Long-range reverberation average intensity attenuation characteristics in shallow water

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ABSTRACT

Reverberation experiments in shallow water showed that reverberation average intensity could be described as a stage function composed of two proximate linear function with different slopes in terms of logarithm of time. In the former section, reverberation came from close range, where the reverberation gradient for logarithm of time was smaller. In the latter section, reverberation came from long range, where the gradient was much larger. The demarcation of this stage function is not dependent on signal pulse length or signal frequency, but dependent on the characteristics of the waveguide. The simulation illustrated this by analyzing the effective normal modes varying range. The characteristics of two-way propagation and backscattering intensity both controlled the position of the cut-off point. The experiment also shows that the demarcation has a close relationship with sediment. For the shallow water with tough sediment, the demarcation of reverberation average intensity attenuation characteristics exhibits a lag performance.

1 INTRODUCTION

Bottom reverberation is the major source of reverberation in shallow water, especially reverberation due to the bottoms rough interface. Both physical modeling and experimental data analysis have been done to study the reverberation characteristics, such as reverberation average intensity, reverberation correlation and reverberation statistic characteristics. The model of reverberation is mainly dependent on the model of sound propagation and bottom backscattering. In shallow water, the propagation model is based on normal mode theory, especially for long range. The bottom backscattering model is based on Lambert's Law from plane wave scattering theory which shows great limitation when analyzing reverberation characteristics except for average intensity. So, more and more researchers seek a model which has clear physical mechanisms and has an obvious difference from the early reverberation model based on empirical law.

M. J. Isaksona and N. P. Chotiros proposed their principle about modeling the bottom roughness reverberation through finite element method in shallow water (M. J. Isaksona and N. P. Chotiros, 2011). N. C. Makris and P. Ratilal developed a unified model for reverberation and submerged target scattering in a stratified medium according to Green's function, where they considered the seafloor and subseafloor (N. C. Makris and P. Ratilal 2001). A. N. Ivakin and Y. P. Lysanov proposed a unified approach to volume and roughness scattering almost 20 years. They considered the roughness as a volume perturbation of a specific kind near flat interfaces and then modelled bottom scattering (A. N. Ivakin and Y. P. Lysanov 1999). Shang E. C. and his team gave an explicit expression of bottom backscattering matrix based on bottom roughness reverberation model (Gao T. F. 1989) and bottom sediment inhomogeneous reverberation (Tang D. J. 1997) in 2008 (Shang, E. C. Gao, T. F. and Wu, J. R. 2008). They named it as the full-wave reverberation theory which is restricted by Green's function. Wu J. R. did some physical analysis about the integrated bottom scattering strength according to the explicit analytic expression (Wu, J. R. 2012).

In this paper, the author illustrates the reverberation average intensity attenuation characteristics, which is a stage function of reverberation time. According to the reverberation mechanism, the incident field propagation, bottom backscattering, backscattering field propagation are simulated to expound this stage function according to the full wave reverberation. The modes present in every process considered in order to explicate how the reverberation average intensity decays quickly in the first stage and gently in the second stage. At the same time, the phenomenon about the demarcation between these stages has also been mentioned which represents a close relationship with sediment.

2 AT-SEA EXPERIMENT

2.1 Monostatic Reverberation with Different Signal

2.1.1 Experiment arrangement

Monostatic reverberation experiment has been made in shallow water with a downward refracting profile as shown in Figure 1. The first layer is a 30m, 1542m/s iso-velocity layer, the second layer is a 40m downward refracting layer with two gradients. The flat sea floor is an average 81m under the pressure free sea surface, and laying on a sand sediment with geoacoustic parameters: 1664m/s (sound speed), 1.77g/cm^3 (density), and 1.25dB/λ (attenuation). The source depth is located at 30m lower than the sea-surface, which is the crossing point between the surface iso-velocity layer and down refracting layer. The vertical linear array, where the 32 hydrophones are dispersed homogeneously, is near the source and covers the downward refracting layer from 20m to 70m. There are several signals transmitted, Line-Frequency-Modulation (or LFM for short) with much pulse length (0.5s, 1s and 2s, respectively), to illustrate the reverberation average intensity attenuation characteristics.

