NLOS Identification Using a Hybrid ToA-Signal Strength Algorithm for Underwater Acoustic Localization

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***Abstract*—The existence of obstacles in harbors or near shore environments leads to Non-Line-Of-Sight (NLOS) links between two underwater acoustic communication (UWAC) nodes. That is, only echoes of the transmitted signal arrive at the receiving node. Mistaking the first (strong) echo as a Line-Of-sight (LOS) measurement and using it for ranging causes significant degradation of the accuracy level of UWAC-based localization. In this paper, we propose a solution for the NLOS identification problem in underwater acoustic localization. Results from both extensive simulations and sea trial experiments confirm our approach and demonstrate a high detection rate of NLOS measurements.**

I. Introduction

Underwater acoustic communication (UWAC) networks are envisaged to fulfill the needs of a multitude of applications such as navigation aids, early warning systems for natural disasters, ecosystem monitoring and military surveillance. The data derived from UWAC networks is typically interpreted with reference to a node's location, e.g., reporting an event occurrence, tracking a moving object or monitoring a region's physical conditions. However, location discovery for underwater nodes is non-trivial in the oceanic medium as its efficacy is impacted by propagation delays, motion-induced Doppler shift, phase and amplitude fluctuations, multipath interference etc. [1].

In particular, since GPS signals do not propagate through water, each *ordinary* underwater node needs to exchange messages with *anchor* nodes (with known positions) to estimate its distance from them (*ranging*), from which its position is then computed. Ranging is typically based on the Time-of-Arrival (ToA), Time-Difference-of-Arrival (TDoA) or Received-Signal-Strength (RSS) of the messages. Most existing underwater acoustic localization schemes, e.g., [2]–[4], implicitly assume that these messages are received based on Line-Of-Sight (LOS) acoustic links, from which distances are estimated, and positions are calculated using multilateration.

However, the underwater acoustic channel is a frequency selective channel with a relatively long delay spread [5], and multipath models [6] have shown that the energy of the direct path of the channel's impulse response is not always the strongest, and therefore Non-Line-Of-Sight (NLOS) reflected signals may be mistakenly treated as the LOS signal (*multipath NLOS*).

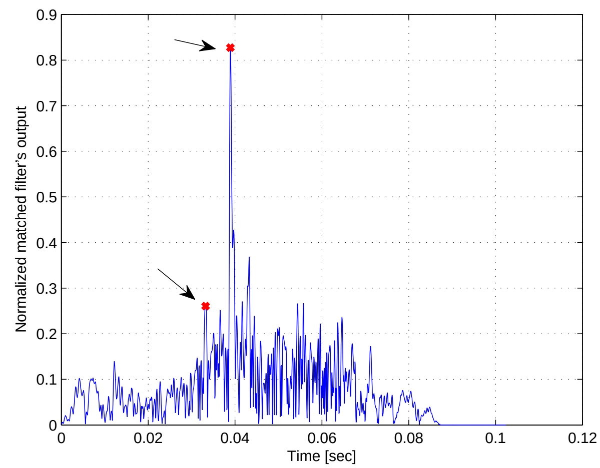

Fig. 1. Example of matched filter's output from the sea trial to illustrate that the strongest path is not the direct path.

In addition, the existence of obstacles such as rocks, ship hulls, in harbors or near shore environments may also result in NLOS scenarios in which two underwater nodes do not share a direct link, but only echoes of the transmitted signal arrive at the receiver. We refer to this scenario as *obstacle NLOS*.

An example of a matched filter's output for a chirp signal transmitted in a sea trial described in this paper (whose setup is described in Section V-B) is shown in Figure 1. Large errors may result from mistakenly using NLOS signals in ranging [7], which in turn leads to inaccurate UWAC-based localization.

