Development and Evaluation of an Ultrasonic Transmitter Using Frequency–Modulated Tones for Biotelemetry

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ABSTRACT
Biotelemetry is widely used to identify the position of aquatic animals. In order to observe micro scale movements of small target species, positioning accuracy is yet to be improved. It is known that frequency modulated signals provides better positioning accuracy. However, the conventional biotelemetry studies have used single-frequency transmitters. The purpose of this study is to develop a new type of ultrasonic transmitter using frequency-modulated tones (FM pinger) to reduce the positioning errors of biotelemetry. We conducted experiments to compare the accuracy of time difference of arrival (TDOA) by using the FM signals and conventional single-frequency signals in an open sea. We tested six patterns of frequency modulation including single-frequency (0, 2, 4, 6, 8, 10 kHz) with two kinds of duration (2, 10 msec.) for each frequency modulation bandwidth. The results showed that the TDOA of frequency-modulated tones provided higher accuracy than single-frequency tones. The average and standard deviation of TDOA of the frequency-modulated tones were close to the theoretical value of TDOA and 0. Therefore, it was considered that the frequency-modulated tones enhance accurate positioning as compared to the single-frequency tones.

Keywords: biotelemetry, ultrasonic transmitter, frequency-modulated tones

INTRODUCTION

Investigating the details of individual behavior contributes to our understanding of the movement of target species. Biotelemetry is widely used to identify the position of aquatic animals. Many methods of evaluation for acoustic biotelemetry have been made and considered (Park et al., 2002). Many studies have been conducted to track the targets at large-scale (Davidsen et al., 2013). A series of 4 km-scale tracking projects was conducted in the Pacific Ocean in 2002 (Welch et al., 2002). This project revealed that an acoustic tag and array can track the movement of Pacific Ocean salmon and its self-resident phase of the life history, suggesting that large-scale tracking has the potential to enhance understand of marine animals. On the other hand, there are also small-scale tracking studies. Although the large-scale tracking can observe wide range information, small-scale tracking can reveal more details of movement. In these small-scale tracking studies, it is important to know the movement or habitat accurately, because target species use only a small area in their lives. Highly accurate positioning is required for such small-scale studies, for example, the short-range homing of black rockfish was revealed within a monitoring area of 10,000 m^2 (Mitamura et al., 2012), and use of limited habitat (815m^2) by black rockfish was shown (Mitamura et al., 2009). These studies revealed fish homing activities accurately and suggested that small-scale tracking helps us to understand detailed behavior and specific activities. However, it has not yet been able to track the targets at micro-scale yet. Micro-scale tracking means that targets are to be localized with positioning errors of less than 1 m. This implies that positioning accuracy has been limiting our understanding of the details of fish behavior. For example, understanding the schooling behavior of small fish that have a body size of 50 cm – an important aspect of conservation – must localize the targets within 50 cm positioning errors. The realization of systems that can conduct micro-scale tracking is an undertaking of high importance.

The acoustic positioning starts with recording ultrasonic signals, emitted from a transmitter attached to the target by an acoustic array, using multiple hydrophones. Then detection time at each hydrophone is examined and TDOA of a signal is calculated to triangulate the position of the source. TDOA was used in telemetry systems like the Vemco Radio Acoustic Positioning (VRAP) system or the VR2W Positioning System (VPS) (Espinoza et al, 2011). In recent years, Automatic Underwater Sound Monitoring System (AUSOMS), a fine-scale acoustic positioning and telemetry system was developed (Shinke et al., 2011). The accuracy of TDOA calculation has a direct effect on the positioning accuracy, apart in addition to from other factors such as deflection of hydrophones caused by wave motions, reflections and reverberations during propagation, and so on.

