Sound Velocity Determination with Empirical Formulas & Bar Check

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SUMMARY

The acoustic sounding method is densely used in hydrographic studies. For depth measurement, elapsed time of an acoustic pulse which travels to the bottom and return again is measured by acoustic depth measurement systems. If the velocity of sound propagation in the water column is known, the depth is computed by using the time-velocity equation. On the other hand, the travel time of the acoustic pulse depends on the sound velocity in the water column which varies with the medium's elasticity and density. Thus, true sound velocity in water should be determined as accurately as possible to obtain depth accurately. There are several different instrument and methods to determine the sound velocity. The aim of this study is to estimate velocity of sound in water with different empirical formulae as well indirectly by bar check calibration to verify the results. For this purpose, some field studies were performed in the Halic and Istanbul Strait. The methodologies of these procedures are explained in detail in the paper.

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1. INTRODUCTION

One of the important components of the hydrographic surveying is depth measurement, or sounding. Depth measurement can be carried out by several techniques and systems such as manual depth measurement techniques, single beam acoustic depth measurement techniques, multiple transducer sweep systems, acoustic multibeam survey systems. These methods are explained in detail several text book such as Ingham (1992), de Jong, et al. (2002), USAGE (2002), IHO (2005).

Although there are several ways to determine the depth, single beam acoustic depth sounding is by far the most widely used depth measurement technique. Acoustic depth measurement systems measure the elapsed time that an acoustic pulse takes to travel from a generating transducer to the waterway bottom and back. Since an echo sounder measure the travel time of the pulse, if the velocity of sound propagation in the water column is known, the depth can be computed by the following equation;

$$depth = \frac{1}{2}(velocity\,of\ sound\,in\,water)(pulse\,travel\,time) + system\ index\,const. \quad (1)$$

It can be clearly noticed from (1) that, sound velocity in water should be known precisely to obtain correct depth. For practical single beam echo sounding work in shallow water, an average sound velocity is usually assumed (by calibration). The sound velocity may be measured directly using a velocity probe or indirectly by a bar check calibration (USAGE 2002).

In this study, sound velocity in sea water is estimated with empirical formulae as well indirectly by bar check calibration to verify and compare the results. For this purpose, two trial studies were performed in the Halic Inlet (Golden Horn) and Istanbul Strait, respectively. Salinity and temperature of the water were measured by a CTD Sensor, and also bar check were performed.

2. DETERMINATION OF SOUND VELOCITY IN THE WATER

Sound velocity in the water varies with the medium's elasticity and density. These properties are, for typical river and harbour project depths, primarily a function of the water temperature and suspended or dissolved contents, i.e., salinity and as well pressure.

These parameters, i.e. temperature, pressure and salinity, affect the bulk properties of the medium. On the other hand, some other parameters such as air bubbles, biological organisms can also affect the velocity of sound (Ingham 1992, de Jong et al. 2002, USAGE 2002, IHO 2005). Furthermore, the sound velocity might be varied from place to place over the survey area and this changing might happen during the surveying intervals. An average value for the velocity of propagation of acoustic waves, *c*, in seawater is accepted as 1500 m/sec under the nominal condition of the water environment which has 0 ^{o}C temperature, 35 parts per thousand salinity and 760 mmHg pressure (Ingham 1992). However, that value might vary between 1387 m/sec and 1529 m/sec intervals depending on the characteristics of the water (Nakiboglu 1993).

The sound velocity determination in water is one of the important issue in hydrographic surveying and should be determined precisely to obtain correct depth. It may be determined mainly with different methods and using different instruments as follows (de Jong et al. 2002, USAGE 2002);

a-) from empirical formulas with the information from CTD (Conductivity, Temperature, and Depth) sensor -or probe,
b-) with bathythermograph,
c-) with velocity meter,
d-) by bar check calibration.

In this study, the sound velocity in water determined by different empirical formulae and by bar check calibration for single beam echo sounder.

