Development of the Parametric Sub-Bottom Profiler for Autonomous Underwater Vehicles and the Application of Continuous Wavelet Transform for Sediment Layer Detections

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Abstract:

The exploration of deposits buried under sea sediment requires high directivity and low attenuation beams. The parametric sub-bottom profiler (PSBP) meets these requirements. Moreover, it is comparatively small and can be easily mounted on autonomous underwater vehicles (AUVs), which are both highly stable and able to operate close to the target. A new PSBP system for AUVs has been developed for this purpose, and we present recent results from its development. The performance of the PSBP system was estimated using a sonar equation with the Biot–Stoll model, and the results showed that the secondary/primary wave with low/high frequency was valid for measurements under thick/thin sediment. A field test was conducted at Beppu Bay, and a new data-processing method based on the continuous wavelet transform (CWT) was applied to the data. The method increased S/N, and some layers under the sea bottom could be clearly detected in the acoustic data. One example of such data obtained during the sea trials was compared with core data (BP09-3), and the peaks in the acoustic data agreed with the positions of the layers in the core. Thus, the PSBP system will be suitable for exploring buried deposits using AUVs in deep-sea areas.

Classification: Physical acoustics · Seabed acoustics, Signal processing

Keywords: parametric sub-bottom profiler, wavelet transform, sediment, Biot–Stoll, autonomous underwater vehicle

1. Introduction

The global demand for metals is increasing with the population and economic growth of countries.1, 2) A number of countries are concerned about the risk of certain metals becoming scarce, and are looking for new sources of these metals, including marine mineral resources.3) In Japan, exploration and mining of marine mineral resources in the exclusive

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The economic zone (EEZ) is required; thus, various exploration methods have been developed under national projects.

Acoustic methods are widely acknowledged to be a useful tool for exploration, since the attenuation of sound waves in water is lower than that of other methods, such as optic and magnetic. Several acoustic devices are used for surveying, including the multi-beam sonar, side-scan sonar (SSS), and sub-bottom profiler (SBP). The multi-beam sonar is usually used for making bathymetry maps, and the survey strategy is developed using the map at the first step of the survey. SSS provides acoustic images based on the backscatter from the seabed, and such images are often used for the detection of targets, or to understand types of sea sediments. The SBP is used to obtain information regarding the layer structure under the sea bottom, or to detect objects buried under the sea sediment. These acoustic devices are usually equipped on survey platforms, such as a survey vessel, deep-tow, remotely operated vehicle (ROV), or autonomous underwater vehicle (AUV), depending on the intended use. For sampling high-resolution, high-quality acoustic data in deep-sea areas, an AUV is one of the best solutions, due to its stability and ability to operate close to the target. AUVs equipped with multi-beam sonar or SSS have provided us with high-quality bathymetry maps and acoustic images, and contributed to the discovery of active hydrothermal deposits, which are a type of marine mineral resource. However, the mining of active hydrothermal deposits is not easy, since the temperature is extremely high and several sulfide benthic species live there. Therefore, the discovery of non-active deposits is urgently needed, and it is assumed that such deposits (referred to as buried deposits) exist under the sea sediment.

The SBP is considered to be a good tool for the exploration of buried deposits, because it provides information regarding what is under the sea sediment. In the past, several types of SBP devices have been developed for different purposes: continuous wave pulse, chirp signal, and parametric, each of which has unique characteristics. The exploration of buried deposits requires a high-directivity acoustic beam in order to minimize sediment reverberation and increase the position accuracy of the detected target. In these devices, the parametric sub-bottom profiler (PSBP) meets the requirement with low-frequency. In addition, PSBPs are comparatively small and light, and can be easily mounted on AUVs. Thus, the PSBP is suitable for exploration. For this reason, we are currently developing a new PSBP system for AUVs to explore buried deposits in deep-sea areas.

This paper presents recent results for the PSBP system we are developing. We introduce the design concept and estimate system performance using a sonar equation with a simple two-layer model. The sound speed and attenuation of several sediments are calculated using the Biot–Stoll model, and then used in the sonar equation. Results of the experimental study conducted at Beppu Bay are also presented, and a new data-processing method based on the continuous wavelet transform (CWT) is proposed and applied to the data. An example of acoustic data obtained during the sea trials is compared with core data revealed by Kuwae et al. and Yamada et al.11, 12)

