Evaluation of multipath effects on depth measurements provided by acoustic transmitters in shallow water

JUNICHI TAKAGI[1]*, KOTARO ICHIKAWA[2, 3], NOBUAKI ARAI[2, 3], YOSHINORI MIYAMOTO[3, 4], KEIICHI UCHIDA[3, 4], KO FUJIOKA[5], HIROMU FUKUDA[5] & HIROMICHI MITAMURA[1, 3]
[1] *Graduate School of Informatics, Kyoto University, 606-8501 Kyoto, Japan*
[2] *Field Science Education and Research Center, Kyoto University, 606-8502 Kyoto, Japan*
[3] *CREST, Japan Science and Technology Agency, 332-0012 Saitama, Japan*
[4] *Tokyo University of Marine Science and Technology, 108-0075 Tokyo, Japan*
[5] *National Research Institute of Far Seas Fisheries, Fisheries Research and Education Agency, 424-8633 Shizuoka, Japan*
* *takagi@bre.soc.i.kyoto-u.ac.jp*

ABSTRACT
Measurement errors caused by multipath effects are one of the problems of acoustic biotelemetry, especially in shallow waters because both the sea surface and bottom can be major boundaries reflecting ultrasonic pulses. We conducted an experiment using transmitters with a pressure sensor to examine occurrence probabilities of multipath effects in a shallow sea area. We deployed seven transmitters with a 1.28-s signal transmitting interval in the same location, and two receivers located 18.5 m (R1) and 38.0 m (R2) horizontally from the transmitters. In order to solve the problems derived from multipath effects, we applied a state-space model to the depth data to estimate the correct values. Then we compared data availabilities, which were percentages of the number of correct values to the number of actual transmissions, between the acquired data and the model estimation. In 15 min recording, the mean proportions of the correct values for all transmitters were 88.4% for R1 and 86.3% for R2. The data availabilities became significantly larger from 65.7% to 96.7% with R1, and from 64.6% to 93.3% with R2 by applying the model. This suggests that we can reduce the measurement errors caused by multipath effects by post processing.

KEYWORDS: **biotelemetry, ultrasonic coded transmitter, multipath effect, state-space model**

INTRODUCTION

Acoustic biotelemetry using transmitters and receivers has been used to investigate behavior, movement and ecology of many aquatic animals (Cooke *et al.*, 2004; Hussey *et al.*, 2015). It allows us to observe indirectly the states and surrounding environment, such as swimming depth, activity, or ambient temperature, of target animals. This information is encoded in signals emitted by transmitters, generally consisting of plural ultrasonic pulses. A Gold code transmitter (AQPX-1040PT, AquaSound Inc., Kobe, Japan), the successor to a transmitter developed in Miyamoto *et al.* (2010; 2011), emits three consecutive 2-ms pulses to encode depth and temperature information in intervals between the 1st and the 2nd, and the 2nd and the 3rd pulses, respectively (Fig. 1a). Due to its short pulse duration of 2-ms and pulse intervals ranging between a few tens of ms, there is a multipath effect that causes measurement errors in coded information. If one of the two pulses were a reflected pulse, the interval between the two pulses would become shorter or longer; that is, correct encoded information would collapse and phantom values might be recorded.

The reflected pulses caused by the multipath effects lead to phantom values for the depth and/or temperature information. Hasegawa *et al.* (2016) developed a real-time depth monitoring system for trolling gear using a type of the Gold code transmitters, and proposed two ways to solve the problems of multipath effects. One method was adding directivity to the hydrophone to detect only direct pulses, while the other method was deploying the hydrophone at the bottom of the boat to block the reflected pulses at the sea surface. The trolling gear with the Gold code transmitter was submerged under the boat and the hydrophone was deployed around the boat, so the pulses from the Gold code transmitter were almost always propagated in an upward direction. The cause of the phantom value in that study was the reflected pulse at the sea surface. Therefore, using a directional hydrophone and deploying the hydrophone under the boat should solve the problems.

