Computer Simulation of Broadband Single-target Echo Waveforms and its Application

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Abstract:
Computer simulations of single-target echo waveforms have been useful for fisheries acoustics. In previous studies, the use of conventional scientific echosounders has been assumed, and therefore a narrowband tone-burst wave has been used as the transmit signal. However, computer simulation methods for recently developed broadband echosounders have not been fully established. In this paper, a method for the computer simulation of broadband single-target echo waveforms using a linear frequency-modulated signal is presented. This simulation method takes into account not only the backscattering amplitude of a target, but also transducer directivities and transmission losses. The simulated broadband single-target echo waveforms will be applicable to various studies. In this study, the broadband signal processing procedure for volume backscattering strength was verified using broadband multiple-target echo waveforms, which were generated by summing a large number of simulated single-target echo waveforms.

Classification: Fisheries acoustics, Bioacoustics
Keyword: computer simulation, linear frequency-modulated signal, broadband echosounder, single- and multiple-target echo waveforms, volume backscattering strength

1. Introduction
The development of methods to estimate meaningful biological information (e.g., numerical density, size, taxonomic group, species, and behavior) from echoes received by echosounders is an important research task in fisheries and plankton acoustics. However, it is difficult to obtain ground-truth data for verifying estimation methods. In particular, it is almost impossible under in situ conditions. Therefore, ex situ experiments using fish aggregations in cages† and dummy scatters2–4 have ever been performed.

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Instead of real echo waveforms, single-target echo waveforms simulated by computers have been used.2,5) Computer simulations are helpful for verification because answers such as ground-truth data can be arbitrarily assumed in advance. Kang,6) Furusawa and Amakasu,7) and Furusawa8) generated multiple-target echo waveforms by summing a large number of single-target echo waveforms, and applied them to studies on species-identification methods. In the aforementioned simulation studies, use of conventional scientific echosounders was assumed, and therefore a narrowband tone-burst
Recently, broadband echosounders, which can transmit linear frequency-modulated (FM) signals, have become practical in scientific use.\(^9\)–\(^{12}\) The author previously built a prototype broadband echosounder,\(^{13}\) and continues to study its potential applications. The advantages of using of broadband signals are: acoustic scattering spectra of marine organisms can be determined, and range resolution can be improved. The spectral information derived from broadband echoes is useful for estimating the size and taxonomic group of marine organisms. Although there are such advantages, the signal processing of broadband echo waveforms, which includes pulse compression processing and Fourier transformation, is more complex than that of conventional scientific echosounders, which basically use echo envelopes and their amplitude. Therefore, it is necessary to carefully verify signal processing methods or procedures for broadband echo waveforms. Computer simulations are helpful for this purpose.

Imaizumi\(^{14}\) simulated a backscattered waveform by a rigid sphere as part of the development of a broadband echosounder. The incident waveform to the rigid sphere was a short tone-burst wave (three cycles) with a center frequency of 100 kHz. The backscattered waveform was obtained by calculating the inverse Fourier transform of the product of the incident wave spectrum and the predicted backscattering amplitude of the rigid sphere. However, transducer directivities and transmission losses were not taken into account in this simulation. In order to simulate single- or multiple-target echo waveforms, some improvements are needed. This paper presents a computer simulation method for simulation studies using broadband signals that takes into account not only the backscattering amplitude of a target but also the transducer directivities and transmission losses. A linear FM signal is used as the transmitted signal from a transducer. Furthermore, as an application study, a signal processing procedure for volume backscattering strengths is validated using simulated multiple-target echo waveforms.

2. Computer simulation of broadband single-target echo waveforms

Acoustic backscattering by a single target and sound propagation between a transducer and the single target can be expressed as a filtering process, as illustrated in Fig. 1. The upper part of Fig. 1 shows the frequency domain, and the lower part shows the time domain. The output of this simulation is the single-target echo “pressure” waveform \(p_r(t)\) (where \(t\) denotes time) received at the transducer. There are two ways of simulating \(p_r(t)\): “working directly in the time domain or working at

![Frequency domain](image)

