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Geoacoustic Inversion for Bottom Parameters in the Deep-Water Area of the South China Sea *

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Bottom acoustic parameters play an important role in sound field prediction. Acoustic parameters in deep water are not well understood. Bottom acoustic parameters are sensitive to the transmission-loss (TL) data in the shadow zone of deep water. We propose a multiple-step TL inversion method to invert sound speed, density and attenuation in deep water. Based on a uniform liquid half-space bottom model, sound speed of the bottom is inverted by using the long range TL at low frequency obtained in an acoustic propagation experiment conducted in the South China Sea (SCS) in summer 2014. Meanwhile, bottom density is estimated combining with the Hamilton sediment empirical relationship. Attenuation coefficients at different frequencies are then estimated from the TL data in the shadow zones by using the known sound speed and density as a constraint condition. The nonlinear relationship between attenuation coefficient and frequency is given in the end. The inverted bottom parameters can be used to forecast the transmission loss in the deep water area of SCS very well.

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Acoustic propagation in the ocean is greatly influenced by the properties of bottom acoustic parameters such as sediment sound speed, density, and attenuation. We can obtain the bottom acoustic parameters by direct measurement. However, direct measurement is hard to make, and the obtained data is not widespread. Moreover, direct measurement in deep water is much harder than that in shallow water. Therefore, it is significant to invert the bottom acoustic parameters in a large-scale area of deep water.

Geoacoustic inversion is an important issue in underwater acoustics. In shallow water, a sound wave involves much bottom information due to interactions with the bottom repeatedly, and thus is a proper choice to invert the bottom parameters. Many inversion methods for shallow water have been developed in recent years, such as match-field processing (MFP) inversion,[1,2] methods based on the mode dispersion,[3,4] methods based on the vertical correlation of propagation or reverberation fields,[5] methods based on bottom reflection coefficient,[6,7] methods using pulsed waveform and transmission loss.[8] However, most methods used in shallow water are invalid in deep water due to the obvious differences of propagation characteristics. In addition, the times of sound wave interaction with the bottom become less in deep water, therefore it is difficult to extract bottom parameters from the sound field. With the development of underwater acoustics from shallow to deep water, geoacoustic inversion in deep water needs to be researched in more depth.

A large amount of sound propagation data are acquired in a deep-sea experiment conducted in the SCS, and the TLs are computed. The mean water depth is 4300 m in the experimental area, and the sound speed at the sea surface is greater than that at the bottom. The environment is an incomplete deep-water sound channel, in which sound waves can interact with the bottom many times for long range propagation. The received signals carry much information of seabed parameters; in particular the signals in the acoustic shadow zone mainly consist of bottom reflection energy.[9] Therefore, the bottom acoustic parameters can be well estimated from this kind of acoustic signals.

In this Letter, TL data obtained in the experiment is used to invert bottom parameters, i.e., sound speed, density and attenuation coefficient. The bottom is assumed to be a uniform liquid half-space sea bottom model, and the Hamilton sediment empirical relationship between the sound speed and the density is used in the inversion to reduce the dimension of unknown parameters. Firstly, we introduce the experiment and ocean environments. Secondly, we analyze the sensitivity of TL data to each seabed parameter, from which the inversion mechanism is given. Thirdly, we give the inversion process and the results.

In June 2014, a sound propagation experiment was performed in the deep-water area of the SCS. The experimental equipment layout is shown in Fig. 1. A

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**Corresponding author. Email: lzhl@mail.ioa.ac.cn vertical receiver array is composed of 27 underwater signal recorders (USR) from depth of 100 m to 1800 m. The sensitivities of the hydrophones are two types (−170 dB and −186 dB). The sampling rate of the hydrophones is 16 kHz. The wide band signals (WBS) charged with 1000 g TNT were dropped from Chinese R/V Shi Yan 1 from the Institute of Acoustics, Chinese Academy of Sciences along two propagation tracks with a nearly flat sea bottom. The nominal detonation depth of WBS is 200 m. The bathymetries along the propagation tracks are given in Fig. 2. The whole distance of the track 1 is 250 km and that of track 2 is 170 km. The average depth is about 4300 m.

