Tracking Individual Fish in a Dense School with a Broadband Split-beam System

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Abstract:

To track individual fish within a dense school, it is necessary to isolate the echoes from multiple individual fish and then estimate their positions accurately. The signals from a broadband split-beam system offer the advantage of high-range resolution for this purpose. The range resolution and localization accuracy of this system were investigated by measuring the echoes from spheres in a tank. A tracking method exploiting the high-range resolution of the broadband signal was proposed. Echoes from schools of Japanese anchovy were measured in the ocean. Individual fish in these schools were measured separately and tracked using the proposed method. The technique allowed for accurate tracking of individual fish within dense schools. The estimated tracks can help us to better understand fish behavior under the sea.

Classification: Fisheries acoustics, Bioacoustics
Keywords: Broadband signal, Split-beam transducer, Tracking

1. Introduction

Split-beam echo sounders are important tools for the investigation of fish behavior, allowing estimation of both range and direction of the target. The spatial information is thus obtained over time, which makes it possible to track moving targets. The tracking results allow the behaviors of individual fish, such as movement and swimming speed, to be studied.

Broadband signals have attracted a great deal of attention in the area of fisheries acoustics. A broadband split-beam echo sounder system allows users to calculate the target strength (TS) spectra of resolvable echoes from individual fish and estimate their positions. Broadband signals can provide high-range resolution, which helps to isolate individual fish within dense schools. To track fish with a split-beam echo sounder, it is necessary to estimate both the range and angular location of the fish of interest. In this study, the characteristics of the broadband split-beam system were used to track individual fish within dense schools. The high-range resolution of the signal helps to isolate echoes from multiple fish. We proposed a
tracking method based on the target range because range estimation is more reliable than directional information, and individual tracks could be measured separately on the echogram. The direction of arrival (DOA) obtained by the split-beam echo sounder was also used to reject association between different individuals. In dense schools, there were observation-to-track conflict situations. To track an individual fish accurately, a multiple hypothesis tracking (MHT) approach was applied.

Matsuo et al.\textsuperscript{10} and Imaizumi et al.\textsuperscript{11} recently showed that dolphin mimetic broadband sonar can be applied in precise acoustic measurements to estimate the position of a target with high-range resolution. In this paper, dolphin mimetic sound, which is one of the broadband signals, was used to validate the accurate estimation of the target positions and to demonstrate the target-tracking method.

2. Broadband Split-Beam System with Dolphin Mimetic Sounds

Echoes were measured by broadband transmitting and receiving systems\textsuperscript{7}. In the transmitting system, a dolphin mimetic signal from a signal generator (WF1946; NF Co., Yokohama, Japan) was amplified using a power amplifier (PRO-100; Accuphase, Yokohama, Japan) then sent to a custom-made transmitting circular transducer (Furuno Co. Ltd., Hyogo, Japan). In the receiving split-beam system, the reflected waves were sensed with a custom-made split-beam receiving circular transducer (Furuno), and the signals were amplified by a preamplifier. The signals were then measured and transformed into digital data by an oscilloscope (WaveRunner 6030A; LeCroy, Chestnut Ridge, NY, USA). The theoretical directivity characteristics of the transducers used are shown in Table 1.

The transmitting and receiving transducers had similar characteristics, and were mounted adjacent to each other. The product of the transmitting and receiving sensitivities had broadband characteristics of 58–140kHz at a level of −10dB; the combined beam width was 19.5° at 50kHz and 7.1° at 130kHz\textsuperscript{11,12}.

Dolphin sonar signals are composed of series of clicks. The click produced by a bottlenose dolphin (\textit{Tursiops truncatus}) was recorded with a hydrophone\textsuperscript{13} (Fig. 1(a)) and used as the emission signal. The sonar sound had its peak energy at a frequency

| Frequency [kHz] | -3dB [°] | -6dB [°] |
|----------------|----------|----------|
| 60             | 13.8     | 18.9     |
| 80             | 10.4     | 14.2     |
| 100            | 8.0      | 11.0     |
| 120            | 6.9      | 9.5      |

Fig. 1  Dolphin sonar sound and incident wave characteristics: (a) original waveform of the dolphin sonar sound; (b) amplitude spectrum of the dolphin sound; (c) waveform of incident wave, obtained by setting the transducers face-to-face; (d) amplitude spectrum of the incident wave.
of around 100 kHz, and the −3dB bandwidth was 60 kHz (ranging from 55–110 kHz; Fig. 1(b)). The incident wave, which was obtained by setting the transducers face-to-face, and the amplitude spectrum are shown in Figs. 1(c) and (d), respectively. The distance between the transducers was 2.2 m. The bandwidth of the incident signal was narrower than that of the emitted signal because it was convolved by the properties of the transducers and the amplifier. The system was calibrated using the incident signal\(^7,10\).