However, the two methods in fact may not solve the problems in biotelemetry. The majority of research using acoustic biotelemetry has been performed in shallow waters such as coastal, estuarine, and freshwater areas (Hussey *et al.*, 2015), where signals from transmitters to receivers mainly propagate in horizontal directions due to limitation of depth range. Animals tagged with a transmitter are free ranging, so signal arrival direction is always unknown. Therefore the two methods mentioned above cannot be applied

because those methods work only in when the direct or reflected signal arrival direction is known. Additionally, in shallow waters, not only sea surface but also sea bottom can be major boundaries to reflect ultrasonic pulses. Thus, an additional or alternative method is required to improve accuracy of data acquisition.

One possible way to overcome this problem is to discriminate phantom values through a mechanical process. If both a receiver and a transmitter remain stationary under a condition of flat sea surface, direct and reflection waves always travel through the same passage, determined geometrically. As a result, phantom value derived from false alarms would concentrate around a specific value, because time difference of arrival between direct and reflection wave is always the same. However, the sea surface is rarely so calm as to be flat, and tagged animals are free-ranging in biotelemetry, so phantom values should not be uniquely decided. These factors make it difficult to cope with the multipath effect through a mechanical process.

Recently, application of state-space models has been widespread in the analysis of various animal movement pathways, as collected by various tools (Patterson *et al.*, 2008). For example, Jonsen *et al.* (2005) analyzed track data for hooded seal (*Cystophora cristata*) and gray seal (*Halichoerus grypus*) collected via the Argos satellite system, and Sibert *et al.* (2003) analyzed geolocation data for bigeye tuna (*Thunnus obesus*) recovered from archival tags. State-space models are time-series models that estimate true states from acquired data by accounting for errors arising from imprecise observations and stochasticity. We hypothesized that the true state of depth measurement by the Gold code transmitters could be also estimated by applying a state-space model.

In this study, we conducted an experiment in a shallow sea area using the Gold code transmitters and receivers manufactured by AquaSound Inc., Kobe, Japan, and evaluated the multipath effects on depth measurement information. In addition, we proposed a method to reduce the phantom values from the acquired data and estimate true states by applying a state-space model. Finally, we evaluated the overall capability of this method.

MATERIALS AND METHODS

The Gold code transmitters (AQPX-1040PT, AquaSound Inc., Kobe, Japan; 9.5 mm in diameter and 36 mm in length, 1.6 g in water) used in this study transmit a signal consisting of three pulses with an interval of 1.28 s with root-mean-square (RMS) sound source level of 155 dB re 1 μPa at 1 m and with frequency of 62.5 kHz (Fig. 1a). Resolution of depth measurement was approx. 0.15 m. We used only the depth information for further analyses.

A field experiment was conducted in an open shallow sea area near Kaminokae fishing port, Kochi, Japan in August 2015. Seven transmitters were deployed at a fixed position (C1−7 in Fig. 1b). Two (C1, C2) of the seven were installed at 3.0 m depth, three (C3, C4, C5) at 4.0 m, and the remaining two (C6, C7) at 5.0 m. Two acoustic monitoring receivers (AQRM-1000, AquaSound Inc., Kobe, Japan; 64 mm in diameter and 300 mm in length) were deployed at a depth of 2.0 m and were located 18.5 m (R1) and 38.0 m (R2) horizontally away from the transmitters. The reason we did not deploy the receivers near the sea surface was to avoid unfavorable environmental conditions for the hydrophones, such as the signal-to-noise ratio (SNR) deterioration due to the noise induced collapse of waves by wind and exposure to the air due to vertical vibration of the sea surface. The bottom depth of installation positions of R1, R2, and the transmitters, were 9.1 m, 8.8 m, and 9.3 m, respectively. Signals from the transmitters were recorded by R1 and R2 for 15 min.