2. Tools and methods
2.1 Parametric sub-bottom profiler system for AUV

The PSBP transmits two signals at slightly different primary high frequencies, and at high sound pressure. The non-linear properties of the two signals in sound propagation at high pressures
interact, and new frequencies (sum, difference, and harmonic) increase. The difference in the transmitted frequencies, referred to as the secondary frequency, is low. The following is a list of the general characteristics of the PSBP:

– A narrow beam similar to the high-frequency primaries, with no side lobes
– Low attenuation in sediment
– Smaller in size than a linear sub-bottom profiler at the same frequency
– Low generation efficiency from primary to secondary wave
– Poor short-range performance

A narrow beam with no side lobes can reduce acoustic virtual images from other reflectors and reverberations, Hence, it is suitable for surveys on slopes and irregular surface areas where sea-floor hydrothermal deposits are found. In addition, the small transducer is good for AUVs, where space and payload are always limited. Therefore, an AUV with a PSBP system is a good tool for high-resolution sampling of data under the sea bottom, and would be able to determine target positions with a high degree of accuracy. This capability of target determination will impact subsequent strategies for exploration and sampling of buried deposits (e.g., drilling).

As mentioned above, the PSBP has many advantages in terms of exploration of buried deposits. For this reason, we are developing a new PSBP system for AUVs. Specifications of our new PSBP are listed in Table 1. As may be seen in the table, we have developed the control unit and power amplifier to be as small as possible, to ensure the PSBP system is compact and suitable for AUVs, which are also comparatively small (e.g., our AUV is 4.0 m long, and weighs 800 kg in air).

In addition to the advantages, the disadvantage of poor generation efficiency from primary to secondary waves should be considered. The generation source level of the secondary wave is 1% less than that of the primary wave. This poor efficiency

| Table 1 Specifications of PSBP. |
|----------------------------------|
| **Transducers**                  |
| Structure                        | Ring array                     |
| Type                             | 1–3 Piezocomposite             |
| Channel                          | Tx: 5ch, Rx: 5ch (embedded alternately) |
| Diameter                         | 0.3 m                          |
| Depth rating                     | 3,000 m                        |
| Water depth range                | 100 m                          |
| Transmitter beam width (−3 dB)   | ca. 6°                          |
| Primary transmitter frequency    | ca. 50 kHz                     |
| Secondary transmitter frequency  | [frequency band (−6 dB) 45–55 kHz] |
| **Primary source level**         | > 230 dB/µPa re 1 m            |
| **Control unit**                 | center frequency 0.5–10 kHz    |
| Ping rate                        | 1 or 2 Hz                      |
| Sampling rate                    | up to 1 Mspfs                  |
| Receiver gain control            | > 42 dB                        |
| Size                             | D 0.3 m × L 0.2 m              |
| **Power amplifier**              |                                |
| Pulse length                     | > 2.0 ms                       |
| Peak power output                | 32 kW (pulse)                  |
| Size                             | D 0.3 m × L 0.7 m              |
| Repetition rate                  | > 2 Hz                         |
limits the performance of the PSBP system. The detection capability of the PSBP system will be estimated in the next section.

2.2 Estimation of detection level

2.2.1 Sonar equation

A simple two-layer model (Fig. 1) was used to estimate the detection capability of the PSBP system. In this model, five types of sediment (clay, silt, fine sand, medium sand, and coarse sand) and one rock type (basalt) were prepared as upper and lower layers. As shown in Fig. 1, the wave travel path between transducers and the top of the rock layer was considered. The wave propagation distance in water and sediment are \( r \) and \( d \) [m]. Sound speeds in water, sediment, and rock are \( c_w \), \( c_s \), and \( c_r \) [m/s], respectively. Density in water, sediment, and rock are \( \rho_w \), \( \rho_s \), and \( \rho_r \) [kg/m\(^3\)], respectively. The attenuation coefficient in sediment is \( \alpha_s \) [dB/m].

The sonar equation was derived to estimate the echo level from the top of the rock layer, known as detection level \( DL \). Two frequencies, 50kHz (primary) and 10kHz, (secondary) were used for the \( DL \) estimations. Here, to formularize the sonar equation, previous papers were referenced\(^{15}\) and changed to fit our situation. In this equation, propagation, reflection, and transmission were treated as linear.

\[
DL = SL - PG - DL_{w,s} - TL_{w,s} - AL_s - RT_{r,s,s} - TL_{s,w} + RVS + RG + SPG,
\]

where \( SL \) is the transmitter source level at 1m, and a design value of 230dB re: 1\( \mu \)Pa/Vrms is used. \( PG \) is the generation efficiency from primary to secondary wave, set to 40dB (1%)\(^{14}\) for the case of 10kHz, and zero for 50kHz. \( DL_{w,s} \) is the diffusion loss in water and sediment. Here, we assumed that the point source was set 1m from the transducer, and the diffusion loss was \(-6\)dB/DD (double distance). In this case, the diffusion loss can be expressed as:

\[
DL_{w,s} = 20 \log 2(r+d).
\]

