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# Comparison of Surface Duct Energy Leakage with Bottom-Bounce Energy of Close Range Propagation

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*For close range (almost 8–15 km) propagation, bottom-bounce energy (BBE) usually suffers from a great transmission loss due to a large grazing angle interacting with the ocean bottom, and the surface duct energy leakage (SDEL) might be able to make a significant contribution to shadow zone insonification. This study aims at making a comparison between SDEL and BBE in a shadow zone with a source depth of 50 m for close range propagation. Analysis of experimental data shows that for lower frequencies the SDEL can be comparable with the BBE up to a range of 12 km. Numerical simulations suggest that the transmission loss (TL) of 90 dB is a proper value to quantify the role of the SDEL in shadow zone insonification. When TL of the SDEL is about 90 dB, it is believed to be comparable with the BBE. Studies on the effect of mix layer depth (MLD) on the SDEL indicate that larger MLD and lower frequencies can help to create favorable conditions for SDEL and that there exists an optimal MLD for SDEL at certain frequency. Statistics of MLD distribution in the South China Sea (SCS) show that winter is favorable for SDEL and the situation reverses in summer. Eddies are known to occur frequently in the SCS and the study on the effect of eddies on the SDEL suggests that the presence of an eddy will influence the SDEL significantly by modifying the MLD.*

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In deep ocean, sonar performance of close range in shadow zone is mainly dependent on bottom-bounce energy and surface duct energy leakage. Compared with the bottom-bounce energy, the surface duct energy leakage is always considered as ignorable. However, for close range (8–15 km) propagation, bottom-bounce energy (BBE) usually suffers from a great transmission loss due to a large grazing angle interacting with the ocean bottom, the surface duct energy leakage (SDEL) might be able to contribute to shadow zone insonification significantly. Plenty of studies have been conducted on SDEL. Labianca[1] described the character of the SDEL with normal mode theory. With numerical simulations and experimental data, Porter *et al.*[2] pointed out that the leakage energy from the surface duct can be strong at lower frequencies and that a receiver in the shadow zone may sense a strong field from a source in the surface duct. Avilov[3] has studied the characteristics of signals penetrating the shadow zone as a result of surface duct leakage. Previous research pointed out that SDEL is sensitive to mix layer depth (MLD) and the source frequency. It is thus assumed that in certain cases the SDEL can be comparable with the BBE. This work aims at figuring out the necessary conditions for the SDEL to be comparable with the BBE in shadow zone insonification.

In August 2014, an acoustic experiment was conducted in the south China sea (SCS). Figure 1(a) shows the sketch map for the experiment. As shown in Fig. 1(a), the water depth is around 4000 m. Core data of the ocean bottom indicates that the sediment density $\rho_b$ is around 1.4 g/cm$^3$, the compressive wave speed $c_p$ is around 1575 m/s and that the compressive wave attenuation $\alpha_s$ is around 0.3 dB/$\lambda$. The depth of the explosion source is 50 m. An array with 16 hydrophones is used to record the acoustic signal. The topmost hydrophone of the array is at a depth of 100 m. Figure 1(b) shows the sound speed profile (SSP) measured there. As shown in Fig. 1(b), the MLD of the SSP is about 80 m. Acoustic data measured in the experiment was used for the comparison between the SDEL and the BBE.

To compare the SDEL with the BBE, the signals of both types were first identified. Figure 2(a) provides the ray pattern calculated from the ray model Bellhop[4] for the acoustic environment. We notice that the range of the direct path and the surface reflected energy are less than 5 km for the upper layers of the ocean, indicating the presence of the shadow zone after the range. Then two kinds of acoustic energy will contribute to the shadow zone insonification. They are the SDEL and the BBE, respectively. Their signals are then picked out for comparison.

Figure 2(b) shows the records of the signals of the explosion source by the topmost hydrophone at 100 m depth with a range of 6–20 km. The arrival delays are the relative delays by subtracting the arrival time of the SDEL. A small time value was then added for a better view of the structure. As shown in Fig. 2(b), when the range becomes larger, the SDEL gradually decreases, while the BBE increases first to the maximum at about 15 km and then decreases with the range. We notice that the amplitude of the SDEL is larger than that of the BBE at closer ranges and is smaller at longer ranges. However, given that the

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SDEL and the BBE both are correlated with signal frequency, a detailed comparison needs to be carried out in the frequency domain.

