Research Note-3

Analysis of Sound Speed Profile and it's Application in Ocean Studies

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Background

Underwater acoustics is the study of the propagation of sound in water and the interaction of the acoustic (sound) waves with the water, its contents and its boundaries [1]. While sound moves at a much faster speed in the water than in air, the distance that sound waves travel is primarily dependent upon the sound speed profile of the ocean [2].

Sound speed being one of the most fundamental aspect, was studied foremost in the field of underwater acoustics. The science of underwater acoustics was initiated back in 1490, by Leonardo Da Vinci when he wrote about his experience of hearing noise generated by ships at great distances, while listening through a large tube half submerged into ocean [3]. Following this, in 1687, Isaac Newton provided the first mathematical expression for sound in his book "Mathematical Principles of Natural Philosophy" [4], wherein he predicted that speed of sound in a medium can be derived by calculating the square root of the pressure divided by the medium's density as given below [5].

$$c = \sqrt{\frac{P}{D}}$$

c = Speed of Sound
P = Pressure Acting on the Sound
D = Density of the medium

Unfortunately his prediction fell short due to the fact that he did not consider the impact of heat on speed of sound, thus the formula was further enhanced by Laplace who suggested inclusion of bulk modulus instead of pressure, thus creating Newton-Laplace equation [6]. The derivation for elastic bulk modulus can be accessed from the important links section present at the end of this research note.

$$c = \sqrt{\frac{K}{D}}$$

c = Speed of Sound
K = Elastic Bulk Modulus
D = Density of the medium

A major step in the development of underwater acoustics was made by Daniel Colladon, a Swiss physicist, and Charles Sturm, a French mathematician in 1826 at Lake Geneva, wherein they measured the elapsed time between a flash of light and the sound of a submerged ship's bell heard using an underwater listening horn. They measured a sound speed of 1435 metres per second (m/s) over a 17 kilometre (Km) distance, providing the first quantitative measurement of sound speed in water. The result they obtained was within about 2% error of currently accepted values [7]. Over the years, multiple incidents such as the sinking of Titanic in 1912 and the start of World War I provided the impetus for the next wave of progress in underwater acoustics, but it was not until World War – II (WW-II) and Cold War that the propagation of sound in the sea was studied intensively and was recognized as an important tool for conducting anti-submarine warfare (ASW) operations [8, 9].

In this research note, we aim to analyse the sound speed estimation techniques that have evolved over the years and discuss usability of these techniques with respect to the environmental conditions of the ocean. Further we look at the different applications that make use of sound speed profiling techniques and discuss the future scope of work that can be performed in this domain.

Sound Speed

Sound Speed describes the speed with which the sound propagates inside the ocean and is a function of Density and Compressibility of water particles [10]. Here, the compressibility defines the capacity of water particle to experience change in volume as a response to pressure. Density in turn can be represented as a function of Temperature (^oC), Salinity (ppm) and Pressure (atm) as discussed below [11]:

$$Density\ \alpha\ \frac{Mass}{Volume}$$

- Temperature: When the water is heated up, the water molecules expand, thereby taking up more space while experiencing no change in mass, and hence increasing the density.
- Salinity: Dissolving salt in water, increases the mass of water molecule, thereby increasing the density.
- Pressure: As we go deeper in the ocean, the pressure increases. The increased pressure compresses the water particles and reduces the volume of water molecules (compressibility). Hence, the density of water increases. This also explains the directly proportional relation between pressure and depth, hence proving pressure to be a function of depth. Hence, Sound Speed (C) can be expressed in terms of Temperature, Salinity and Depth.

Over the years, right from 1969 up to 2008, multiple expressions, varying in accuracy, parameters and number of terms, have been derived by researchers, all of which have been briefly identified below in Table I. The usability of these equations depend upon the environmental conditions of the ocean, such as the Temperature (at all depths), Salinity and Depth/Pressure. Furthermore as described by Leroy.et al 2008 [12] in his work, all equations which used old UNESCO formula [13] suffered from major drawback of inaccurate results under pure water, high pressure conditions, since the basic UNESCO formula in itself was found to be incorrect for calculating the speed of sound in pure water under high pressure. The formula was later updated and adapted by Leroy in his work.