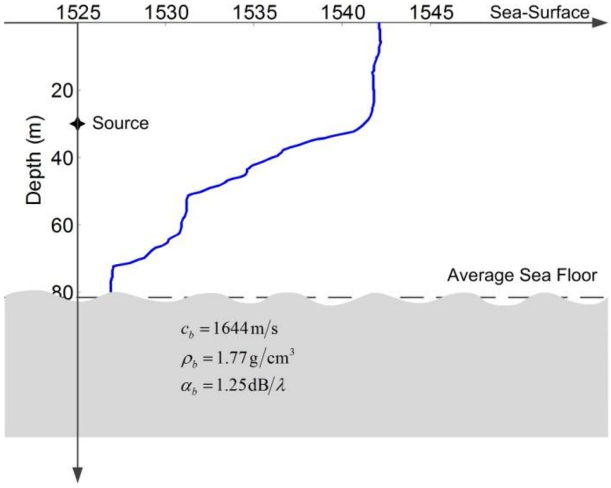


Figure 1: Geometry of shallow water waveguide with downward refracting profile

2.1.2 Experiment phenomenon

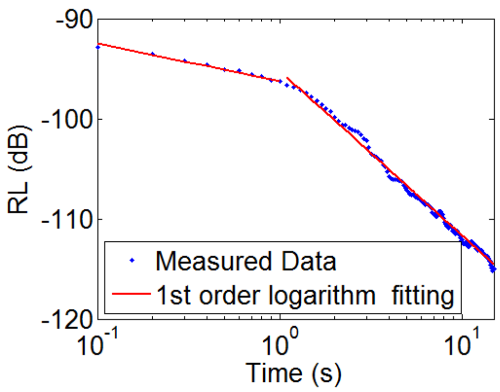


Figure 2: 450Hz Reverberation average intensity attenuation characteristics

Figure 2 shows reverberation average intensity attenuation curves for a Line-Frequency-Modulation (LFM) with frequency varying from 380Hz to 460Hz linearly and 450Hz as the center frequency and logarithm fitting measured data. The Y-axis is reverberation level in decibel and X-axis is time in logarithm form. The blue points are measured data from the monostatic reverberation experiment, and the red line is the fitting data with a linear approximation in logarithm of time. They are stage functions clearly and 1s is the demarcation of such stage function. The former section of stage function satisfied the following relationship

$$RL_{former} = -3.4\log_{10} t - 97.7 \tag{1}$$

While the latter has another relationship, which varies with logarithm of time much more quickly

$$RL_{latter} = -15\log_{10} t - 96.7 \tag{2}$$

Make Eq.(1) and Eq.(2) convert into reverberation average intensity

$$I_{former}^{rev} \propto t^{-0.34}, \qquad I_{latter}^{rev} \propto t^{-1.5} \tag{3}$$

Another reverberation data is shown in Figure 3 for LFM with 290Hz (frequency varies from 260Hz to 300Hz) and 750Hz (from 600Hz to 900Hz) as center frequency, respectively. They also have the demarcation at 1s, while the gradient of time in logarithm is different for both sections.

