Localization of a bubble source in water tank for oil spill detection

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***Abstract*— Localization of active acoustic source using TOA (Time of Arrival) estimate from acoustic sensors has been recently getting a lot of attention because of its numerous applications in defense, oil-spill detection etc,. Several localization algorithms can be used to estimate the acoustic source location with different accuracy levels. This paper focuses on giving the comprehensive experimental results of localizing acoustic source (active hydrophone) that generates $10KHz$ audible signal by the use of randomly deployed several passive hydrophones in a $2m$x$2m$x$2m$ water tank and followed by localization of a bubble source that mimics oil leak from the sea bed. We use first arrival to estimate TOA and linear localization algorithms like LSE (Least Square Estimate), TSE (Taylor Series Estimate) to approximate the active hydrophone and bubble source locations. The simulation and measurement results are provided to compare the performance of the localization techniques.**

***Index Terms*— acoustic localization; active hydrophone; bubble source; passive hydrophone; time of arrival; first arrival; least square estimation; taylor series estimation**

I. INTRODUCTION

Marine pollution caused by oil spills are devastating and alarmingly hazardous. These hydrocarbon leakages can be caused by either natural events, such as seeping from fissures in the ocean seabed and eroding sedimentary rock [1], or by anthropogenic accidents, such as leaking from broken wellheads and pipelines by mechanical failures - like the Macondo well blowout and Deepwater Horizon mobile offshore drilling unit explosion in April 2010 [2]. Oil spills can cause a lot of adverse effects on many organisms which are either short-term or long-term. The short-term effects would be mammals, fish and birds ingesting them. The long-term devastating effect would be accumulation of oil through food chain which can lead to ecological imbalance and extinction of several species [3].

Oil spills spread rapidly. Extraction is difficult and expensive upon expansion of oil layer to wide area. Usually only 20% of the total quantity of oil is recovered from a typical spill [3]. For this reason, detecting oil spill source location properly and rapidly minimizes the destruction. The spilled crude oil is a mixture of natural gases and oil with considerable amounts of gases. These gases in the form of bubbles can generate underwater sound that can be recorded by hydrophones in the water column at far distances.

In order to test the detection of the oil spill location, we deploy passive hydrophones to listen to the audible signal generated by active hydrophone. It mimics the bubbles generated by oil spill using $10KHz$ pseudo-random pulse signal. Frequency range of acoustic oceanic bubbles range from several KHz to few hundred KHz [4]. We obtain TOA from data collected by the passive hydrophones and use localization algorithms to estimate the active hydrophone source location. The experiment is repeated by replacing the active hydrophone with a bubble generator that closely imitates the natural gas leak from the sea bed.

The paper is organized as follows. Sec II represents TOA estimation. Section III explains the estimation of acoustic source from TOA information using localization algorithms, followed by results in section IV and conclusion.

II. TOA ESTIMATION

TOA is the simplest and most common ranging technique used in the localization [5]. This method assumes that exact time of transmission by the target ($t_{transmit}$) and time of reception by the sensor ($t_{receive}$) node are known. Let velocity of sound (c) is determined then the distance from the reference location can be calculated by using the equation [6]:

$$d = c * (t_{receive} - t_{transmit}) \tag{1}$$

Let (x_a, y_a, z_a) be the known anchor node location and (x_s, y_s, z_s) be the unknown target location. The set of possible locations of the target in three dimensional space can be determined from the equation of a circle [6]:

$$d = \sqrt{(x_s - x_a)^2 + (y_s - y_a)^2 + (z_s - z_a)^2} \tag{2}$$

Once this distance equation is calculated for sufficient number of nodes (at least four for three dimensional case). The exact position of the target node can be calculated by finding the intersection. Lets consider a case where we have four anchor nodes (blue, orange, green and brown) surrounding a target node (black) as shown in Figure 1.

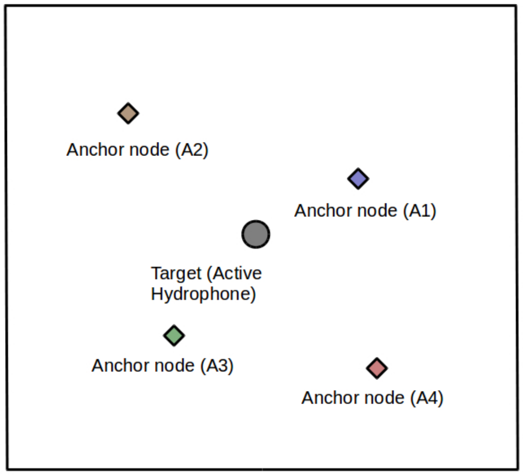

Fig. 1. Target node and Anchor node locations.