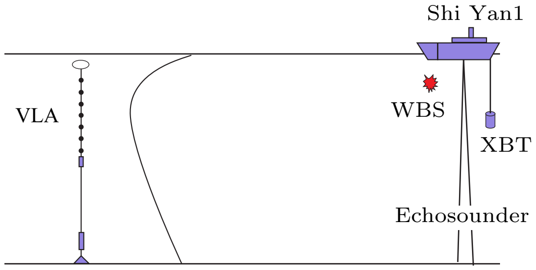

Fig. 1. Experimental configuration.

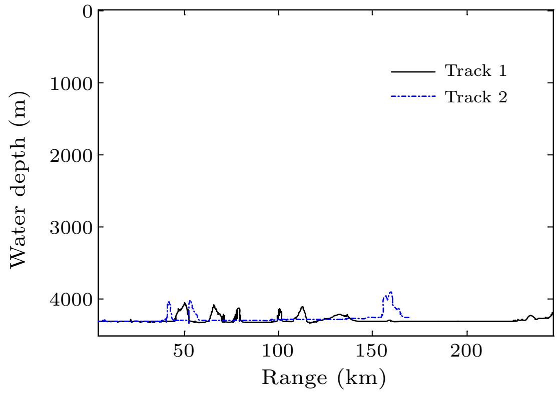

Fig. 2. Bathymetries along two propagation tracks.

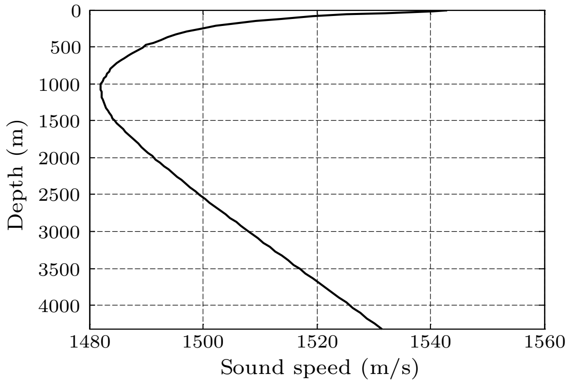

Fig. 3. Sound speed profile in the experimental site.

The sound speed profile shown in Fig. 3 was measured by XBT during the experimental period. The channel axis is at the depth of 1100 m, and the speed at the bottom is 1531 m/s, which is less than that at the sea surface, 1543 m/s.

In the inversion, a uniform liquid half-space sea bottom model is used, which includes parameters, i.e., sound speed c_b, density ρ_b and attenuation coefficient α_b. Under certain conditions, the equivalent model of a single layer can be used to explain some phenomena of acoustic propagation in the ocean.[6]

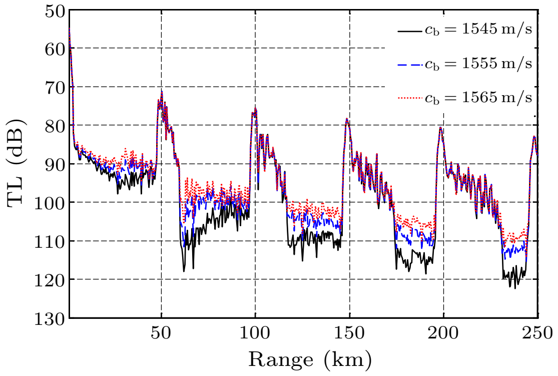

Fig. 4. TLs for different bottom sound speeds ($\alpha_\text{b} = 0.2\,\text{dB}/\lambda$).