To illustrate the effects of obstacle NLOS measurements on localization accuracy, consider a scenario in Figure 2 where signals from three anchor nodes, a_1, a_2, a_3, are received by node n, and are used for its localization. Assume that reference nodes a_2 and a_3 are connected to n via LOS links. However, node n is "blocked" from node a_3, e.g., due to the presence of a physical obstacle between them such that it only receives the reflected signal from a_3. Consequently, the propagation delay corresponds to $d_{31}+d_{32}$, where d_{31} and d_{32} is the path length of the signal from a_3 to the reflecting surface and from the reflecting surface to n respectively, whereas the actual distance between a_3 and n is d.

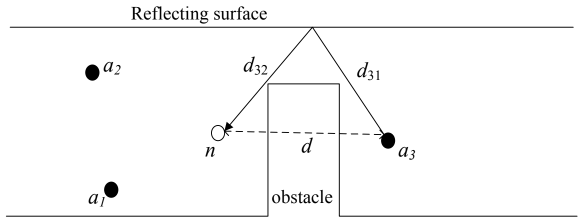

Fig. 2. Illustration of deployment scenario with NLOS signals.

If the difference between $d_{31} + d_{32}$ and d is large enough, the localization accuracy will be significantly affected. Hence, obstacle NLOS measurements need to be identified and discarded prior to performing multilateration.

In this paper, we propose a solution for the identification of obstacle NLOS links in UWAC-based localization, which is a problem that has not been treated in previous literature. The novelty of our approach lies in combining both time based ranging techniques (ToA or TDoA) and signal strength based ranging techniques (RSS) using an attenuation model. By comparing these distance estimates, we classify received signals as stemming from NLOS or LOS links. Considering the difficulty in acquiring an accurate attenuation model, we require only a simplified model with upper and lower bounds. Results from both extensive simulations and sea trial experiments demonstrate the validity of our approach through achieving a high detection rate for obstacle NLOS measurements.

The remainder of this paper is organized as follows. In Section II, we describe the state of the art in dealing with the NLOS problem in localization. System model and assumptions are described in Section III. In Section IV, we describe our hybrid ToA-signal strength algorithm and show the performance of the algorithm obtained for synthetic UWAC environments and in a sea trial in Section V. Finally, conclusions are offered in Section VI.

II. NLOS Problem in Localization

In a multipath environment such as the underwater acoustic channel, NLOS measurements affect the accuracy of ranging considerably. These errors are usually regarded as part of the measurement noise [8]. In [2], these noises were modeled as the Ultra Wideband Saleh-Valenzuela (UWB-SV) underwater acoustic fading channel model [9], while a method for developing a lower bound for multipath noise mitigation for a given multipath model was introduced in [10]. To limit measurement noise, the authors in [8] suggested using direct sequence spread spectrum signals (DSSS) which have narrow auto-correlation. Following this approach, curve fitting of ToA measurements based on DSSS was suggested in [11]. Incoherent integration of ToA measurements from different signals is suggested in [12] where results show considerable reduction in measurement errors, and a Kalman filter for the evaluation of both range and its rate of change was suggested in [13].

In [14], measurements which increase the global variance are rejected, assuming that NLOS measurements have larger variance than LOS measurements. In [15], it was shown that the best performance is achieved by selecting ToA measurements based on minimal statistical mode. Alternatively, the authors in [16] suggested a method of reducing the effect of NLOS measurements by assigning each measurement with a weight inversely proportional to the difference between the measured and expected distances from previous localization. In [17], NLOS measurements are not rejected but rather, they are utilized by estimating the NLOS factor (i.e., the difference $d_{31} + d_{32} - d$ in Figure 2) using a maximum likelihood estimator based on an attenuation model and incorporating those measurements after a factor correction.