2.1 Sound Velocity Determination with Empirical Formulas

The value of sound velocity, *c*, could be determined by means of empirical formulae using the temperature *T*, pressure *P* (or depth *D*) and salinity *S* measured by CTD sensor. There are number of formulae available to calculate the sound velocity in water given in literature such as Wilson (1960), Chen and Millero (1977), Del Grosso (1974), Mackenzie (1981), Medwin (1975). Pike and Beiboer, (1993) made an extensive comparison of several algorithms and they suggested the following order of preference:

1-) Chen & Millero (only for water depths less than 1000 m)
2-) Del Grosso (only for water depths greater than 1000 m)
3-) Mackenzie (for rapid computations in oceanic waters to 8000 m water depth)
4-) Medwin (for rapid computations in oceanic waters to 1000 m water depth).

In this study, sound velocity is estimated from Chen & Millero and Medwin formulae which are appropriate to our data ranges.

i-) Chen&Millero Formulae

This is the international standard algorithm was adopted by UNESCO in 1983 and is as follows (Pike and Beiboer 1993):

$$c = C_W(T,P) + A(T,P)S + B(T,P)S^{3/2} + D(T,P)S^2 \tag{2}$$

where,

$$\begin{aligned} C_W(T,P) = {} & C_{00} + C_{01}T + C_{02}T^2 + C_{03}T^3 + C_{04}T^4 + C_{05}T^5 + \\ & (C_{10} + C_{11}T + C_{12}T^2 + C_{13}T^3 + C_{14}T^4)P + \\ & (C_{20} + C_{21}T + C_{22}T^2 + C_{23}T^3 + C_{24}T^4)P^2 + \\ & (C_{30} + C_{31}T + C_{32}T^2)P^3 \end{aligned} \tag{3}$$

$$\begin{aligned} A(T,P) = {} & A_{00} + A_{01}T + A_{02}T^2 + A_{03}T^3 + A_{04}T^4 + \\ & (A_{10} + A_{11}T + A_{12}T^2 + A_{13}T^3 + A_{14}T^4)P + \\ & (A_{20} + A_{21}T + A_{22}T^2 + A_{23}T^3)P^2 + (A_{30} + A_{31}T + A_{32}T^2)P^3 \end{aligned} \tag{4}$$

$$B(T,P) = B_{00} + B_{01}T + (B_{10} + B_{11}T)P \tag{5}$$

$$D(T,P) = D_{00} + D_{10}P \tag{6}$$

In this equations, *T* is temperature in degrees Celsius, *S* is salinity in parts per thousand (ppt) and *P* is pressure in bar. That formulae is based upon comprehensive observations on seawaters in the ranges 0<*T*<40 ^{o}C, 0<*S*<40 ppt, 0<*P*<1000. The coefficients in the equations are defined in the following:

A_{00}	1.389	A_{21}	9.1041E-9	C_{01}	5.03711	C_{21}	-1.7107E-6
A_{01}	-1.262E-2	A_{22}	-1.6002E-10	C_{02}	-5.80852E-2	C_{22}	2.5974E-8
A_{02}	7.164E-5	A_{23}	7.988E-12	C_{03}	3.3420E-4	C_{23}	-2.5335E-10
A_{03}	2.006E-6	A_{30}	1.100E-10	C_{04}	-1.47800E-6	C_{24}	1.0405E-12
A_{04}	-3.21E-8	A_{31}	6.649E-12	C_{05}	3.1464E-9	C_{30}	-9.7729E-9
A_{10}	9.4742E-5	A_{32}	-3.389E-13	C_{10}	0.153563	C_{31}	3.8504E-10
A_{11}	-1.2580E-5	B_{00}	-1.922E-2	C_{11}	6.8982E-4	C_{32}	-2.3643E-12
A_{12}	-6.4885E-8	B_{01}	-4.42E-5	C_{12}	-8.1788E-6	D_{00}	1.727E-3
A_{13}	1.0507E-8	B_{10}	7.3637E-5	C_{13}	1.3621E-7	D_{10}	-7.9836E-6
A_{14}	-2.0122E-10	B_{11}	1.7945E-7	C_{14}	-6.1185E-10		
A_{20}	-3.9064E-7	C_{00}	1402.388	C_{20}	3.1260E-5		

ii-) Medwin Formula

The simple formula of Medwin is given as;

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016D \qquad (7)$$

The formula is valid for realistic combinations of *T*, *S* and *P* in the ranges, 0≤*T*≤35°C, 0≤*S*≤45 ppt, 0≤*D*≤1000 m.