At time t_1, a signal is sent from the target node to anchor node 1, which is received at t_2. The distance (d1) between the target and anchor node 1 is calculated, then the circle of possible locations is represented as in Figure 2.

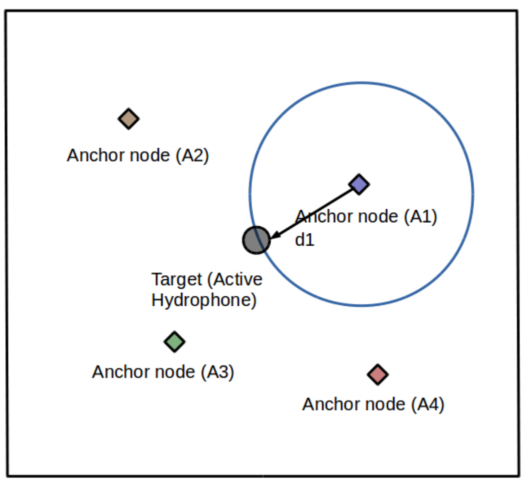

Fig. 2. Circle of locations with respect to anchor node 1.

The procedure is continued for remaining three anchor nodes and the intersection of all four circles would give you the location of the target node as shown in Figure 3. TDOA (Time Difference of Arrival) is the next most used ranging technique. It doesn't need transmitter and receiver synchronization, it also doesn't require the time of signal transmission from the source node. This gives TDOA little edge over TOA in terms of ranging accuracy.

The prime difference between the two ranging techniques is that in TDOA we have a reference node. It is generally considered to be closest to the target node. The difference in arrival time is calculated from difference in distance between target node and reference node, target node and rest of the nodes. Let c be the velocity of sound and Δt be the difference in the arrival times, then the difference in the distance Δd is calculated as [7]:

$$\Delta d = c * \Delta t \tag{3}$$

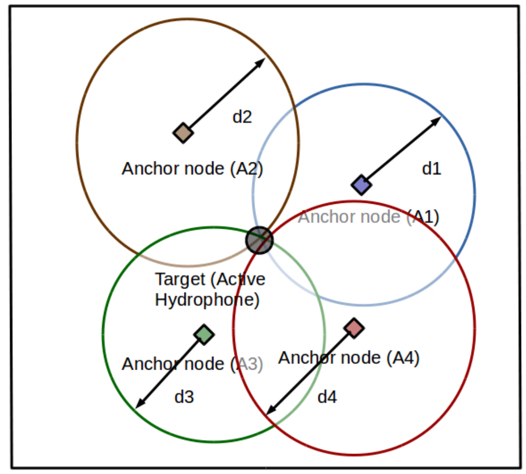

Fig. 3. Circle of locations with respect to all the anchor nodes.

In three dimensional space this can be represented as [8]:

$$\begin{aligned}\Delta d =& \sqrt{(x_s - x)^2 + (y_s - y)^2 + (z_s - z)^2} - \\ &\sqrt{(x_s - x_{ref})^2 + (y_s - y_{ref})^2 + (z_s - z_{ref})^2}\end{aligned} \tag{4}$$

Where $(x_{ref}, y_{ref}, z_{ref})$ is the known reference node co-ordinates and (x, y, z) are the known anchor node co-ordinates. This equation takes a form of hyperbola and with enough number of them calculated, the intersection of these hyperbolas gives the location of the target node [5]. TOA methods are more efficient for WSNs (Wireless Sensor Network) than cross-correlation based techniques. Due to limited size of the experimental setup ($2m$x$2m$x$2m$ water tank), we experience multi-path reflections and it makes the cross-correlation based techniques inaccurate [9]. Alternatively, we use first arrival-cross zero method to calculate TOA that is used to estimate the unknown source location. This is done by the program developed in LabVIEW software. It acquires the data collected by the passive hydrophones and calculate the first arrival time for every received signal, with the help of an amplitude threshold and signal start-time at first prominent signal valley. The GUI window of TOA estimation is shown in Figure 4.