Due to NLOS links and measurement errors, location ambiguities such as flips and rotations might exist. This problem was considered in [18] where additional anchor nodes are used to resolve such ambiguities. In [19], a three phase protocol is suggested for this problem. First, an ambiguous-free sub-tree of nodes is determined; then, localization based on triangulation is performed where the node is first assumed to be located in the center of a rectangular area; and finally, a refinement phase is performed using a Kalman filter to mitigate noise arising from ranging. A robust protocol for mitigating localization ambiguities is suggested in [20] by rejecting measurements leading to ambiguities, e.g., when there are insufficient anchor nodes or when the location of anchor nodes is almost collinear. However, these protocols are only applicable when a large number of anchor nodes are available.

While the above protocols offer NLOS error mitigation, only a few considered the case where all measurements are NLOS, i.e., no direct path exists. This issue is regarded in [21] where the relationship between base station distances and NLOS factor are considered and the problem of evaluating the NLOS factors is formalized as an optimization problem. However, to the best of our knowledge, no prior work considered NLOS error mitigation for the special characteristics of the underwater acoustic channel.

III. System Model and assumptions

Our system comprises one ordinary node (to be localized) and L anchor nodes (with known locations). We denote the ordinary node as n, the reference nodes as a_i, $1 \leq i \leq L$ and the link between node n and a_i as (n, a_i).

In our algorithm, we identify obstacle NLOS links based on a comparison between ranging based on signal strength, $d_{\mathrm{SS},i}$, and time of arrival, $d_{\mathrm{time},i}$, for the link (a_i, n).

Considering the difficulty in acquiring reliable attenuation model for the underwater acoustic channel, we rely on the following widely used simplified attenuation model [22] for underwater acoustic communications to estimate $d_{\mathrm{SS},i}$,

$$\mathrm{TL}_{\mathrm{LOS}}(d_i) = \mathrm{PL}_{\mathrm{LOS}}(d_i) + \mathrm{AL}(d_i), \qquad (1)$$

where d_i is the transmission distance, $\mathrm{PL}_{\mathrm{LOS}}(d_i) = \gamma \log(d_i)$ is the propagation loss, $\mathrm{AL}(d_i) = \alpha \frac{d_i}{1000}$ is the absorption loss and γ, α are the propagation and absorption coefficients, respectively. Using (1), we estimate the lower and upper bounds of $d_{\mathrm{SS},i}$, $d_{\mathrm{SS,min},i}$ and $d_{\mathrm{SS,max},i}$, respectively, by setting γ and α according to the environment in which the system is expected to operate. We assume that node n knows the transmitted power, such that it can estimate $\mathrm{TL}_{\mathrm{LOS}}(d_i)$ by measuring the power of the received signals.

We assume that $d_{\mathrm{time},i}$ can be directly estimated via either ToA (e.g. [23]) or TDoA (e.g. [2]) techniques. However, since we are only interested in link classification, we do not require accurate evaluation of $d_{\mathrm{time},i}$ and measurement errors of the order of the channel's delay spread is acceptable.

We further assume that the transmission loss of the reflected signal in an obstacle NLOS link is [5]

$$\begin{aligned}\mathrm{TL}_{\mathrm{NLOS}}(d_{i1},d_{i2}) &= \mathrm{PL}_{\mathrm{LOS}}(d_{i1}+d_{i2}) \\ &\quad +\mathrm{AL}(d_{i1}+d_{i2})+\mathrm{TS}+\mathrm{SL},\end{aligned} \tag{2}$$

where d_{i1}, d_{i2} are the distance from node a_i to the reflecting surface and from the reflecting surface to node n, respectively, as illustrated in Figure 2, and SL and TS are the reflecting surface spreading loss and target strength (i.e., power absorbed by the surface), respectively. These parameters depend on the surface material and structure and the carrier frequency of the transmitted signals and are assumed to be large such that

$$\mathrm{TL}_{\mathrm{NLOS}}(d_{i1},d_{i2}) \gg \mathrm{TL}_{\mathrm{LOS}}(d_{i1}+d_{i2}). \tag{3}$$

IV. Hybrid Algorithm for NLOS Identification

Referring to Figure 2, our proposed hybrid algorithm to identify whether a link (a_i, n) is LOS or NLOS comprises three basic steps, described in the following.