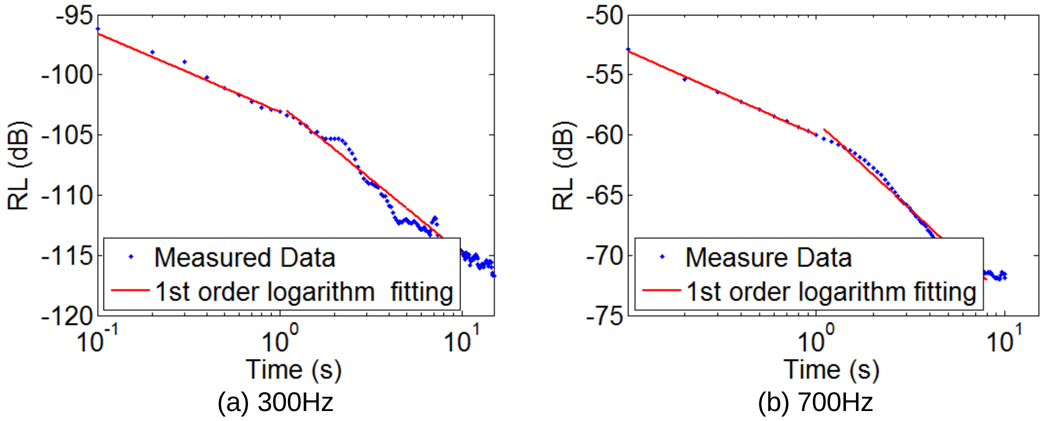


Figure 3: Reverberation average intensity attenuation characteristics

2.2 Monostatic Reverberation with Different Sediment

2.2.1 Experiment arrangement

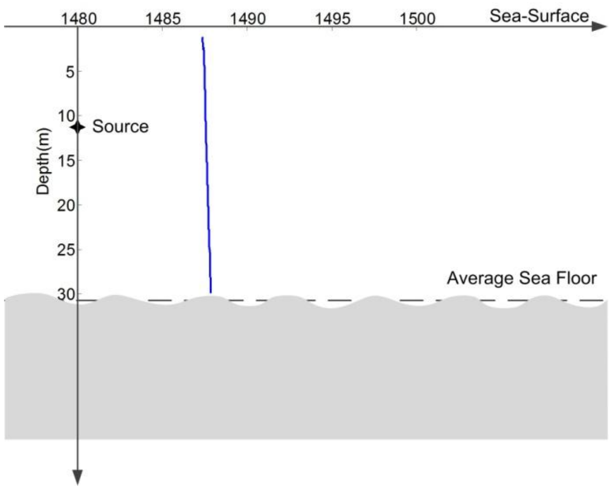


Figure 4: Shallow water with isovelocity profile

This experiment aims to illustrate the sediment has an important effect on the reverberation average intensity decay characteristics, especially the location of demarcation. So another monostatic reverberation experiment was conducted in two experiment areas selected, where the A area has gravel sediment and the B area has silty-clay sediment. Both areas are 35m range-independent shallow water with 1488m/s isovelocity profile as Figure 4 shows.

Standard explosive sound signals, containing the equivalent of 1kg TNT, detonate at depth of 25m and about 100m horizontally from the research vessel. A vertical line array of 37 homogeneous hydrophones with an over-all length of 29.6m is suspended from an anchored research vessel and the deepest hydrophone is located at depth of 31.6m.

2.2.2 Experiment phenomenon

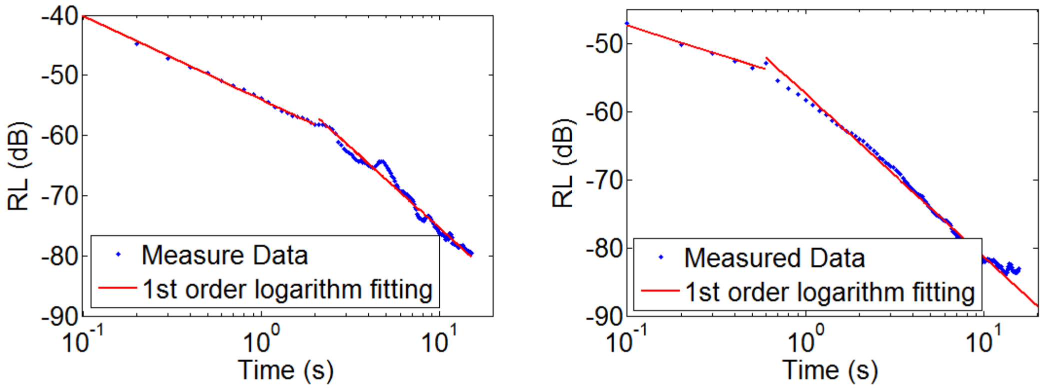


Figure 5: 600Hz reverberation average intensity attenuation characteristics (a) is gravel sediment;(b) is silty-clay sediment

Here, 600Hz reverberation average intensity decay curve in Figure 5 is used to show how the demarcation of the above stage function is effected by sediment. The reverberation data shown in Figure 5(a) came from shallow water waveguide with gravel sediment and Figure 5(b) from waveguide with silty-clay sediment.

Firstly, reverberation average intensity decay curves at both areas have the same characteristics of stage function. Both sections are linear approximate in logarithm of time, and the latter has much greater gradient of time in logarithm than the former. Secondly, the two stage function have different demarcation. Demarcation in Figure 5(a) is at 2s, where the sediment is gravel. While the demarcation is at 0.8s in Figure 5(b), where the sediment is less hard than (a).