Fig. 1 Simple two-layer model for the DL estimation. The sonar equation was derived based on the model. Five types of sediments (clay, silt, fine sand, medium sand, and coarse sand) were prepared for this model.
Here, \( c_w \) was 1,521 m/s and \( \rho_w \) was 1,025 kg/m
\(^3\) for a water temperature of 20°C, and salinity of 35 ppt. The parameters \( c_w \) and \( \rho_s \) vary depending on the types of sediments, and will be calculated in the next section. \( AL \) is absorption loss in sediment, and is expressed as follows,

\[
AL_s = 2\alpha_s d. \tag{5}
\]

Here, absorption loss in water was much smaller than the other loss; hence, it was neglected in Eq. (1). The parameter \( \alpha_s \) also varied, depending on the types of sediments, and will be calculated in the next section.

\( RL_{s,r} \) is a reflection loss at the boundary between the sediment and rock, and reflection coefficient \( R_{s,r} \) is given by

\[
R_{s,r} = \frac{\rho_f c_r - \rho_s c_s}{\rho_f c_r + \rho_s c_s}, \tag{6}
\]

and

\[
RL_{s,r} = -20 \log(R_{s,r}). \tag{7}
\]

Here, \( c_r \) was 5,700 m/s, and \( \rho_r \) was 2,900 kg/m
\(^3\). \( RVS \) is the receiver voltage sensitivity and a design value of −210 dB re: 1 V rms/µPa at 50 kHz and −190 dB re: 1 V rms/µPa at 10 kHz were used. \( RG \) is receiver gain and was set to 40 dB, which was used for the actual situation. \( SPG \) is the signal processing gain, and was set to zero, because it depends strongly on the types of noise and the signal processing method. \( SPG \) usually increases the \( DL \). To detect the echo signal from the rock under the sediment, the \( DL \) needs to exceed the noise level \( NL \). Here, \( NL \) means the total noise, which includes a variety noises (e.g., undersea, other artificial, platform, and electrical noises), determined by the conditions around the survey site.

2.2.2 Biot-Stoll model

As discussed in the previous section, the physical parameters in sediment, \( c_s, \rho_s, \) and \( \alpha_s \), vary depending on the types of sediments, and affect the \( DL \). Therefore, these physical parameters are important, and we calculated them using the Biot–Stoll model.\(^{17-19}\) The Biot–Stoll model is a widely used and useful tool for analyzing complex acoustic wave propagation in porous marine sediment.\(^{17-21}\) Porous marine sediment is composed of grains, which make a skeletal frame, and porous seawater. Kimura et al. summarized the characteristics of the Biot–Stoll model, and reported some comparisons between numerical and experimental results.\(^{20, 21}\) Calculation of the parameters requires 13 physical parameters, and the longitudinal wave equations in porous saturated media are expressed as follows:

\[
\nabla^2(He - C\zeta) = \frac{\partial^2}{\partial t^2}(\rho e - \rho_f \zeta),
\]

\[
\nabla^2(Ce - M\zeta) = \frac{\partial^2}{\partial t^2}(\rho_f e - m\zeta) - \frac{F_y}{k} \frac{\partial \zeta}{\partial t}. \tag{8}
\]

In Eq. (8),

\[
e = \text{div}(u),
\]

\[
\zeta = \beta \text{div}(u - U) \tag{9}
\]

where \( u \) is the displacement of the frame, \( U \) is the displacement of the pore fluid, and \( \beta \) is the porosity. Here, \( H, C, M, \) and \( D \) are calculated by the bulk moduli of the pore fluid and grain (\( K_f \) and \( K_r \)), and the bulk and shear moduli of the frame (\( K_s \) and \( \mu \)) [detailed information is given in ref. (21)]. The total density of the sediment \( \rho_s \) is derived by,

\[
\rho_s = \beta \rho_f + (1-\beta) \rho_r, \tag{10}
\]

where \( \rho_f \) and \( \rho_r \) are the densities of the pore fluid
and grain. The density parameter $m$ in Eq. (8) is expressed as,

$$m = \alpha \frac{\beta f}{\beta}$$

(11)

where $\alpha$ is the structural factor when considering the non-uniformity of the pore fluid. The viscous resistance to fluid flow is given by the ratio $\eta/k$ ($\eta$ is the fluid viscosity and $k$ is the permeability) and the viscous correction factor $F$.\(^{21)}\)