S.No	**Reference**	**Temperature Range (^oC)**	**Salinity Range (PPM)**	**Pressure / Depth Range**	**Standard Error (m/s)**	**No. of Terms**
1	Wilson (1960) [14]	-4 to 30	0 to 37	1 to 1000 kg/cm^2	0.30	23
2	Leeroy (1969) [15]	-2 to 34	20 to 42	0 to 8000 m	0.2	13
3	Frye and Pugh (1971) [16]	-3 to 30	33.1 to 36.6	1.033 to 984.3 kg/cm^2	0.1	12
4	Del Grosso (1974) [17]	0 to 35	29 to 43	0 to 1000 kg/cm^2	0.05	19
5	Medwin (1975) [18]	0 to 35	0 to 45	0 to 1000 m	0.2	06
6	Chen and Millerro (1977) [19]	0 to 40	5 to 40	0 to 1000 bar	0.19	15
7	Lovett (1978) [20]	0 to 30	30 to 37	0 to 10,000 dbar	0.063	13
8	Coppens (1981) [21]	-2 to 35	0 to 42	0 to 4000 m	0.1	08
9	Mackenzie 1981 [22]	-2 to 30	25 to 40	0 to 8000 m	0.07	09
10	Leroy et.al 2008 [12]	-1 to 30	0 to 42	0 to 12000 m	0.2	14

Pike and Beiboer [23] in their work have performed a detailed study of several sound speed algorithms and reported their practical applicability for real oceans. For the present study, we use the simplest equation of Medwin et.al 1975 [18], as described below.

$$C = 1449.2 + 4.6T - 0.55T^2 + 0.00029T^3 + (1.34 - 0.01T)(S-35) + 0.16*Z$$

Here,
C = Sound Speed (m/s)
T = Temperature (oC)
S = Salinity (PPM)
Z = Depth (m)

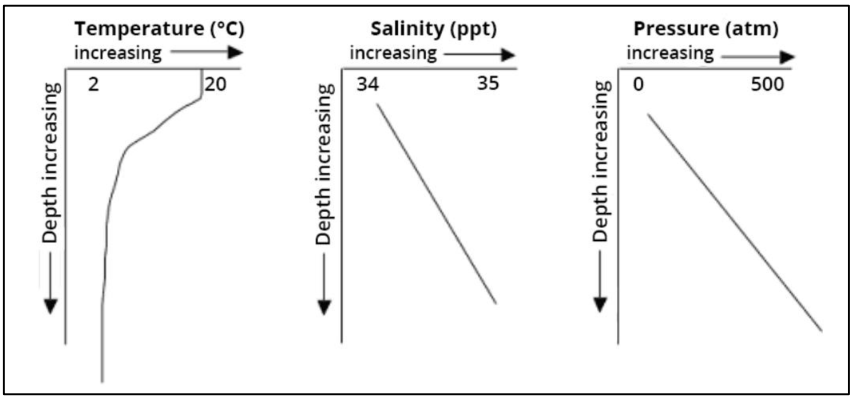


Fig 1. Temperature, Salinity and Pressure Depth Profile. Copyright University of Rhode Island

Change in oceanographic parameter with water depth is called as profile. As depicted in Fig 1, both salinity and pressure experience a constant increase with increase in ocean depth whereas the temperature experiences a decrease with increasing depth. Salinity has a much smaller effect on sound speed than temperature or pressure at most locations in the ocean. This is because salinity changes in the open ocean are small. Near shore and in estuaries, where the salinity varies greatly, salinity can have a more important effect on the speed of sound in water.

