Evaluation of Reflection Error Using Ultrasonic Telemetry System

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(Received March 5, 2016)

Abstract:
Most ultrasonic transmitters (pingers) used for behavioral surveys of aquatic animals send a variety of information by changing the interval of the pulses. The reflection of a pulse generally occurs at the sea surface and/or the bottom. Reflection is a critical problem in considering the measurement error generated by the arrival-time delay of the reflected pulse. We conducted a field experiment to evaluate the effect of reflection, and discussed ways to prevent the effect. In this paper, we used a tracking-type ultrasonic telemetry system. The pinger of the system measures its depth by changing the interval of two pulses. In order to evaluate the paths of the reflected pulses, we measured the difference in arrival time between a direct pulse that propagated the direct path to the hydrophone and reflected pulses. We observed the variation in arrival-time difference in field experiments. Results showed that reflected surface pulses easily affected the system. Improvements to the ultrasonic telemetry system helped to prevent the effect of reflection, and we demonstrated the effectiveness of the improved system in an additional field experiment. The improved system could measure the depth data without the effects of reflection. We also discuss a more optimal configuration for preventing the measurement error from the additional experimental data.

Classification: Fisheries acoustics · Bioacoustics
Keywords: ultrasonic telemetry, transmission data, signal reflection, measurement error

1. Introduction
In research using ultrasonic telemetry systems, the travel time of an acoustic signal from an ultrasonic transmitter (pinger) is used to obtain various data. For example, the horizontal position of a target object is calculated from the relative arrival time of an acoustic signal from a pinger at three or more receivers.1–3) The acoustic signal generally consists of two or more consecutive pulses sent to identify the pinger and/or various data such as its depth and water temperature by changing the interval of the pulses.4,5)

Multi-path signals are critical problem in considering the measurement error of ultrasonic telemetry.
systems. As behavioral surveys for aquatic animals are largely conducted in shallow water, multi-paths easily occur by the reflection of a signal. In shallow water, the signal propagates on the direct path to the hydrophone (direct signal) or arrives at the hydrophone after one or more reflections at the sea surface or bottom (reflected signal). The reflected signal arrives at the hydrophone later than the direct signal, and the time delay causes the measurement error. Even in deep water, reflections at the surface may affect the measurement if the hydrophone is installed close to the surface. Using the first arrival of a signal at each hydrophone reduces the effect of reflection on the positioning data. However, this method cannot overcome the error of data sent by consecutive pulses from a pinger, because it is not possible to discriminate the first pulse of subsequent pulses. Although such errors can be misleading, there is a lack of research on the effect of reflection on measurement error. In this study, we evaluated how reflection affects measurement error. We also propose a more optimal configuration with the goal of preventing such error.

2. Equipment and data processing

In this study, we used a one-channel receiver (FRTD-600A, FUSION Inc.), an omni-directional hydrophone (FRTD-405A, FUSION Inc.), and a pinger (FRTD-100D, FUSION). The frequency of the pinger was 62.5 kHz, and its source level was 155 dB re µPa at a 1 m.

The pinger was equipped with a depth sensor. The pinger transmitted two consecutive pulses to send depth information (Fig. 1). The pulse width was 2 ms. The interval of the two pulses had the following proportional relation with the depth,

\[ D_p = (I-b) \cdot a \]  
(1)

where \( D_p \) is the pinger depth (m), \( a \) and \( b \) are constant calibrated values for each pinger, and \( I \) is the interval of consecutive pulses (ms). The interval changed within a range of approximately 30–90 ms. The receiver measured the interval, and calculated the pinger depth using Eq. (1).

The pulses were assigned a pseudo random noise (PN) code for identification of the pinger, 32 PN codes were available in this system. The receiver identified pulses from the pinger by cross-correlation. Sound waves detected by the hydrophone were correlated with replica codes, allowing the receiver to calculate correlation values (Fig. 2). The cross-correlation function \( C(t) \) is expressed in the following equation.