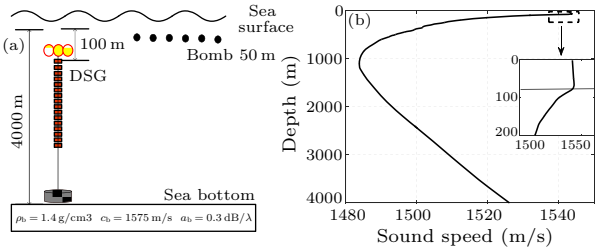


**Fig. 1.** Acoustic environment of the experiment: (a) the sketch map for the experiment and (b) the measured SSP.

Figure 3 shows the transmission loss (TL) at different frequencies of the SDEL and the BBE, and their difference along with range. As shown in Fig. 3(a), the TL of the SDEL reaches 90–95 dB in a frequency range of 60–800 Hz and a spatial range of 8–13 km. The TL of the SDEL with frequencies larger than 800 Hz or ranges larger than 13 km grows towards a level about 110 dB or more. Figure 3(a) suggests that the SDEL might contribute to the shadow zone insonification significantly at relatively lower frequencies and closer ranges. In Fig. 3(b), compared with the SDEL, the TL of the BBE reaches 90–95 dB at frequencies lower than 500 Hz and the range extends from 8 to 19 km. Figure 3(c) presents the difference between the TL of the SDEL and BBE. We notice that the difference is within 5 dB for frequencies lower than 800 Hz and closer ranges smaller than 13 km, while the difference reaches almost 10 dB for higher frequencies or larger ranges. Figure 3(c) suggests that the TL of the SDEL may be comparable with that of the BBE in certain cases. Given that the TL of the BBE is mainly dependent on the bottom type which remains stable and that the TL of the SDEL is sensitive to MLD of SSP which is a fluctuating parameter, an investigation on the effect of MLD on the TL of the SDEL will be necessary in helping us to understand the role of SDEL in shadow zone insonification.

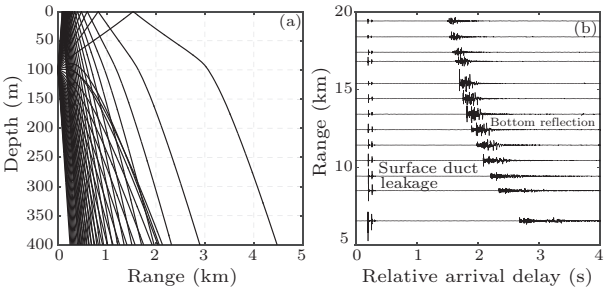


**Fig. 2.** (a) Ray pattern for the acoustic environment in the close range. (b) Records of the signals of the explosion source by the topmost hydrophone (at 100 m depth). The second peak of the SDEL signal results from the bubble pulse of the explosion source.

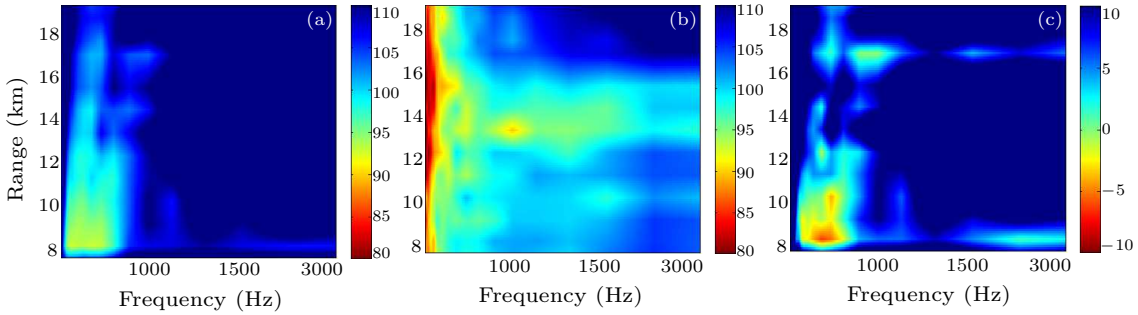


**Fig. 3.** The TL at different frequencies and ranges of the acoustic signal: (a) SDEL and (b) BBE. (c) The difference between the spectra of SDEL and BBE (in units of dB).