We calculated detection rates of each transmitter by R1 and R2 as percentages of the number of signal detected to the number of actual transmissions, which were estimated by dividing the recording duration (15 min = 900 s) by the signal-transmitting interval (1.28 s). Measurement accuracies of the depth of each transmitter by R1 and R2 were defined as mean of absolute values of difference between the recorded depths and the actual installation depths. The depth data were categorized into the following 4 groups:

(A) Correct values.

The correct values range within plus or minus 0.15 m to the average depths of each transmitter in accordance with the resolution of depth censor in the transmitters.

(B) Phantom values caused by reflection at the sea surface, and

(C) Phantom values caused by reflection at the sea bottom.

By using the installation depths of the transmitters and the receivers, the distances between them, and a sound velocity (1500 m/s), time difference of arrival between direct and reflected pulse at the sea surface and bottom were estimated, assuming that a pulse was reflected only once at either of the boundaries. Two types of measurement depth affected by the reflection were then calculated – the measurement depth between the direct 1st pulse and the reflected 2nd pulse, and between the reflected 1st pulse and the direct 2nd pulse. The phantom values caused by reflection at the sea surface and bottom were within plus or minus 0.30 m of the measurement depth affected by the reflection of each transmitter.

(D) Other values.

The remaining values that did not match with the estimated values of cases (A), (B) and (C) were categorized into 'other values'.

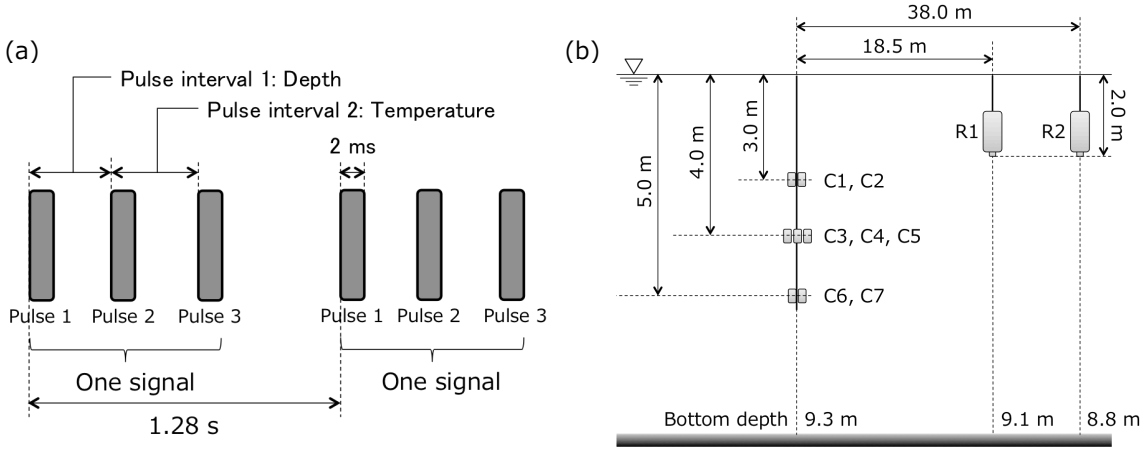

Fig. 1. (a) Transmission of depth and temperature information from the Gold code transmitter. Depth information is included in the 1st and the 2nd pluses, and temperature information in the 2nd and the 3rd pluses. (b) A schematic figure of vertical profile of the experimental arrangement. Seven transmitters and two receivers are represented as C1−7, and R1−2, respectively.

In order to reduce the phantom values in the depth data, we estimated actual depths of the transmitters by applying a state-space model to the depth data using the dlm package (Petris, 2010) in R ver. 3.1.3 (R Core Team, 2000). We assumed a random walk plus noise model using a process model, $x_t = x_{t-1} + v_t$, and an observation model, $y_t = x_t + w_t$, where x_t is actual depth of the transmitters at time t, y_t is the measurement depth at time t. Both the process and the observation model included an error parameter, w_t~Normal(0, W) and v_t~Normal(0, V). We postulated the acquired data as swimming depth data of free-ranging fish, correct values of which are never known and data type of which is time-series data. Actual installation depth of the transmitters was used as the reference to determine whether values estimated by the model were correct or not. The model estimated correct values at each point of measurement, including missing values. The estimated result would therefore have a larger number of data points than the raw depth data. We defined data availability as a percentage of the number of the correct values, that is the number of data category (A), to the number of the actual transmission. In order to evaluate capability of our method to solve multipath effects, we compared the data availabilities between the acquired data and the data estimated by the model using paired t-test in R ver. 3.1.3 (R Core Team, 2000).