Fig. 1  Transmission depth information from a pinger. The pinger transmits two pulses assigned a different PN code at one transmission every configured transmission cycle.
\[ C(t) = \frac{1}{N} \sum_{\tau=1}^{N} S(t + \tau) \cdot R(\tau) \]  

Where \( S(\tau) \) and \( R(\tau) \) are input signal and replica signal, respectively, with length \( N \). When the correlation value was higher than a configured threshold level, the receiver detected the arrival of a pulse from a pinger. The receiver was able to identify the codes of pulses one by one. With the pinger used in this study, two pulses including depth data were assigned different PN codes as shown in Fig. 1. The receiver was also set to a configuration time called "peak window (PW)" to prevent the reflection from generating multi-peaks of the correlation value for a few milliseconds. This function eliminated the interference of the reflection by referencing the correlation values of detected pulses. If a pulse with a PN code was detected by the receiver and another pulse with the same PN code was also detected during PW, the receiver compared the correlation values of the two and ignored the pulse with the lower correlation value as interference due to reflection. If the pulse that arrived later had a higher correlation value than the first pulse, the receiver continued this function for the PW from the arrival time of the second pulse. The PW default time was 10 ms.

The identification, arrival time, and correlation value of the pulse deemed the true pulse was collected with a PC using a USB.

3. Effect of reflection on the measurement
3.1 Equations

It is necessary to distinguish between surface reflected pulses and bottom reflected pulses in the experimental data of a particular situation. The error value caused by the reflection depends on the arrival time difference between the direct and reflected pulse. In this study, arrival time difference (ATD) was determined by the difference of propagation distance between the direct pulse and the reflected pulse (see Fig. 3) given by

\[ ATD = \frac{L}{c} \]  

\[ L = (l_1 + l_2) - l_3 \]  

Where \( L \) was the difference of the propagation distance, \( c \) was sound speed, \( (l_1 + l_2) \) was the shortest propagation distance among the paths of the reflected pulses, and \( l_3 \) was the propagation distance of the direct pulse. Consider a particular situation in which the pinger was positioned below the hydrophone; when the hydrophone detected a surface-reflected pulse, as shown in Fig. 3(a), \( l_1 - l_3 \) was equal to \( l_2 \), and \( l_2 \) was equal to the installation depth of the hydrophone \( (D_H) \). Therefore, the following equations were given.

\[ D_H = \frac{L}{2} \]  

\[ D_H = \frac{ATD \cdot c}{2} \]  

Fig. 2 Correlation process for identification of pingers.
The equations indicate that ATD changes depending on hydrophone depth. On the other hand, when the hydrophone detected a bottom-reflected pulse, \( l_2 - l_3 \) was equal to \( l_1 \), and \( D_{H} \) in Eqs. (5) and (6) was replaced with the distance between the pinger and the bottom (Fig. 3(b)). Measuring the variation of ATD enabled us to evaluate the propagation path of the reflected pulse.

Because all pulses were not recorded due to the threshold set for correlation value and PW, ATD could not be measured directly. Hence, ATD was estimated from depth data measured in the following experiment. The error of depth occurred when the receiver used the arrival time of a direct pulse and a reflected pulse for the calculation (Fig. 4). ATD could be estimated if the true depth of the pinger and an error depth datum caused by the reflection were measured simultaneously. By substituting the true depth \( (D_T) \) and the error depth \( (D_E) \) into Eq. (1), the interval of each depth was derived, giving the following equations.

\[
D_T - D_E = (I_T - I_E) \cdot a
\]

where \( I_T \) was the true interval and \( I_E \) was the error interval. Since \( (I_T - I_E) \) indicates ATD in Fig. 4, ATD was given by,

\[
ATD = \frac{D_T - D_E}{a}
\]

ATD could be estimated from experimental depth data using the equation. If ATD varied with hydrophone depth, the error was generated by a surface-reflected pulse; meanwhile, if ATD varied with the distance between the pinger and the bottom, the
3.2 Measurement of experimental data