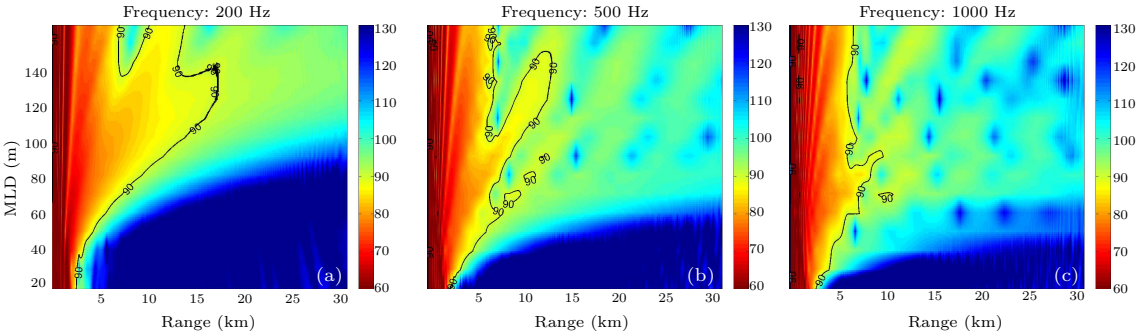


**Fig. 4.** The TL of the SDEL at a depth of 200 m with varying MLD for three frequencies: (a) 200 Hz, (b) 500 Hz and (c) 1000 Hz (in units of dB). The results were calculated with the parabolic equation model RAM.

To examine the effect of MLD on acoustic energy leakage, three frequencies 200 Hz, 500 Hz and 1000 Hz were chosen. The parabolic equation acoustic model RAM[5] was used for acoustic simulation. The TLs of the SDEL at a depth of 200 m for the frequencies with varying MLD of 10–150 m were then calculated. The source depth is 50 m and the acoustic environment is the same as that in Fig. 1(a). Figure 4 presents the

results for the three frequencies. The black curves in Fig. 4 are the 90 dB contours. Since we aim at comparison of SDEL with BBE, the TL of the BBE with a receiver depth of 200 m for the frequencies was calculated. Figure 5 shows the results, where the solid line refers to the TL of 200 Hz, the dashed line refers to the TL of 500 Hz and the dashed-dotted line refers to the TL of 1000 Hz. Due to the fact that the BBE suffers from greater transmission losses when interacting with the ocean bottom with a larger grazing angle at closer ranges, the TL of the BBE is greater at closer ranges than that at farther ranges.

