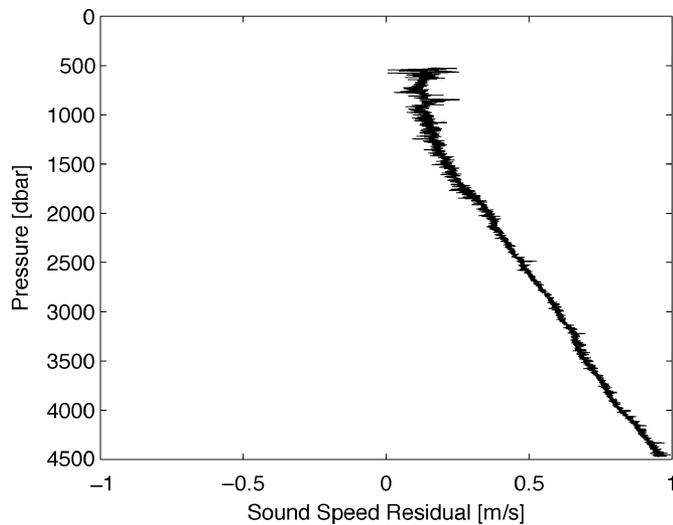


Fig. 5. Comparison of sound speeds with pressure for a down cast of the CTD and sound velocimeter. The sound-speed residual is equal to the sound velocimeter sound speed minus the CTD-derived sound speed. The velocimeter sound head was located 30 cm below the CTD sensors and pointed toward the direction of travel. Note the linear divergence with increasing pressure.

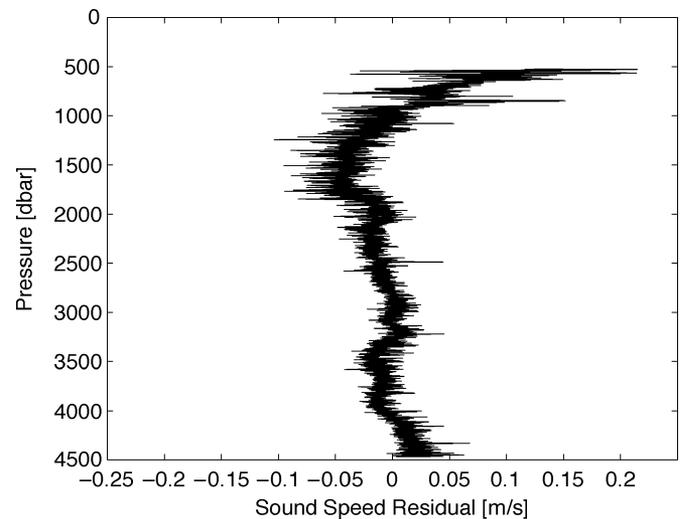


Fig. 6. CTD and sound velocimeter show  $\pm 0.05$  m/s agreement after removal of a constant offset and a pressure-dependent trend from the data in Fig. 5. Note the scale change from Fig. 5.

This equation was applied to the velocimeter sound speed to make it agree with Del Grosso's sound speed (Fig. 6). An overall fit of 0.05 m/s was achieved with parameter values of  $\partial SV_V / \partial P = 0.23$  m/s per 1000 dbar and  $SV_{V0} = -0.09$  m/s. The repeatability of  $\pm 0.05$  m/s implies that the resolution of the travel time is consistent with a timing precision of a few nanoseconds and that knowledge of the pathlength is good to within a few microns.