3. Measurement of Echoes

3.1 Measurement of spherical objects in a tank

Localization performance was evaluated by two experiments performed in a freshwater tank. The objective of the experiments was to examine the accuracy of the estimated position of a single sphere, and the separation of two spheres located close to each other.

3.1.1 Localization of a single sphere

In the first experiment, we tested the system's ability to localize a single sphere. The three-dimensional (3D) position of a tungsten carbide (WC) sphere (diameter: 38.1 mm) was estimated using the broadband split-beam system. The sphere was suspended at the end of a nylon monofilament fishing line (diameter 0.522 mm), and its position was varied within a plane parallel to the transducers (Fig. 2(a)). The distance between the centers of the two transducers was 186 mm. The freshwater tank had an area of 15 m×10 m, and was 10 m deep. The echo signals were measured at a 5-MHz sampling frequency with an 8-bit amplitude resolution. Before processing, the signals were downsampled at 400 kHz for ease of data processing. Received signals contained echoes from surrounding objects, such as the walls, floor and so on. Background noise signals were also measured and then subtracted from the echo signals to satisfy the high signal-to-noise ratio (SNR) conditions.

3.1.2 Localization of two neighboring spheres

The second experiment used two identical expanded polystyrene (EPS) spheres (diameter 30.0 mm), suspended on a nylon fishing line (Fig. 2(b)). The distance between the spheres was fixed at 100 mm, and they were tilted so as to vary the detected range difference between the spheres and the incident beam. The spheres were tilted from −60 to 60° using a stepper motor. The tilt angle was defined as 0° when the two spheres were hori-
3.2 Measurement of echoes from fish schools at sea

The tracking performance of the system described above was then tested by targeting dense schools of Japanese anchovy (*Engraulis japonica*) at sea. The echoes were recorded in Tateyama Bay (Chiba Prefecture, Japan; 35°01′N, 139°49′E) in March 2008. Echoes from wild fish were recorded at sea on the research vessel *Takamaru* (length: 29.5 m, gross tonnage: 61 tons) of the National Research Institute of Fisheries Engineering, Fisheries Research Agency, Japan. When measuring the echoes, the vessel was at anchor. The measurement system was the same as that used in the tank experiment, but the received signals were digitized at a 10-bit resolution. Two transducers, with centers located 240 mm apart, were placed on the side of the ship, facing downward. The periodic interval for the transmission of the pings was 0.3 s. A conventional 38-kHz quantitative echo sounder (QES) (KAIJO, KFC-3000) was also mounted on the bottom of the vessel and run simultaneously to provide measurements for comparison with the proposed system. The broadband system and the QES emitted alternately, to avoid interference between transmitted signals. The pulse duration of the QES was 0.53 ms. The specific fish species within the schools were identified by catching sample fish with fishing lines during the measurements.

4. Tracking Method with the Broadband Split-Beam System

The tracking process was carried out after echo detection and 3D position estimation. The echo detection process was used to extract the fish echoes from the measured signals. The 3D positions of individual fish were then estimated using delay times from emission and the time differences between the receiving channels. The detected echoes were tracked using the range information with MHT.

4.1 Detection and localization

We used the envelope pattern to detect and extract the temporal peaks of the echoes. Initially, correlated signals were obtained by cross-correlation between the emitted signal and measured signals in each receiving channel. Then, a full-beam signal was formed from the sum of four channels of the correlated signals. We compensated for the range dependence of the cross-correlated signals by using a time-varied gain (TVG) function. Absorption of the sound was not considered, because it was supposed that the effect of the absorption was much smaller than that of the radiation of the sounds. The full beam envelope was calculated via a Hilbert transform. All peaks of the envelope over a threshold of −70 dB re m² (above the noise level) were regarded as echoes from fish, and thus as targets to be tracked.