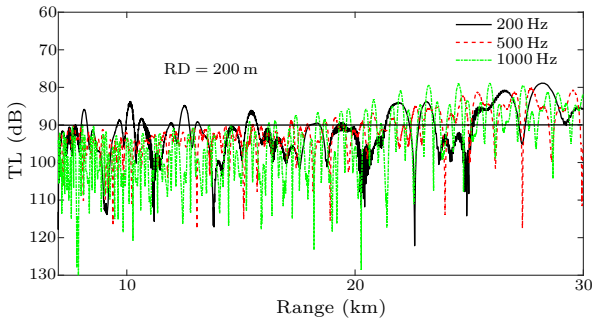


**Fig. 5.** The TL of the BBE with a receiver depth of 200 m for three frequencies of 200 Hz, 500 Hz and 1000 Hz.

As shown in Figs. 4 and 5, the TL of 90 dB is a nice choice for the comparison between the SDEL and the BBE. This is due to the fact that the TL of the BBE varies near 90 dB with a small range. When the TL of the SDEL approximates to 90 dB, the SDEL is believed to be comparable with the BBE. Then the contribution of the SDEL to the shadow zone insonification is significant. In Fig. 4, when the source frequency is 200 Hz, the range limit of the 90 dB contour reaches 15 km with an MLD of 120 m. We need to notice that the range limit for 200 Hz in Fig. 4(a) is not the range limit for all the MLDs, due to the fact that the variation range of the MLD is only 10–150 m and the contour line in Fig. 4(a) has been cut off by the upper boundary of the MLD of 150 m. As the frequency increases, the range limit decreases to 12 km at 500 Hz and 10 km at 1000 Hz, and the limit occurs at the MLD of 120 m and the MLD of 80 m for each frequency. In Fig. 4(b), when the MLD deviates from 120 m, the range limit decreases. The same thing occurs in Fig. 4(c) when the MLD deviates from 80 m. This phenomenon suggests that there exists an optimal MLD for the SDEL at certain frequencies.

Avilov[3] points out that there is an optimal frequency of the shadow zone insonification, which corresponds to the critical frequency of the surface duct. Given that the formula[6] to calculate the critical frequency is $f_c = 183700 z_d^{-2/3}$, there will be an optimal MLD for each source frequency. Here $f_c$ is the critical frequency, which is the frequency corresponding to the direct ray grazing the bottom of the surface duct, and $z_d$ refers to the MLD. When the MLD approaches the optimal value, the range limit of the 90 dB contour reaches maximum. Compared with BBE, SDEL will make comparable contributions to shadow zone insonification within this range limit.

The analysis suggests that larger MLD and lower frequencies are helpful to create favorable conditions for SDEL to be comparable with BBE for the range of 8–20 km. Further investigation of the climatology of MLD distribution will help us learn about whether the ocean climatology is in favor of forming necessary conditions for the SDEL to be comparable with the BBE. The reanalysis dataset of the South China Sea (REDOS) provided by South China Sea Institute of Oceanology is used to obtain statistics of MLD in the SCS. The dataset used are monthly averaged data with a spatial resolution $0.1^\circ \times 0.1^\circ$. The dataset has 24 depth layers with a maximum depth of 1200 m. Figure 6 presents the MLD distribution of four months in the year 2011 in the SCS. Given that we focus on deep water in the SCS, data points with water depth smaller than 200 m have been eliminated.

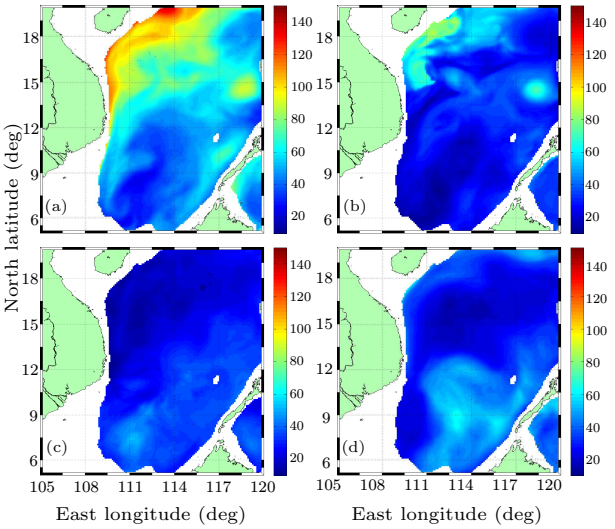


**Fig. 6.** MLD distribution of four months in the SCS: (a) January, (b) April, (c) July and (d) October (in units of m).

In January 2011, as shown in Fig. 6(a), the MLD of the northern part of the SCS reaches about 100 m. The value decreases with the latitude, with the MLD about 80 m in the central part of the SCS and about 40 m in the southern part of the SCS. When it is April, MLD of the majority part of the SCS approaches 40 m, as shown in Fig. 6(b). Exceptions occur in the northern part of the SCS, where the MLD reaches about 60 m. Figure 6(c) provides the MLD distribution in July. The MLD of the majority part of the SCS is near 40 m with slight deviations in the southern part of the SCS. In Fig. 6(d), when it is October, the MLD of the northern part of the SCS is about 40 m, while the MLD of the southern part of the SCS is about 50 m.

