ESTIMATION OF ACOUSTIC FLUCTUATIONS OF RECIPROCAL TRANSMISSION IN LONG-RANGE PROPAGATION AT THE CENTRAL EQUATORIAL PACIFIC

PACS: 43.30.Re

Hachiya, Hiroyuki; Wang, Yong; Nakamura, Toshiaki[1]; Nakano, Iwao[2]
Department of Information & Image Sciences, Chiba University
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, JAPAN
Tel: +81-43-290-3251
Fax: +81-43-290-3269
E-mail: office@hachiya.net
[1] Department of Earth and Ocean Sciences, National Defense Academy
Hashirimizu 1-10-20 Yokosuka-shi, Kanagawa 239-8686, Japan
[2] Japan Marine Science and Technology Center
2-15 Natsushima, Yokosuka 237-0061, Japan

ABSTRACT

We present the estimation results of acoustic fluctuations of the reciprocal acoustic transmission data collected during the tomography experiment performed by Japan Marine Science and Technology Center (JAMSTEC) in 1999 in the Central Equatorial Pacific.

It is important to estimate the stability of signals of reciprocal transmission because travel-time perturbations due to ocean currents are correspondingly one to two orders of magnitude smaller than travel-time signals due to sound-speed perturbations.

Between reciprocal transmissions, the overall structures of the signal are similar, however, the fine structures are different.

The 200 Hz ray signal within about 130 s is very stable and the phase change is smaller than 1 rad.

INTRODUCTION

Recently, ocean acoustic tomography, a global monitoring technique that inverts acoustic travel times through many sections of media, has been developed as a practical method for observing mesoscale ocean fluctuations[1)2)]. This system enables determination of the sound speed and the current speed structure between each of a number of source-receiver pairs in the ocean. Underwater sound propagates along various paths depending on the sound speed and the current speed profile in the intervening ocean volume, so it involves information of a large area during the process of propagating. The quality of acoustic travel time measurements depends on the coherence as well as the bandwidth of a signal. We estimated the stability of signals through 200 - 300 km range paths[4)5)]; the phases of correlated signals during one-way observation were stable within 50 s.
However, ocean current measurement by tomographic techniques requires the difference between the travel times of opposite directions. Ocean currents are typically of the order of 10 cm/s rms or less, except in strong western boundary currents such as the Kuroshio, where ocean sound-speed perturbations are typically of the order of 5 m/s rms. Travel-time perturbations due to ocean currents are correspondingly one to two orders of magnitude smaller than travel-time signals due to sound-speed perturbations. It is important to estimate the stability of signals of reciprocal transmission. The measurement of reciprocal acoustic transmissions performed by Japan Marine Science and Technology Center (JAMSTEC) in the Central Equatorial Pacific in January 1999 has enabled the investigation of acoustic fluctuations in the range of 500 km to 1920 km.

EXPERIMENT

The area with a flat seabed in the Central Equatorial Pacific shown in Fig. 1 was chosen for the tomography experiment. The average depth of this area is approximately 6,000 m. Five transceivers were deployed at T1 through T5 in this figure. The maximum distance between transceivers is approximately 1,800 km. Two transceiver moorings T3 and T4 were deployed at 13.620.N, 172.05.W, and 9.144.N, 172.05.W, respectively. The range, between T3 and T4, was about 500 km which is the minimum distance in this configuration. In this study, we used the data of the signals between T3 and T4. All instruments were placed near the sound fixing and ranging (SOFAR) axis at about 1000 m depth. The mooring motion was tracked using a local long-baseline acoustic navigation system.