The parameters in the above formulae, i.e. temperature *T*, pressure *P* (or depth *D*) and salinity *S* should be measured with enough accuracy. Table 1 gives a general idea about the effect of the variations in the parameters on the results. It can be seen from Table 1 that, sound velocity is most sensitive to variations in temperature.

Table 1. The Effects of Temperature, Salinity, Pressure (Depth) Variation on the Sound Velocity Results

Error Type	Chen&Millero (m/sec)	Medwin (m/sec)
Nominal Conditions*	**1449.30**	**1449.36**
Temperature error of 0.1 °C	1449.76	1449.82
Temperature error of 1.0 °C	1453.83	1453.91
Salinity error 0.1 ppt	1449.44	1449.50
Salinity error 1.0 ppt	1450.64	1450.70
Depth Error of 0.5 meter	1449.30	1449.37
Depth Error of 1.0 meter	1449.30	1449.38
Pressure Error of 0.1 bar	1449.30	1449.36
Pressure Error of 1.0 bar	1449.31	1449.36

* 0°C, 35 ppt and 1.01325 bars.

2.2 Sound Velocity Determination with Bathythermograph

Bathythermograph is a simple and relatively inexpensive instrument. Temperature as a function of depth is measured by lowering the instrument into the sea. The expendable bathythermograph is capable of providing the temperature profile without having to retrieve the sensing unit afterward. The bathythermograph converts the temperature-depth trace to sound velocity with the assumption of the salinity gradients are known or non-existent (de Jong et al. 2002).

2.3 Sound Velocity Determination with Sound Velocity Profiler (SVP)

Profiler, SVP, is the most common instrument used to determine the sound velocity profile through the water column. SVP, has one pressure sensor to measure depth, a transducer and a reflector a certain distance. The sound velocity is calculated using two-way travel time of acoustic signal between transducer and reflector (IHO 2005). Another instrument is the velocity meter which measures sound velocity. Velocity meter output is typically sound velocity as a function of water depth (USACE 2002).

2.4 Bar Check Calibration

The effect of a varying velocity of sound propagation is measured by performing bar check calibration which is the most common depth calibration technique used for depths about 20-30 meters (IHO 2005). The suspended bar as a bar check apparatus is constructed of flat stainless steel or aluminium plate suspended by two precisely marked lines to a known depth below the water surface and under the transducer. For applying the bar check method, a reflective bar or plate, is lowered beneath the transducer on marked lines at various depths (Figure 1). A series of depth intervals are observed during a bar check, down to the project depth. The observed depths are compared with the known depths on the lowering bar or plate.