**Time domain**

Fig. 1. Schematic diagram of acoustic backscattering and sound propagation as a filtering process. Variables are described in the text.
first in the frequency domain and then coming back
to the time domain via the inverse Fourier trans-
form,” as described in Sun et al.\textsuperscript{15} In this paper,
p_{r}(t) is basically computed in the time domain. The
incident waveform to the single target \(p_{\text{inc}}(t)\), the
backscattered waveform by the single target \(p_{\text{scat}}(t)\), and \(p_{r}(t)\) illustrated in the time domain of Fig. 1 are
expressed as

\[
p_{\text{inc}}(t) = \{p_{t}(t) \ast d(t)\} \ast l(t) \quad (1)
\]

\[
p_{\text{scat}}(t) = p_{\text{inc}}(t) \ast f_{\text{bs}}(t) \quad (2)
\]

\[
p_{r}(t) = \{p_{\text{scat}}(t) \ast l(t)\} \ast d(t) \quad (3)
\]

where \(p_{r}(t)\) is the transmitted waveform from a
transducer, the symbol “\*” denotes convolution,
and \(d(t)\) is the inverse Fourier transform of the
directivity function \(D(f)\) (where \(f\) is the frequen-
cy). If the transducer is a circular piston source,
\(D(f)\) can be calculated by

\[
D(f) = \frac{2J_{1}(ka \sin \theta)}{ka \sin \theta} \quad (4)
\]

where \(J_{1}\) is the Bessel function of the first kind
of order 1, \(k\) is the wave number expressed as \(2\pi f c^{-1}\) (where \(c\) is the speed of sound in water), \(a\)
is the radius of the transducer, and \(\theta\) is the target
angle measured from the beam axis. \(l(t)\) is the
inverse Fourier transform of the transmission loss
\(L(f) = r^{-1} e^{dr} 10^{-0.05\alpha(f)}\) (where \(r\) is the range from
the transducer to the target and \(\alpha\) is the absorption
coefficient in dB/m\textsuperscript{16}). \(f_{\text{bs}}(t)\) in Eq. (2) is the back-
scattering impulse response of the backscattering
amplitude of the target \(F_{\text{bs}}(f)\) and can be obtained
by calculating the inverse Fourier transform of
\(F_{\text{bs}}(f)\).\textsuperscript{15,17} \(F_{\text{bs}}(f)\) is given by theoretical scattering
models.

Three examples of \(p_{r}(t)\) are shown in Fig. 2. The
single target was a 38.1-mm-diameter tungsten
carbide sphere; \(p_{t}(t)\) was a linear FM signal with
a frequency sweep of 40–200 kHz; and \(F_{\text{bs}}(f)\) was
the exact modal series solution.\textsuperscript{18–20} Three target
positions were assumed. All simulation conditions,
including the target positions, are listed in Table 1.

The amplitude of the Case 1 waveform clearly
depends on the magnitude of \(F_{\text{bs}}(f)\) (data not
shown). Although it is difficult to ascertain

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
Transmitted signal & Linear frequency modulated signal \\
Frequency sweep of 40– & \200 kHz \\
Pulse duration of 5 ms & \\
\hline
Transducer radius & 5.5 cm \\
Environments & \(c = 1500\) m/s \\
Temperature = 15\(^{\circ}\) & \\
Salinity = 34 psu & \\
\hline
Target & 38.1-mm-diameter tungsten carbide sphere \\
\hline
Target positions & Case 1: \(r = 25\) m, \(\theta = 0^{\circ}\) \textsuperscript{°} \\
& Case 2: \(r = 25\) m, \(\theta = 2^{\circ}\) \textsuperscript{°} \\
& Case 3: \(r = 50\) m, \(\theta = 2^{\circ}\) \textsuperscript{°} \\
\hline
\end{tabular}
\caption{Simulation conditions of Fig. 2.}
\end{table}

Fig. 2 Simulated single-target echo waveforms of
38.1-mm-diameter tungsten carbide sphere.
Simulation conditions are listed in Table 1.
from the Case 1 waveform, the amplitude at a higher frequency range (i.e., at the later part of the waveform) gradually decreases. This is due to the frequency dependence of absorption loss, 

\[ 10^{-0.05 \alpha(f)} \]

The amplitude decrease at a higher frequency range, as in the Case 2 waveform, is greater than that of the Case 1 waveform. This is due to \( D(f) \) as a function of \( \theta \). The Case 1 waveform was not affected by \( D(f) \), because the target was positioned on the beam axis (\( \theta = 0° \)). However, \( D(f) \) at \( \theta = 2° \) greatly decreases in Case 2 depending on the frequency. The amplitude of the Case 3 waveform is smaller than that of the Case 2 waveform. This is due to spherical spreading loss \( r^{-4} e^{ikr} \). The range of the Case 3 \( (r = 50\, \text{m}) \) is greater than that of Case 2 \( (r = 25\, \text{m}) \), and therefore the effect of the spherical spreading loss is greater.