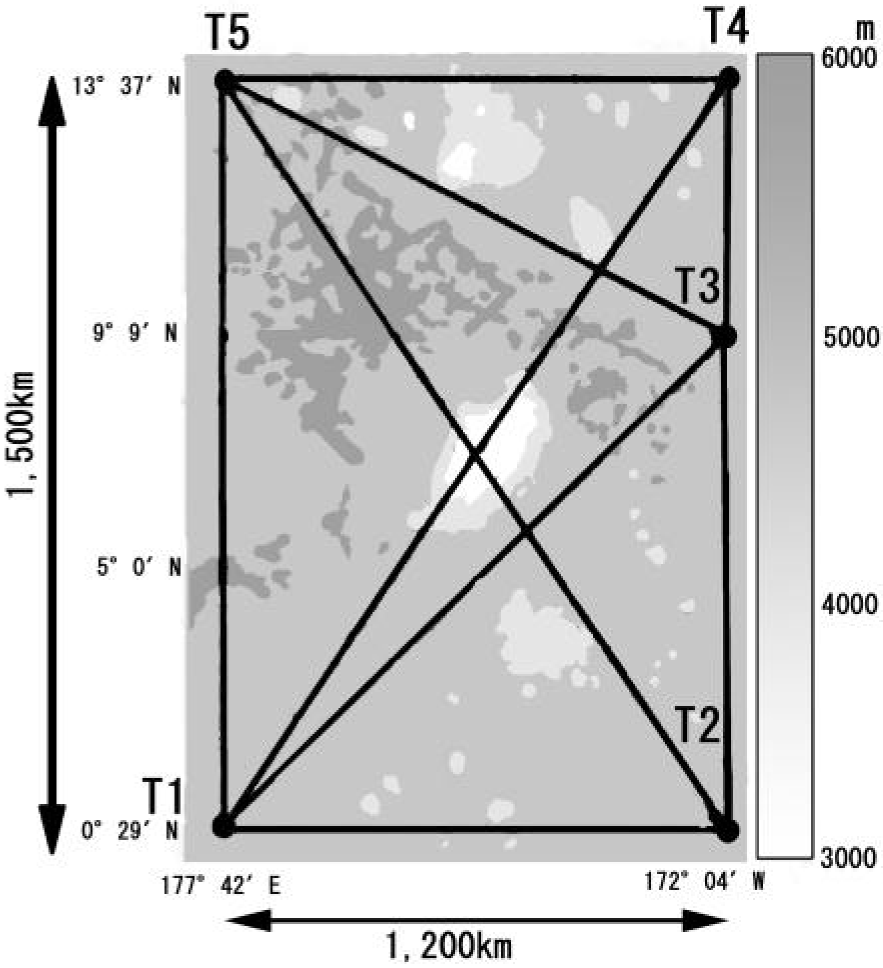

Fig.1 - Location of the acoustic transmission experiment

The M-sequence code is a pseudorandom code generated by shift-registers and exclusive-Or logic. Degree-10 code with 1024 digits consists of 10 shift registers. A code-number such as 2033 or 3471 written in octal form shows the pickup position of the feedback signal from the shift register.[10] This means that various patterns of M-sequences can be generated. In this experiment, a degree-10 M-sequence is used, and the five selected code numbers, 2033, 3471, 2377, 2553 and 2767, are applied in five transceivers. The code number of degree-10 M-sequence at T3 and T4 are 2767 and 2377. Between T3 and T4, the 200 Hz M-sequence acoustic signals were transmitted simultaneously every 3 h for a duration of one day. The transmission period of one day and the idle period of three days were alternately repeated. The transmitted signal is a periodic repetition of the 10th-order M-sequence signal with the following characteristics:

a) carrier frequency f_0 = 200 Hz,
b) digit length = 2 cycles of 200 Hz = 0.01 s,
c) sequence length L = 1023 digits = 10.23 s, and
d) transmission length = 13 sequence periods = 132.99 s.

The vertical hydrophone array at the station under the transceivers consisted of five hydrophones, and the distance between each hydrophone was about 4.8 m. The transmitted signal was received by each hydrophone. The received signal was digitized at a sampling rate of 800 Hz. The digitized signal was cross-correlated with a replica of the transmitted sequence to achieve an adequate signal-to-noise ratio and a high travel-time resolution. The predicted improvement of the signal-to-noise ratio for the Gaussian noise was 30 dB.

RESULTS

<u>Amplitude</u>

Figure 2 shows the plot of the amplitude of a correlated signal at 1999/5/8. Upper and lower panels show the signal from T4 to T3, and from T3 to T4, respectively. Amplitudes were normalized using the maximum amplitude of this period. The *x*-axis corresponds to the relative time for the appropriate display. There were 13 periods of consecutive shots received by the hydrophones at T3 and T4. The total length of the 13 consecutive shots of the signal which were transmitted every 10.23 s is 132.99 s. The 13 amplitude waveforms are superposed in this one figure. In this figure, there are 6 groups of arrived signals that were received during about 2 seconds. The pulse width of the correlated signal was about 0.01 s due to two waves of frequency at 200 Hz. There are many signals in the group 6 at 1.75 s which propagate near the axis. From only the amplitude information, it is difficult to determine whether or not the small peak like the group 3 is a ray signal.