- **Estimation of** $d_{\mathrm{time},i}$
  By applying TDoA or ToA techniques, we estimate the propagation delay, $T_{\mathrm{pd},i}$, of signal transmission from node a_i to node n at node n. Then, using simple least square estimations we estimate $d_{\mathrm{time},i}$ utilizing several measurements of $T_{\mathrm{pd},i}$.
- **Estimation of** $d_{\mathrm{SS,min},i}$ **and** $d_{\mathrm{SS,max},i}$
  By measuring the power of the received signals at node n and using a-priori knowledge of the transmission power at node a_i, we estimate the transmission loss of arriving signals at node n. Next, applying the attenuation model in (1), we estimate $d_{\mathrm{SS,min},i}$ and $d_{\mathrm{SS,max},i}$ using upper and lower bounds of γ and α reflecting the accuracy of our model.
- **Thresholding**
  Finally, we compare $d_{\mathrm{time},i}$ with $d_{\mathrm{SS,min},i}$ and $d_{\mathrm{SS,max},i}$: if $d_{\mathrm{SS,min},i} \leq d_{\mathrm{time},i} \leq d_{\mathrm{SS,max},i}$, then link (a_i, n) is classified as a LOS link; otherwise, it is determined as an NLOS link.

We note that the classification in the last step of our algorithm is based on the assumption in (3) that a noticeable difference between $d_{\mathrm{SS},i}$ and $d_{\mathrm{time},i}$ is expected when the link is NLOS. We note that the accuracy of our NLOS identification algorithm relies on the validity of the assumption that the difference between $\mathrm{TL}_{\mathrm{NLOS}}$ and $\mathrm{TL}_{\mathrm{LOS}}$ is much larger than the effects of measurement noise or attenuation model inaccuracies and validate this assumption in a sea trial described in a later section.

A. Performance analysis

In this section, we analyze the expected performance of our hybrid NLOS identification algorithm, assuming that estimation noise is Gaussian distributed with zero mean and variance of σ^2. We consider both false detection probability, P_{false}, in which LOS links are falsely identified as NLOS, and detection probability, P_{detect}, in which NLOS links are correctly classified.

For the case where the link in a LOS link, assuming the bounds of our attenuation model are accurate, the transmission distance, d_i, is such that $d_{\mathrm{SS,min},i} \leq d_i \leq d_{\mathrm{SS,max},i}$. Therefore, the false detection probability is

$$\begin{aligned}P_{\mathrm{false}} &= 1-Q\left(\frac{d_{\mathrm{SS,min},i}-d_i}{\sigma\sqrt{(2)}}\right)\cdot \\ &\quad \left[1-Q\left(\frac{d_{\mathrm{SS,max},i}-d_i}{\sigma\sqrt{(2)}}\right)\right],\end{aligned} \tag{4}$$

where $Q(x)$ is the tail probability, and $d_{\mathrm{SS,min},i}, d_{\mathrm{SS,max},i}$ are evaluated numerically according to (1).

When the link is an obstacle NLOS, $d_{\mathrm{SS,min},i}$ is expected to be higher than the estimated $d_{\mathrm{time},i}$ since the measured transmission loss is affected by both SL and NL as in (2). Here, we use the upper bound of our model, $d_{\mathrm{SS,max},i}$, to further increase the detection probability. Denoting the true transmission distance in the obstacle NLOS link as $d_{\mathrm{NLOS},i} = d_{i1} + d_{i2}$, the detection probability is

$$\begin{aligned}P_{\mathrm{detect}} &= 1-Q\left(\frac{d_{\mathrm{SS,min},i}-d_{\mathrm{NLOS},i}}{\sigma\sqrt{(2)}}\right)\cdot \\ &\quad \left[1-Q\left(\frac{d_{\mathrm{SS,max},i}-d_{\mathrm{NLOS},i}}{\sigma\sqrt{(2)}}\right)\right].\end{aligned} \tag{5}$$