In general, a single echo detection (SED) algorithm can be used to detect isolated single target echoes from all detected targets. However, no SED algorithms were applied to the detected peaks here, and so none of the targets were rejected, even if they were overlapping echoes from multiple fish. Conventional SED algorithms reject many targets because they are not designed for tracking purposes.

The position of a detected target was estimated from the range and the DOA of the echo. The alongship and athwartship angles were estimated using the arrival time differences measured by the split-beam echo sounder. Half-beam signals were...
formed by summing two adjacent channels of the signals. The phase differences between the two signals received on the transducer half-beam pairs were then calculated via fast Fourier transforms. The phase differences in each frequency bin were then converted into time differences. A time difference was obtained using a weighted average with the amplitude spectrum of the received signal. The DOAs of the echoes were estimated using the time differences. The Hanning window was then used to extract an echo from a particular fish and suppress the echoes from the other fish. In this study, we selected the Hanning window because it is so commonly used. However, other windows, such as a Gaussian or a Chebyshev window, could also be used. In the tank, the effect of the window length was evaluated as a result of the estimation of the positions of both single and multiple spheres. The range from the receiving transducer to the target was estimated based on the speed of sound in water, the delay of the received echo, and the distance between the two transducers. In the experiment at sea, however, the range estimation process was affected by the heaving motion of the ocean waves. To account for this effect, we measured the ping-to-ping coherence of the sea floor echoes\(^{15}\).

The pitch and roll angles were not considered in this case, because they did not have a significant effect on the range estimation for a short distance of less than 15 m.

Previous studies have demonstrated that multiple reflections could be obtained from a single fish because of the very high-range resolution of the broadband emission signal\(^6,10\). It was therefore important to determine whether the reflections came from single or multiple individual fish. We concluded that the signal was from a single fish if the following conditions were met: 1) the range difference was less than the threshold \(\Delta r\); and 2) the directional differences were also less than a given threshold. This threshold, \(\Delta \theta\), had a value that was inversely proportional to the range \(r\) and was defined as:

\[
\Delta \theta = \arctan\left(\frac{S_{\text{body}}}{r}\right) + \varepsilon
\]  

(1)

where \(S_{\text{body}}\) was the apparent body size of the target, \(r\) was the target range, and \(\varepsilon\) was the tolerable directional error, which was adjusted depending on the SNR condition. The most intense reflection was taken to be representative of the group.

4.2 Tracking

To track individual fish, the temporal peaks belonging to successive pings must be connected. The range to a tracked fish was predicted by linear extrapolation using the range values of the two previous pings. The predicted range was used as the representative point of the track. If the previous two pings were not available, then the range at the previous ping was used as the representative point at the beginning of the track. The range differences among all combinations of the observed peaks and the representative points of the tracks were calculated, then used to determine the observation-to-track association matrix\(^{16}\), whose elements were distances from observations to tracks. If an element of the matrix exceeded the gating threshold \(r_{G}\), then the pairing was eliminated from the tracking candidate.

The MHT method was used to solve the assignment problems of the tracks and the targets\(^{16}\). The solutions were given using the auction algorithm\(^{16,17}\), which seeks to maximize gain of the assignment matrix. When there were observation-to-track conflicts, data association hypotheses were formed. The N-best solutions to the assignment of the matrix were found, and multiple hypotheses of data association were provided. Each hypothesis
was evaluated using the following equations:

\[ p_H = \prod_{i,j} g_{ij} P_D^M (1-P_D)^{N_T-M} \beta^{N_T-M} \]  

(2)

where \( N_O \) and \( N_T \) were the number of observed echoes and the number of tracks, respectively. \( M \) denoted the number of pairings of tracks and targets, \( P_D \) was the detection probability, \( \beta \) was the extraneous return density, including new targets and false targets, and \( g_{ij} \) was the Gaussian likelihood function associated with the assignment of a target \( j \) to a track \( i \); in addition, 

\[ g_{ij} = e^{-d_{ij}^2/2} \sqrt{2\pi} \]  