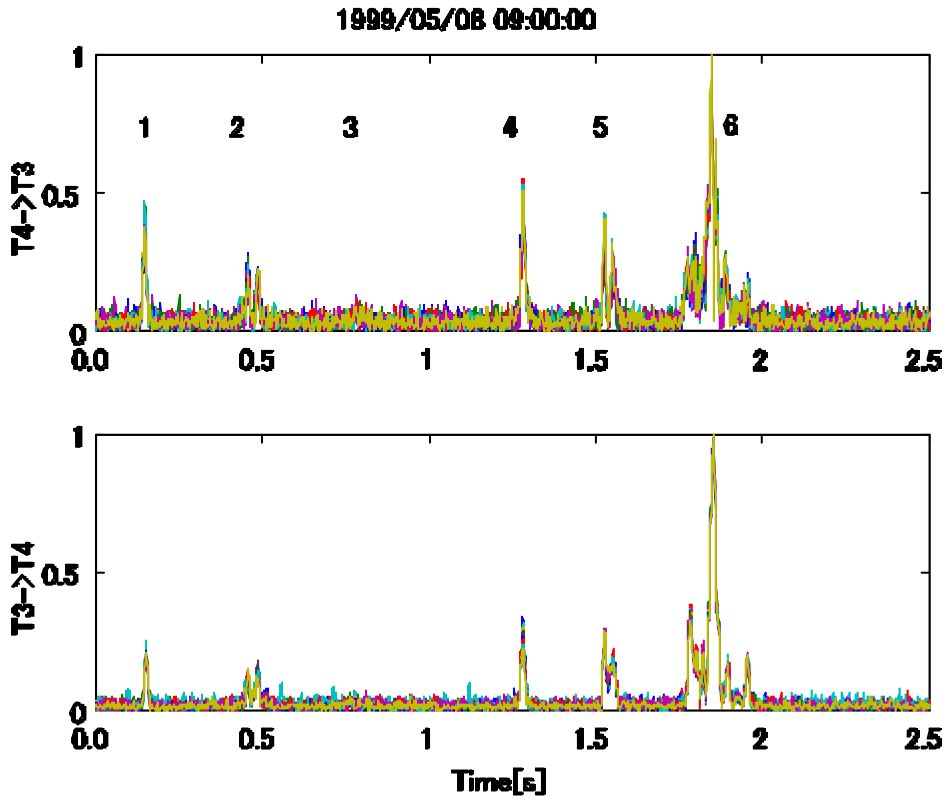

Fig.2. – Amplitudes of the correlated signals of reciprocal transmission between T3 and T4.
Upper panel : from T4 to T3 Lower panel : from T3 to T4

Compared to the reciprocal transmission data, the overall structures of the signal are similar to each other. On the other hand, the fine structures, particularly the structure of the overlapped signal passing through the axis of the sound-speed profile at 1.75 – 2 s, are different. This difference of fine structure is probably caused by the influence of factors such as current structure or the short term change of the ocean structure.
Figures 3, 5 and 7 show the amplitudes of each signal group of a correlated signal at 1999/5/8. The amplitudes were normalized by the maximum amplitude of each signal group in the figure. The 13 amplitude waveforms are superposed in one figure. The total length of the 13 consecutive shots of the signal is 132.99 s. The amplitudes of correlated signals were very stable within 130 s.

<u>Phase</u>
Figures 4, 6 and 8 show the phases of correlated signals which correspond to the amplitudes shown in Figs. 3, 5 and 7. The 13 phase waveforms are superposed in one figure. The phase waveform is divided into two patterns. One is the region where the phase changes smoothly in time; the other is the region where the phase changes rapidly. In the region with the gradually changing phase pattern, the phases of correlated signals were very stable within 130 s. On the other hand, the phases were not stable within 130 s in the region with the rapidly changing phase pattern. The amplitude and the phase can essentially be treated on the complex plane. However, the amplitude and the phase are treated separately in this paper. Comparing Figs. 3, 5 and 7 with Figs. 4, 6 and 8, we note that the phase is useful information for detecting weak signals and for separating overlapping ray signals. The phases have no relation when the ray does not exist. The phases are in good mutual agreement between each shot when the ray exists. The variation pattern of the reciprocal transmission signals between T3 and T4 have similar overall structures, but different fine structures.
Figure 9 shows the standard deviation of the phase of the 13 consecutive shots between T3 and T4 on May 8. The standard deviation of the phase, s_j is defined by