RESULTS AND DISCUSSION

The detection rates of R1 and R2 were 79.3% (range: 57.6-81.4, N = 7) and 74.5% (range: 55.5-89.1, N = 7) as the median values, respectively (see detail in Takagi et al, 2016). The mean accuracy of the depth measurement was 0.38 ± 0.37 m for R1 and 0.46 ± 0.50 m for R2. Mean proportions of categorized depth data to the total number of the depth data recorded in R1 were (A) 88.4 ± 6.5%, (B) 8.1 ± 4.5%, (C) 0.6 ± 0.9%, and (D) 2.9 ± 2.5%. Those values in R2 were (A) 86.3 ± 4.8%, (B) 3.2 ± 2.5%, (C) 5.3 ± 3.2%, and (D) 5.2 ± 2.0% (Fig. 2). The data availabilities of the acquired data were 65.7 ± 9.0 and 64.6 ± 12.3% for R1 and R2, respectively (e.g. C7 at R2 in Fig. 3a). The data availabilities of the model-estimated data were 96.7 ± 6.5 and 93.3 ± 13.7% for R1 and R2, respectively (e.g. C7 at R2 in Fig. 3b). The data availabilities became significantly larger after applying the model at both R1 (paired t-test, $p < 0.001$) and R2 ($p < 0.01$).

Our results showed that the phantom values caused by multipath effects reduced and the correct values were successfully estimated by the state-space model. Mean intervals of non-correct values (the phantom values, the other values, and missing values) of the seven transmitters ranged from 2.64 s to 6.10 for R1 and from 2.53 s to 6.17 s for R2. The mean intervals were at least approximately two times larger than the signal-transmitting interval (1.28 s). This means that the non-correct values would not concentrate at a certain period of the depth data. Thus, under conditions where the detection rates were relatively high, it is likely that the error values did

not prevent the model from estimating the correct values. It should be considered that a state-space model may not properly estimate true states if the detection rate is relatively low, such as with biotelemetry in fish.

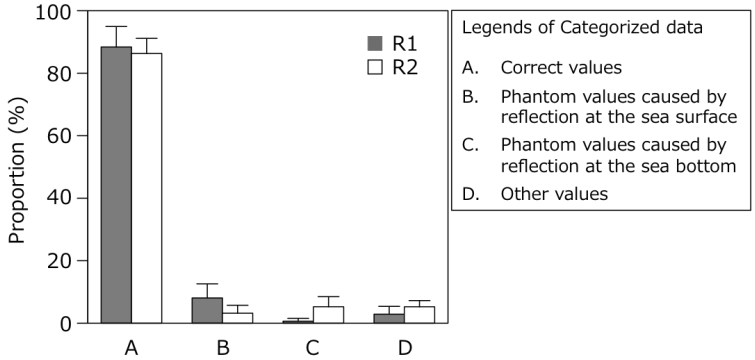

Fig. 2. Proportions of four types of categorized depth measurements (Mean + SD, N = 7 transmitters) recorded in receiver1 (R1) and receiver2 (R2). Horizontal distances between the transmitters and R1, and R2 were 18.5 m, and 38.0 m, respectively.