To obtain a frequency equation, the solutions of the form

$$e = A_1 \exp[j(\omega t - k_x)]$$

and

$$\xi = A_2 \exp[j(\omega t - k_x)],$$

(12)

are considered with the $k_x$ complex ($k_x = \tilde{k}_0 + jk_l$), the angular frequency $\omega$, and the wave propagation distance $x$. When this is done, the following frequency equation is given as,

$$\begin{bmatrix}
Hk_t^2 - \rho \omega^2 & \rho_j \omega^2 - Ck_t^2 \\
Ck_t^2 - \rho_j \omega^2 & m\omega^2 - Mk_t^2 - \frac{\omega F \eta}{k}
\end{bmatrix} = 0.\quad (13)
$$

The roots of this frequency equation yielded the sound speed of the longitudinal wave $c_s = \omega/k_t$ [m/s] and the attenuation coefficient $\alpha_s = 8.86k_t$ [dB/m].

In this study, we calculated the parameters $c_s$ and $\alpha_s$ for five types of sediment (clay, silt, fine sand, medium sand, and coarse sand). The values of the parameters used for the calculation are listed in Table 2.

2.3 Field data sampling

A field test was carried out to activate the PSBP and obtain acoustic data. The data was acquired in July 2015 in Beppu Bay, southwest Japan. The survey boat (Kaiko-maru), equipped with the PSBP, was used for the field test, and the control unit and power amplifier were installed in the operation room of the boat. Boat position was recorded by global positioning system (GPS) (BR-344-S4, Globalsat Technology, Taiwan). The 45kHz and 55kHz sinusoidal pulses were electrically added and used for the transmit signal. Therefore, the averaged frequency of the primary waves was set to 50kHz, and the frequency difference was 10kHz. The receiver gain was set to 40dB. The acoustic surveys were carried out at an approximate speed of 3–4 knots, and with a ping rate of 2Hz. In this paper, the two sets of acoustic data acquired in survey line A (from 33.265558°N, 131.607869°E to 33.273935°N, 131.604479°E, survey length was 1,008 m) and line B (from 33.273248°N, 131.538352°E to 33.273282°N, 131.528911°E, survey length was 917 m) are shown in the results section. Beppu Bay is a good area to test the PSBP because some of the preserved sediments have already been located, and sedimentary core results have been reported.\(^{11, 12)}\) Core sample BP09-3, with a 9.1-m void free length, was recovered from a point in Beppu Bay (33.273347°N, 131.536647°E) in March 2009, during cruise KT-09-1.\(^{11)}\) Survey line B includes the core sampling position.

2.4 Data processing

2.4.1 Continuous wavelet transform

Acoustic data is usually processed to reduce noise and extract the appropriate data information, which is called filtering. For acoustic data processing, the spectra of acoustic data are usually calculated, and the Fourier transform (FT) or the fast Fourier transform (FFT) is one of the more popular tools used for the calculation. However, the
FT is not suited for localized spectrum analysis in time, and it is not appropriate to apply it to a non-stationary time series. The PSBP provides high-resolution acoustic data at primary and secondary frequencies with different acoustic characteristics; therefore, a method that reflects the time-frequency structure would be more appropriate for the analysis of the high-resolution data. One of the basic techniques for time-frequency analysis is the short-time Fourier transform (STFT). The signal is multiplied by a window function for a short period of time, and as the window is slid along the time axis, the FT is taken for the windowed acoustic data. This operation generates a non-stationary spectrum represented with time, and it enables time-frequency analysis.

STFT also, however, has a limitation of resolution in time and frequency domains due to the indeterminacy principle. Since the window size is fixed in STFT, the frequency resolution is also fixed, and the window size is related to the frequency resolution. Therefore, it is not possible to increase both the resolution of time and of frequency in the time-frequency analysis. It also means that the time-frequency analysis of high (primary) and low (secondary) frequency components with optimal resolution is difficult by STFT.

To circumvent the problems in STFT, the wavelet transform (WT) was proposed in the early 1980s for the analysis of seismic data, and has since been applied in various other scientific fields. The WT enables us to obtain orthonormal basis expansions of a signal using wavelets that have good properties for localization in time and frequency domains. Therefore, the WT is suitable for the both time-frequency analysis of high (primary) and low (secondary) frequency components.