These single-target echo waveforms cannot be strictly verified. However, the author validated that their target strengths, which were determined by the same signal processing used for actual single-target echo waveforms, including pulse compression processing, coincided with predicted target strengths \( TS_{\text{pred}}(f) = 10\log_{10}|F_{bs}(f)|^2 \), where \( F_{bs}(f) \) is the exact modal series solution used for the simulation (Fig. 3).

3. Application: Verification of a signal processing procedure for volume backscattering strengths

In order to verify a signal processing procedure for volume backscattering strengths, multiple-target echo waveforms, including a specific volume backscattering strength (assumed value), were generated. Verification of the signal processing procedure was performed by comparing the volume backscattering strength, determined by processing these multiple-target echo waveforms, with the assumed volume backscattering strength.

3.1 Generation of broadband multiple-target echo waveforms

An aggregation of 38.1-mm-diameter tungsten carbide spheres was assumed. Although not realistic, this assumption was simple from the viewpoint of acoustic scattering and suitable for the purposes of this study. The aggregation shape was assumed as a rectangular parallelepiped with a size larger than twice the 95% beam width for the volume reverberation theory (e.g., Ref. 23). Its dimensions were 25 m long × 25 m wide × 20 m thick. The depth of the upper end of the aggregation was 20 m. The number of targets (i.e., the number of simulated single-target echo waveforms) was 100,000. The volume of the aggregation was 12,500 m\(^3\), and thus, the numerical density of the targets \( n \) was 8 number/m\(^3\). Each target position \((x, y, z)\) in a rectangular coordinate system was given by uniform random numbers. The rectangular coordinates were then converted into spherical coordinates \((r, \theta, \varphi)\). The origin of the coordinate systems was the center of the transducer face. Using \( r \) and \( \theta \), each single-target echo waveform was simu-
lated by the method described in Sec. 2. \( p(t) \), \( a \), \( c \), temperature, and salinity were the same as the simulation conditions listed in Table 1. A multiple-target echo waveform for one ping was obtained by summing all single-target echo waveforms. In this study, multiple-target echo waveforms of 120 pings were generated. The target positions were changed for each ping. An example of a multiple-target echo waveform for one ping is shown in Fig. 4.

3.2 Signal processing procedure for volume backscattering strength

The signal processing procedure that was used, including pulse compression processing, was mostly followed that described in Stanton et al.\(^9\) Volume backscattering strength \( SV(f) \) is expressed as \( SV(f) = 10 \log s_v(f) \), where \( s_v(f) \) is the volume backscattering coefficient. Using the variables shown in Fig. 5, \( s_v(f) \) is expressed as

\[
s_v(f) = \frac{|P_{\text{gate}}(f)|^2}{|P_t(f)|^2 |L_{\text{vol}}(f)|^2 (c \ t_{\text{gate}} / 2) r_{\text{vol}}^2 \Psi(f)}
\]

(5)

where \( P_{\text{gate}}(f) \) is the Fourier transform of a multiple-target echo waveform for a time gate \( t_{\text{gate}} \); \( t_{\text{gate}} \) is equal to the time gate of echo integration (i.e., the thickness of the gated volume \( c t_{\text{gate}} / 2 \) shown in Fig. 5 is equal to the echo integration layer); and \( P_t(f) \) is the Fourier transform of \( p_t(t) \). Pulse compression processing\(^9,17,21\) can be applied to the multiple-target echo waveform and to \( p_t(t) \) before the Fourier transformation. \( L_{\text{vol}}(f) \) is the transmission loss \( (= r_{\text{vol}}^{-1} e^{ikr_{\text{vol}}} 10^{-0.05\alpha(f)r_{\text{vol}}}) \), where \( r_{\text{vol}} \) is the range from the transducer to half of the thickness of the gated volume), and \( \Psi(f) \) is the equivalent beam angle.

\( s_v(f) \) is obtained by the following procedure. The processing is performed for each ping.

1) Pulse compression processing is applied to a multiple-target echo waveform. \( p_t(t) \) is used as the replica signal.

