Analysis, Verification and Optimization of AUV Navigation Using Underwater Acoustic Models

Salman I. Siddiqui†, Martin Ludvigsen‡, Hefeng Dong†, *Member*, *IEEE*

†Department of Electronics and Telecommunications, Norwegian University of Science and Technology,
NO-7491 Trondheim, Norway.

‡Centre for Autonomous Marine Operations and Systems (AMOS), Norwegian University of Science and Technology,
NO-7491 Trondheim, Norway.

{salman.siddiqui,martin.ludvigsen,hefeng.dong}@ntnu.no

***Abstract*—Autonomous Underwater Vehicles (AUV) are becoming significant in many underwater applications due to accessibility, autonomous features and data collection functionalities. In order to achieve greater operational efficiency, there is a need of effective techniques for self-localization and tracking of the vehicles. In the current AUVs, long base line (LBL) techniques are used for localization. LBL techniques use acoustic ranging between the transponders (at known locations) and the AUVs. The acoustic signals are greatly affected by different underwater environment parameters, therefore it is necessary to study their impacts on the acoustic signal propagation. Some of the parameters include water column temperature, salinity, depth and source-receiver configuration. In this paper these environmental effects are studied using acoustic models and compared with the AUV data obtained from the experiment at the Trondheim Fjord in April 2015. The real data and the simulated data show good match which proves that the LBL acoustic signals are affected by the environment. An environmental parameter analysis is also presented, using the acoustic model, to show the effect of sound speed profile and transponder depth on the acoustic signals. The results show that the sound speed profile has great impact on acoustic signal propagation and the transponder depth should be selected based on the sound speed profile to achieve better performance. Therefore, the environmental parameters should be considered for effective path planning and optimizing the navigation performance of the AUV.**

I. Introduction

Autonomous Underwater Vehicles (AUV) are becoming significant in many underwater applications due to accessibility, autonomous features and data collection functionalities. AUVs are employed for different tasks like seabed exploration, minerals exploration, port security, pipeline inspections, geological and biological inspections. For all these applications multiple AUVs covering wider area would increase operational efficiency. In order to achieve greater operational efficiency, there is a need for coordination and communication between the vehicles. In the current AUVs, long base line (LBL) techniques are used for localization. LBL is a positioning system where one or more than one transponders exchange acoustic signals with the AUV. The locations of the transponders are known and the AUV localizes itself based on the time-of-flight (ToF) of the signal [1].

The acoustics-based localization techniques rely mainly on the acoustic propagation of the signal through underwater environment. The underwater environment provides many challenges to the acoustic propagation [2]. Some of the channel parameters which greatly affect the signal propagation are; sound speed profile and source-receiver configuration [3]. Sound speed profile is a function of water temperature and salinity and varies along the water depth. It also varies spatially (along the source-receiver range) and temporally. The underwater channel is a bounded medium, therefore the acoustic signals propagate by interacting with the boundaries. Due to these interactions, multiple replicas of the received signals are obtained and these acoustic signals lose energy at each interaction which limits the propagation range.

Different localization algorithms have been proposed in the literature based on the acoustic signal propagation. In [4] the localization is performed based on the propagation time with respect to anchor nodes with pre-determined position. Using this algorithm the AUVs are tracked with an accuracy of 7-9 meters in a roughly 3 km by 4 km area. In [5] a localization algorithm is proposed for underwater sensor networks based on time synchronization between the source and the receiver clocks. Some signal processing techniques are performed with time synchronization in order to improve the accuracy of the localization in [6] but the sound speed is considered constant. It is shown in [7] that the localization performance of the underwater sensor networks can be improved by including the actual sound speed profile.

LBL techniques have attracted great research interest in the past decade and several techniques have been developed [8]. Due to robustness of LBL techniques, they have been tested in different challenging environments like under-ice operations [9]. In [10], it is reported that the AUV is navigating near the bottom of a deep sea and it is tracked using LBL techniques. The LBL transponders are GPS-referenced before the start of the experiment. A detailed analysis on the precision of LBL systems is presented in [11].