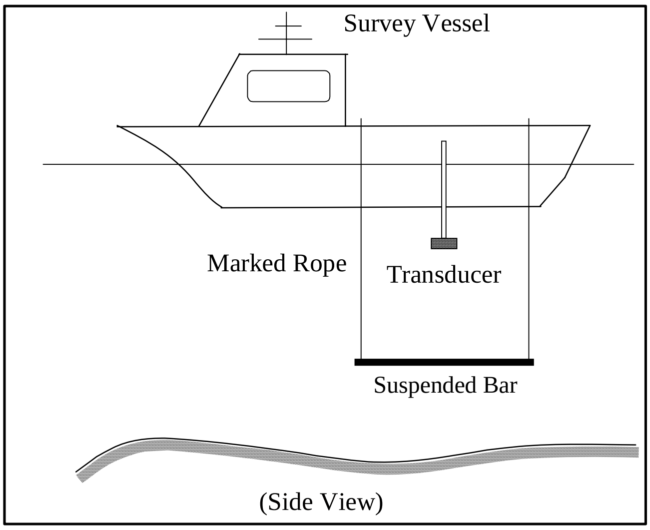

Figure 1. Schematic Depiction of Bar Check Calibration

Bar check not only measure the sound velocity errors due to temperature, salinity, or other suspended or dissolved sediment variations, but also static draft fluctuations resulting from varying vessel displacement and instrumental errors-index, mechanical, and electrical (USAGE 2002). The necessary corrections for velocity of sound propagation can be computed by comparing the observed depths against known depths on the plate or bar which are lowered to the transducer (Ingham, 1992). Bar check should be carried out on a daily basis at start and end of day for critical studies directly at the work site. If the echo sounder has multiple frequencies, each one is to be calibrated independently. There is more detailed information about bar check procedure included depth correction methods based o the bar check data can be found USAGE (2002).

3. APPLICATION

The aim of this study is to estimate sound velocity in water with different empirical formulae as well by bar check calibration and how the results come close to each other. For this purpose, two trial measurements were performed at Haliç (Golden Horn)-Istanbul in February 1999 and in Istanbul Strait in September 2005 (Figure 2). These studies made up of two parts; Oceanographic Parameters Collection for empirical formulae and bar check.

Figure 2. Application Areas (*from Google Earth*)

3.1 Oceanographic Parameters Collection Methodology

The first trial study was carried out parallel with the "Water Quality Monitoring Project" by Istanbul University Research and Aid Foundation and Istanbul Water and Sewage Administration-ISKI (ISKI 1999). The necessary parameters of our study, i.e. conductivity, salinity, temperature, depth were already measured under the scope of this project totally 6 station in Halic restrict, but, only 3 of them are considered in this study because, bar check was realized on only 3 stations. Our research vessel was equipped with a Backman Rs-5 CTD Probe to assess the in-situ values of the necessary parameters. In the second application, temperature, salinity and pressure were measured with Seabird (SBE19) CTD probe (Figure 3).

Figure 3. CTD Instrument (*from second application*)

With the data from the CTD probes, the sound propagation velocities are estimated using the Chen & Millero and Medwin equations (from equations 2-6 and 7, respectively). The results are given in Table 2.a, b and c for the first application and Table 3 for the second application. In these applications, depth/pressure conversion is carried out by using Leroy equation (Leroy and Parthiot 1998). Pressure/depth conversion is carried out by using UNESCO standard formulae (Pike and Beiboer 1993).

Table 2.a Sound Velocity for the 1st Sampling Station (m/sec)

Probe Depth (m)	Chen&Millero	Medwin
1	1440.67	1440.03
2	1451.67	1451.30
3	1452.95	1452.62
5	1459.45	1459.21
8	1460.45	1460.28
10	1464.72	1464.61
14	1472.27	1472.28
17	1479.01	1479.13
20	1488.72	1488.95
23	1504.52	1504.90
26	1508.82	1509.27
30	1510.60	1511.12
32	1510.67	1511.22
34	1510.69	1511.28

Table 2.b Sound Velocity for the 2nd Sampling Station (m/sec)

Probe Depth (m)	Chen&Millero	Medwin
1	1443.77	1443.21
2	1451.42	1451.04
3	1453.10	1452.76
4	1456.39	1456.11
6	1459.30	1459.09
8	1463.19	1463.04
10	1466.49	1466.40
13	1471.78	1471.78

Table 2.c Sound Velocity for the 3rd Sampling Station (m/sec)

Probe Depth (m)	Chen&Millero	Medwin
1	1436.14	1435.43
2	1437.11	1436.43
3	1450.54	1450.13
4	1453.11	1452.78
4.5	1453.76	1453.44

Table 3. Sound Velocity for the Second Application (m/sec)