(3)

where \( d_{ij} \) was the range difference between the target \( j \) and the track \( i \) in meters. The directional information obtained by the split-beam system was also used to reject the associations between different individuals. If the directional change of a target-to-track pairing exceeded the given threshold, \( \text{Th}_\alpha \), then the pairing was eliminated before the association problem was solved. \( \text{Th}_\alpha \) was defined as:

\[ \text{Th}_\alpha = \arctan \left( \frac{v_h \Delta t}{r(t)} \right) + \varepsilon \]  

(4)

where \( v_h \) was the supposed velocity of fish in the horizontal plane, and \( \Delta t \) was the ping interval. In the past, decisions were made based on the current data. In this study, the data in the last two pings were used to make the decisions. No missing connection was allowed in a track to reduce associations between different individuals because the fish were so closely distributed. If a track had missed connections, then it was terminated.

An extended Kalman filter and a Rauch-Tung-Striebel smoother (or Kalman smoother), were applied to filter the obtained tracks. The Kalman smoother was used to estimate the states from a series of measurements containing noise. As a result of the filtering process, both the positions and velocities of individual fish could be estimated.

5. Localization and Tracking Results

5.1 Estimation of 3D positions of a WC sphere

The performance of the proposed system was evaluated in the laboratory by localization of a single sphere in various positions. Figure 3 shows the two-dimensional results of the localization experiment in the tank with a Hanning window of 30μs. It is apparent that the spheres were accurately localized. The mean distance error from the correct position was 22.4mm or 0.14° at a range of 9.39m. The errors at the edges of the transmitting and receiving beams were greater than those in the centers of the beams. The positions within a −3 dB beam width at 100kHz were localized more accurately; the mean distance errors were 13.5mm and 0.08°. However, it seems there existed a bias in the sphere position. It may have been caused by the placement of the transducers and the sphere. The face of transducer was not completely parallel to the plane where the sphere was placed. Such placement error could have caused the bias in the
positions. It was thus confirmed that the proposed system could accurately localize the sphere.

The positions were estimated by changing the Hanning window length every 10 $\mu$s from 10 to 100 $\mu$s. The shortest length of 10 $\mu$s corresponded to a cycle of the center frequency of the emitted signal (100kHz), and the time of 100 $\mu$s was nearly equal to the duration of the emitted signal. Performance was evaluated using between 1 and 10 cycles of the received signals. Figure 4 depicts the localization performance when Hanning window length was varied. When the window size was small, performance was poor, because the window length was too short to calculate the phase differences accurately. Performance was improved by using longer windows, but became almost stabilized at a length of 30 $\mu$s. As a result, we used a window length of 30 $\mu$s to localize a single sphere precisely. At a central emitted signal frequency of 100kHz, 30 $\mu$s corresponded to three emission cycles, indicating that the signal with three cycles could provide an accurate estimate of the sphere position.

5.2 Estimation of 3D positions of two EPS spheres

To test for the localization of multiple targets in the tank, two closely located spheres were localized with the broadband split-beam system using various tilt angles. The tilt angle of the spheres was estimated by the relative positions of the spheres; distance between spheres was also estimated. The ground truth of the tilt angle was given by the controlling value of the stepper motor. Estimated angle and distance are shown in Figs. 5(a) and (b), respectively. When the tilt angle was greater than 10° (i.e., when the spheres were more than 20mm apart along the range axis), then the positions of both spheres could be estimated.

The effect of window length was also considered. The distance between the two spheres and the tilt angle that was estimated from their relative positions were evaluated. Estimation errors with respect to distance and tilt angle are shown in Figs. 6(a) and (b), respectively. When a short window was used, the localization performance was...
affected by noise. As with the localization performance for a single sphere, the performance became stabilized when longer windows were used. It was found that a window length of at least 20 μs was required to localize multiple spheres accurately. The results for the localization of a single WC sphere and two EPS spheres indicated that a window of 30 μs could provide satisfactory localization of individual fish in dense schools.