Neglecting the absorption loss in (1), when the link is an obstacle NLOS, we have

$$d_{\mathrm{SS,min},i} = (d_{\mathrm{NLOS},i})^{\frac{\lambda}{\lambda_{min}}} \cdot e^{\frac{SL+TS}{\lambda_{min}}} \tag{6a}$$

$$d_{\mathrm{SS,max},i} = (d_{\mathrm{NLOS},i})^{\frac{\lambda}{\lambda_{max}}} \cdot e^{\frac{SL+TS}{\lambda_{max}}}\ , \tag{6b}$$

where λ is the correct propagation parameter in the channel and $\lambda_{\min}, \lambda_{\max}$ are the lower and upper bounds of the attenuation model respectively. Thus, for a worst case scenario where $\lambda = \lambda_{\min}$, we get

$$\begin{aligned}P_{\mathrm{detect}} &= 1-Q\left(\frac{d_{\mathrm{NLOS},i}(e^{\frac{SL+TS}{\lambda_{\min}}}-1)}{\sigma\sqrt{(2)}}\right)\cdot \\ &\quad \left[1-Q\left(\frac{(d_{\mathrm{NLOS},i})^{\frac{\lambda_{\min}}{\lambda_{\max}}}\cdot e^{\frac{SL+TS}{\lambda_{\max}}}-d_{\mathrm{NLOS},i}}{\sigma\sqrt{(2)}}\right)\right].\end{aligned} \tag{7}$$

Thus, the detection probability increases with SL and TS.

V. Results

In this section, we evaluate the performance of the hybrid NLOS identification algorithm from both extensive simulations and sea trial. We start with a simulation in which the simplified attenuation model in (1) is used, and then validate our assumptions of the boundaries of this model in the sea trial.

A. Numerical Results

To obtain a better insight of the analysis made in Section IV-A, we conducted extensive simulations in which we placed 3 anchor nodes and one ordinary node randomly in a square area of size 1 km $\times$ 1 km. Four horizontal obstacles and one vertical obstacle were placed at random positions (but not on a node) and with lengths that are uniformly distributed in $[100, 200]$ m. A link between the ordinary node and an anchor node is a LOS link if there is no obstacle obstructing the line-of-sight between them; otherwise, the link is a NLOS link where signals are reflected from the edges of the square area. In the example simulation scenario depicted in Figure 3, (n,a_3) is a LOS link while (n,a_2) is a NLOS link due to obstruction by the vertical obstacle.

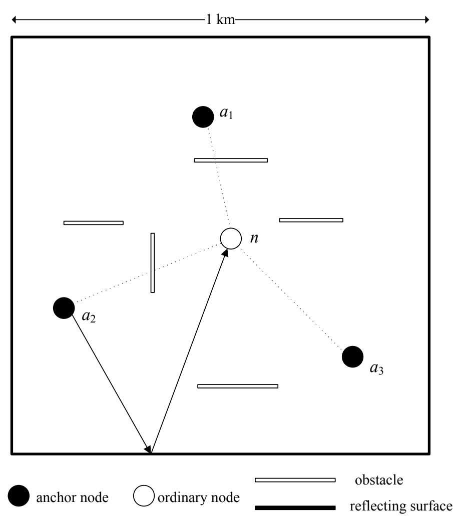

Fig. 3. An example of a simulation scenario.

For each link, we calculated the attenuation of signals in the channel according to the model in (1), where γ was a simulation parameter and α was fixed at $2[dB/km]$ to correspond to a carrier frequency of the order of 20 kHz according to Thorp's formula [5]. If a certain link was determined to be an obstacle NLOS link, the attenuation in the channel was further increased by simulation parameter, TS+SL. For each link, the value of $d_{\text{time},i}$ was set according to the Euclidean distance for LOS links and the sum of Euclidean distances to and from the reflecting surface for obstacle NLOS links, as illustrated in Figure 2). A zero-mean Gaussian distributed measurement noise with variance was added to $d_{\text{time},i}$.