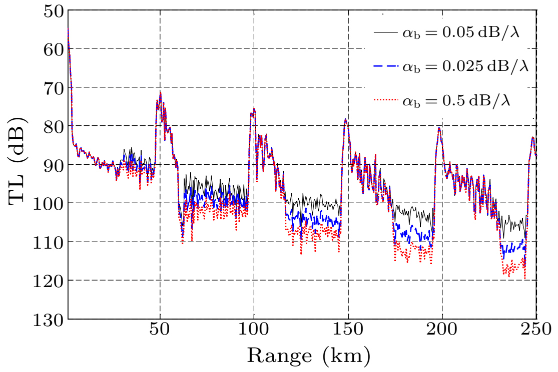

Fig. 5. TLs for different attenuation coefficients ($c_\text{b} = 1555$ m/s)

To determine the inversion method, we first analyze the effects of the bottom parameters on the TL in the experimental area. The BELLHOP[10] ray model is used to calculate the numerical TLs. The TLs with different bottom sound speeds are shown in Fig. 4, in which the source depth is 200 m, the receiver depth is 200 m, the source frequency is 300 Hz, and the attenuation coefficient is $0.2\,\text{dB}/\lambda$.[11] For a given bottom sound speed, the density is obtained by the Hamilton sediment empirical relationship for continental terrace bottom[12] in the calculation,

$$c_\text{b} = 2330.4 - 1257.0\rho_\text{b} + 487.7\rho_\text{b}^2. \tag{1}$$

Reference [12] also provides an empirical relationship for abyssal plain bottom, which is not suitable for this experiment area due to differences of bottom property between SCS and abyssal ocean. Sound speed calculated by Eq. (1) is more reasonable than that calculated by the abyssal empirical relationship. Moreover, the sensitivities of the bottom attenuation are shown in Fig. 5 for the sound speed of 1555 m/s. The other parameters are the same as those in Fig. 4.

As shown in Figs. 4 and 5, the TL in the convergence zones changes slightly with the bottom parameters. In contrast, the TL in the shadow zones are more sensitive to the bottom parameters. Thus the TL data in the shadow zones can be used effectively in the geoacoustic inversion. In addition, the TL in the shadow zones of long distance is affected greater by bottom parameters than that in the first shadow zone. The reason is that as the sound signals propagate a longer distance, the sound waves interact with the bottom more times, then the received signals take more bottom information. Therefore, it is reasonable to use the TL data in the shadow zones of long distance for inversion. In fact, the signal-to-noise ratio (SNR) of propagation signals in the shadow zones might be lower due to larger TL. Thus the TL data in the proper ranges should be chosen in inversion.

Comparing TLs within the range of 20–70 km in Figs. 4 and 5, we can find that TLs are more sensitive to the bottom sound speed than the attenuation coefficient in the first and second shadow zones. Therefore, the inversion method for deep water bottom parameters is proposed, as shown in Fig. 6. We invert the sound speed $c_{\rm b}$ from the low-frequency TLs in the range of 20–70 km and obtain the bottom density from the Hamilton sediment empirical relationship at the same time by choosing a reasonable bottom attenuation coefficient. Then, the attenuation coefficients at different frequencies are inverted from TLs within the range of 70–250 km, which are more sensitive to the bottom attenuation coefficient.

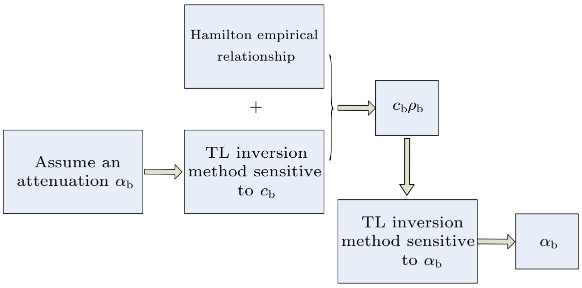

Fig. 6. Flow chart of geoacoustic inversion.