The window length of 30 μs corresponded to approximately three cycles of the echo signal, since the periodicity of the signal was about 10 μs, as shown in Fig. 7(a). When the length of the Hanning window was less than 30 μs, the periodicity of the extracted signals was largely lost, as may be seen in Figs. 7(b) and (c), and localization error consequently increased (Figs. 4 and 6). For accurate localization, window length was required to be at least 30 μs. When longer windows were used, however, the signals might then include echoes from other fish or from the sea floor. Attention should also be paid to the time-resolution capability of the sonar signal. This can be indicated by the Woodward time-resolution constant \( \Delta T^{19,20} \), which is defined as follows:

\[
\Delta T = \frac{\int_0^\infty |S(f)|^4 df}{\left[ \int_0^\infty |S(f)|^2 df \right]^2}
\]  

(5)

The time-resolution constant of the incident signal was 25.7 μs, which corresponded to a minimum discriminable difference of 20 mm along the range axis. As the 30 μs window length was close to \( \Delta T \), the length was appropriate for distinguishing between two closely spaced targets and accurately estimating their positions. Thereafter, window length of 30 μs was used to calculate the positions of the fish.

5.3 Tracking individual fish in schools

Figures. 8(a) and (b) show echograms from a school of Japanese anchovy measured by the
broadband split-beam and the narrowband split-beam echo sounder, respectively. These echoes are from School 1 (of 3). The broadband system could isolate most of the echoes, whereas the conventional narrowband system produced overlapping echoes. Individual Japanese anchovy in the school were tracked as described earlier, and the final tracks were filtered using the Kalman smoother. The tracking parameters are shown in Table 2. Tracking results are superimposed on the echogram in Fig. 9(a). An example of a tracked and filtered fish is shown in Fig. 10. The red lines in Fig. 10(a) denote tracked individual fish on the echogram. The localized and filtered positions of the tracked fish were plotted in 3D space (Fig. 10(b)). The behavior of the fish could therefore be visually displayed. Two other schools of Japanese anchovy, designated as Schools 2 and 3, were also analyzed. The tracking results for these schools are shown in Figs. 9(b) and (c). To evaluate tracking accuracy, the indices proposed by Handegard were
calculated. In School 1, the individuals in the dense area (from 250 to 350 pings, and from 10 to 15 m) were used for the evaluation. In Schools 2 and 3, all data were used. The numbers of manually and automatically tracked fish are shown in Table 3.

Ground truths for the tracking process were determined by manual tracking, which was conducted by a human assisted by a customized program on a PC. The auto-tracked fish, tracked by the proposed method, and the true-tracked or manually tracked fish were given identification numbers. The auto-track IDs were then compared with the true-track IDs. If the auto-track ID number changed along a true-track, then a split error occurred. In contrast, if the true-track ID changed along an auto-track, then a connection error occurred. The splitting and connection errors were defined as follows:

\[
\begin{align*}
J_{\text{split}} &= \frac{\sum_i C^s_i}{\sum_i (L_i - 1)} \\
J_{\text{connect}} &= \frac{\sum_i C^c_i}{\sum_i (L_i - 1)} \\
J_{\text{alloc}} &= \frac{1}{2} \left( J_{\text{split}} + J_{\text{connect}} \right)
\end{align*}
\]

where \(L_i\) was the length of tracked echoes \(i\), and \(C^s_i\) and \(C^c_i\) were the numbers of split and connection errors, respectively. The former represented the missing rate and the latter was the false alarm rate. The two measures were then combined into a single measure,

\[
J_{\text{alloc}} = \frac{1}{2} \left( J_{\text{split}} + J_{\text{connect}} \right)
\]

The calculated measures for the three schools are shown in Table 4, and the \(J_{\text{alloc}}\) values were 0.105, 0.107 and 0.042.

### Table 3 The number of fish estimated by automatic and manual tracking methods (maximum densities of the schools are indicated)

| School 1 (Dense area) | School 2 | School 3 |
|-----------------------|----------|----------|
| Density (fish/m³)     | 2.7      | 2.1      | 1.5      |
| Manual tracking       | 256      | 752      | 127      |
| Automatic tracking    | 234      | 769      | 130      |

6. Discussion

In this study, individual fish echoes from Japanese anchovy were tracked using a broadband split-beam system. The tracking performance of the system was evaluated using the measures proposed by Handegard et al.\(^8\). Considering the measures of the tracking errors presented in Table 4, in the dense schools (Schools 1 and 2), the measures were both 0.11. This means that a tracking error level of 11% had occurred. For the sparser school (School 3), the measure was 0.04. This result was similar to the findings of conventional research. In denser schools, the measures tended to be worse;
however, 89% of the connections were correctly obtained by the proposed method with the broadband split-beam tracking system. This indicates that the broadband split-beam system was beneficial when tracking fish in dense schools.