For each topology, we classified the communication links using the hybrid NLOS identification algorithm and compared the results with the true nature of the link. Average results over transmission distance for P_{false} of LOS links and for P_{detect} of obstacle NLOS links are presented in Figure 4 and Figure 5, respectively, as a function of γ and TS+SL. Figure 4 shows that P_{false} decreases close to the model boundaries with γ and reaches its minimum at $\gamma = 15$, which is between the propagation coefficient boundaries of our attenuation model. This result was expected since the attenuation model achieves the best accuracy at this point. Figure 5 shows that, as expected, P_{detect} increases with TS+SL. We also observe that P_{detect} monotonically increases with γ. This result is obtained since the larger the difference between $d_{\text{SS},\min,i}$ and $d_{\text{time},i}$, the better obstacle NLOS identification is and since such a difference increases as the attenuation of signals in the channel increases.

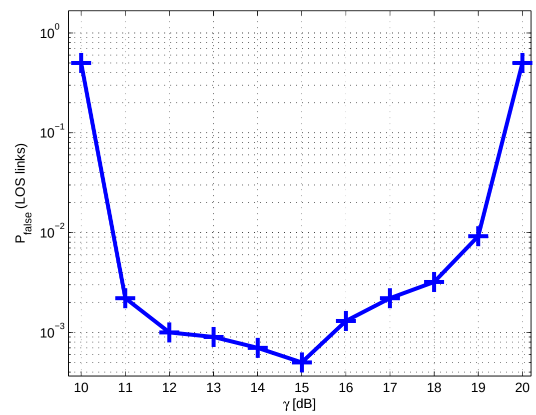

Fig. 4. Simulation results of P_{false} for LOS links.
Results are presented as an average over transmission distance.

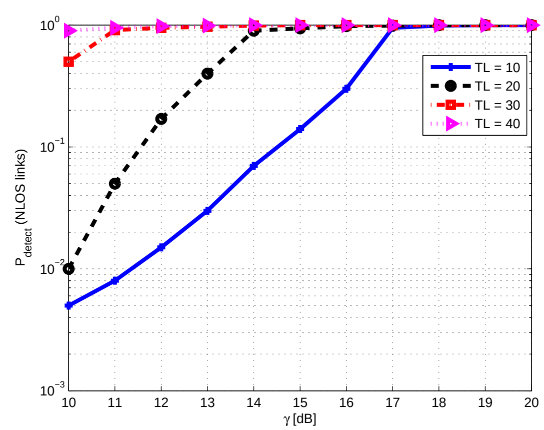

Fig. 5. Simulation results of P_{detect} for NLOS links.
Results are presented as an average over transmission distance.

Although the results show relatively low P_{false} and high

P_{detect} for expected values of attenuation in the underwater acoustic channel, we note that the accuracy of the attenuation model determines the performance of the algorithm. Since we relied on the boundaries of a rather simplified attenuation model in this paper, the results need to be validated in a real sea environment, which we show next.

B. Sea Trial Results

To validate the boundaries of the simplified attenuation model used in our simulations, we conducted a sea trial at a harbor in Haifa, Israel. The trial included four vessels, each of which represented an individual node in the network. In each vessel, a transceiver was deployed at a fixed depth of 3 m. The four vessels were placed in various locations inside the harbor where the maximum distance in the harbor was 1500m.

Throughout the trial, both obstacle NLOS and LOS scenarios occurred. The ordinary node, node 2, was placed at a fixed location $2A$, while the reference nodes 1,3 and 4 moved between various locations, as presented in Figure 6. For example, node 1 moved between locations $1A$, $1B$, $1C$ and $1D$. The obstacle NLOS links are $(2A, 1D), (2A, 3C), (2A, 1C), (2A, 1B)$, where the last link was determined as an obstacle NLOS since a ship hull blocked the LOS link between location $1B$ and $2A$.