We can get the following conclusions about the reverberation average intensity attenuation characteristic in above two experiments :

- Reverberation average intensity decay curve is a stage function and each stage is linear approximate in logarithm of time.
- The gradient of time in logarithm in the former stage is less than the latter.
- The demarcation of stage function has a close relationship with sediment. The tough sediment makes the demarcation delay.

3 NUMERICAL SIMULATION

In order to illustrate the above experimental results, the simulation has been made about the percent of modes intensity varying with range in propagation and reverberation average intensity based on the full wave reverberation theory. The 100m range-independent water with 1500m/s iso-velocity profile layer on a homogeneous half-space sediment is considered during the simulation. The velocity, density and attenuation of sediment geoacoustics parameters is: 1623m/s, 1.77g/cm3 and 1.09dB/λ, respectively. The source transmits 600Hz signal at 25m depth and the receiver locates at 10m. In this shallow water waveguide, the reverberation average intensity due to bottom roughness is

$$I^{rev}(r) = (\frac{2\pi}{r})^2 A \cdot \sum_{n=1}^{M}\sum_{m=1}^{M} \varphi_m^2(z_s)\varphi_m^2(H) M_{mn} \varphi_m^2(H)\varphi_n^2(z) \frac{e^{-2(\beta_m+\beta_n)r}}{\sqrt{k_m k_n}} \tag{4}$$

Where, k_m and β_m is the real and imaginary part of eigenvalue, respectively. $\varphi_m(z)$ is the eigenfunction at z depth in water. Both the eigenvalue and eigenfunction can be obtained through Kraken algorithm, which was developed forming the normal mode modeling. The relationship between scattering range r and reverberation time t is $r = c_0 t/2$, where c_0 is the velocity in water. A is the backscattering area, which is constant because the scattering is isotropy. M_{mn} is the coherence coefficient of the mth incident mode and the nth scattering mode.

$$M_{mn} = P(2k_0)[k_0^2 - \frac{k_b^2}{\rho_b} + (1-\frac{1}{\rho_b})k_m k_n + (\frac{1-\rho_b}{\rho_b^2})\sqrt{(k_m^2-k_b^2)(k_n^2-k_b^2)}]^2 \tag{5}$$

Where, ρ_b and c_b is the density and velocity of sediment, respectively. $P(2k_0)$ is the bottom roughness spectrum. $k_{0,b} = 2\pi f/c_{0,b}$ is the wavenumber with subscript 0 in water and b in bottom sediment. The tough sediment has great value of velocity and density, then the coherence coefficient becoms larger than the soft sediment according Eq.(5).

In the full-wave reverberation theory, the bottom roughness is considered as "sub-source" to radiate source intensity. Therefore, Eq.(4), which describes reverberation average intensity in terms of normal modes, can be divided into four parts: incident modes propagation, bottom backscattering, backscattering modes propagation and reverberation. So the theoretical analysis will be completed through these four parts.

First is the incident modes propagation. The incident intensity of the mth mode propagates horizontal distance r from source to bottom according to Eq.(4) is

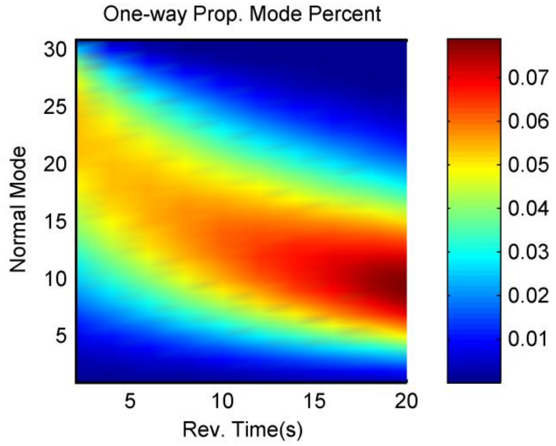
$$I_m^{in-pro}(r) = \frac{2\pi}{k_m r}\varphi_m^2(H)e^{-2\beta_m r} \tag{6}$$

