ACOUSTIC DETECTION OF TSUNAMIS IN THE OPEN SEA*

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ABSTRACT

One of the important but difficult problems in the Tsunami Warning Service is the development of effective methods of early tsunami detection in the open sea. Acoustic waves can serve as powerful tool for the diagnosis of ocean processes. The main physical factor influencing sound propagation in the ocean is water motion altering the sound speed and, consequently, the travel time of the acoustic signal. Thus, measurements of signal travel time can identify water movements, including tsunami waves. This paper describes the method and results of an experimental investigation of acoustic signal travel time fluctuations on a super-long path Hawaii – Kamchatka. It is shown that tidal currents are responsible for relatively fast (with time scales of days) fluctuations. The suggested method can be used for the development of an efficient system of acoustic monitoring and early warning of tsunami and other dangerous sea phenomena.

INTRODUCTION

One of the important but difficult problems in the Tsunami Warning Service is the development of effective methods of early tsunami detection in the open sea. Acoustic waves can serve as powerful tool for the diagnosis of ocean processes: tides, currents, and waves. The main physical factor influencing sound propagation in the ocean is water motion of altering the sound speed and, consequently, the travel time of acoustic signals. Thus, measurements of the signal travel time enable us to identify water movements, including tsunami waves. It is known that phase methods can provide highly accurate measurements of signal travel time. Therefore, the phase method based on analysis of harmonic signals is widely used to measure the travel time fluctuations. However, for multi-ray sound propagation in the ocean this method does not allow separation of signal arrivals associated with different rays. Recently, complex signals began to be used in acoustics. These signals are based on the M-sequence, which is a long series of pulses with phase modulation. Such signals have a wide spectrum and long duration that allow the compression of these signals in time by correlation processing. Using the M-sequence allows one to measure travel time fluctuations of acoustic signal propagating along different ray groups [Zverev and Stromkov, 2001].

In this paper, the phase-difference method and the results of an experimental study of travel time fluctuations of signals along the acoustic path Hawaii – Kamchatka (4800 km long) are described. Correlation of these fluctuations with tidal currents is examined. We suggest a theoretical model of tidal fluctuations of signal travel time and compare this model with observational data. The experiments on long-distance sound propagation were carried out in 1998-1999 within the framework of the program of Acoustic Thermometry of Ocean Climate (ATOC) [Dushaw *et al.*, 1999].

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EXPERIMENT

The length of the acoustic path was about 4800 km. Signals were radiated by the stationary point source, placed at the depth of 800 m near the Hawaiian Islands, and recorded by the USA and Russian stationary receiving multi-element systems in the Pacific Ocean (Figure 1).

The radiated signal represented a series of 44 identical pulses on carrier frequency of 75 Hz. The phase of each tone-frequency pulse was modulated by the M-sequence of length 1023 units. Duration of one unit was equal to two periods of the carrying frequency. To reduce the correlation noise of the M-sequence, the phase varied from one unit to the other by ±88.2092°. The frequency bandwidth of the radiated signal was 37.5 Hz. Duration of one pulse was 27.28 s, and duration of the whole series was approximately 20 minutes. Such series of pulses were radiated 6 times on every fourth day.

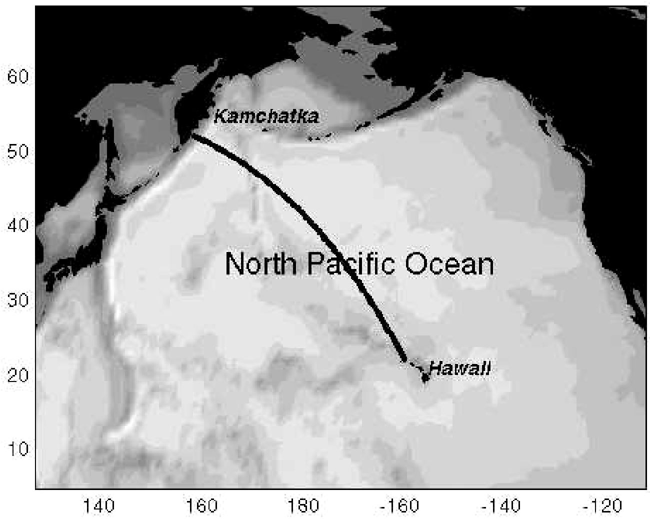

Figure 1. Stationary acoustic path Hawaii – Kamchatka.

The acoustic path crossed several areas with various types of waveguides, a cold front and the Kuroshio Current. This makes numerical modeling of the signal propagation much more difficult. Besides, the long length of the acoustic path resulted in significant signal attenuation. The received signals were so small that the signal/noise ratio for the signal bandwidth did not exceed –10 dB.