Possible sources for the 0.23 m/s per 1000 dbar trend include either pressure related changes in the velocimeter or an unmodeled systematic effect in Del Grosso's equation. Dushaw *et al.* [1] suggest a negligible correction to Del Grosso's equation of  $0.05 \pm 0.05$  m/s at 4000 m depth. In other words, Del Grosso's equation is too slow at high pressure, yet the magnitude of the

correction is within their estimated precision. Meinen and Watts [15] speculate that Del Grosso's equation is too fast at depths greater than 1000 m, but admit the difference is not statistically significant based on the estimated precision of their approach. We, therefore, assume that Del Grosso's equation is accurate. In the present comparison at high pressure (Fig. 5), the velocimeter sound speed is faster than the sound speed calculated from Del Grosso's equation. If the trend is attributed to a velocimeter travel time error, it corresponds to delaying the arrival by 20 ns per 1000 dbar. The internal electronics are never exposed to high pressure and should be unaffected. A frequency response change of the transducer with pressure is unlikely because a controlled pressure test of the transducer at ambient temperature showed no change in amplitude of the echo. At the time, no phase change measurement could be performed, so our evidence based on no amplitude change is indirect. If the effect is

attributed solely to pathlength change in the velocimeter, then it corresponds to shortening the pathlength by  $30 \mu\text{m}$  per 1000 dbar. This is significant because the pathlength must be known to  $1 \mu\text{m}$  to achieve 1 part in  $10^5$  resolution in sound speed. Compression of each element comprising the sound path separately (i.e., the Invar rods, the stainless steel reflector and standoff, and the transducer mount) can only account for about 25% of the required shortening. The major source of a trend with pressure may be due to complex deformation associated with an air-filled cavity behind the transducer. The velocimeter has since been rebuilt with an oil-filled, pressure-release cavity behind the transducer which will equalize the pressure on both sides of the transducer to minimize this contribution to pathlength changes.

Equation (14) was used to fit the sea data over the limited range of 523 to 2450 dbar, below the thermocline, where the salinity calibration was most precise and the change in temperature with pressure was small. We did not compare velocimeter and CTD-derived values in and above the thermocline because of the lack of a salinity calibration point at the sea surface and a lack of knowledge of the response times of the instruments. The sound-speed offset of 0.09 m/s was therefore a parameter in the fit to the deep sea data, and should not be interpreted as a surface offset. Applying these parameters, we achieved agreement of  $\pm 0.05$  m/s.

## V. CONCLUSION

We calibrated a sound velocimeter to a precision of  $\pm 0.034$  m/s, using Del Grosso's equation for sound speed in seawater. The calibration was performed in a temperature-controlled laboratory tank containing seawater at one atmosphere. The sound velocimeter makes acoustic travel time measurements to a precision of  $\pm 1$  ns by adjusting the acoustic carrier frequency until the pulse and its echo are in-phase. The advantage of an adjustable carrier frequency is that measurements of the same sound speed may be made at several different carrier frequencies, permitting the internal timing characteristics to be overdetermined. Similarly, because each tank temperature corresponds to a unique sound speed, varying the temperature allows the sound velocimeter pathlength to be overdetermined. The new sound velocimeter has better timing and less sensitivity to temperature than the prototype sound velocimeter [13]. No sound velocimeters currently used at sea measure the pathlength, hence, they all require calibration against an equation of state. A further improvement of the sound velocimeter would be to vary the pathlength by a known amount. Such an approach would make the sound velocimeter independent of the equation of state.

We conducted an at-sea comparison between the laboratory-calibrated sound velocimeter and CTD-derived sound speeds and achieved an overall misfit of  $\pm 0.05$  m/s, after applying a linear fit to the sound-speed difference at pressures greater than 500 dbar. Del Grosso's equation was again chosen for the calculation of at-sea, CTD-derived sound speeds for consistency with the sound velocimeter's laboratory calibration and because Del Grosso's equation has been reported to be the most accurate seawater sound-speed equation [1], [15]. This is an improvement over the  $\pm 0.07$  m/s misfit achieved during a similar at-sea

comparison using the prototype sound velocimeter [13]. The pressure dependence may be related to a linear change in the sound velocimeter pathlength, resulting from a complex pattern of deformation due to compression of the pathlength elements and an air-filled cavity behind the transducer. The system has been redesigned with an oil-filled, pressure-release cavity to reduce this effect.

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