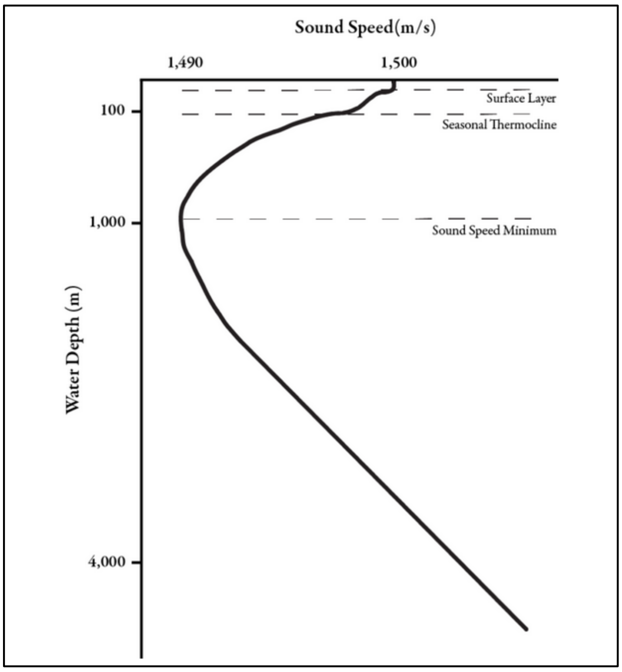


Fig 2. Sound Speed Profile in water. Copyright University of Rhode Island

- <u>Surface Layer</u>: Near the surface layer, the sound speed is maximum. This is because, the temperature is highest near the surface layer. After the surface layer, the sound speed starts reducing.
- <u>Thermocline Layer</u>: As we go deeper, the temperature starts to reduce (hence called the thermocline layer) and thus the Sound speed also reduces.
- <u>Sound Speed Minimum</u>: After a certain depth, the temperature stops reducing and is almost constant, but the pressure keeps on increasing and has dominant effect on sound speed. Hence the sound speed again starts to rise. The point where the sound speed hits minimum is called as sound speed minimum. This is also where the SOFAR channel (Sound Fixing and Ranging channel) exists. SOFAR channel allows the low frequency sound waves to travel for comparatively longer distances before dissipating [24]. This is because, here the sound wave interacts neither with ocean surface nor with the ocean bottom. Hence, very less transmission loss occurs and the sound is able to travel longer distances. The phenomenon is an important factor in Anti-Submarine Warfare (ASW).

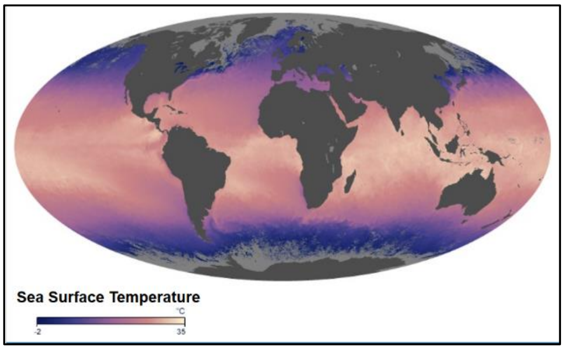
Applications of Sound Speed Estimation in the Ocean

1. **Ray Tracing**: An acoustic propagation model is responsible for simulating the travel of acoustic waves from source to receiver within the modelled environment. There exist several mathematical/numerical models based on different approaches, all of which perform ray tracing in order to account for the surface and bottom backscattering which in turn contributes to the total transmission loss. J.Hoven [25] in his work on ray tracing, has explained how sound speed has direct implications on the path of ray. A constant sound speed leads to straight line path for the ray whereas for an inconsistent sound speed, the rays follow curved path rather than straight ones
2. **Estimating Impact on Geo-acoustic Parameters**: Y.Jiang et.al (2009) [26] in his paper investigated the influence of water column variability on the estimates of geo-acoustic model parameters obtained from matched field inversions [27]. He mentioned how most of the inversion studies to date were carried out by assuming that the water column sound speed profile is both range independent and time invariant. In his work, he investigated the impact of temporal and spatial variations of the water column SSP on geo-acoustic inversion. His work is for low frequency, long range propagation in shallow water, where seabed geo-acoustic properties usually play a dominant role due to the multiple interactions of sound with the sea bottom. Hence, determining geo-acoustic properties in an ocean environment having variable sound speed is a practical issue for applications such as sound propagation interpretation and sonar performance prediction.
3. **Estimating Impact on Localizations in Underwater Sensor Networks**: The field of Underwater Sensor Networks attempts to set up a Wireless Sensor Network (WSN) underwater for the purpose of exploration and monitoring by addressing challenges unique to the oceanic environment. In an Under Water Sensor Network (UWSN), the knowledge of the location of a node can both improve the operation of the network (e.g. geographical routing) and add significance to the data that is collected. Many localization techniques used in UWSN are based on multi-lateration [28], which assumes the underwater speed of sound to be constant. However, several studies have shown that this speed varies with salinity, temperature and pressure. This variation incorporates an error into the results obtained from localisation. S.Misra et.al (2011) [29] in their work, designed an algorithm to calculate SSP for a particular location & time, and performed simulation to provide validation as to how their algorithm improves the localization accuracy over a pure multi-lateration technique that assumes the underwater speed of sound to be 1500 m/s.
4. **Estimating Effect on Shallow Water Sound Maps**: Sound mapping over large areas can be computationally expensive because of the large number of sources and large source-receiver separations involved. In order to facilitate computation, a simplifying assumption sometimes made is to neglect the sound speed gradient in shallow water. The accuracy of this assumption is investigated for ship generated sound in the Dutch North Sea, for realistic ship and wind distributions by H.O Sertelk et.al (2016) [30]. They generated sound for selected frequency bands (56 Hz to 3.6 kHz) and found that effect of sound speed profile for the deci-decade centred at 125 Hz is less than 1.7 dB.
5. **Sound Speed Comparisons:** K.Williams et.al (2002) [31], performed comparison of sound speed and attenuation measured in sandy sediments during sediment acoustics experiment in 1999 against the predictions based on Biot theory of porus media [32]. His results indicated that the variation of sound speed with frequency is fairly well modelled by Biot theory but the variation of attenuation with frequency deviates from Biot theory predictions for homogeneous sediment. Similar comparison work was performed by M.Kido et.al (2008) [33]. They monitored temporal variation of sound speed profile through a GPS/acoustic survey and compared it with in-situ expendable bathythermograph (XBT) measurements periodically carried out during the survey in Peninsula. They found that the relative change of the two independent measurements are in good agreement within 5%.
6. **Estimating SOFAR Channel Depth of Ocean:** P.Bhaskaran et.al (2009) [34], in his work has studied the variability in sound speed structure and SOFAR channel depth in Indian Ocean throughout the year (January to December) in 2009, by using the existing World Ocean Atlas (WOA) and Ocean Atlas dataset [35]. His results showcased a difference of nearly 50 meters in SOFAR channel and +0.5 m/s across the period of January to December 2009.