In most of the above-mentioned LBL techniques, the AUV data are used in an optimal way to improve the localization results. In this work, the main emphasis is to study the effect of underwater channel on the localization results. In [7], an analysis is performed based on the sound speed profile only, while in this work all the parameters are included using the

978-0-933957-43-5 ©2015 MTS

acoustic ray tracing model called PlaneRay [12]. By using all the environmental parameters, a more comprehensive analysis is performed and the effect of different parameters is studied in a more effective manner. In this paper the modeled results are verified with the AUV navigation data sets collected at Trondheim Fjord in April 2015. During the experiment, the AUV traversed the water column in vertical zigzag pattern and traveled approximately 2 km away from both the transponders. By analyzing the navigation data, it is observed that there were instants where the AUV lost the acoustic link with both the transponders. By modeling the same environment using PlaneRay model, it is observed that the deterioration in the acoustic link is due to the long range between the AUV and the transponder and also when the AUV is at larger depths in the water column. The modeling results show a good match with the navigation data obtained during the experiment, which shows the potential of using the acoustic propagation models to predict the acoustic field. The effect of these environmental parameters is also studied by changing the transponder depth and sound speed profile. Based on the results it is shown that the acoustic link is very sensitive to these parameters.

The paper is organized as follows: In Section II the problem formulation is presented. Section III elaborates the theoretical background. Section IV presents the technique for analyzing the navigation data. Section V explains the experimental setup and data acquisition for simulating the underwater environment. Section VI illustrates the results and observations obtained from the comparison of experimental and modeled results and section VII concludes the paper.

II. Problem formulation

The LBL localization techniques rely mainly on the underwater acoustic propagation. The underwater channel poses great challenges for acoustic signal propagation. Some of the main factors affecting the acoustic signals are water temperature, salinity, source-receiver configuration and water depth. Water temperature and salinity dictate the propagation of acoustic rays and also cause the bending of the acoustic rays in the water column. By ignoring this effect, a great deal of error is induced in the prediction of the operational range between the transponder and the AUV. This will be studied using simulations in the paper by comparing a constant and a depth dependent sound speed profile.

Source-receiver configuration is also an important factor in determining the acoustic propagation scenarios. Due to depth varying sound speed profile, different underwater propagation scenarios take place namely convergence zone, ducts, etc [13]. Due to these phenomena, the positioning of the source and the receiver becomes very beneficial to achieve reliable transmission between the AUV and the transponder. The effect of transponder position is also studied using acoustic modeling.

III. Theoretical background

The underwater acoustic signal propagation is affected by different environmental factors like sound speed profile, source-receiver configuration and bottom properties. In this paper, the main emphasis is on sound speed profile and source-receiver position.

The sound speed profile is dependent mainly on the water temperature, salinity and water depth. It is represented by a simplified formula [14].

$$c = 1448.6+4.618T-0.0523T^2+1.25(S-35)+0.017D \quad (1)$$

where T is the water temperature, S is the salinity and D is the water depth. Due to depth dependency of the sound speed, the acoustic propagation varies in different part of the water column. In order to explain some of these effects, the actual sound speed acquired by the AUV is discussed in this section. The details of the experiment will be presented in section V. Fig. 1 shows the measured sound speed profile. The experiment was carried out in April, and a winter profile was observed. There is a mixed water layer in the top part of the water column which is approximately 5 m thick. Below the mixed layer, there is an increase in the water temperature which resulted in a steep slope in the sound speed profile. The water temperature remains constant below 20 m in the water column and the steady slope in the sound speed is due to the depth change which can be explained by equation (1). The acoustic energy is attracted towards the region of low sound speed profile [13]. Some observations about the acoustic propagation can be deduced from the sound speed profile. During the experiment the transponder depth was approximately 20 m. From Fig. 1 it can be seen that the sound speed profile is increasing steadily in the bottom part of the water column, so the acoustic rays are reflected within the water column. Most of the acoustic rays are trapped in the water column and there is least interaction with the sea bottom. The acoustic link is highly attenuated when the AUV is performing seabed mapping in the bottom part of the water column. This effect will be elaborated more in section VI with real data and simulated data.