Figure 7 shows the two-dimensional numerical TL for the environment of track 1, in which the source depth is 200 m, the central frequency is 300 Hz, and the solid and the dotted lines indicate the receiver depths of 200 m and 600 m, respectively. It can be seen that the receiver depth near the sea surface has a narrow range of convergence zone and the range of the shadow zone is wide. To obtain more experimental TL data in the shadow zone, we choose the hydrophones close to the surface in geoacoustic inversion.

The cost function used in the bottom sound speed and density inversion is expressed as

$$E(c_{\rm b},\rho_{\rm b})=\frac{1}{\sqrt{NM}}\{\sum_i^N\sum_j^M[TL_{\rm exp}(f_0,r_i,z_j)-TL_{\rm cal}(f_0,r_i,z_j,c_{\rm b},\rho_{\rm b})]^2\}^{1/2},\quad(2)$$

where N and M are the numbers of range and receiver depth, respectively. The measured $TL_{\rm exp}(f_0,r_i,z_j)$ has been analyzed as a function of range r_i and the receiver depth z_j by performing frequency integration over the 1/3-octave bandwidth corresponding to the central frequency f_0. The numerical $TL_{\rm cal}(f_0,r_i,z_j,c_{\rm b},\rho_{\rm b})$ calculated by the BELLHOP model are averaged from coherent TL as Eq. (10) in Ref. [13] at eight frequency points within 1/3-octave bandwidth corresponding to the central frequency f_0.

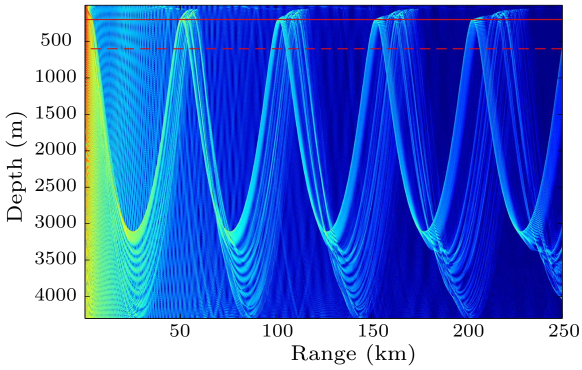

Fig. 7. Two-dimensional TLs for the environment of track 1.

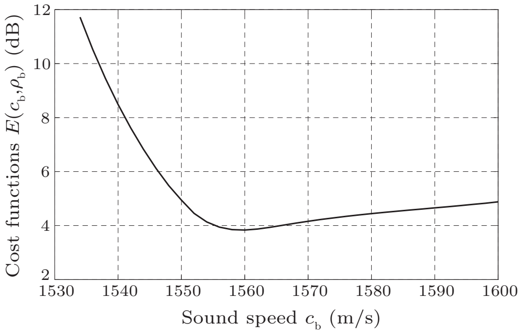

Fig. 8. Cost function for different bottom sound speeds $c_{\rm b}$.

The TL data from 5 hydrophones near the surface (the depths are 141 m, 171 m, 231 m, 272 m and 311 m, respectively) within the range of 20–70 km are used to invert the bottom sound speed and the density at the frequency of 300 Hz. The seabed attenuation coefficient is assumed to be 0.2 dB/λ and the density is estimated from the empirical relationship Eq. (1). The cost functions $E(c_{\rm b},\rho_{\rm b})$ at different bottom sound speeds are shown in Fig. 8. The minimal cost function is derived at the bottom sound speed 1558 m/s. The bottom density is inverted to 1.57 g/cm^3 according to the empirical relationship of Eq. (1).

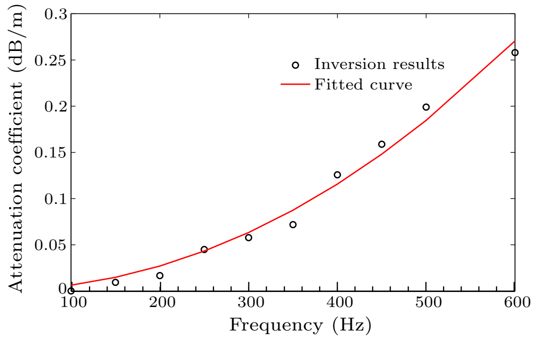

Fig. 9. Inverted attenuation coefficient at different frequencies.