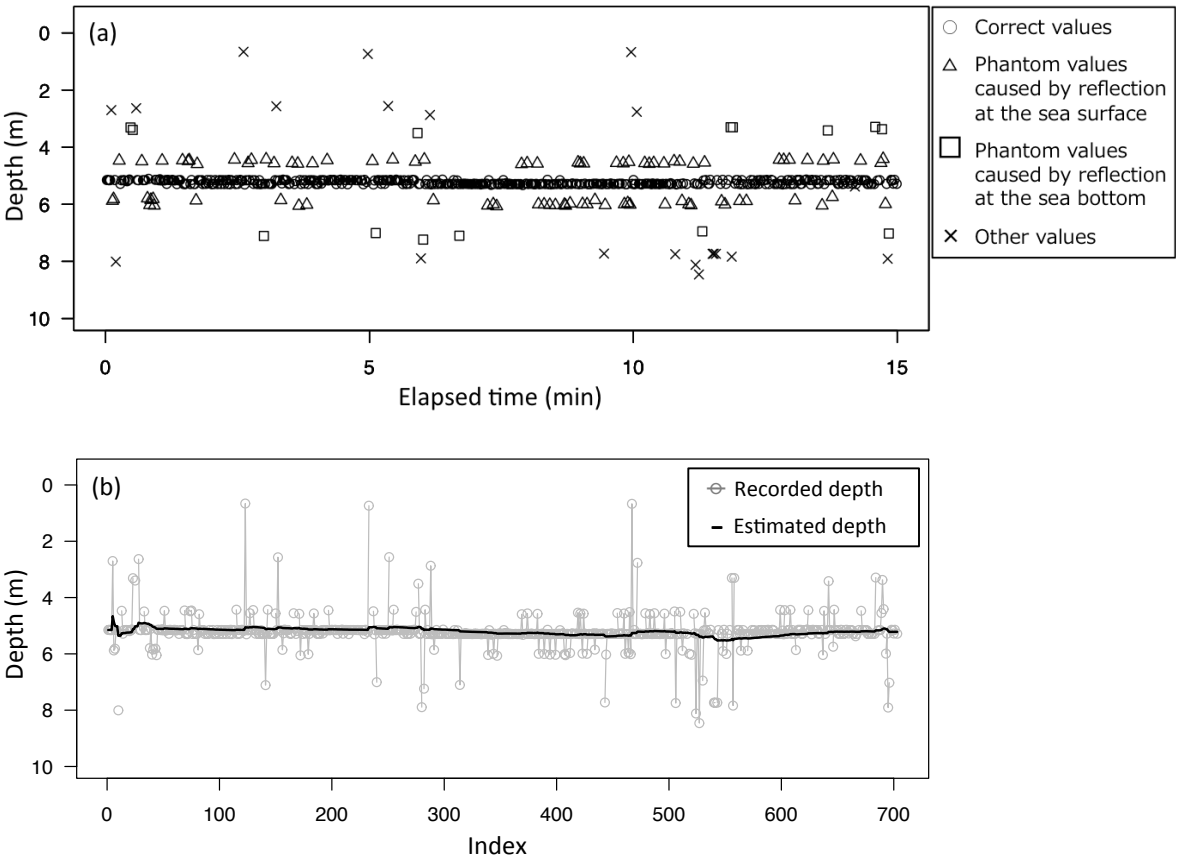

Fig. 3. Depth data from transmitter (C7) recorded in receiver (R2). (a) The data were categorized into 4 groups indicated with 4 symbols. (b) Depths estimated by the state-space model using the recorded depth data. To fit the model, the recorded data were converted into pseudo time series data, that is even interval data including missing values.

We applied a state-space model because we postulated the data as time-series data, such as swimming depth of fish. The model used in this study was a random walk plus noise model, which is the simplest

state-space model. Thus, this would admit some improvements such as considering explanatory variables or linear trends, especially when we analyze biotelemetry data, such as swimming depth of fish in a future study. However, in this study, the data availabilities of the estimated data had small standard deviations although installation depth was different among the transmitters and installation positions were different between the receivers. This indicates that the model properly estimated the correct values independent of geometrical relationship between the transmitters and the receiver. Therefore, we believe it is possible to apply a state-space model to biotelemetry data.