Table 2 Biot–Stoll parameters of marine sediments.

| Physical parameters | Clay | Silt | Fine sand | Medium sand | Coarse sand |
|---------------------|------|------|-----------|-------------|-------------|
| Grain               |      |      |           |             |             |
| Grain Diameter* $d_i$ (mm) | 0.0049 | 0.0221 | 0.0884 | 0.354 | 0.75 |
| Grain Density $\rho_i$ (kg/m$^3$) | 2650 | 2650 | 2650 | 2650 | 2650 |
| Bulk modulus $K_i$ (Pa) | $3.6 \times 10^{10}$ | $3.6 \times 10^{10}$ | $3.6 \times 10^{10}$ | $3.6 \times 10^{10}$ | $3.6 \times 10^{10}$ |
| Pore fluid         |      |      |           |             |             |
| Pore fluid Density $\rho_f$ (kg/m$^3$) | 1025 | 1025 | 1025 | 1025 | 1025 |
| Bulk modulus $K_f$ (Pa) | $2.37 \times 10^9$ | $2.37 \times 10^9$ | $2.37 \times 10^9$ | $2.37 \times 10^9$ | $2.37 \times 10^9$ |
| Viscosity $\eta$ (Pa·s) | 1.01 $\times 10^{-3}$ | 1.01 $\times 10^{-3}$ | 1.01 $\times 10^{-3}$ | 1.01 $\times 10^{-3}$ | 1.01 $\times 10^{-3}$ |
| Frame              |      |      |           |             |             |
| Porosity $\beta$   | 0.73 | 0.61 | 0.50 | 0.39 | 0.33 |
| Permeability $k$ (m$^2$) | $7.46 \times 10^{-12}$ | $4.22 \times 10^{-12}$ | $2.25 \times 10^{-11}$ | $1.15 \times 10^{-10}$ | $2.61 \times 10^{-10}$ |
| Pore size $a$ (m)  | $0.45 \times 10^{-5}$ | $1.17 \times 10^{-5}$ | $2.99 \times 10^{-5}$ | $7.65 \times 10^{-5}$ | $12.5 \times 10^{-5}$ |
| Structure factor $\alpha$ | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |
| Bulk modulus $K_b$ (Pa) | $1.25 \times 10^{9}$ | $1.25 \times 10^{9}$ | 3.69 $\times 10^{9}$ | 1.09 $\times 10^{9}$ | 1.95 $\times 10^{9}$ |
| Bulk logarithmic decrement $\delta$ | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| Shear modulus $\mu_s$ (Pa) | $2.18 \times 10^{9}$ | $4.45 \times 10^{9}$ | $6.32 \times 10^{9}$ | $7.91 \times 10^{9}$ | $8.66 \times 10^{9}$ |
| Shear logarithmic decrement $\delta_s$ | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |

* $\phi = - \log_2(d_i)$
of base functions formed by scaling and the translation of a function called the ‘mother wavelet.’ Continuous wavelet transform (CWT) is expressed as follows \(25\):

\[
W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \psi\left(\frac{t - b}{a}\right) dt,
\]

where \(\psi\) is the mother wavelet, \(a\) is the scaling factor, and \(b\) is a translation of the mother wavelet.

As shown in Eq. (14), CWT calculates the correlation between the objective data and the wavelet function. Translation of the wavelet function is related to the localization, and the scaling operation is similar to frequency changes. Therefore, the CWT provides a flexible time-scale window, and represents the time-frequency structure of the data without the indeterminacy principle. The noise includes a variety of noises (e.g., undersea, other artificial, platform, and electrical noises) and is affected by the conditions around the survey site. Therefore, the flexible time-scale window is suitable for the time-frequency analysis of the noise. Some mother wavelet functions have been proposed for the WT, and the choice is usually guided by certain considerations. Based on the features of mother wavelets that have been reported, we selected the Gabor wavelet for this analysis.\(^{25, 26}\)

The Gabor wavelet is a multiplied exponent function by Gaussian window expressed as follows:

\[
\psi(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{t^2}{2\sigma^2}} e^{j\omega_0 t},
\]

where \(\sigma\) is the dispersion in the Gaussian window. One property of the Gabor wavelet is that it minimizes the standard deviation between the time and frequency domains; hence, it provides optimal resolution in both domains. In addition, the Gabor wavelet is good for the extraction of local features and seems to be suitable for the analysis of acoustic data provided by the PSBP.