$$s_j(t) = \frac{1}{13}\sum_{n=1}^{13}\left(j(n,t) - j_{avr}(t)\right)^2 ,$$

where

$$j_{avr}(t) = \frac{1}{13}\sum_{n=1}^{13} j(n,t)$$

and n is the shot number.
The standard deviation of the phase is a quantitative index of phase stability. As shown in Fig. 9, the standard deviation of phase of an arrived ray signal is almost less than 1.0 rad, however, in the non signal portion it is more than 1.0 rad.
The signals whose amplitudes are different each other, such as the group 1 and the group 2 in Figs. 3 and 5, have almost the same phase standard deviation of 0.1 rad. The amplitudes at 0.8 s in Fig. 2 are very small, however the standard deviations of phases are about 0.5 rad which is clearly less than the value in the non signal portion. Therefore, we can confirm that this is a ray signal. The standard deviation of the phase is very useful information for distinguishing the ray signal.
From this figure, we use standard deviation s_j as an evaluation criterion of the signal. If s_j is less than 1.0 rad, we judge the ray signal arrived. Compared with Fig. 2, we can clearly see the six groups of the arrived ray signals. Since the phase of a ray signal is very stable, there is the possibility of the detection of the small change of ocean structure.
As shown in Fig. 9, the standard deviation of phase of an arrived ray signal is almost less than 0.2 rad, which corresponds to about 0.16 ms. This indicates that there is little change in the ocean structure in a period of less than 130 s. An estimation of the travel time can be made with an error of less than 0.2 ms.