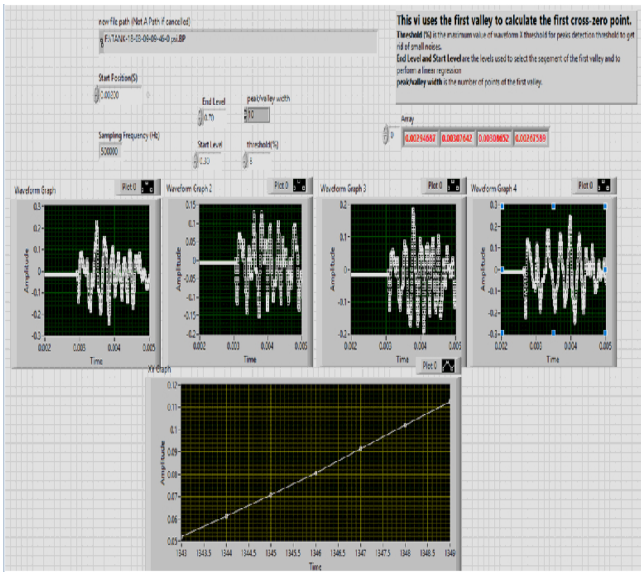

Fig. 4. LabVIEW GUI window for TOA estimation.

Generally, the smallest TOA value represents the closest node from the target node and the largest TOA value represents the farthest. The node corresponding to the smallest TOA value is considered as a reference node. This reference TOA value is subtracted from the rest to obtain corresponding TDOAs. These values are fed as a prior information to localization algorithms in estimating the location of unknown target/source node. This is explained in the next section.

III. Localization

The accuracy of localization depends on ranging techniques and localization algorithms as they go hand in hand. Here we are using two algorithms namely LSE [10] and TSE [11] for estimating unknown target source location. Figure 5 displays the algorithm of LSE. Firstly the anchor node (Known node) locations are arranged in ascending order of their distance from the source, followed by moving the origin to the closest anchor node to source for easy calculation and updating it to zeros in all the dimensions. The parameter, velocity of sound is initialized to a known value. The distance equations between anchor nodes and source node are manipulated, solved using least square method to estimate the unknown source location. The detailed mathematical derivation of this localization algorithm can be found in [10].

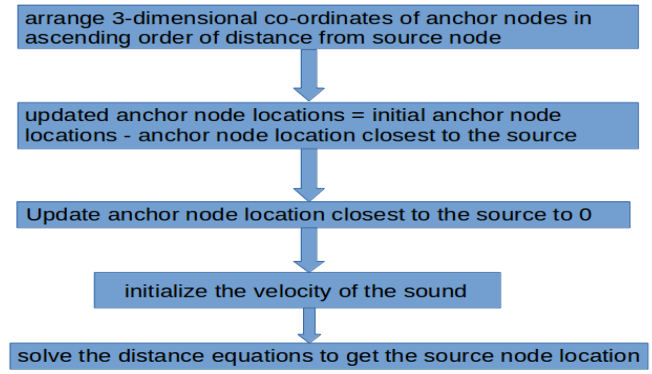

Fig. 5. Algorithm of LSE.

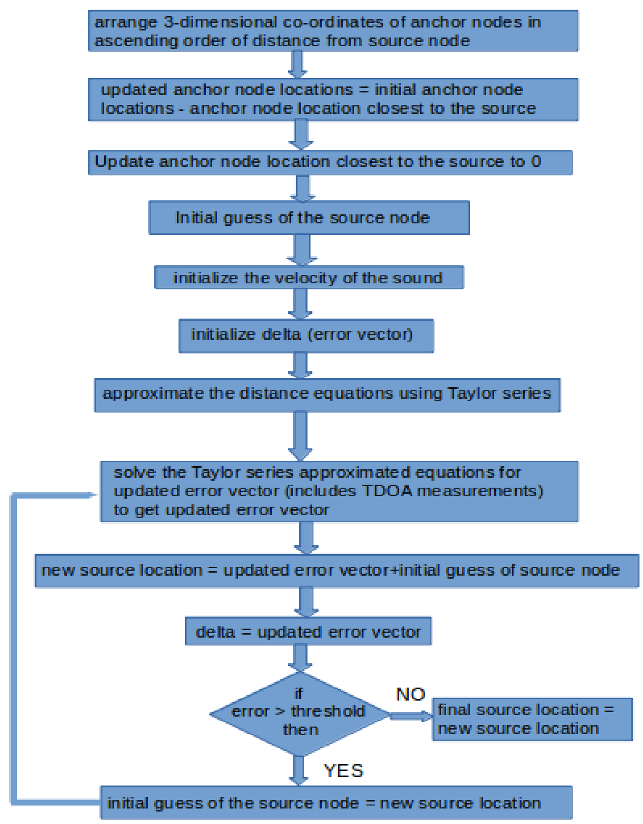

Fig. 6. Algorithm of TSE.