The expression, without weighting of mode at source depth, is from the premise that the source can transmit all modes and the modes intensity is equal conveniently, such as 0dB here. Because the decaying characteristics of modes is only interested. The percent of modes intensity during sound intensity incident propagation is shown as the top left hand in Figure 6: The percent of normal modes varies with scattering range. The X-axis is reverberation time and the Y-axis is the order of normal mode. The color represents the percent of modes intensity. In this figure, the high order modes contribute the main intensity but not very obviously, when reverberation time is less than 5s, because the percent of every mode is small and close. But the percent of every mode has a great difference when the reverberation time is longer than 5s. This figure also shows clearly that the percent of high order modes attenuates quickly and the percent of low order modes rises gradually with reverberation time increasing. It means that the sound intensity forcus on lower order modes and the percent of these modes rise, which means the modes furth from central mode has much less contribution to sound intensity almost. It can be illustrated through modes intensity attenuation chatacteristics. High order modes have large imaginary of eigenvalue which make it decays quickly and the percent is from large to small. While low order modes have small imaginary of eigenvalue and it decay slowly, So the percent gets from small to lage.

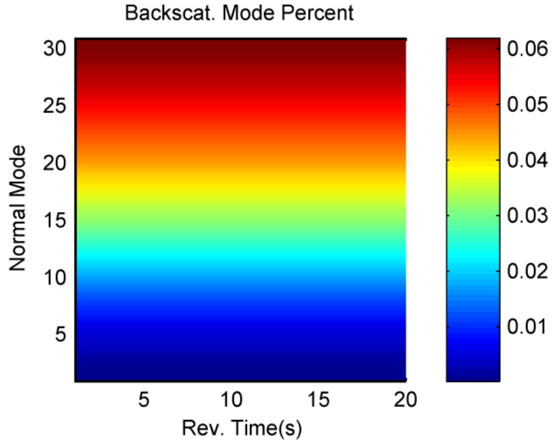
Then, the nth mode in bottom backscattering field due to bottom rough interface at horizontal distance r is

$$I_n^{sc}(r) = \varphi_n^2(H)\sum_{m=1}^{M} M_{mn} I_m^{in-pro}(r)\varphi_m(z_s) \tag{7}$$

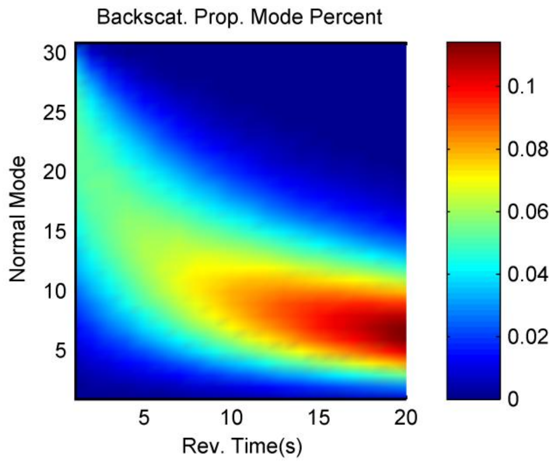
This expression describes the nth mode intensity due to bottom backscattering by bottom rough interface, where the superposition term represents the incident sound field. The simulation shows that bottom backscattering intensity is almost controlled by higher modes as shown in the top right hand in Figure 6: The percent of normal modes varies with scattering range. The higher order modes, the higher backscattering intensity. The percent of every mode due to bottom backscattering persists constant with reverberation time. In other words, high order modes play the control place in bottom backscattering field due to rough interface. Then, another result is the tough sediment makes bottom backscattering strong because it



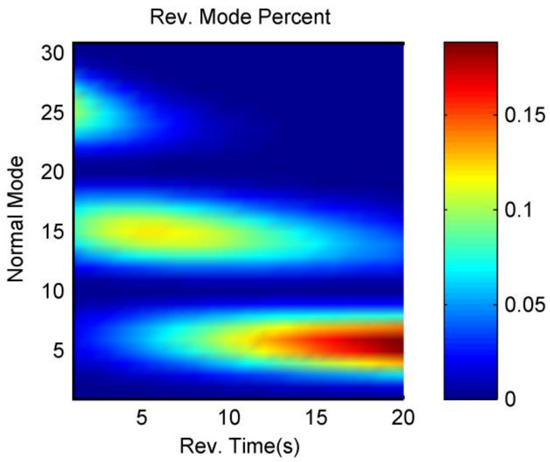
(a)One-way propagation



(b)Bottom backscattering



(c)Backscattering propagation



(d)Reverberation average intensity

Figure 6: The percent of normal modes varies with scattering range

causes great modes coherence according to M_{mn} shown as Eq.(5). It is easy to understand, the tough sediment has weak attenuation coefficient makes sound field attentuats less, then scatters into water more.