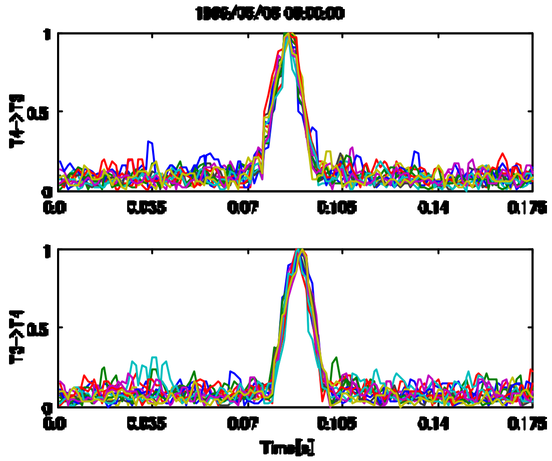

Fig.3- Amplitudes of the correlated signal of the group 1

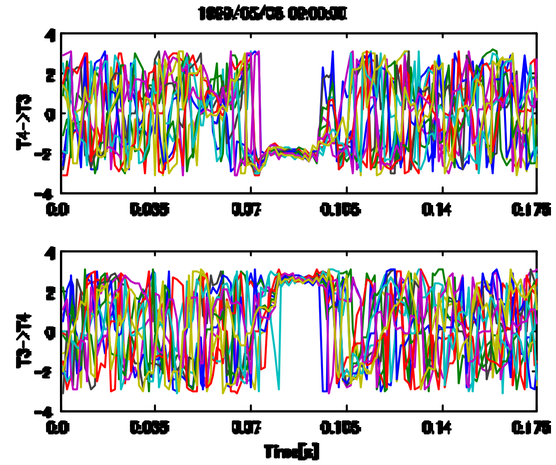

Fig.4- Phases of the correlated signal of the group 1

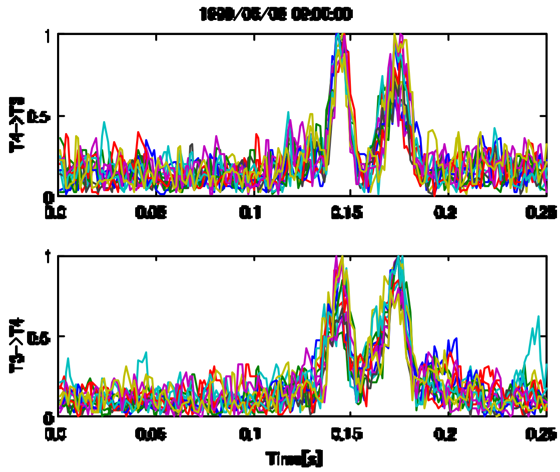

Fig.5- Amplitudes of the correlated signal of the group 2

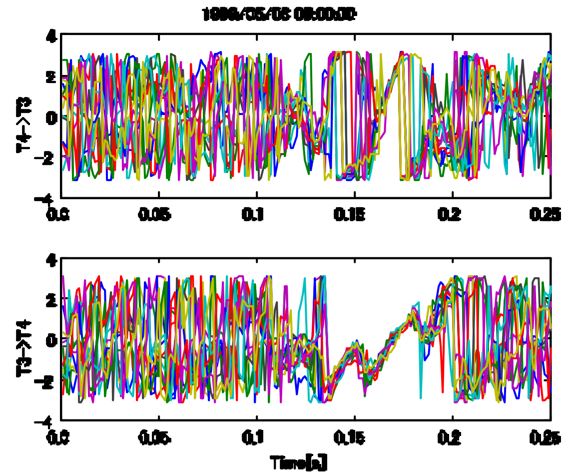

Fig.6- Phases of the correlated signal of the group 2

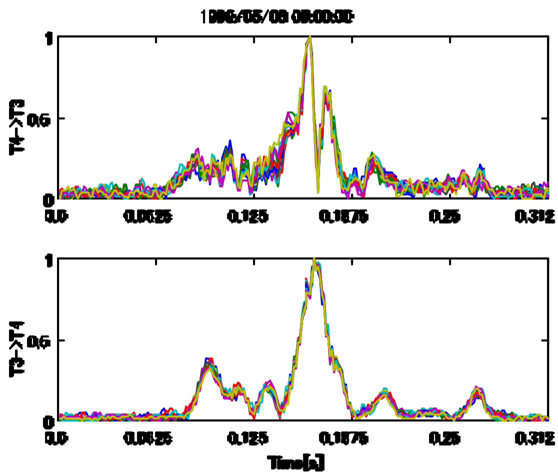

Fig.7- Amplitudes of the correlated signal of the group 6

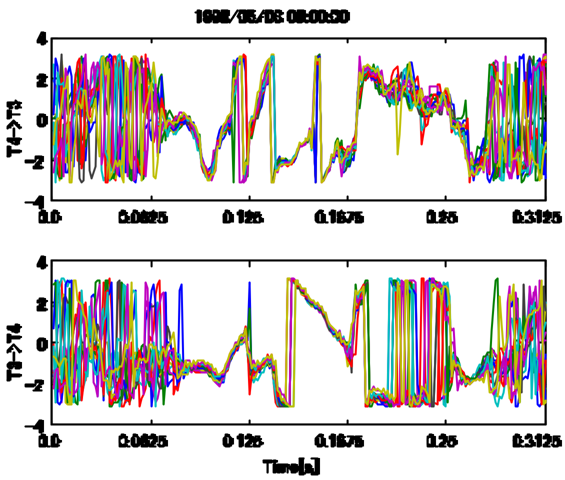

Fig.8- Phases of the correlated signal of the group 6

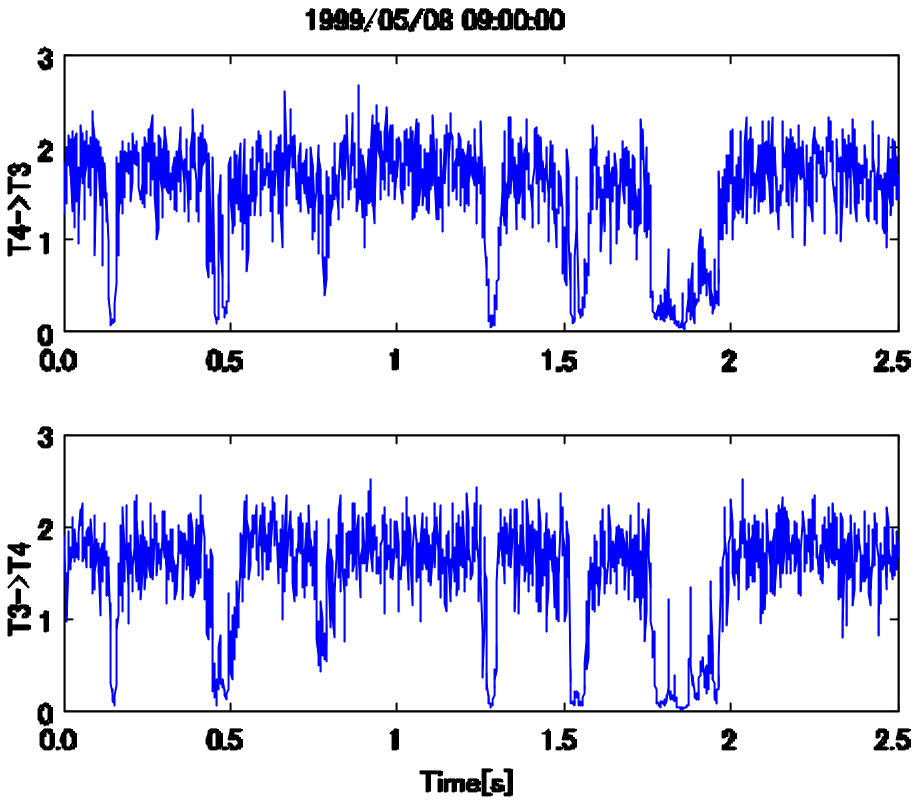

Fig.9. – Standard deviation of the phase of correlated signal

CONCLUSTIONS

We have presented the stability estimation results of the data collected during the sound transmission experiment performed by JAMSTAC in 1999 at the Central Equatorial Pacific. The standard deviation of the phase of the ray signal is very stable within 130 s. Between the reciprocal transmissions, the overall structures of the signal are similar, however, the fine structures are different. The standard deviation of the phase is a useful index for determining whether or not the ray exists. We proposed the evaluation criterion of the ray signal utilizing the phase stability. The received signal is judged to be an arrived ray when the standard deviation of the effective phase of 13 consecutive shots is less than 1 