3.2.1 Setup and data analysis

A field experiment was conducted to collect ATD data in Tateyama bay, Chiba prefecture, Japan. The water depth in the experimental area was approximately 120 m. In order to apply Eq. (8), we obtained depth data from the pinger, as well as the true depth of the pinger by means of a depth data logger (DEFE-D20HG, JFE Advantech Co., Ltd.). The pinger sent depth information every 1 s, and the data logger also recorded depth every 1 s. The pinger and depth data logger were tied to a rope connected to a fishing line. These instruments were positioned below the hydrophone, their depth adjusted with an electric reel. The depth of the pinger was changed every few minutes to vary the distance between the pinger and the bottom. In order to also evaluate the variation of ATD with hydrophone depth, measurements were taken four times hydrophone depths of 2, 5, 8, and 10 m. The threshold level of the receiver was set to 0.45, and PW was set to 10 ms.

The difference in depth data between the pinger and depth data logger was defined as the error value. The error due to the effect of reflection was extracted by reference to the error value, and ATD was calculated by Eq. (8). Data in which the instruments were at a shallower depth than the hydrophone were not used for the analysis because these data did not meet the precondition for the Eqs. (5) and (6).

3.2.2 Evaluation of measurement error

Figure 5 illustrates the four depth measurements obtained with the ultrasonic telemetry system. The measured depth often deviated from both previous and subsequent data. Deviation in the depth data was more than 8 m when compared with data logger depth measurements (Fig. 6). This was defined as the error data. ATD was constant in one measurement and increased with hydrophone depth (Table 1). The hydrophone depth was also calculated by substituting the average value of ATD obtained in each measurement into Eq. (6). Sound speed was defined as 1500 m/s for the calculation. The calculated hydrophone depth almost coincided with the actual installation depth. The results indicated that the measurement error was generated by surface-reflected pulses and that the correlation value of these pulses was often higher than that of the direct pulse.

Error data were larger when the hydrophone was...
installed at an 8 m or 10 m depth (Table 1). The relation between length of ATD and PW caused the difference in number of generated error data. When the hydrophone was installed at a 2 or 5 m depth, ATD was shorter than PW (10 ms). In this situation, the reflected pulse was not recorded unless it had a higher correlation value than the direct pulse. On the other hand, when the hydrophone was installed at an 8 or 10 m depth, ATD was equal to or longer than PW. The surface-reflected pulse was recorded regardless of the relative correlation value between the direct and reflected pulse. Since the receiver
used only the later interval of the two pulses for the calculation of the depth (Fig. 7), direct pulses were detected, but these were not used for the calculation of the depth, and the error data were generated.

The effect of bottom-reflected pulses was not observed in this experiment. This was likely due to the fact that the transmission loss of the reflection was generally larger at the bottom than at the surface. The reflection at the bottom also easily deformed the waveform of the pulse, and the correlation value of the reflected pulse was relatively lower than the direct pulse. Therefore, the bottom-reflected pulses were probably eliminated by the PW function, or they had correlation values lower than the configured threshold level.

Transmission loss due to surface reflection varied depending on the roughness of the sea. When the surface was smooth, the correlation value of the surface-reflected pulse was assumed to be high, and the number of data errors increased. Careful setting of PW was effective in reducing the error data, but this effect was insufficient depending on the conditions. Therefore, we concluded that setting PW alone was not optimum for preventing the effect of reflection on measurement error.

4. Preventing the effect of reflection

4.1 Outline of improved system

We improved the system for preventing the effect of reflection by changing the signal process of the receiver. The transmission signal from the pinger was not changed. PW could not remove the measurement error when the correlation value of the reflected pulse was higher than that of the direct pulse. We therefore tried a different way to prevent the error. The receiver of the improved system detects pulses that have higher correlation value than the threshold level of the previous system. Since the experimental data showed that error data were generated by the reflection, those errors could be removed by not using the reflected pulses for the calculation of the pinger depth. Hence, the receiver defined the first arrival pulse of detected pulses as the direct pulse for each PN code, and the interval of the two first arrival pulses was used for the calculation of depth. This method can be applied only if the two pulses including the depth information are assigned a different PN code.