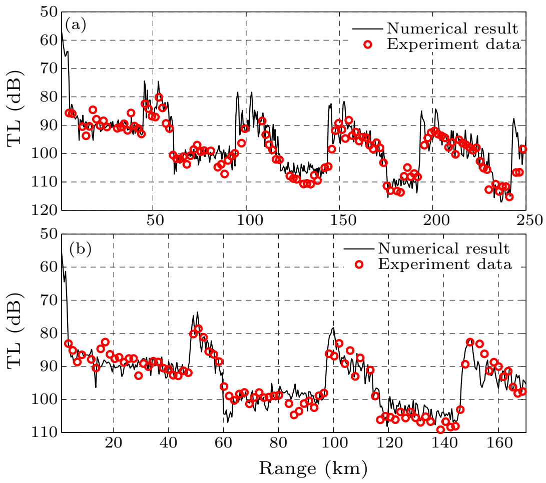

Fig. 10. Comparison of the numerical and experimental TLs. (a) For the receiver depth of 535 m in track 1; and (b) for the receiver depth of 192 m in track 2.

After obtaining the sound speed and the density, we next invert the attenuation coefficient. The cost function is similar to Eq. (2) as

$$E(\alpha_{\rm b}) = \frac{1}{\sqrt{NM}}\{\sum_{i}^{N}\sum_{j}^{M}[TL_{\rm exp}(f_0, r_i, z_j) - TL_{\rm cal}(f_0, r_i, z_j, \alpha_{\rm b})]^2\}^{1/2}. \qquad (3)$$

The definition of each parameter in Eq. (3) is the same as that in Eq. (2). The experimental TLs within the range of 70–250 km, which are sensitive to the attenuation coefficient, are selected to invert the attenuation coefficients by treating the bottom sound speed and density as known parameters. The attenuation coefficients in the frequency range from 100 Hz to 600 Hz are inverted, as shown by circles in Fig. 9. The solid line in Fig. 9 is the fitted curve with the nonlinear relationship

$$\alpha_{\rm b} = 0.78 f^{2.08}\,{\rm dB/m}, \qquad (4)$$

where f is in units of kHz. The results are similar to the relationship between the bottom attenuation coefficient and frequency provided by Zhou *et al.*[14]

To illustrate the applicability of the inversion results, Fig. 10 gives the comparisons of the experimental TLs and the numerical results calculated by using the inverted bottom parameters for two different propagation tracks. Figure 10(a) is for the source frequency of 300 Hz and the receiver depth of 535 m in the track 1. Figure 10(b) is for the source frequency of 200 Hz and the receiver depth of 192 m in the track 2. In Figs. 10(a) and 10(b), the sound source depth is 200 m. It can be seen that the experimental $TL_{\rm exp}$ and numerical $TL_{\rm cal}$ can be compared very well in both tracks 1 and 2, indicating the validity of the inverted parameters.

In summary, bottom parameters are inverted by using high SNR acoustic signals received in the experiment conducted in the SCS in 2014. Considering the sensitivity of shadow-zone TLs at different ranges to different bottom parameters, a geoacoustic inversion method is proposed for deep water. The bottom sound speed and density are first inverted combining with the Hamilton sediment empirical relationship, and then the attenuation coefficients in different frequency are obtained. For the uniform liquid half-space sea bottom model, the inverted bottom sound speed $c_{\rm b}$ = 1558 m/s, and the bottom density $\rho_{\rm b}$ = 1.57 g/cm^3 for the experimental sea area. The inverted attenuation coefficients are well described by a nonlinear relationship of $\alpha_{\rm b} = 0.78 f^{2.08}$ dB/m (f is in units of kHz) in the frequency range of 100–600 Hz. The inverted bottom parameters can be used to forecast the TLs in the deep water area of SCS very well.

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