If we assume that the MLD distribution in January 2011 is typical of winter, April is typical of spring, July is typical of summer, and October is typical of autumn, conclusions are drawn as follows: in the SCS, winter is the favorable season in forming larger MLD,

especially in the northern part of the SCS. If the hydrophone is located in the northern part of the SCS and the source depth is 50 m, the received signal of SDEL will be comparable with that of BBE up to a range of 15 km for frequencies about 500 Hz or lower. Meanwhile the spring or the summer is not a good time for SDEL, since the MLD of the majority part of the SCS during this period is only about 40 m. As shown in Fig. 4, when the MLD is about 40 m, the SDEL can hardly make contributions to shadow zone insonification for any frequency with the boundary limit of the 90 dB contours reaching about 5 km. In autumn, the MLD distribution in the northern part of the SCS is still not favorable for SDEL. However, the southern part of the SCS might be favorable for SDEL under certain conditions with an MLD near 50 m.

Energetic eddies frequently occur in the SCS. Wang *et al.*[7] used satellite altimetry data from 1993 to 2000 to study the structures of eddies and their movements. The distribution of eddies is grouped into four geographical zones depending where they first formed, that is, southwest of Taiwan, northwest of Luzon, southwest of Luzon, and offshore of central Vietnam. The acoustic experiment was conducted offshore of central Vietnam where eddies frequently occur.

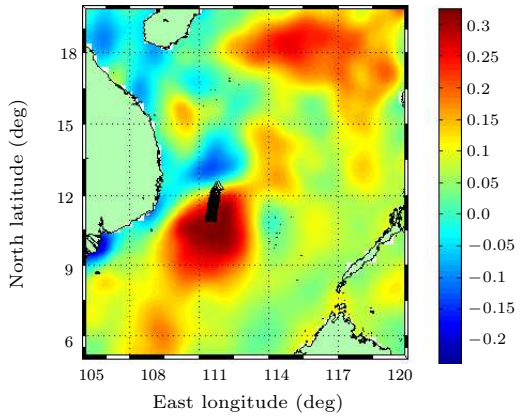


**Fig. 7.** SSH field in the SCS.

Eddies are known to yield significant influence on sound speed structure and the influence has been intensively studied.[8–10] Despite the numerous studies already conducted on the effects of eddies on acoustic propagation, most of them are based on the assumption that eddy strength is sufficient to affect sound speed structure considerably. However, the majority of eddies in the ocean are not as energetic as those in the Gulf stream or the Kuroshio Extension area. Chaigneau *et al.*[11] used altimetry and Argo profiling floats to conduct a composite analysis of the vertical structure of mesoscale eddies in the eastern South Pacific Ocean. Zhang *et al.*[12] found that despite remarkable regional differences in factors such as amplitude and extent polarity, mesoscale eddies have a universal structure in normalized stretched coordinates. Both the studies show that not all eddies are as energetic as assumed in previous research. The majority of eddies in the ocean yield limited influence on the upper layers of the ocean, including the mix layer and part of the thermocline layer. Given that the acoustic propagation in the surface duct is sensitive to the mix layer depth, the presence of an eddy may greatly influence acoustic propagation in the surface duct.

The acoustic experiment described above was conducted in summer time, when the ocean climatology is not favorable for SDEL with the MLD climatology about 40 m. However, Fig. 1(b) suggests that the MLD is near 80 m in the measured SSP, and the acoustic data analysis shown in Fig. 3 suggests that the SDEL is comparable with BBE up to a range about 12 km, which is not consistent with the previous analysis of MLD distribution in summer. To find out the cause for the anomaly of MLD in our experiment, the sea surface height (SSH) field of the same day is displayed in Fig. 7, representing the expendable bathythermographs (XBT) stations as well as the ship tracks of the experiment.

As shown in Fig. 7, a warm eddy with amplitude about 0.3 m exists where the experiment was conducted. An eddy is known to be able to induce great fluctuations to the thermal structure of the upper ocean layers. Figure 8 is the upper structures of the SSPs measured with XBT, which shows that the MLD gradually decreases as the measurements go outward of the eddy. The MLD varies from almost 80 m near the center of the eddy to about 40 m at the edge.