<table>
<thead>
<tr>
<th>Table 1  Summary of the calculation results in the field experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation depth of hydrophone</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of calculated depth measures</td>
</tr>
<tr>
<td>Number of error depth measures</td>
</tr>
<tr>
<td>ATD by Average ± S.D. (ms)</td>
</tr>
<tr>
<td>$D_H$ (m)</td>
</tr>
</tbody>
</table>

Fig. 7  Diagram showing occurrence of the measurement error when ATD was longer than PW. In this situation, a reflected pulse with higher correlation value than the threshold was recorded, and the receiver calculated the depth from the $I_E$ value.
the same PN code is assigned to two pulses, the "second first arrival pulse" cannot be discriminated by the receiver.

The failure to detect the direct pulse can make the receiver recognize a reflected pulse as the first arrival pulse. To reliably receive direct pulses, configuring an appropriate threshold level is important. If the threshold level is too high, the receiver will easily fail to detect a direct pulse. On the other hand, if the threshold level is too low, the receiver can detect incorrect signals, such as noise.

4.2 Evaluating the performance of the improved system

4.2.1 Data collection by field experiment

We conducted an additional field experiment using the improved system. The depth of the experimental area was approximately 40 m. We selected a shallower area than the previous experiment so that the reflection could more easily occur. Pinger and logger depth were measured in the same way as in the previous experiment. The threshold level of the receiver was lowered from 0.45 to 0.37 so that it would be sure to detect direct pulses. The arrival time and correlation value of the detected pulses were also recorded. The measurement was made three times at hydrophone depths of 2, 5, and 10 m. For each measurement, the data were recorded at 10, 20, and 30 m of the pinger depth.

The depth of the pinger was calculated using the previously described method and the improved method, and number of error data was compared. In this experiment, all arrival times and correlation values of all pulses detected by the receiver were recorded. Hence, ATD could be calculated directly from the arrival time of the first arrival pulse and the other pulses for each PN code. The correlation values of the first arrival pulses were compared with those of the other pulses, and the relation between ATD and the condition of the measurements or the correlation value of the reflected pulses was discussed. The recorded data were used for these analyses; data during depth changes of the pinger were excluded.

4.2.2 Comparison of depth data measured by improved and previous system

The calculation results of the pinger depth shown Fig. 8 indicated that the improved system was more effective in preventing error data than the previous system. There were 5 error data with the improved method (Fig. 8(a)), compared to 56 with the previous method (Fig. 8(b)). The error data of the improved system were generated by different causes from the reflection. Four of the 5 error data were caused by detection of an incorrect signal before the arrival of a true direct pulse (Fig. 9). Since the correlation values of these wrong signals were low, the signals were determined to be noise. The other error was caused by the failure to detect the direct pulse.
4.2.3 ATD and correlation value

1291 direct pulses and 1083 reflected pulses were obtained in this experiment (Table 2). The number of reflected pulses was almost constant regardless of the installation depth of the hydrophone, while the number of reflected pulses with higher correlation value than the direct pulse decreased with increasing hydrophone depth. The large number of reflected pulses was obtained at constant ATD by the installation depth of the hydrophone (Fig. 10(a)). The average of the appropriate data was 2.6 ms when the hydrophone depth was 2 m, 6.5 ms at 5 m, and 12.6 ms at 10 m. ATD for these reflected pulses showed that they were surface-reflected pulses. The ratio of the correlation value of the reflected pulse to that of the direct pulse was also calculated. Reflected pulses that had a higher correlation value than the first arrival pulse (the ratio was more than 1) were extracted and charted in an ATD histogram (Fig. 10(b)). The histogram indicated that the surface-reflected pulses had a relatively higher correlation value than other reflected pulses. As for the surface-reflected pulses, the ratio of their correlation value tended to decrease with hydrophone depth. The average of the ratio was 0.88 when hydrophone depth was 2 m, 0.85 at 5 m, and 0.79 at 10 m. This was probably caused by the increasing effect of scattering as the distance between the hydrophone and surface increased.