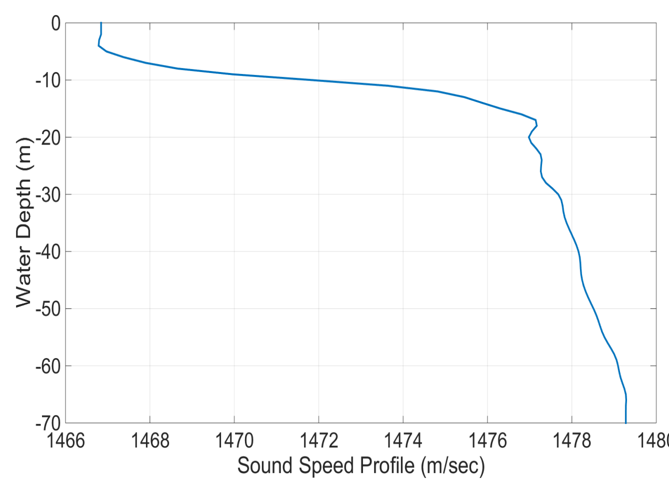

Fig. 1. Sound speed profile obtained from the AUV data

IV. Data Analysis Technique

This section elaborates the proposed method for the analysis of the navigation data of the AUVs. In this paper, the PlaneRay model is used to study the acoustic environment between the transponders and the AUV. The LBL localization techniques use the travel time between the source and the receiver for localization. In order to localize the AUV successfully, it is necessary to have a reliable acoustic link between the transponder and the AUV. The reliability of the acoustic link is studied using the PlaneRay model and transmission loss is used as the parameter to quantify the quality of the acoustic link.

In order to perform the acoustic modeling, the environmental data is obtained from the different sources which will be explained in detail in section V. By running the acoustic model for each position of the AUV, the transmission loss is obtained. This transmission loss is analyzed along the AUV trajectory. By comparing the modeled data to the localization results obtained during the experiment, it is observed that the communication link between the transponder and the AUV is lost at the points of high transmission loss. Based on this analysis, it can be deduced that the transmission loss can be used as a metrics for optimal path planning of the underwater vehicle.

V. Description of the Experiment

This section provides the details of the experiment and different environmental parameters obtained for modeling purposes. During the experiment REMUS 100 was used. REMUS 100 uses micro-modem for acoustic communication. The micro-modem can communicate with four REMUS transponders at center frequencies of 24 kHz and 25 kHz, using broadband PSK codes. On receiving replies, it publishes one-way travel time which can be used to calculate position. The interrogation frequency is 26 kHz at a bandwidth of 4 kHz. REMUS 100 is also equipped with depth sensor and temperature sensor for computing the sound speed profile along the AUV trajectory.

The bathymetry information is obtained from the archives and smoothed and interpolated. Fig. 2 shows the trajectory of the vehicle (stars) and the positions of the two transponders (red circles). The position and the depth of the transponders are hard coded in the log file of the vehicle. The sound speed profile is obtained from the AUV data. Fig. 3 shows the motion of the AUV along the water column. It can be observed that the vehicle traverses most of the water column leaving only the bottom part of the water column. The sound speed values from the AUV logs are used during the first dive and the sound speed values for the bottom part of the water column are considered constant. Fig. 1 shows the sound speed profile obtained from the AUV data. It is assumed that the sound speed profile remains constant during the rest of the mission which lasted for two hours.

The bottom properties are not available for the area of operation, therefore a hard bottom is considered. This approximation may cause some modeling errors but the magnitude of the error will be minimal based on the source-receiver position. The bottom properties affect the transmission loss through bottom reflected arrivals. As explained in section III, the source is placed in the top part of the water column, so the acoustic energy is dominated by the direct arrivals, surface reflected arrivals and water column bounded arrivals. Most of the arrivals are reflected within the water column and the rays emerging at very steep angles have to traverse all the water column resulting in great degradation and therefore their contribution in the transmission loss is minimal.