2.4.2 Model for validation

To validate the CWT technique, a simple wave model was prepared (Fig. 2). The wave model included 6 mixed pulses, formed by the summation of 5 pulses at 50kHz and 1 pulse at 10kHz (center frequencies). The sampling interval of the data was 1 \(\mu\)s (1 Msps) and the data number was 13,568. The intervals between the 6 mixed pulses were labeled T, 2T, 3T, 4T, and 5T, respectively. T was the time period of the wave at 10kHz. Although, as already mentioned, the CWT is suitable for the time-frequency analysis, the effects of \(\sigma\) in the Gabor wavelet should be considered. Therefore, CWT was applied to the wave model at \(\sigma=1.0, 2.0,\) and 3.0, and spectrograms were represented for validation.

3. Results and Discussion

3.1 Sound speed and attenuation in sediments calculated by Biot–Stoll model

The calculation results of sound speeds in sediments are shown in Fig. 3(a). The sound speed at 50kHz increased when grain size increased. The minimum value was 1,481 m/s in clay, and the maximum was 1,860 m/s in coarse sand. The sound speed at 10kHz also increased when the grain size increased, and the minimum value was 1,472 m/s in clay, while the maximum value was 1,853 m/s in coarse sand. The results show that both the reflection loss \(RL_{s,r}\) and transmission loss \(TL_{r,t}\) depend on the type of sediment. The \(RL_{s,r}\) at 50kHz was 2.3 dB in clay and 4.2 dB in coarse sand, and the \(RL_{s,r}\) at 10kHz was 2.2 dB in clay and 4.2 dB in coarse sand. The \(TL_{r,t}\) at 50kHz was 0.2 dB in clay and 1.8 dB in coarse sand, and the \(TL_{r,t}\) at 10kHz was 0.2 dB in clay and 1.8 dB in coarse sand. Therefore the sum of \(RL_{s,r}\) and \(TL_{r,t}\) loss in clay was smaller than that in coarse sand. In addition, sound speed at 50kHz was faster than at 10kHz, and the differ-
ence in speed between 50 and 10 kHz changed with grain size. The maximum difference was about 42 m/s in silt (ca. 2.6%).

The attenuations in sediments calculated by the Biot–Stoll model are shown in Fig. 3(b). The attenuation at 50 kHz decreased when grain size increased. The minimum value at 50 kHz was 4.5 dB/m in coarse sand, and the maximum value was 27.7 dB/m in silt. On the other hand, attenuation at 10 kHz showed a maximum value of 7.1 dB/m in silt, and a minimum value of 1.1 dB/m in clay. As shown in Fig. 3(b), attenuation was strongly influenced by type of sediment and frequency. For these reasons, sound, speed, and attenuation in sediment affect the losses in Eq. (1).

3.2 Detection level

The estimated DLs at 50 kHz (primary) and 10 kHz (secondary) are shown in Fig. 4(a)–(b). Here, the NL was set to 36 dB, which was measured during the field test at Beppu Bay. The PSBP system has a “listening mode” in which the system does not transmit waves but only records data. In this case, we activated the PSBP system and recorded the data while the boat was running, and then calculated the root-mean-square deviation as the NL in the data. As previously mentioned, the NL changes depending on the survey conditions (e.g., platform, survey site, water depth), which required to be measured for each survey. The distance $d$ indicates the maximum thickness of the sediment that the echo signal detected from the rock layer. In the case of 50 kHz, the $d$ were 1.2 m in clay, 1.0 m in silt, 1.4 m in fine sand, 3.2 m in medium sand, and 5.5 m in coarse sand. In the case of 10 kHz, the $d$ were 14.1 m in clay, 2.3 m in silt, 2.9 m in fine sand, 5.0 m in medium sand, and 7.9 m in coarse sand. Therefore, the value of $d$ at 10 kHz
was larger than at 50 kHz. This means that the secondary wave was appropriate for detecting rock under the sediment, in particular that with a thickness of ca. 15 m. On the other hand, the primary wave was appropriate for detecting rock under the sediment when the sediment is thin, because of the low generation efficiency from the primary to the secondary wave. The \( d \) at the cross points of the \( DL \) at 50 kHz and 10 kHz were 0.5 m in clay, 0.5 m in silt, 0.8 m in fine sand, 2.0 m in medium sand, and 3.7 m in coarse sand. Therefore, the value of the \( DL \) at 50 kHz was larger than that at 10 kHz when the thickness of sediment was thinner than the distance at the cross point. Thus, the primary wave is suitable for detecting rock under thin sediment, the secondary wave for detecting rock under thick sediment, and the condition is dependent on the type of sediment. Consequently, the primary wave is appropriate for detecting the surface of the sea bottom.