Figure 6 displays the algorithm of TSE. The main difference between this algorithm and LSE is the approximation of distance equations using Taylor series expansion and randomly guessing an initial location of unknown source for iterative solving implementation. After this, an iterative solver is implemented to find the deviation in all the co-ordinates. If the deviation is small enough (usually sum of deviations is compared to user specified value as an iterative condition), the final source location is initial guess added with deviation in each direction. Else, the initial guess is updated by adding the deviation to it and passed through iterative solver until the criteria is satisfied.

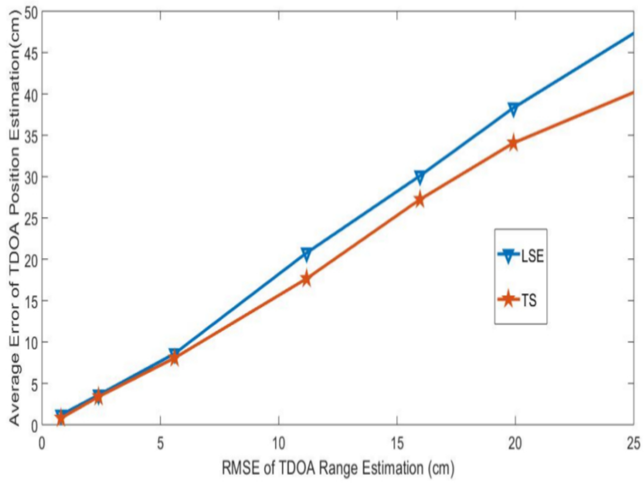

Fig. 7. Simulation of TSE and LSE performance.

Figure 7 is the simulation plot between RMSE (Root Mean Square Error) of localization algorithm on x-axis and average error in TDOA estimation on y-axis caused by the noise. It can be noticed that in the low noisy environment both algorithms have similar performance. But, at highly corrupted environment TSE outperforms LSE.

IV. RESULTS

Active Hydrophone Source:

Figure 8 shows the experimental setup that consists of a $2m$x$2m$x$2m$ water tank. It consists of two active hydrophones (S_1, S_2) located at (1.74m, 0.73m, 1.36m) and (0.90m, 0.64m, 1.15m). The six passive hydrophones (CH_1, CH_2, CH_3, CH_4, CH_5, CH_6) are located in the tank at (0.52m, 0.31m, 1.15m), (0.25m, 0.95m, 1.27m), (0.54m, 1.70m, 1.24m), (1.33m, 1.59m, 1.21m), (1.90m, 1.12m, 1.39m), (1.63m, 0.43m, 1.33m) respectively.

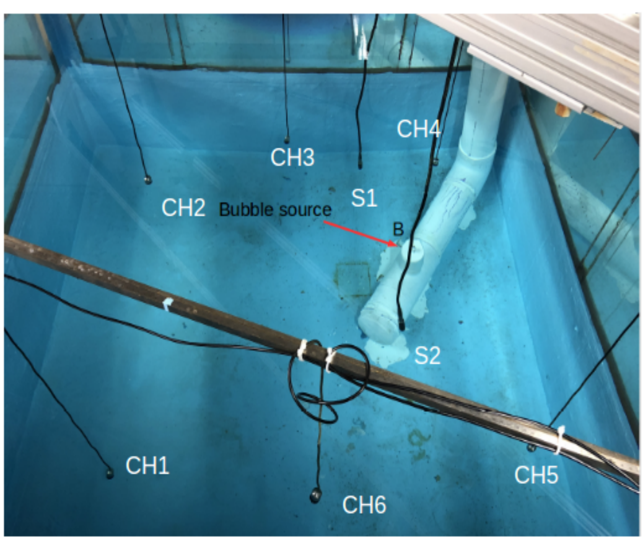

Fig. 8. Experimental setup.