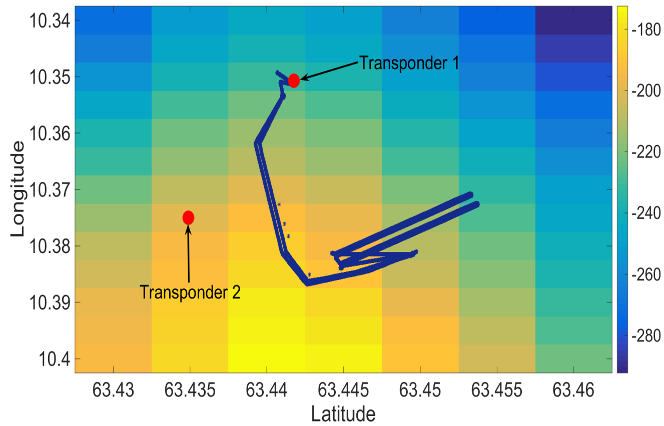

Fig. 2. Bathymetry of the area of operation. The AUV trajectory is shown by the blue stars and transponder positions are indicated by red circles

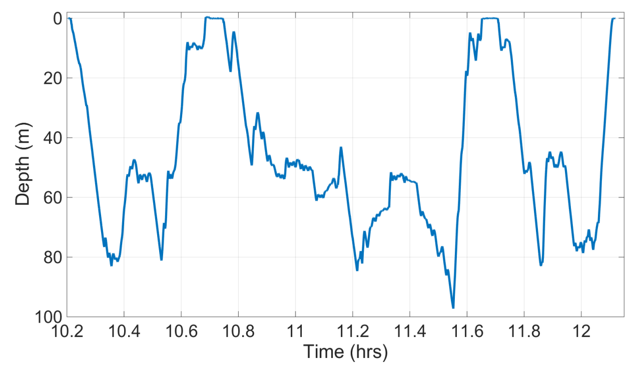

Fig. 3. The water depth of the AUV during the experiment.

VI. Results and Observations

This section is divided in two parts. In the first part, the real data are presented from the AUV and some observations are made on these data sets. These observations are validated using the underwater acoustic modeling results. In the second part, the effect of two environmental factors is discussed on the acoustic link between the AUV and the transponder 2. The idea of presenting this analysis is to show that acoustic models can be an effective tool for planning the AUV trajectories and transponder positions.

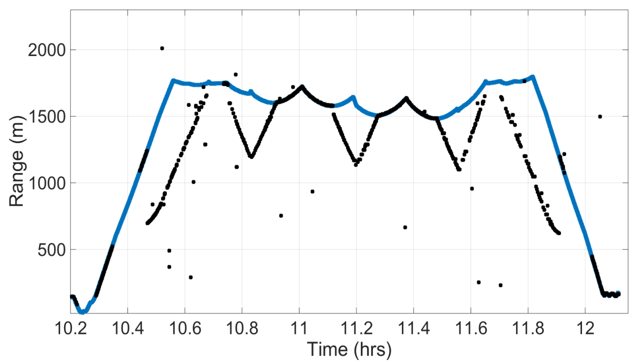

Fig. 4. Comparison of the range data from transponder 1 (black) with the range data calculated from the longitude and latitude data stored in the log file of the AUV (blue).

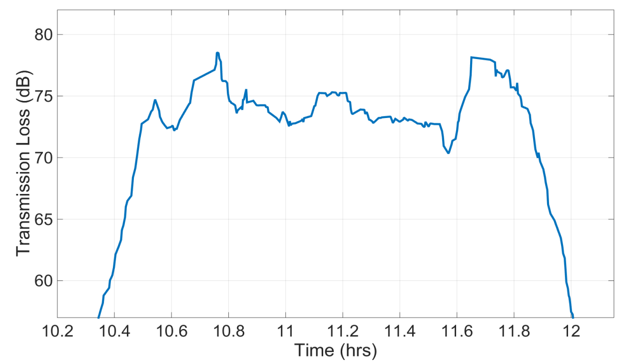

Fig. 6. Transmission loss along the trajectory of the AUV with respect to transponder 1