SIGNAL PROCESSING TECHNIQUE

The first stage of the processing was a bandpass signal filtering to eliminate noise outside of the signal frequency band. The output of the receiving system represents the sum of the signals passed by different channels (rays) and additive noise. For the acoustic path Hawaii – Kamchatka, the signal travel time was about 1 hour, while the maximum difference between arrivals of "fast" and "slow" rays did not exceed 15-20 sec.

The correlation function of the signal, calculated on an interval equal to the length of the sequence, represents a tone-pulse with a triangle-shape envelope with the basis equal to the double length of the M-sequence:

$$R(\tau) = \begin{cases} (2^n - 1)\cdot(1 - \frac{|\tau|}{\tau_0})\cos(\omega_0 \tau), & |\tau| \le \tau_0, \\ 0, \quad |\tau| > \tau_0 \, . \end{cases} \qquad (1)$$

For measurement, the variations of the travel time of the received signal were divided into intervals equal to one M-sequence. For each k-th interval the mutual correlation $R_k(\tau)$ with a replica was estimated as:

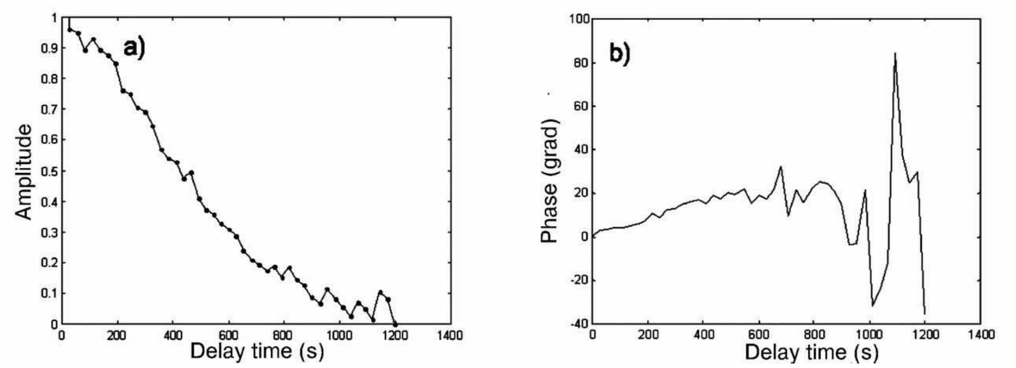

Figure 2. The logarithm of the amplitude $|\rho_k(m)|$ (left) and the phase $\varphi_k(m)$ (right) for one of sessions of radiation.

$$R_k(\tau) = \int_{t_k}^{t_k+T} y_k(t) M(\tau - t) \mathrm{d}t , \quad (2)$$

where $R_k(\tau)$ is the estimation of the pulse response of the system, $M(t)$ is the replica of the radiated signal, T is the length of the M-sequence, $y_k(t)$ is the k-th sample of the received signal. Presenting $R_k(\tau)$ as $R_k(\tau) = h_k(\tau)\exp(i\omega_0\tau_k)$, i.e. as a pulse response of the system shifted in time by τ_k., we can introduce function $\rho_k(m)$ as

$$\rho_k(m) = \int_T R_k(\tau)^* R_{k+m}(\tau) d\tau = e^{i\omega_0(\tau_k - \tau_{k+m})} \int_T h_k(\tau) h^*_{k+m}(\tau) d\tau \ , \quad (3)$$

where $|\rho_k(m)| = \int_T h_k(\tau) h^*_{k+m}(\tau) d\tau$ is the amplitude of the function $\rho_k(m)$, and $\varphi_k(m) = \omega_0(\tau_k - \tau_{k+m})$ is the phase. For the stationary propagation conditions (without fluctuations) $\varphi_k(m) \equiv 0$, since in the stationary system travel time does not change: $\tau_k = \tau_{k+m}$. Nonzero values of the phase at points m = 0,1,2 … are possible only if there are dynamic processes changing the travel time of the signal, i.e. when $\tau_k \neq \tau_{k+m}$. To increase the accuracy of the estimation of $\rho_k(m)$ we made the following averaging:

$$\hat{\rho}_k(m) = \frac{1}{M-1} \sum_{i=k}^{k+M} \rho_i(m) \ . \quad (4)$$

Due to the limited number of the received signals, estimation error increases with increasing m (Figure 2). At the same time, it is seen from Figure 2 that the phase $\varphi_k(m)$ changes almost linearly within the time interval up to 500 s. That means that the basic processes influencing variations of the signal travel time have characteristic path times exceeding 500 s. One may assume that the phase $\varphi_k(m)$ on this interval (0<τ<500 s) may be approximated by a polynomial of the first order to increase the accuracy of measurements.