Figure 9 shows the block diagram of data acquisition system. We use function generator to generate a complete cycle of $10KHz$ tone-burst signal. It is converted to acoustic signal by the active hydrophone and propagates through the water tank. The six passive hydrophones listen to the signal and this data is collected using oscilloscope (see Figure 4 for the recorded signals). After that the TOA estimates are calculated using LabVIEW. We use Matlab to implement localization algorithms. The TOA information obtained from LabVIEW is fed as a prior information to obtain target/source location. The results presented below has velocity of sound as one variable and RMSE as the other. We have velocity as a variable because in the ocean, the velocity of sound is approximately $1500m/s$. But, can vary slightly with salinity, depth and temperature [12].

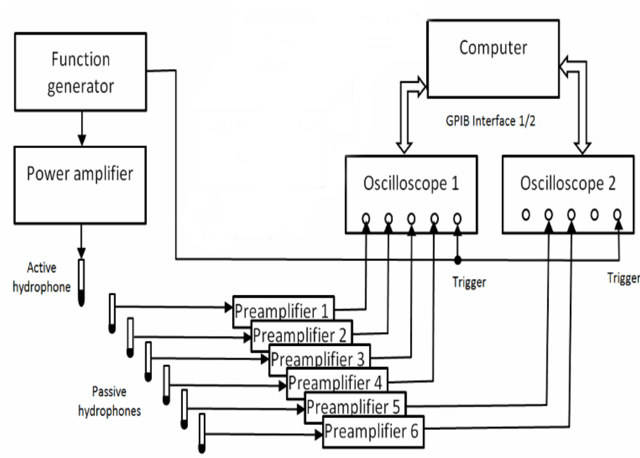

Fig. 9. Block diagram of the system.

Figure 10 shows the graph between RMSE and velocity of the sound inside the water. It can be noticed that TSE outperforms LSE with the increase of velocity. Here the actual target node location S_1 is (1.74m ,0.73m ,1.36m) and the estimated target node location $\hat{S_1}$ is (1.8061m, 0.7578m, 1.3478m) for LSE and (1.7961m, 0.7665m, 1.3561m) for TSE respectively.

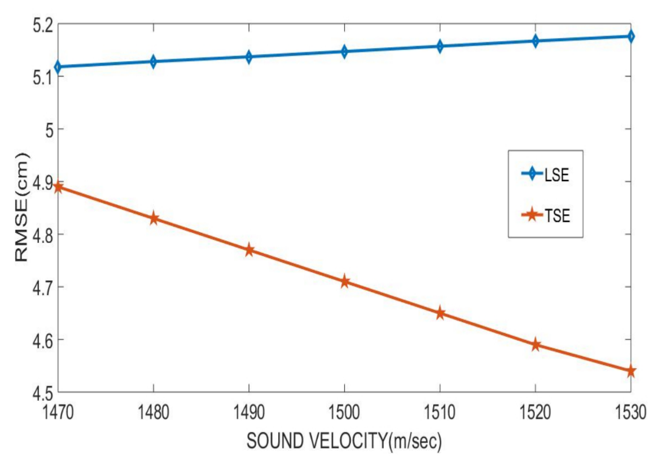

Fig. 10. RMSE vs VELOCITY OF SOUND for source location 1.

Figure 11 shows the graph between RMSE and velocity of the sound inside the water for target node location S_2. It can be seen that TSE slightly outperforms LSE at intermediate velocities and converse for lower velocities. Here the actual target node location is at (0.90m ,0.64m ,1.15m) and the estimated target node location $\hat{S}_1$ is (0.905977m, 0.650772m, 1.055257m) for LSE and (0.9026m, 0.6529m, 1.0696m) for TSE respectively at a velocity of $1500 m/sec$.

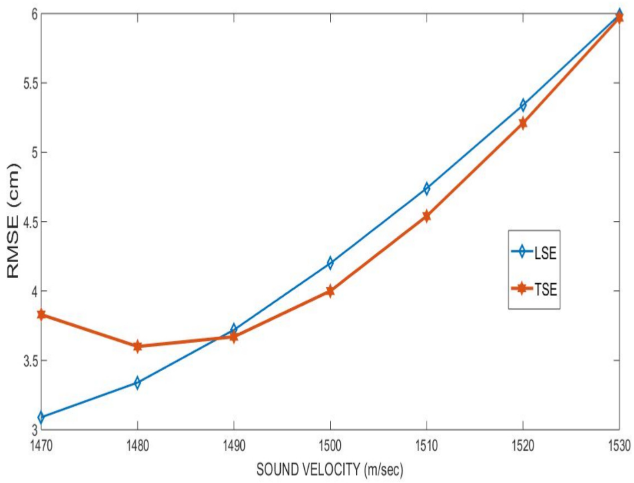

Fig. 11. RMSE vs VELOCITY OF SOUND for source location 2.