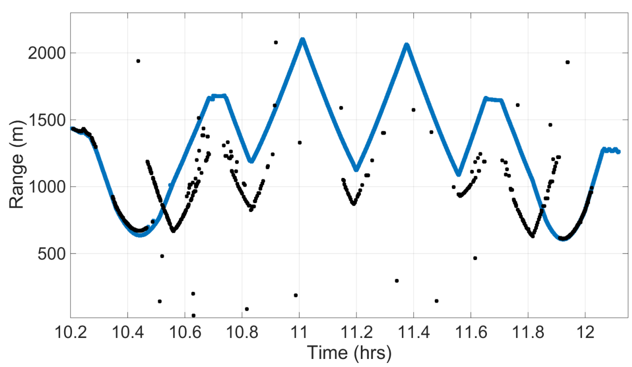

Fig. 5. Comparison of the range data from transponder 2 (black) with the range data calculated from the longitude and latitude data stored in the log file of the AUV (blue).

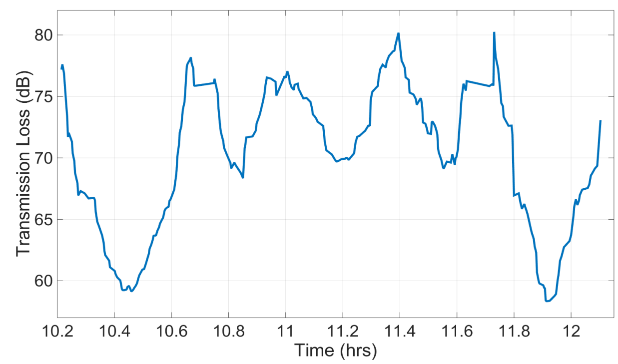

Fig. 7. Transmission loss along the trajectory of the AUV with respect to transponder 2

A. Analysis of AUV navigation data

Fig. 4 shows the comparison of the range data acquired by AUV from transponder 1 (black) and the range calculated from the latitude and longitude obtained from the log file of the AUV (blue). The range data from transponder is acquired by the AUV through acoustic signal. There is a good match between both data sets. It is highly probable that the AUV was successful in self localizing itself most of the time with respect to the transponder 1 whose location was known during the experiment. There are some deviations between both data sets. Observing two instants 10.7 and 11.7, there are no AUV navigation data available for those ranges. It can be explained using the AUV depth data in Fig. 3 that the AUV was on the surface at these instants and it was very difficult to obtain an acoustic link. Once the AUV lost the acoustic link, it used the pitch and heading of the vehicle to approximate the range which resulted in a deviation of approximately 500 m. After attaining the acoustic link, it converged back to the GPS location data at 10.9. There are two more instants of deviations which are 11.2 and 11.55. Analyzing the AUV depths at these instants, it can be seen that the AUV was descending in the water column. In both cases the water depth of the AUV was below 70 m, so it seemed that the AUV lost the acoustic link with the transponder below 70 m and established the link again when it moved above 70 m. This hypothesis is validated with modeling results. From Fig. 4 it can be deduced that there was an acoustic duct in the water column between 10 m and 70 m where the AUV obtained an acoustic link with the transponder 1.

Figs. 5 shows the comparison of the range data acquired by AUV from transponder 2 (black) and the range calculated from the latitude and longitude obtained from the log file of the AUV (blue). Similar behavior was observed when the AUV surfaced at the instants 10.7 and 11.7. There are two sudden jumps at instants 10.5 and 11.7, which requires some further investigation. The localization performance is degraded greatly in this case. Firstly, the distance between the AUV and the transponder was larger in this case, therefore the AUV lost acoustic link with the transponder resulting in no range information. Secondly when the AUV established the acoustic link for a very short period of time, the AUV failed to complete the auto-correction and match the original location resulting in a constant bias between the two datasets.