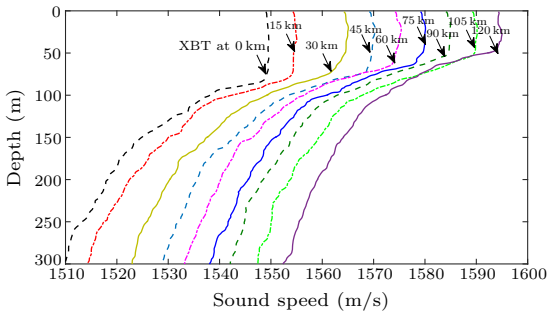


**Fig. 8.** Upper structures of sound speed profiles measured by XBT along the track shown in Fig. 7.

To investigate the effect of eddy on SDEL, we define a parameter $\alpha_a$ to refer to the signal attenuation rate of SDEL for certain receiver depth out of the surface duct,

$$\alpha_a = \frac{\mathrm{TL}_1 - \mathrm{TL}_2}{R_1 - R_2}, \tag{1}$$

where $\mathrm{TL}_1$ is the transmission loss at range $R_1$, and $\mathrm{TL}_2$ is the transmission loss at range $R_2$. Figure 9 describes the dependence of the signal attenuation rate $\alpha_a$ on frequency for several values of the MLD, i.e., 100 m, 80 m, 70 m and 50 m, referring to the signal attenuation calculated with the acoustic data recorded by the topmost hydrophone of the array, which is at a depth of 100 m. As shown in Fig. 9, the acoustic data agrees well with the simulation result when the MLD is in the range of 70–80 m. The range for the SDEL signal we picked out is within 15 km, which is a

relatively short range compared with the scale of the eddy on the order of 100 km. For the warm eddy, this range corresponds to a small MLD variation about 10 m, meaning that the MLD decreases from 80 m to about 70 m.

Considering that the source/receiver may be anywhere in the eddy, the effect of the eddy on the SDEL may vary due to the MLD variation at different parts of the eddy. As shown in Fig. 9, for the same frequency of 300 Hz, if the source/receiver is near the edge of the eddy where the MLD is 50 m, the signal attenuation reaches 3 dB/km. If the source/receiver is near the center of the eddy where the MLD is 80 m, the signal attenuation reduces to 0.7 dB/km. The presence of a warm eddy may help to form favorable conditions for the SDEL to be comparable with the BBE.

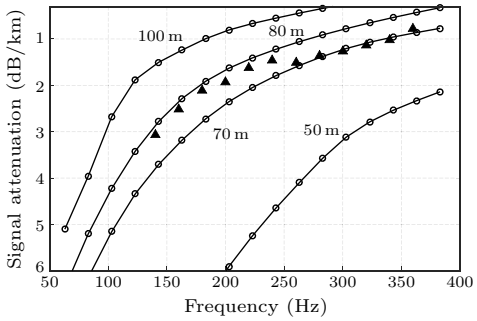


**Fig. 9.** Dependence of the signal attenuation on frequency for several values of the MLD (100 m, 80 m, 70 m and 50 m), referring to the signal attenuation calculated with the acoustic data recorded by the topmost hydrophone of the array which is at a depth of 100 m. The source depth is 50 m.

In summary, the analysis of the experimental data has demonstrated that for lower frequencies and larger MLD the SDEL can be comparable with the BBE in shadow zone insonification of close range with a source depth of 50 m. The effect of MLD on SDEL has been studied. Analysis shows that the TL of 90 dB is a reasonable choice to quantify the role of SDEL in shadow zone insonification, since the TL of the BBE of close range varies near the value. When the TL of the SDEL approximates to 90 dB, it is believed to be comparable with BBE. Simulation results show that for a frequency of 200 Hz and an MLD of 120 m, the range limit of the 90 dB contour of SDEL reaches 15 km. The range limit decreases as the frequency increases. For certain frequency, there is an optimal MLD for the range limit to reach the maximum.

Statistics of MLD distribution in the SCS suggests that winter is a good time to form favorable conditions for SDEL and that the situation reverses in summer when the climatology of MLD approximates to 40 m in most cases. Furthermore, acoustic data analysis has confirmed the influence of the eddy on SDEL, when the presence of the eddy is able to modify the MLD significantly. The presence of a warm eddy will help to form favorable conditions for SDEL to be comparable with BBE.

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