These conventional biotelemetry studies have used single-frequency transmitters. It is known that the positioning error becomes smaller if the bandwidth of the frequency becomes wider (Cramer-Rao lower bound, eq. 1) (Shinke et al., 2011). Therefore this study aims to reduce positioning error and to verify the effectiveness of frequency-modulated (FM) tones for biotelemetry. *Bw* in eq1 is the bandwidth of signal, while σ is the angular error. If FM were used as the signal, *Bw* would increase and σ would decrease. This means that FM makes the positioning accuracy higher.

$$\text{(eq1)} \quad \sigma_\theta = \frac{c}{\sqrt{2}\pi d \cos\phi \sqrt{f_0^2 + \frac{Bw^2}{12}}} * 10^{-\frac{SNRr}{20}}$$

MATERIALS AND METHODS

The accuracy of TDOA using single-frequency tones and FM tones was compared. The experiment was conducted in Tateyama Bay, Chiba, Japan (N34°59’39.9” E139°49’49.0”) from January 28 to February 1, 2013. During the recording experiment, the average depth was 14m and the average temperature was 15℃. The ultrasonic transmitter and two hydrophones were deployed, as shown in Fig 1. The depth of the transmitter was 6 m below the sea surface, and the hydrophones were set at depth of 6.37 m and 7.0 m. The transmitter and the hydrophones were fixed to a steel stick, so the distance between the transmitter and two hydrophones was fixed during the recording experiment. The theoretical value of TDOA was 0.353 msec, using a fixed underwater sound speed of 1500 m/s. The transmitter was connected to a function generator to generate the signal patterns. The hydrophones were connected to a D/A converter connected to a laptop computer to record the signals, using a recording software (Audacity).

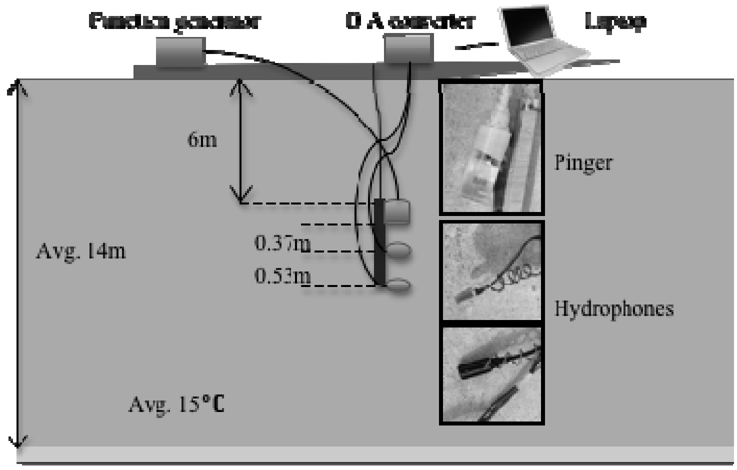

Fig.1 Arrangement of the experiment

A total of 12 different signal patterns controlled by the function generator was recorded. The frequency of all signals was swept linearly with the central frequency of 69 kHz. Two patterns of signal duration were tested; 2 and 10 msec. Together with the altering signal duration, six patterns of frequency modulation bandwidth were tested; 0, 2, 4, 6, 8 and 10kHz. Signals with 0-kHz bandwidth were single-frequency tones and others were FM signals. All signals were emitted for 30 sec at a 0.5 sec interval.

The TDOA was calculated by taking a cross correlation in the time domain for all signals. Accuracy for each signal pattern was compared by average and standard deviation of TDOA. In addition to TDOA, the estimated positioning values ε_{100m}, when 100 m scale positioning was conducted, were calculated using eq2 below.

$$\text{(eq2)} \quad \varepsilon_{100m} = \frac{50\pi\sigma_{Td}}{\sigma_{0.53m}}$$

In eq2, σ_{Td} means max error of TDOA and $\sigma_{0.53m}$ means theological value of TDOA at 0.53 m distance, 0.353 msec.

RESULTS

A total of 12 signal patterns were recorded. However, 3 patterns of signal were failed in analysis of the software. TDOA and estimated positioning error of each pattern was calculated using the software (Table 1 and 2). Wider bandwidth provided higher accuracy, because the average was close to the theoretical value and the standard deviation was also close to 0. Moreover, a longer duration provided higher accuracy under the same frequency bandwidth. As a result, signals with wider bandwidth or longer duration were better in terms of the accuracy of positioning.

Table1: Average and standard deviation of the time difference of arrival using 2 msec duration (msec) and estimated positioning error with 100 m tracking (m). Blank spaces show software analysis failures.

Bandwidth	0kHz	2kHz	4kHz	6kHz	8kHz	10kHz
Average	0.208		0.281	0.323	0.338	
SD	0.095		0.028	0.007	0.004	
Estimated error	106.7		44.5	16.5	8.5	

Table2: Average and standard deviation of the time difference of arrival using 10 msec duration and estimated positioning error with 100 m tracking. Blank spaces show software analysis failures.