In order to validate these observations and study the behavior of the acoustic link, the acoustic wavefield is modeled using PlaneRay model. For running the model, different environment parameters are obtained from the log files of the AUV as

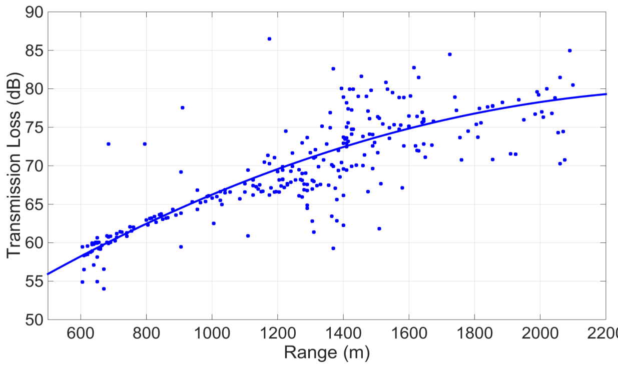

Fig. 8. The transmission loss at different ranges considering the actual sound speed profile. The blue line shows the curve fitting result for the data set.

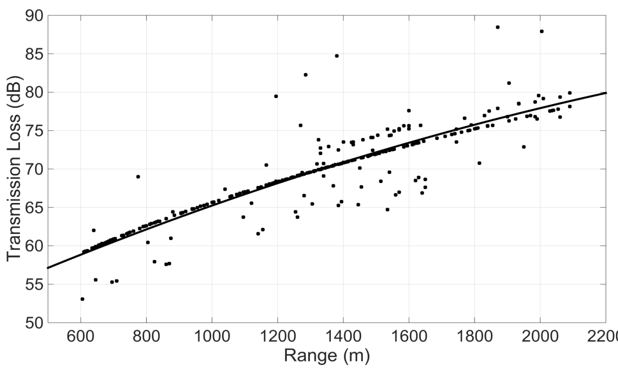

Fig. 9. The transmission loss at different ranges considering a constant sound speed profile. The black line shows the curve fitting result for the data set.

explained in detail in section V. Using these parameters, the acoustic wavefield is simulated for different positions of the AUV along the trajectory and transmission loss is calculated for each of these positions.

Figs 6 and 7 show the transmission loss between the AUV and transponder 1 and transponder 2 respectively. The transmission loss for transponder 1 is truncated below 53 dB to show the variations more clearly. From Fig. 6 it can be observed that there are two peaks in the transmission loss which coincides with the instants when the AUV was surfaced. There is an increase in the transmission loss at the instant 11.2 where the AUV reaches 80 m in depth. All three of these instants match with the instants in Fig. 4 where the AUV lost the acoustic link with the transponder 1. In Fig. 7 there are four peaks in the transmission loss. The first and the last peaks at instants 10.7 and 11.7 are the same as in Fig. 6 where the AUV was surfaced, while the other two peaks at 11.0 and 11.4 are the instants when the range of the AUV was maximum from the transponder 2 as seen in Fig. 5. From Figs 6 and 7, it can be deduced that there is a good match between the observations made from range data in Figs 4 and 5 and acoustic modeling results. This shows that channel modeling can be used to explain the degradation in the localization performance. Another important purpose of this analysis is to emphasize the use of acoustic models for planning the AUV

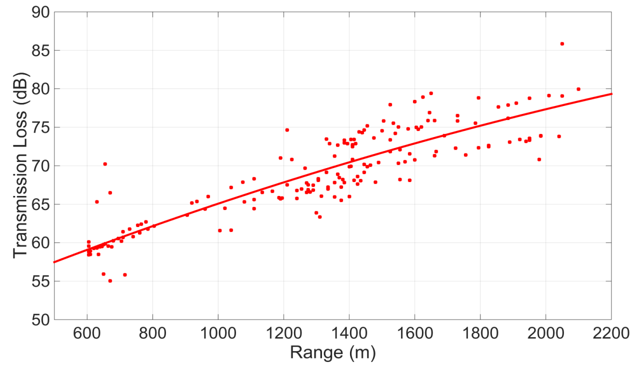

Fig. 10. The transmission loss at different ranges considering the transponder depth of 35 m. The red line shows the curve fitting result for the data set.