2) The compressed echo waveform is split into \( t_{\text{gate}} \) segments (layers). \( t_{\text{gate}} \) is chosen to be much longer than pulse duration after pulse compression processing.\(^9\) In this study, \( t_{\text{gate}} \) was 1.024 ms (the thickness of the gated volume is approximately 0.77 m at \( c = 1500 \) m/s). This is equal to 512 points at a 500-kHz sampling rate.

3) \( P_{\text{gate}}(f) \) in each layer is calculated. Although the number of points in each layer is 512, the waveform in each layer is zero-padded to 1024 points before the Fourier transformation. Thus,
spectral resolution is approximately 0.5 kHz.

4) The variables in Eq. (5) are all determined, and then the \( s_v(f) \) of each layer is calculated. \( \Psi(f) \) is given by the approximate expression 
\[ 5.78/(ka)^2 \]
for an ideal circular piston source.\(^{24} \)

The \( s_v(f) \) obtained by the above procedure is the volume backscattering coefficient for a small cell, 1 layer \((0.77 \text{ m}) \times 1 \text{ ping}\). This is close to the “raw” volume backscattering coefficient,\(^{25} \) and the variation between layers or pings is large. Therefore, the raw \( s_v(f) \) results in a region of interest are averaged over layers and pings to reduce their variations.

3.3 Results and discussion

The volume backscattering strengths determined from the generated multiple-target echo waveforms are shown in Fig. 6. The assumed volume backscattering strengths \([SV_{asmd}(f) = 10 \log n + TS_{pred}(f)]\) for generating the multiple-target echo waveforms are also shown for verification purposes. The number of pings and layers used for averaging was varied. The upper left plot of Fig. 6 shows a raw \( s_v(f) \). The difference in \( \varepsilon \) between \( SV_{asmd}(f) \) and \( SV(f) \) is shown in the upper right in each plot. The definition of \( \varepsilon \) is expressed as
\[
\varepsilon = \frac{1}{N} \sum_{j=1}^{N} |SV_{asmd}(f_j) - SV(f_j)|
\]
where the subscript \( j \) denotes the \( j \)th frequency in the 40–200 kHz range and \( N = 329 \).

\( SV(f) \) for 13 layers \( \times 30 \) pings (the lower right plot of Fig. 6), the highest number of layers and pings used for averaging, coincided with \( SV_{asmd}(f) \) very well \((\varepsilon = 0.3 \text{ dB})\). \( SV(f) \) for 13 layers \( \times 5 \) pings, 13 layers \( \times 15 \) pings, 7 layers \( \times 15 \) pings, and 7 layers \( \times 30 \) pings also coincided well with \( SV_{asmd}(f) \) \((\varepsilon \leq 0.5 \text{ dB})\). Therefore, the signal processing procedure for determining volume backscattering strengths from multiple-target echo waveforms was verified. In the cases where few layers and pings were used for averaging (e.g., the left plots and upper plots of Fig. 6), \( \varepsilon \) was clearly large. This was due to insufficient values for averaging processing.

Fig. 6 Comparison of the volume backscattering strengths derived from the simulated broadband multiple-target echo waveforms (red lines) and the assumed volume backscattering strengths (black lines) for different numbers of pings and layers.
4. Summary and conclusion

In this study, a computer simulation method of broadband single-target echo waveforms that takes into account not only the backscattering amplitude of a target but also transducer directivities and transmission losses was presented for simulation studies using broadband signals. For the study, a 38.1-mm-diameter tungsten carbide sphere was assumed as a target to simplify the backscattering process by a target (i.e., effects of orientation on the backscattering could be ignored). However, if the modal-series-based prolate spheroid model and the distorted wave Born approximation-based prolate spheroid model were used, swimbladder fish and krill could be assumed as targets, and their orientation distribution could also be taken into account in the simulation.

The presented computer simulation method was applied to validate the signal processing procedure for determining volume backscattering strengths from broadband multiple-target echo waveforms. As a result, the validity of the signal processing procedure was confirmed. It is noteworthy that if not for computer simulation methods, exact validation could not be performed. The verified signal processing procedure will be applied to fieldwork using a broadband echosounder.

More realistic aggregation shape, size- and orientation distributions can be taken into account in the simulation, as in Furusawa. The generated multiple-target echo waveforms will be applicable to studies on species-identification methods. A noise can be added to single- or multiple-target echo waveforms, allowing investigation of the effect of signal-to-noise ratio on measuring target strengths and volume backscattering strengths. Additionally, the simulation can be applied to studies on single-target detection algorithms, the validation of post-processing software, and others.

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