Pressure (dbar)	Chen&Millero	Medwin
1.0	1512.88	1512.35
2.0	1512.73	1512.21
3.0	1512.45	1511.95
4.0	1512.30	1511.82
5.0	1512.18	1511.71
6.0	1512.20	1511.75
7.0	1512.14	1511.70
8.0	1512.08	1511.66
9.0	1512.05	1511.65
10.0	1512.05	1511.66
11.0	1512.05	1511.67

3.2 Bar Check Methodology

The bar check was also applied on the oceanographic data collection places. For the first applications, a bar which has a diameter of about 5 cm was lowered beneath the transducer on marked lines at various depths such as 1, 2 and 3 meters. The method cannot be applied beyond of 3-meter depth due to the sea state. These measurements were done with an 8-meter long vessel. In that application, Atlas Deso-15 dual frequency (33 kHz and 210 kHz) echo sounder was used. The Atlas Deso-15 echo sounder has a built in bar check calibration facility which enables these sound propagation velocity to be calculated automatically.

The method was also applied for the second application (Figure 4).

Figure 4. Bar Check Calibration

In the second application, Atlas Deso-14 echo sounder was used. The Atlas DESO 14 is a portable survey echo sounder. Bar check records shown in Figure 5 is given as a sample.

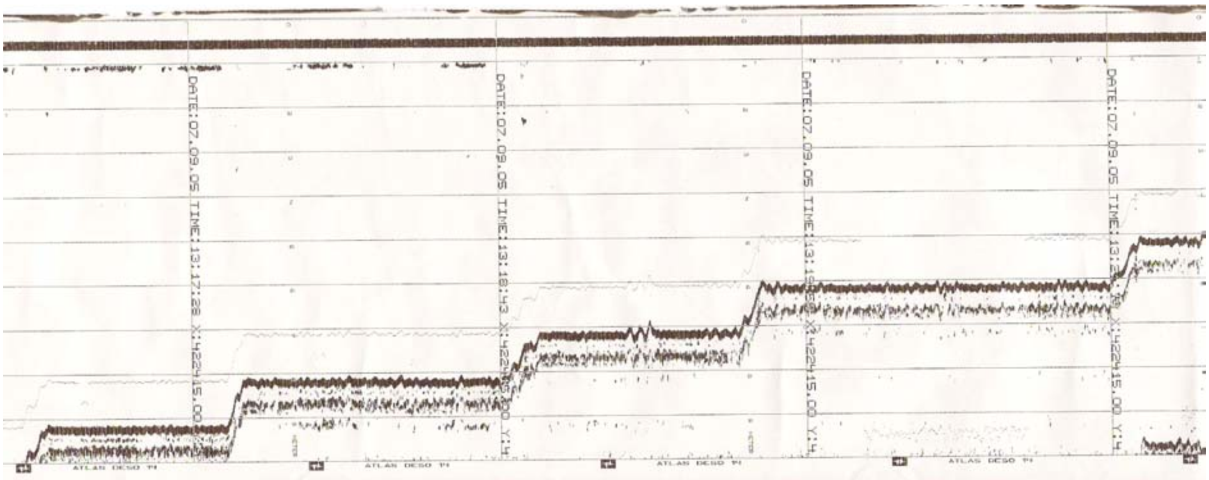

Figure 5. Bar Check Records

The sound velocity in water is calculated for the each bar depth. The results are given in Table 4 for the first applications.

Table 4. Sound Velocity Calculated from Bar Check (m/sec) (for Trial-1)

Bar Depth (m)	Sampling Station-1	Sampling Station-2	Sampling Station-3
1	1416.89	1435.38	1441.18
2	1434.39	1448.83	1436.44
3	1447.39	1455.87	1446.10
Average	**1432.89**	**1446.69**	**1441.24**

If there is a linear relation between two variables, we can use a straight line to mathematically describe the relationship like in Figure 6 (Teng 2003). According to that approach, the sound velocity is computed as 1521.19 m/sec using all measurements 0 to 10 meters depths for the second application.