Unlike Hasegawa *et al.* (2016), the phantom values originated from the pulses reflected at not only the sea surface but also the sea bottom (Fig. 2). This may have resulted from propagation characteristics in shallow waters with multipath effects. Other values might include a plurality of reflections at both surface and bottom. Even though most of the recorded depth values were near the correct values with high accuracy, applying the model largely improved the data availabilities. This suggests that multipath effects can be reduced after data collection by post processing without pre-filtering, such as a directional hydrophone. By combining a state-space model with the real-time depth monitoring system for trolling gears (Hasegawa *et al.*, 2016), more accurate and continuous depth data can be provided to fishermen and will facilitate more efficient fisheries. This estimation method would also help us to monitor free ranging aquatic animals around the receivers. Swimming depths of bigeye tunas have been monitored *in situ* using the Gold code transmitters and the receivers used in this study, and it was revealed that the tunas started moving around sunrise (Imaizumi *et al.,* 2013). More accurate data on state of swimming depth of tunas estimated by the state-space model would provide us with better and more detailed understanding of their behavior. However, although aquatic animals might gradually change their swimming depth, installation depths of the transmitters were fixed in our experiment. Therefore, the next logical step for future work is to examine whether our method is feasible for depth data of moving objects.

ACKNOWLEDGEMENTS

We profoundly thank all participants who kindly supported the fieldwork and the analyses. We would like to thank Mr. Deki and Mr. Oki for support of the experiment. This work was partly supported by a Grant-in-Aids for Young Scientist (A) (25712022 to H.M.) Japan, a Cooperative research organization for the Promotion Program of International fisheries stock assessment from the Fisheries Agency of Japan, and JST CREST Grant Number JPMJCR13A5, Japan.

REFERENCES

Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, Butler PJ (2004) Biotelemetry: a mechanistic approach to ecology. Trends Ecol Evol 19(6):334−343

Hasegawa K, Miyamoto Y, Uchida K (2016) Development of a real-time depth monitoring system for small fishing gear using an acoustic telemetry technique. Fish Sci 82:213−223.

Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT, Harcourt RG, Holland KN, Iverson SJ, Kocik JF, Flemming JEM, Whoriskey FG (2015) Aquatic animal telemetry: a panoramic window into the underwater world. Science 348(6240):1255642

Imaizumi T, Akamatsu T, Oshima T, Yokota K, Iga H, Fusejima I, Wang Y, Ito M, Matsuo I, Takao Y, Hasegawa S (2013) Observation of in situ tuna behavior around the fisheries aggregating devises (FADs) by using passive and active acoustic methods. In Underw Tech Symp 2013 IEEE Int:1−4

Jonsen ID, Flemming JM, Myers RA (2005) Robust state-space modeling of animal movement data. Ecology 86(11):2874−2880.

Miyamoto Y, Takao Y, Sasakura T (2010) Development of a small and long-life ultrasonic biotelemetry system strong against sea ambient noise. Proc ICA 2010:1−4

Miyamoto Y, Uchida K, Takao Y, Sasakura T (2011) Development of a new ultrasonic biotelemetry system using a maximum length sequence signal. J Mar Acoust Soc Jpn 38(3):119−127 (In Japanese with English abstract)

Patterson TA, Thomas L, Wilcox C, Ovaskainen O, Matthiopoulos J (2008) State–space models of individual animal movement. Trends ecol evol 23(2):87−94

Petris G (2010) An R package for dynamic linear models. J Stat Softw 36(12):1-16

R Core Team (2000) R Language Definition. R Foundation for Statistical Computing, Vienna, Austria.

Sibert JR, Musyl MK, Brill RW (2003) Horizontal movements of bigeye tuna (*Thunnus obesus*) near Hawaii determined by Kalman filter analysis of archival tagging data. Fish Oceanogr 12(3):141−151

Takagi J, Ichikawa K, Arai N, Miyamoto Y, Uchida K, Fujioka K, Fukuda H, Shoji J, Mitamura H (2016) Simultaneous identification of multiple signals from phase modulation-coded transmitters for acoustic biotelemetry of fish school. J Adv Mar Sci Technol Soc 22(2):5-9