Bubble Source:

After localizing the active hydrophone source and successfully verifying localization algorithms, we move on to localizing the bubble source. This source produces series of air bubbles that imitates the natural gas leak from the sea bed. Figure 8 also shows the bubble source (B) immersed in a water tank. The whole equipment is enclosed in a PVC white pipe to protect it from water damage. Figure 12 shows the picture of stream of air bubbles coming out from the bubble source. Figure 13 shows the bubble source equipment that is enclosed in a PVC pipe. We have a pipe connecting the gas cylinder to the solenoid valve 1, it is connected to the flow meter which is connected to the solenoid valve 2. The solenoid valve 2 is cascaded to a check valve which has a needle (G20 in this case) protruding from the PVC pipe to generate bubbles into the water tank. To counteract the water buoyancy force when submerged in the tank, we place lead brick on the either side of the PVC enclosed bubble source. parameters like air pressure, size of the needle source (G12,G14,....,G20,G22,etc..) and flow rate can be controlled for bubble frequency characterization.

Fig. 12. Bubbles generating from the bubble source.

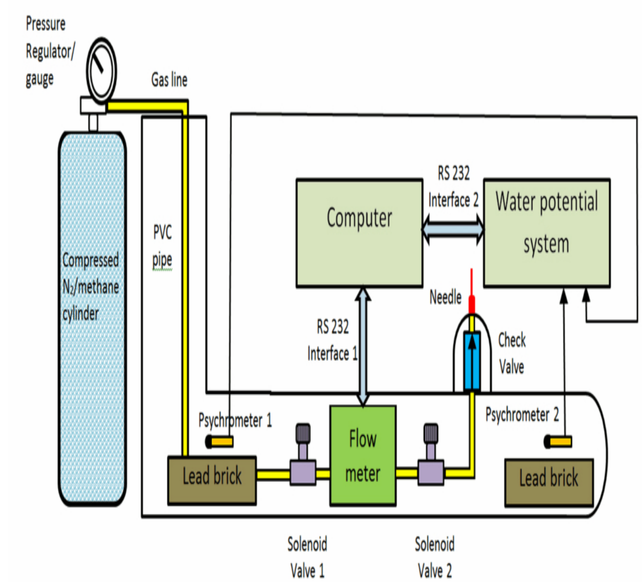

Fig. 13. Bubble source block diagram.

Figure 14 shows the bubble signal registered by the six passive hydrophones. This received signal can be fed as a prior information to the LabVIEW based program to estimate TOA values like described in figure 4. Figure 15 shows the graphical representation between velocity of sound and RMSE for localizing bubble source using LSE and TSE localization algorithms. It can be seen that localization error is reduced with the increase of velocity for TSE algorithm and converse in case of LSE algorithm. As an overall performance TSE outperforms LSE.

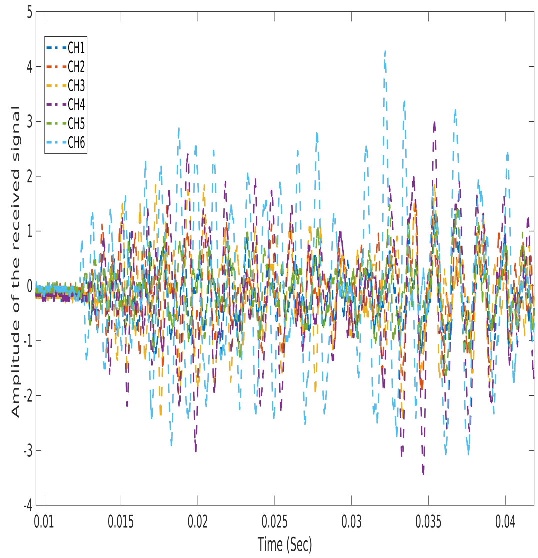

Fig. 14. Bubble signal received by the passive hydrophones.