rad. Since the phase of a ray signal is very stable, we can observe the very small phase change of 0.2 rad and the travel time change of 0.16ms between the reciprocal transmissions. The combination of the amplitude and phase information is effective for observing the ocean structure change.

BIBLIOGRAPHICAL REFERENCES

[1] W. H. Munk and C. Wunsh: Deep Sea Res. 26(1979) 123.

[2] B. Cornuelle, C. Wunsch, D. Behringer, T. Birdsall, M. Brown, R. Heinmiller, R. Knox, K. Metzger, W. Munk, J. Spiesberger, R. Spindel, D. Webb and P. Worcester: J. Phys. Oceanogr. 15 (1985) 133.

[3] P. F. Worcester, R. C. Spinel and B. M. Howe: IEEE J. Oceanic Eng. 10 (1985) 123.

[4] H. Hachiya, S. Ohtsuki and M. Okujima: Proc. 7th Symp. Ultrasonic Electronics, Jpn. J. Appl. Phys. 26 (1987) Suppl. 26-1, p. 73.

[5] T. Nakamura, I. Nakano and I. Kaihou: Jpn. J. Appl. Phys. 37 (1998) 3172.

[6] H. Hachiya, S. Ohtsuki and M. Okujima: J. Marine Acoust. Soc. Jpn. 17 (1990) 106 [in Japanese].

[7] P. F. Worcester, B. D. Cornuelle, M. A. Dzieciuch, W. H. Munk, B. M. Howe, J. A. Mercer, and R. C. Spindel, J. A. Colosi, K. Metzger, T. G. Birdsall and A. B. Baggeroer: J. Acoust. Soc. Am. 105 (1999) 3185.

[8] H. Hachiya, T. Nakamura and I. Nakano: Jpn. J. Appl. Phys. 38 (1999) 3366.

[9] Y. Miyakawa, H. Hachiya, T. Nakamura and I. Nakano: Jpn. J. Appl. Phys. 40 (2001) 3811.

[10] T. Nakamura, H. Fujimori and I. Nakano: Jpn. J. Appl. Phys. 38 (1999) 3374.