3.3 Effects of parameter \( \sigma \)

The spectrograms at \( \sigma=1.0, 2.0, \) and 3.0 are shown in Fig. 5(a)–(c). The amplitudes of spectrograms are normalized at each maximum value. Time and frequency resolutions changed with \( \sigma \). The time resolution was best at \( \sigma=1.0 \), and expanded when \( \sigma \) increased. At 50 kHz in the spectrogram, 6 mixed pulses are divided clearly in \( \sigma=1.0, 2.0, \) and 3.0. However, at 10 kHz, the 6 mixed pulses are divided clearly only at \( \sigma=1.0 \). The mixed pulses were not divided when the intervals between pulses were less than 2T at \( \sigma=2.0 \), and 5T at \( \sigma=3.0 \). Therefore the time resolutions at 10 kHz were approximated at T (100 µs) at \( \sigma=1.0 \), 2T (200 µs) at \( \sigma=2.0 \), and 5T (500 µs) at \( \sigma=3.0 \). In addition, strong peaks appeared between the mixed pulses. On the contrary, frequency resolution was best at \( \sigma=3.0 \) and expanded when \( \sigma \) decreased. The frequency resolution affected the performance of noise filtering in the frequency domain. Thus, time and frequency resolutions represent a trade-off, and the \( \sigma \) should be considered for the time-frequency analysis.

3.4 Application of CWT to field data

An acoustic image reconstructed from the acoustic data acquired on Line A is shown in Fig. 6. The envelope of the acoustic data without filtering was used for the image. The round-trip distance was estimated by multiplying the time by a sound speed of 1500 m/s. In actual practice, the sound speed would not be 1500 m/s; however, it helps us to understand the distance in the acoustic image. We were able to find the sea bottom at ca. 35–55 m in the acoustic image, but it includes noise and the layer under the sea bottom is not clear. The waveform at Point A, which is normalized by the
maximum amplitude, is shown in Fig. 7. The echo from the sea bottom was found at ca. 55 m, but the echoes from other layers are not detected clearly. The waveform includes all information from primary and secondary waves, as well as noise. Thus, the S/N was not good.

To analyze the acoustic data in the time-frequency domain, the CWT was applied. The spectrograms are shown in Fig. 8(a)–(c). The components of the primary and secondary waves appear to be ca. 45 kHz and ca. 10 kHz, respectively. In addition, the components of the noise appear to be ca. 13 kHz but less than ca. 5 kHz. We assumed the noise around 13 kHz was generated from the electric circuit in the control unit, and that at less than 5 kHz derived from the boat screw. The degree to which the noise component expanded in the frequency axis changed with $\sigma$. At $\sigma=1.0$, the noise component overlapped the component of the secondary wave, causing problems in terms of filtering. In the spectrograms, at $\sigma=2.0$ and $\sigma=3.0$, however, the components of the noise and secondary wave were separated, and so it is an appropriate filter. As mentioned above, time resolution was better at lower $\sigma$; hence, we use $\sigma=2.0$ for the further analysis and processing of data in this study.

In this case, the time resolution at 10 kHz was more than $2T$ (0.15 m for one-way distance, and 0.075 m round-trip, which means vertical resolution in the acoustic image). The center frequencies of primary and secondary waves were around 45 kHz and 9 kHz, respectively. The center frequency of the secondary wave was slightly lower than the
designed value. The components at the center frequencies of the primary (gray line) and secondary (black line) waves are shown in Fig. 9. The amplitude was normalized by the maximum amplitude of the primary component. The S/N improved, as shown in Fig. 7. The amplitude of the primary component from the sea bottom was clear, but decreased with propagation distance under the sea bottom and disappeared within 2 m. In contrast, the amplitude of the secondary component could be detected within ca. 10 m of the propagation distance under the sea bottom, and echoes from other layers were found. Thus, the application of CWT and the extraction of the primary and secondary components (called filtering) in the time-frequency domain were useful for improving the S/N and detecting the layers under the sea bottom. An acoustic image generated from the data after filtering is shown in Fig. 10. The image uses the summation of the primary and secondary components, and some layers and shapes of the mount around the center under the sea bottom can clearly be seen. From these results, filtering based on the CWT was shown to be a useful tool for detecting the layers under the sea bottom.