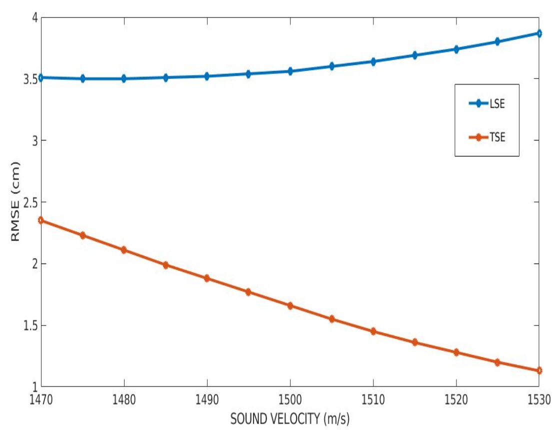

Fig. 15. RMSE vs SOUND VELOCITY for the bubble source.

The six passive hydrophones (CH_1, CH_2, CH_3, CH_4, CH_5, CH_6) are located in the tank at (0.52m, 0.31m, 1.22m), (0.25m, 0.97m, 0.76m), (0.51m, 1.70m, 1.61m), (1.32m, 1.60m, 0.89m), (1.89m, 1.11m, 1.40m), (1.63m, 0.45m, 1.11m) respectively and the bubble source (B) is located at (1.395m, 0.525m, 1.45m). The estimated target node location $\hat{B}$ is (1.3836m, 0.5242m, 1.5107m) for LSE and (1.369m, 0.5312m, 1.4396m) for TSE algorithms.

V. CONCLUSION

In this paper we use a $2mx2mx2m$ water tank for the measurement setup, it consists of six passive hydrophones for data acquisition through which the signals of the bubble source and active hydrophone are received. Two localization techniques namely LSE and TSE are used to estimate the unknown source location. Although both methods give you good approximations for the unknown source location, TSE is less erroneous and more accurate in estimating the location of the unknown source. We also obtained graphical information of the error in the localization methods along the velocity of the sound. This is done to examine the error trend along the change in the velocity of the sound as it varies with depth, salinity and temperature of the water.

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REFERENCES

[1] ”Natural Oil Seepage Facts.” SOS California. Accessed July 02, 2018. http://www.soscalifornia.org/natural-oil-seepage-facts/.

[2] ”Final Report on the Investigation of the Macondo Well Blowout.” Deepwater Horizon Study Group. Accessed July 02, 2018. https://ccrm.berkeley.edu/pdfs_papers/bea_pdfs/DHSGFinalReport-March2011-tag.pdf.

[3] Greenpeace International ”Oil spills - Philippines Indian Ocean and Lebanon ” greenpeace. org Aug. 18 2006.

[4] John H. Steele, Karl K. Turekian, and Steve A. Thorpe. Encyclopedia of Ocean Sciences (2nd Edition). Academic Press, 2008. Pages 439-444.

[5] Brian OKeefe. Finding Location with Time of Arrival and Time Difference of Arrival Techniques. ECE Senior Capstone Project. Indoor Navigation for the Visually Impaired, 2017 Tech Notes.

[6] Shi, Guowei, and Ying Ming. ”Survey of indoor positioning systems based on ultra-wideband (UWB) technology.” In Wireless Communications, Networking and Applications, pp. 1269-1278. Springer, New Delhi, 2016.

[7] Roberts, R. (2004). Tdoa localization techniques. Harris Corporation, 4

[8] Mahajan, Ajay, and Maurice Walworth. ”3D position sensing using the differences in the time-of-flights from a wave source to various receivers.” IEEE Transactions on Robotics and Automation 17, no. 1 (2001): 91-94.

[9] Reddy, Prashanth G. ”Efficient Time of Arrival Calculation for Acoustic Source Localization Using Wireless Sensor Networks.” PhD diss., Cleveland State University, 2011.

[10] Guido, J. (2018). TDoA Page. [online] Jeffreyguido.com. Available at: http://jeffreyguido.com/work/tdoa_page.html#background [Accessed 28 Jun. 2018].

[11] Shen, Guowei, Rudolf Zetik, and Reiner S. Thoma. ”Performance comparison of TOA and TDOA based location estimation algorithms in LOS environment.” In Positioning, Navigation and Communication, 2008. WPNC 2008. 5th Workshop on, pp. 71-78. IEEE, 2008.

[12] ”Tutorial: Speed of Sound.” Discovery of Sound in the Sea. April 30, 2018. Accessed July 03, 2018. https://dosits.org/tutorials/science/tutorial-speed/.