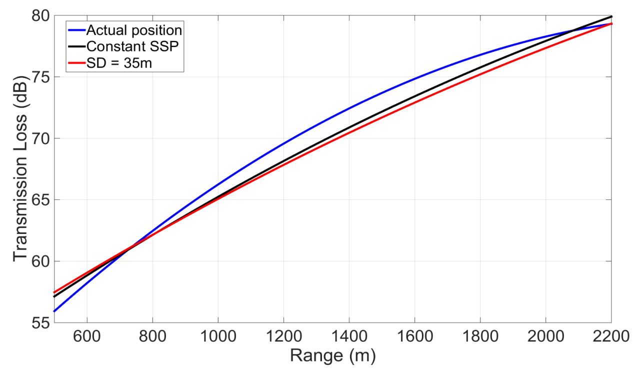

Fig. 11. Comparison of the curve fitting results for three data sets. Blue : Actual sound speed, Red : Constant sound speed, Black : Transponder depth of 35 m

trajectory and transponder positions.

B. Effects of environmental parameters

In this part of the section, the effect of two environmental parameters are studied; (i) Sound speed profile, (ii) Transponder depth. In order to illustrate these effects, the transmission loss is plotted for different ranges between the transponder 2 and the AUV. Fig. 8 shows the transmission loss along the AUV trajectory during the experiment where the transponder depth was 20 m. In this case the actual sound speed profile is considered. The curve fitting is applied to the data to compare with other data sets. The blue line shows the curve fitting result. Fig. 9 shows the transmission loss along the AUV trajectory where the transponder depth is 20 m but the sound speed is considered constant with the value of 1477.1 m/sec which is the mean value of the measured sound speed profile presented in Fig 1. The black line shows the curve fitting result for this data set. Fig. 10 illustrates the transmission loss along the AUV trajectory using the actual sound speed profile and the transponder depth of 35 m. The red line shows the curve fitting result of the data set. Fig. 11 shows the three curve fitting results to study the effects of different parameters.

Different observations can be made from these Figs. It can be seen in Fig. 8 that the variance of the transmission loss is high between 1100 - 1600 m range. At these ranges the

AUV was traversing in the water column and positioned at different depths. As seen in Fig. 1 that the sound speed is a depth dependent function and acoustic propagation is strongly dependent on it. Therefore the transmission loss varies at different AUV positions, resulting in a high variance in the transmission loss. This observation can be validated by Fig. 9 where the sound speed is considered constant throughout the water column.

In Fig. 9 the sound speed profile is considered constant which results in a more linear distribution of the transmission loss along the range. The variance of the data is minimum in this case and the curve fitting result is almost linear along the range which shows that the transmission loss is increasing linearly along the range. In this case, the AUV is moving at different depths but the sound speed is the same at each depth so the transmission loss is almost the same at a particular range regardless of the position of the AUV.

In Fig. 10, the actual sound speed is used but the transponder depth is changed from 20 m to 35 m. It can be seen that the transmission loss increases at longer ranges which is due to the sound speed profile variations along the water depth. Comparing Figs 8 and 10, it can be deduced that the transmission loss is reduced at the ranges from 1100 m to 1600 m by changing the transponder depth to 35 m. By analyzing the position of the transponder in Fig. 1, it can be observed that variation in sound speed is much smaller at 35 m depth as compared to 20 m where there is a strong slope due to change in the water temperature. The acoustic rays have lesser impact of the sound speed variations along the water column and the transmission loss is smaller.

By comparing the trends of the transmission loss in Fig. 11, it is observed that the transmission loss is almost linear in the case of constant sound speed profile (black line). The non-linear behavior is observed when depth-dependent sound speed profile is considered (blue line). By changing the transponder depth (red line) the transmission loss remains linear which is due to the consistent behavior of the sound speed at the transponder position as explained earlier. Also the transmission loss is reduced at longer ranges which improves the acoustic link between the AUV and the transponder and enables the AUV to self-localize more efficiently at longer ranges. Both these simulated scenarios clearly show the importance of environmental parameters like sound speed profile and transponder depth. It should be emphasized that these environmental factors must be kept in mind while planning the experiment including the trajectory of the vehicle and positions of the transponders.