Our technique could localize a target with high accuracy; it could also localize neighboring targets if they were more than 20 mm apart along the range axis. When the two spheres were too close along the range axis, the peaks could not be resolved separately, and thus position estimation was impossible. This implies that the broadband split-beam system can localize multiple fish within a dense aggregation if they are separated by more than 20 mm along their range-axis direction. Therefore, a combination of the broadband split-beam sonar and the current signal processing method would allow for separation of closely distributed fish.

The probability of overlapping or isolating of fish echoes was investigated with various densities of fish schools. In order to calculate the probability, the fish schools were simulated on a PC. The density and the range of the school were set, and it was assumed all echoes had the same intensity. When the echoes from simulated fish were separately located by more than 20 mm along with range axis, they were regarded as separated fish. The averaged result of 100 random simulations was calculated. When the beam width was 8 degrees (equal to the \(-3\) dB beam width of the transducer of our system at 100 kHz), the target range was from 5–10 m, the density of school were 2, 5 and 10 fish/m\(^3\), and approximately 92, 82 and 67% of fish echoes could be separately measured, respectively. If the target range was farther or the density greater, the probability of separating fish was reduced.

Fish abundance in dense schools has conventionally been measured by the echo integration method\(^{21}\). As these results depend on the tilt angle and size of the fish or on the species composition within the school, it is difficult to estimate for any unknown species. However, our tracking technique allows the number of fish to be counted directly using high range resolution to track individual fish and provide accurate estimates of fish abundance. In Table 3, the numbers of tracked fish are shown. The numbers of fish obtained by automatic tracking corresponded closely with those obtained by manual tracking. This indicates that the automatic tracking process would be effective for estimation of fish resources.

Although the current paper describes the use of an emitted dolphin mimetic sonar signal, chirp signals are often used in broadband split-beam sonar\(^4,5\). However, our method uses general processing techniques, and thus it could be useful for improving localization performance and high-range resolution when using other broadband signals. The performance of the dolphin mimetic signal and the chirp signals was evaluated with respect to SNR improvement, range resolution and main lobe-to-side lobe ratio (MSR). Original dolphin signal, dolphin signal convolved by the transducer response, chirp signal with uniform amplitude, and tapered chirp signal convolved by the transducer response were used for the evaluation. The minimum duration of the chirp signals was 40 μs, which approximately corresponded to the duration of the dolphin signal, and the maximum was 10 ms. The duration of the dolphin signals were equal to \(-20\) dB width of the pulses. In order to evaluate SNR improvement, random Gaussian noises were artificially added to the signals. The noise level was set to make SNR be 30 dB. The SNR improvement was defined as the difference between the SNR after the pulse compression and the original SNR, 30 dB. The result is shown in Fig. 11(a). The range resolution was defined as the \(-6\) dB width of the
The dolphin mimetic signal outperformed the chirp signal, which had the same duration with respect to the SNR, range resolution and MSR. When a longer chirp signal was used, the SNR unsurprisingly improved. It was confirmed that the SNR improvement and the range resolution of the dolphin signal were superior to the chirp signals of the same duration.

7. Conclusion

To track individual fish accurately within a dense school, it is necessary to separate the multiple echoes and estimate the individual positions accurately. The broadband signal was efficient for this purpose because of its high-range resolution. The targets were localized by a split-beam echo sounder emitting broadband sound ranging from 55 to 110kHz. Within the beam of the receiving transducer, the average estimation error of the target at 9.39 m was 0.08°. In laboratory experiments, we found that two spheres could be discriminated acoustically if they were more than 20 mm apart along the range axis. Accurate position-estimation results were followed by the development of the tracking process, and individual fish within a school were tracked using MHT. It was confirmed that approximately 90% of the tracking connections were correctly obtained by the proposed method with the broadband split-beam system. Such tracking results could be used to estimate behavior and swimming speed of individual fish in the schools, and could thus improve our understanding of fisheries biology.

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