The four nodes were time synchronized using GPS and transmitted with equal transmission power. Each reference node sent frequent broadcast messages which were detected by the ordinary node. The transmission time of each packet was globally known using a spatial reuse time division multiple access (STDMA) medium access control (MAC) protocol [24]. For each link, $(2, j)$, j={1,3,4}, we evaluated (i) $d_{\text{time},i}$ using ToA measurements and (ii) the transmission loss according to the value of the first peak of the matched filter's output for the received signals. Since we locked on a single path for the transmission delay evaluation, we considered a free space propagation loss such that $\gamma = 20$ and set $\alpha = 1.5$ according to Thorp's equation for a carrier frequency of 12 kHz [5]. To determine $d_{\text{SS},\min,i}$ and $d_{\text{SS},\max,i}$, we considered inaccuracies in our attenuation model such that $\text{TL}_{\text{LOS,Max}}(d) - \text{TL}_{\text{LOS,Min}}(d) = 10$ dB.

Throughout the trial, 9 different communication links were classified, and the evaluated values of $d_{\text{SS},\min,i}$, $d_{\text{SS},\max,i}$, $d_{\text{time},i}$ in meters from the sea trial for both NLOS and LOS links are presented in Table I. Using our proposed hybrid algorithm, all 4 obstacle NLOS links were correctly classified and none of the LOS links were falsely classified as NLOS links.

Referring to Table I, we observe that all the estimated $d_{\text{time},i}$ were much lower than $d_{\text{SS},\min,i}$ for all obstacle NLOS links, which implies that the spreading loss and target strength of the reflecting surfaces (which could have been the harbor dock, ship hulls, etc.) are relatively high. In addition, comparing the values of $d_{\text{SS},\min,i}$, we observe that although the propagation distance of a link i was longer than that of link j, e.g., link $(2A, 1D)$ compared with link $(2A, 1C)$ and link $(2A, 1B)$, it was not always that $d_{\text{SS},\min,i} > d_{\text{SS},\min,j}$. This is due to the highly complex environment in the harbor where reflections do not necessarily hold the same values of SL and TS.

LOS			
Link	$d_{\text{SS},\min,i}$	$d_{\text{time},i}$	$d_{\text{SS},\max,i}$
$(2A, 3B)$	579	780	1549
$(2A, 4A)$	179	242	529
$(2A, 4B)$	343	415	973
$(2A, 1A)$	428	610	1188
$(2A, 3A)$	647	817	1707
Obstacle NLOS			
Link	$d_{\text{SS},\min,i}$	$d_{\text{time},i}$	$d_{\text{SS},\max,i}$
$(2A, 1B)$	1957	1105	4197
$(2A, 3C)$	1639	740	3659
$(2A, 1D)$	1549	1254	3499
$(2A, 1C)$	1816	950	3966

TABLE I
SEA TRIAL RESULTS FOR NLOS AND LOS CLASSIFICATION.

VI. CONCLUSIONS

In this paper, we suggested a novel algorithm for the identification of NLOS links in the underwater acoustic channel. We argued that such an identification is crucial for underwater acoustic localization in which NLOS links can be mistaken for LOS links, leading to considerable localization errors. Based on a comparison between time of arrival based range estimations and signal strength based range estimations, we presented a simple thresholding condition for determining if a certain communication link is NLOS or LOS. Accounting for possible inaccuracies in the attenuation model for signal strength based range estimations used, we only assumed loose lower and upper bounds of the model and considered a simplified attenuation model for the underwater acoustic channel in both extensive simulations and a sea trial. The results show that our algorithm can achieve a low probability of mistakenly identifying LOS links as NLOS links while maintaining high detection probability of actual NLOS links.

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Fig. 6. Satellite picture of the sea trial location (picture taken from Google maps on September 29, 2009.).

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