Bandwidth	0kHz	2kHz	4kHz	6kHz	8kHz	10kHz
Average	0.412	0.354	0.354	0.354	0.354	
SD	0.075	0.033	0	0	0	
Estimated error	59.6	15.1	0.4	0.4	0.4	

DISCUSSION

Positioning errors are caused not only by calculation of TDOA but also by other factors such as deflection of hydrophones, reflections and reverberations of the signal, and so on. However, fixing hydrophones firmly onto a frame, which surrounds the monitoring area in an open sea, can control these other factors relatively easily. Such experimental conditions can be represented by acoustic tracking in a fish pen. In this study, we focused on improving accuracy of TDOA and compared the difference in the accuracy between single-frequency tones signal and FM signal. The results have two implications. First, the accuracy of calculating TDOA increases as the duration gets longer with the same frequency bandwidth. Second, the accuracy of TDOA calculation increases as the frequency bandwidth gets wider with the same duration. Longer duration and wider bandwidth increase S/N ratio and entropy of the frequency modulated signals (Urick, 1983). Under the experimental conditions of this study, the frequency-modulated tones of 4-kHz linear sweep with 10 msec duration provided the best performance, because the narrow frequency bandwidth is better for multiple tracking of different targets. Narrower bandwidth achieves more results with using different frequency area for different targets. If 100m scale tracking was conducted with these results, single frequency signals with 2 msec duration, which gave the worst results in terms of TDOA error, would get a positioning error of more than 100 m. A 4-kHz linear sweep with 10 msec duration, which gave the best results in terms of TDOA error, would get a positioning error of approximately 0.4 m, although these errors would obtained a lesser degree of error in real positioning with AUSOMS. Generally, single-frequency signals resulted in over 50 cm estimated positioning error, although all frequency-modulated test signals resulted in under 50 cm positioning error. This indicated that only frequency-modulated signals are very useful in trackinging the schooling behavior of small fish with 50 cm body size. This finding holds high potential for contributing to successful conservation fish populations in the future.

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REFERENCES

Davidsen, J. G., Rikardsen, A. H., Thorstad, E. B., Halttunen, E., Mitamura, H., Præbel, K. and Næsje, T. F. (2013) Homing behaviour of Atlantic salmon (*Salmo salar*) during final phase of marine migration and river entry. *Canadian Journal of Fisheries and Aquatic Sciences*, **70(5)**, 794-802.

Espinoza, M., Farrugia, T. J., Webber, D. M., Smith, F. and Lowe, C. G. (2011) Testing a new acoustic telemetry technique to quantify long-term, fine-scale movements of aquatic animals. *Fisheries Research*. **108(2)**, 364-371.

Klimley, A. P., Le Boeuf, B. J., Cantara, K. M., Richert, J. E., Davis, S. F. and Van Sommeran, S. (2001) Radio-acoustic positioning as a tool for studying site-specific behavior of the white shark and other large marine species. *Marine Biology*. **138.2**: 429-446.

Mitamura, H., Uchida, K., Miyamoto, Y., Kakihara, T., Miyagi, A., Kawabata, Y., ... & Arai, N. (2012) Short-range homing in a site-specific fish: search and directed movements. *The Journal of Experimental Biology*. **215(16)**, 2751-2759.

Mitamura, H., Uchida, K., Miyamoto, Y., Arai, N., Kakihara, T., Yokota, T., ... & Yasuda, T. (2009) Preliminary study on homing, site fidelity, and diel movement of black rockfish Sebastes inermis measured by acoustic telemetry. *Fisheries Science*. **75(5)**, 1133-1140.

Park, J., and Furusawa, M. (2002). The evaluation and design method of ultrasonic biotelemetry system. *Nippon Suisan Gakkaishi*. **68**, 334-344

Shinke, T., Kamoshida, T., Ichikawa, K., Mitamura, H. and Arai, N. (2011) Development of a fine-scale acoustic positioning and telemetry system. *IEICE*. **111.191**, 11-16.

Uric, R. J., (1983) *Principles of underwater sound.* McGraw-Hill Ryerson, Limited

Welch, D. W., Boehlert, G. W. and Ward, B. R. (2002) POST–the Pacific Ocean salmon tracking project. *Acta Oceanologica*. **25(5)**, 243-253.