As for reflected pulses that arrived later than the surface-reflected pulses, a large number of reflected pulses also arrived at around 60 ms of ATD while the hydrophone was installed at 2 m (Fig. 11). The difference in propagation distance between the direct pulse and these pulses was about 90 m. Since the distance was approximately half of the water depth, these pulses were reflected twice, first at the surface, and then at the bottom. For the other pulses, the results also showed ATD had a negative correlation with the pinger depth. This result indicated that the ATD of the pulses had a proportional relationship with the distance between the pinger and the bottom. These reflected pulses were thus

<table>
<thead>
<tr>
<th>Installation depth of hydrophone</th>
<th>2 m</th>
<th>5 m</th>
<th>10 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct pulse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of data</td>
<td>432</td>
<td>429</td>
<td>430</td>
</tr>
<tr>
<td>Correlation value (medians)</td>
<td>0.50</td>
<td>0.49</td>
<td>0.51</td>
</tr>
<tr>
<td>Reflected pulse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of data</td>
<td>390</td>
<td>333</td>
<td>360</td>
</tr>
<tr>
<td>Correlation value (medians)</td>
<td>0.41</td>
<td>0.40</td>
<td>0.39</td>
</tr>
<tr>
<td>Number of data with higher correlation value than direct pulse</td>
<td>28</td>
<td>21</td>
<td>12</td>
</tr>
</tbody>
</table>

Fig. 9 Diagram showing occurrence of the measurement error when the receiver detects an incorrect pulse before the arrival of the true direct pulse.
4.3 Discussion of optimal design and configuration

The improved system was effective for preventing measurement error due to reflection, although a few error data were generated by incorrect pulses such as noise. Incorrect pulses could be removed if a threshold level was set as the previous experiment. We discussed only the improvement of the receiver signal process. Improving the transmission signal could also possibly reduce the error data. In this experiment, 90% of reflected pulses were recorded within 65 ms of ATD in all measurements (Fig. 12). If the interval of the two pulses were set to a longer time, the error data could be prevented. The pulse interval of the pinger used in this study was too short to discriminate the second arrival pulse from the detected pulses if two consecutive pulses were assigned the same PN code. From the results of the experiment, we found that if the interval were longer than 80 ms, the ratio of the error by reflection decreased to within 5%. However, the optimum interval of pulse would change with the source level of the pinger, positional relation between the pinger and hydrophone, water depth, and circumstances such as ambient noise. Thus, the configuration of the optimal interval is difficult to determine from only the results of the experiments in this study.

5. Conclusions

We evaluated the effect of reflections on data sent by consecutive pulses. The results of the field experiments clearly revealed that the ultrasonic
telemetry system used in this study easily generated measurement error due to reflections. Using the interval of the first arrival times of consecutive pulses was more effective for solving the problem than comparing the correlation values of pulses. The interval of consecutive pulses should also be considered not to overlap reflected pulses of the first pulse and "the second first arrival pulse."

We showed that the experimental data were useful for the discussion of how to improve the system. In this study, however, we could collect data only on the conditions where the hydrophone was installed close to the surface and the pinger was below the hydrophone. Further investigations for collecting experimental data on various conditions are needed for more optimal configuration and design of the ultrasonic telemetry system.

Acknowledgements
This study was supported by JSPS KAKENHI Grant Number 2510728. We would like to thank Dr. Toyoki Sasakura and Mr. Yuzo Abe of FUSION Inc. for their technical support.

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