Future Scope

Although quite an amount of work has been accomplished in the domain of sound speed profile estimation and it's usage inside other applications, there substantial efforts needed to enhance underwater signal processing, especially in the tropical littoral waters of the Indian Ocean Region (IOR), a few of which have been discussed below.

1. **Studying the Sound Speed Profile in the IOR**: Estimation of Sound Speed Profile and SOFAR Channel depth across Indian Ocean Region is of extreme importance considering the India's 7th position as top naval powers in the world [36]. It will enhance accuracy of naval systems when deployed in the IOR. Variations in sofar channel depth needs to be studied in high resolution to appreciate the importance. Although similar work was performed previously by S.Prasannakumar et.al in 1992 [37] and P.Bhaskaran in 2009 [34], the environmental condition of the ocean such as temperature, which has the dominant impact on sound speed profile has experienced notable change between March 2009 and March 2019, as depicted in Fig 3 extracted from NASA Earth Observatory [38]. Furthermore both the studies were performed with the then available limited low resolution dataset and even the latest study of sound speed profiling has been performed only up to a depth of 1000 meters. The currently available high resolution dataset of (World Ocean Atlas) WOA-2018 would provide better results and encompasses much higher depth range.



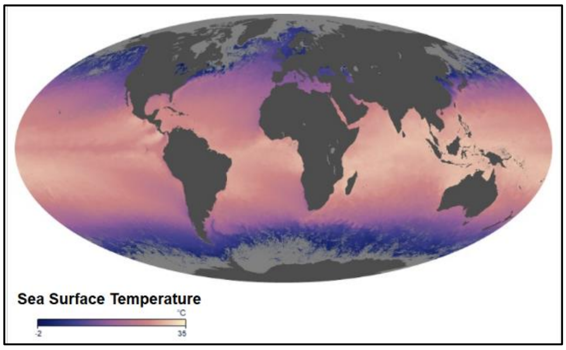


Fig 3. Sea Temperature during (L) March 2009 and (R) March 2019.

2. **Effect of varied sound speed profile on ambient noise propagation and Ocean Global Warming in IOR**: Determining the impact of change in sound speed profile on noise propagation within the ocean, by comparison against the 2009 study of P.Bhaskarn's, will prove to be useful for multiple applications in naval defence tactics of sub-surface as well as surface vessels. Fig 3, which depicts the change in sea temperature over the period of one decade, also depicts the ocean warming scenario which is cause of serious concern today. This study will also help us analyse the effect of ocean warming on SSP in IOR.
3. **Development of SSP equation, tailored for Indian Ocean Region**: The existing sound speed equations, including that of Leroy et.al 2008, are not tailored for major parts of Indian Ocean. Due to unavailability of data of other parts, only deep waters of East Indian basin (Bay of Bengal) was considered while creating the equation [12]. As on the date of the formation of this research note, to the best of our knowledge, there has also been no study that validates the accuracy of any sound speed profile equation in IOR. Furthermore, Leroy (2008) in his work mentioned that other existing equations developed before are erroneous due to inaccurate results obtained by using UNESCO equation, in fresh water high pressure conditions. The Indian Ocean being a focal point of maritime trade and geopolitical hotspot, experiences massive vessel traffic for various activities. Obtaining accurate Sound Speed Profile of the ocean is crucial for monitoring the ambient noise levels of the ocean.

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IMPORTANT LINKS

1. Derivation of Elastic Bulk Modulus