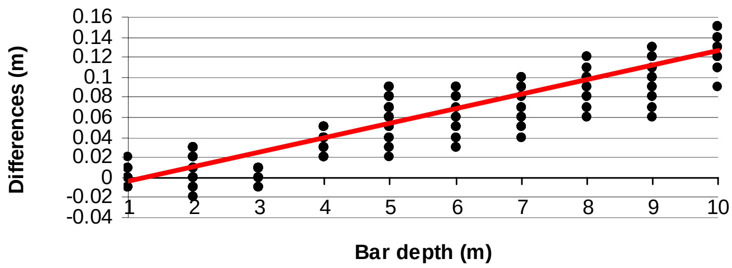

Figure 6. Sound Velocity Computation between 0 to 10 meters Depths

The sound velocity is also computed as 1515.75 m/sec between 0 to 4 meters depths as seen Figure 7 applying same approach.

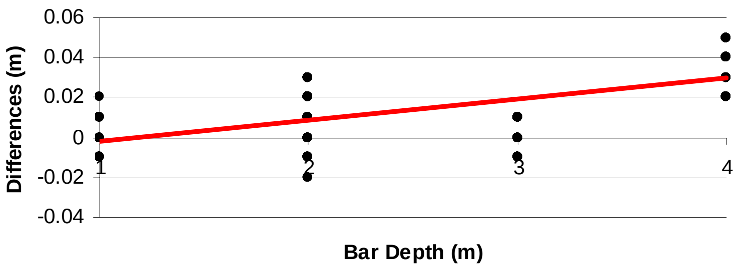

Figure 7. Sound Velocity Computation between 0 to 4 meters Depths

4. CONCLUSION REMARKS

In this study, velocity of sound in water is estimated with two empirical formulae and bar check. According to our field experience and obtained results, some conclusions and suggestions are emphasized below:

- In case of the empirical formulae are used based on the STD probe measurement, the necessary data, i.e. temperature, salinity and pressure (or depth) should be determined accurately. Especially, as it can be seen from the Table 1 that, the sound velocity is most sensitive to variations in temperature.

- The sound velocities from both two empirical formulae and bar check are compared with each other for 1, 2 and 3 meters depths separately and it is found that they are close to each other between approximately 5 m/sec to 24 m/sec. However, according to comparing of the average values, the differences reach up approximately 15.3 m/sec and 2.5 m/sec for the 1st and 2nd sampling station, respectively. The minimum deviation is found for the 3rd sampling station as 0.3 m/sec in average. The reason of that convergency for this station is that, the bar-check method was almost continued about the deepest point of the sampling station. For the second application, depth 0 to 10 meters the average sound velocity is calculated as 1521.19 m/sec from bar check. If we compare this value with sound velocity that determined by empirical formulae, the difference is found as 8.91 m/sec. This difference decreases to 3.47 m/sec for 0 to 4 meters depth and translates to 2 cm error for even 4 meters depth.

- During the bar check, the bar should be hold as possible as horizontal. Vessel alignment must be held toward the sea to minimize roll or pitch. If the bar check is carried out with a small vessel, personnel movement during the bar check may affect the trim of the boat. Care must be taken to ensure that this variation is minimized. Besides, the rope connected to bar plate must be calibrated and the length of the rope will not change.

- In some case, the bar check method is impossible because of wave action, currents, etc similar to our experiment. In general it can be said that, if the bar check is not performing due to the sea states (wind, currents, etc.), other methods introduced in this study should be used to determine the velocity of sound at the project site. However, on critical projects, it is recommended that by the USAGE (2002), both a bar check and a velocity probe should be simultaneously performed in a protected area near the project vicinity.

It can be concluded that, the sound velocity determination has play big importance in hydrographic studies and it should be determined with proper methods and correct way for obtaining accurate and reliable depth data.

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BIOGRAPHICAL NOTES

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