VII. Conclusion

In this paper the AUV navigation data is presented from Trondheim Fjord which is obtained using LBL techniques. The LBL techniques are based on acoustic signal propagation between the transponder and the AUV. The underwater acoustic wavefield between the AUV and the transponder is modeled using PlaneRay model and compared with the navigation results obtained during the experiment. The results show that acoustic modeling tools are effective in estimating the acoustic wavefield and predicting the acoustic link between the AUV and the transponder. The effects of sound speed profile and transponder depth are studied in detail and it is deduced that both these factors have great impact on the acoustic wavefield. The main idea of the paper is to use the acoustic models for effective path planning of the AUVs and selecting the transponder depths. In future work, a detailed analysis will be performed in order to optimize the AUV trajectory based on the transponder positions and vice versa. This analysis will make sure that the AUV will have continuous acoustic link with transponders and the AUV will keep track of itself throughout the mission.

References

[1] K. Yao L. Collins, S. Azou and G. Burel. On spatial uncertainity in a surface long base-line positioning system. In *Proceedings of the 5th European Conference on Underwater Acoustics*, 2000, Lyon, France.

[2] J. S. STAMBAUGH and R. B. THIBAULT. Navigation requirements for autonomous underwater vehicles. *Navigation*, 39(1):79–92, 1992.

[3] G. Casalino, A. Turetta, E. Simetti, and A. Caiti. Rt2: A real-time ray-tracing method for acoustic distance evaluations among cooperating auvs. In *OCEANS 2010 IEEE - Sydney*, pages 1–8, May 2010.

[4] M. Hahn and J. Rice. Undersea navigation via a distributed acoustic communication network. In *Proceedings of the Turkish International Conference on Acoustics*, July 2005, Istunbul, Turkey.

[5] A.A. Syed and J. Heidemann. Time synchronization for high latency acoustic networks. In *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, pages 1–12, April 2006.

[6] Joshua N. Ash and Randolph L. Moses. Acoustic time delay estimation and sensor network self-localization: Experimental results. *The Journal of the Acoustical Society of America*, 118(2):841–850, 2005.

[7] J.E. Garcia. Positioning of sensors in underwater acoustic networks. In *OCEANS, 2005. Proceedings of MTS/IEEE*, pages 2088–2092 Vol. 3, 2005.

[8] A. Caiti, A. Garulli, F. Livide, and D. Prattichizzo. Localization of autonomous underwater vehicles by floating acoustic buoys: a set-membership approach. *Oceanic Engineering, IEEE Journal of*, 30(1):140–152, Jan 2005.

[9] Michael V. Jakuba, Christopher N. Roman, Hanumant Singh, Christopher Murphy, Clayton Kunz, Claire Willis, Taichi Sato, and Robert A. Sohn. Long-baseline acoustic navigation for under-ice autonomous underwater vehicle operations. *J. Field Robot.*, 25(11-12):861–879, November 2008.

[10] Dana R. Yoerger, Michael Jakuba, Albert M. Bradley, and Brian Bingham. Techniques for deep sea near bottom survey using an autonomous underwater vehicle. In Sebastian Thrun, Rodney Brooks, and Hugh Durrant-Whyte, editors, *Robotics Research*, volume 28 of *Springer Tracts in Advanced Robotics*, pages 416–429. Springer Berlin Heidelberg, 2007.

[11] B. Bingham. Predicting the navigation performance of underwater vehicles. In *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*, pages 261–266, Oct 2009.

[12] Jens M. Hovem and Hefeng Dong. Planeray: An underwater acoustic propagation model using ray tracing and plane wave reflection coefficients. *The Journal of the Acoustical Society of America*, 120(5):3221–3221, 2006.

[13] Finn B. Jensen, William A. Kuperman, Micheal B. Porter and Henrik Schmidt. *Computational Ocean Acoustics*. American Inst. of Physics, 2000.

[14] V. A. Del Grosso. New equation for the speed of sound in natural waters (with comparisons to other equations). *The Journal of the Acoustical Society of America*, 56(4):1084–1091, 1974.