3.5 Comparison between acoustic data and core sample

The survey Line B included the position of the BP09-3 core, and the layer structure under the sea bottom that had already been reported\(^1\), \(^1\). Therefore, we could compare the results of the acoustic data with the core sample. The acoustic image, reconstructed from the filtered data acquired in Line B, is shown in Fig. 11, and the position of the BP09-3 is also illustrated. The water depth of the position was about 71 m, and some layers could be clearly observed in the image. According to Kuwae et al. and Yamada et al., the BP09-3 was classified mainly into two types of sediments: low-density sediments and high-density event layers.\(^1\), \(^1\) The low-density sediments are mainly composed of silt and clay, whereas the high-density event layers include sand with a high bulk density.
Accordingly, the attenuation in low-density sediments were comparatively low for the secondary wave, as shown in Fig. 3(b).

Eighteen major event layers were revealed in BP09-3, and it was reported that the percentage of very fine sand was relatively high, especially in event layers Ev. 3, 5, 14, and 15. This increase of sand content brought about the change in bulk density around the boundaries at each event layer, and as a result, the reflection coefficient also changed substantially around layers Ev. 3, 5, 14, and 15. The simple structure of BP09-3 is shown in Fig. 12(a). We defined four layers from the results in (12) as follows: Lay. 1 between the top and middle position of Ev. 3; Lay. 2 between Ev. 3 and Ev. 5; Lay. 3 between Ev. 5 and Ev. 14; and Lay. 4 between Ev. 14 and Ev. 15. The thickness of the layers were as follows: Lay. 1=1.1 m; Lay. 2=1.1 m; Lay. 3=3.6 m; and Lay. 4=0.8 m.

The filtered waveforms at the position of the BP09-3 core are shown in Fig. 12(b). Considering the accuracy of the GPS (≤2.5 m) and the handling of the survey boat, we used an average of the waveforms acquired in 10 consecutive pings (acquired in about a 10-m length of the survey line) around the position of the BP09-3 core for comparison. The gray lines in Fig. 12(b) are each waveform in the 10 pings, and the black line shows the averaged data of the 10 pings.
sound speed of 1500 m/s, which would not be the case in the sediments [shown in Fig. 3(a) at 10 kHz; 1,472 m/s (98% of 1,500 m/s) in clay and 1,522 m/s (101% of 1500 m/s) in silt]. Therefore, the error of the peaks detection was estimated to be ca. 0.1 m. From these results, it was assumed that D4 (3.9 m) reflected Lay. 3 (3.6 m). Hence, D1 (0.6 m) and D2 (1.2 m) reflected Lay. 1 (1.1 m), and D3 (0.9 m) reflected Lay. 2 (1.1 m). Lay. 4 could not be clearly observed in Fig. 12(b). In addition, the difference between D1 and Lay. 1 was relatively high, and the value was 0.5 m. We assume that this difference derived from the potential problem of the piston coring technique. Fluid mud was often on the surface of the sediment, and it is usually difficult to get it correctly, especially in the case of piston coring in deep water. From these results, we detected the five peaks in the acoustic data after filtering based on the CWT, and the peaks showed good consistency with the positions of the layers in the BP09-3 core.

4. Conclusion

The following major conclusions can be drawn from the results of this study.
– The PSBP system for AUVs has been developed and activated without major problems.
– The performance of the PSBP was estimated using a simple two-layer model (sediment and rock). In this estimation, the modified sonar equation was constructed based on the Biot–Stoll model, and the maximum thickness of sediment for the detection of rock layer strongly depended on the type of sediment and frequency. It was shown that the secondary wave with low frequency was valid for thick sediment, while the primary wave with high frequency was effective for thin sediment.
– The CWT was applied to the filtering in time-frequency domains and the effect of $\sigma$ was validated using the simple wave model. The $\sigma$ affected the resolutions of time and frequency, and was set to 2.0 in this study.
– Filtering based on the CWT was performed on the acoustic data acquired in the field test at the Beppu Bay. The filtering improved the S/N of data, and the layers in the sediments could be clearly seen up to around a 10-m depth from the sea bottom in the acoustic image.
– The acoustic data acquired by the PSBP system was compared with the results from the BP09-3 core. The peaks in the acoustic data were consistent with the positions of the layers in the BP09-3 core.

As shown in this paper, the PSBP system has limitations in terms of low generation efficiency from the primary to secondary wave. However, it has the advantages of high resolution and portability. Therefore, the PSBP system is suitable for use in exploring deposits under the sediment with AUVs in deep-sea areas, particularly for a layer thickness of ca. 15 m. In future work, we will test the frequency changes in the secondary wave and optimize the system, including the analysis technique, through field tests in deep-sea areas with the AUV.

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