The third is about the backscattering mode propagation from bottom rough interface to receiver

$$I_n^{sc-pro}(r) = (2\pi)^2 I_n^{sc}(r) \frac{e^{-2\beta_n r}}{k_n r} \tag{8}$$

The bottom scattering field, propagating from bottom roughness to receiver, is processed as one-way propagation with source being unequal to 0dB, which means the intensity of scattering modes depend on the incident propagation from the source to bottom roughness. The higher order modes in scattering, the higher intensity as analyzing above. But it decays quickly. The scattering modes attenuation characteristics are shown in the bottom left hand in Figure 6: The percent of normal modes varies with scattering range, where the percent of every mode varies severely than the top left hand one. It means that the modes distribution in bottom backscattering field is much more concentrative than the incident propagation field. At the same time, the concentrated mode is lower than the one-way incident propagation at the same reverberation time. Because the high order modes control bottom backscattering intensity, which decay quickly and make the concentrated mode turn to low order modes.

Finally, the reverberation average intensity of the nth mode is

$$I_n^{rev}(r) = (2\pi)^2 I_n^{sc-pro}(r)\varphi_n^2(z_r)A \tag{9}$$

So, the reverberation average intensity can be expressed as the superposition of $I_n^{rev}(r)$

$$I^{rev}(r) = \sum_{n=1}^{M} I_n^{rev}(r) \tag{10}$$

The percent of every mode in reverberation is shown as the bottom right hand in Figure 6: The percent of normal modes varies with scattering range. In this figure, the modes intensity at receiver have strong weight to scattering modes propagation. For example, the 10th and 20th modes intensity have almost 0 percent in reverberation field because their eigenfunction at receiver depth are 0 . Another result is about the control modes. The main modes in reverberation have tendency from high order to low order modes with reverberation time increasing. For example, the 15th mode controls reverberation average intensity at 5s and the 5th mode controls the reverberation average intentsity from 12s to 20s.

The above analysis gives the proof that the reverberation average intensity attenuation characteristics is the complex integrate of two-way propagation and bottom backscattering due to bottom rough interface. At the first stage, high order modes control the propagation intensity and backscattering intensity. So, the reverberation average intensity attenuation characteristics is mainly controlled by high order modes propagation and the backscattering characteristics. With the range increasing, the high order modes decay quickly, lower modes play the dominant role during propagation, while the high order modes from backscattering are still on an important place. So the reverberation average intensity decay characteristics is combined by low order modes incident propagation and the high order backscattering modes propagation for long range. The demarcation is a little delay for tough sediment, because it has stronger backscattering than the soft one.

4 CONCLUSIONS AND FUTURE STUDY

The several monostatic reverberation experiments in shallow water all have expressed the same characteristics of reverberation average intensity, which is a stage function of scattering range or reverberation time. This phenomenon is combined effect of modes propagation and backscattering. The higher order mode, the higher loss. At the same time, the bottom backscattering due to bottom roughness make modes distribute much more concentrative and the percent of modes intensity is almost stable versus reverberation or scattering range. So, in the first stage, reverberation average intensity decays very quickly because the high order modes control the backscattering intensity and decay quickly. While, in the second stage, reverberation average intensity decays relatively gently. The low order modes, which is much more concentrative due to bottom backscattering, control the reverberation average intensity and make it represent a slow attenuation characteristics. Then it is easy to illustrate the demarcation of this stage function can delay for the shallow water waveguide with tough sediment. The tough sediment has less attenuation coefficient and greater backscattering ability which make the first stage persist long time. The analysis in this paper is still only theoretical. So the next step is to give a quantization expression according sediment geoacoustics parameters, especially the attenuation coefficient which discribes the modes attenuation characteristics.

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