If acoustic travel time would be time-independent, the phase $\varphi_k(m)$ would be equal to zero. Due to the time variability of the phase speed of the signal, phase $\varphi_k(m)$ has positive or negative values, which change with time. Variations of Assuming that during one session of the sound radiation, the travel time is constant, i.e. that the typical times of the processes are much larger than 28 min, we can use the observational data to estimate the rate of the travel time change. This derivative may be presented as the travel time at length *m* of the M-sequence may be presented as

$$\delta\tau_k(m) = \tau_k(k+m) - \tau_k(m) = \frac{\varphi(k,m)}{2\pi f_0} \ . \quad (5)$$

Assuming that during one session of the sound radiation, the travel time is constant, i.e. that the typical times of the processes are much larger than 28 min, we can use the observational data to estimate the rate of the travel time change. This derivative may be presented as

$$\frac{d\tau_k}{dt} \approx \frac{\varphi(m,k)}{2\pi f_0 mT} \quad (6)$$

To increase the signal-to-noise ratio we made the coherent summarizing of 44 consecutive samples (each having the length of the M-sequence) of the received signal recorded during one session. The number of the averaged samples depended on the distance, *m,* between the samples in the signal and due to the finite number of M-sequences during one session it varied for different delays from 44 to 1.

The error of measurements of the rate (derivative) of the travel time in these experiments was $4\cdot10^{-7}$–$1.7\cdot10^{-6}$. This value may be accepted as a typical error of the frequency variations of the received signal.

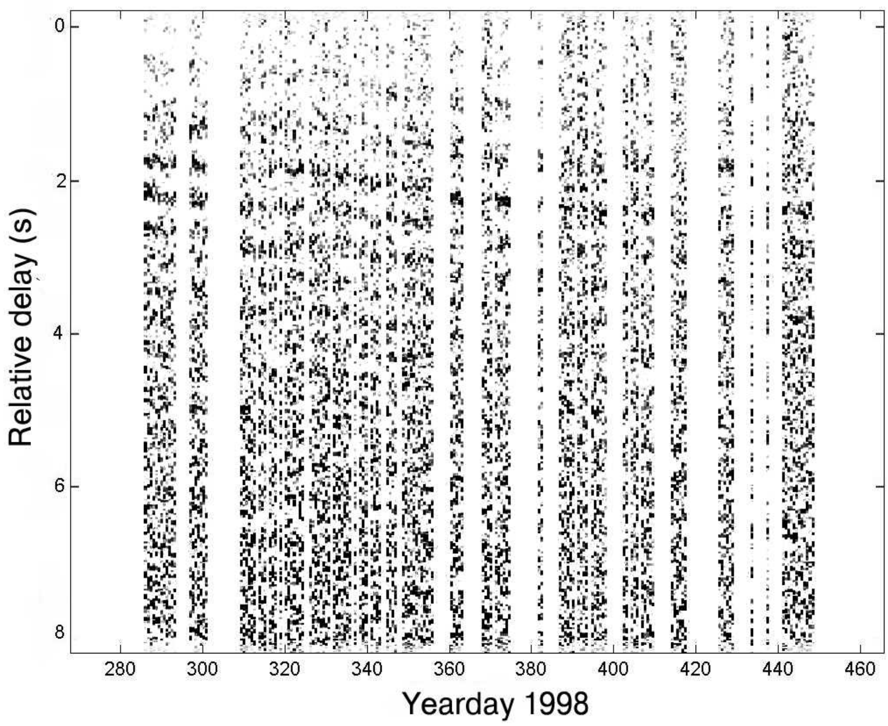

Figure 3. The signal level (displayed by blackening) after the processing as function of the time delay (vertical axis) and the day of 1998 (horizontal axis) Days with numbers exceeding 365 corresponds to year 1999.

ANALYSIS OF THE EXPERIMENTAL DATA

Figure 3 shows the signal level as function of the time delay and day of 1998. We should emphasize that in these experiments we used GPS time, which allowed us precise comparison of the data obtained over many months. Due to technical problems there were some gaps in measurements marked as blanks in Figure 3. Nevertheless, the seasonal fluctuations of the signal arrival time, as well as groups of the ray arrivals, are clearly seen in Figure 3. Seasonal variations of the travel time are up to 1 sec, which are significantly larger than the annual trend (50 ms) associated with the climate warming.

Figure 4 presents the rate of the sea level change[1] and the rate of the travel time change for several days of 1998. In order to compact the figures, the days of the year without measurements have been removed. The labels on the horizontal axis correspond to 24 hours, and the dotted line and asterisks designate values of the phase $\varphi_k(m)$. Data presented in the figure allows for the estimation of the time delay associated with the tidal influence in the vicinity of the Hawaiian Islands in the travel time of the acoustic signals received at Kamchatka, which is about 2.49-2.51 hours. As the acoustic path is extended along a meridian by approximately 41 degrees, the difference between the geographical times at Kamchatka and Hawaii is 2.73 hours.

Values of the phase for the time delay corresponding to the length of the M-sequence is as large as 0.02 radians which corresponds to $5.6 \cdot 10^{-4}$ degrees per one period of the carrier signal. Consequently, for 6 hours (half of the semidiurnal tidal period) the delay of the signal

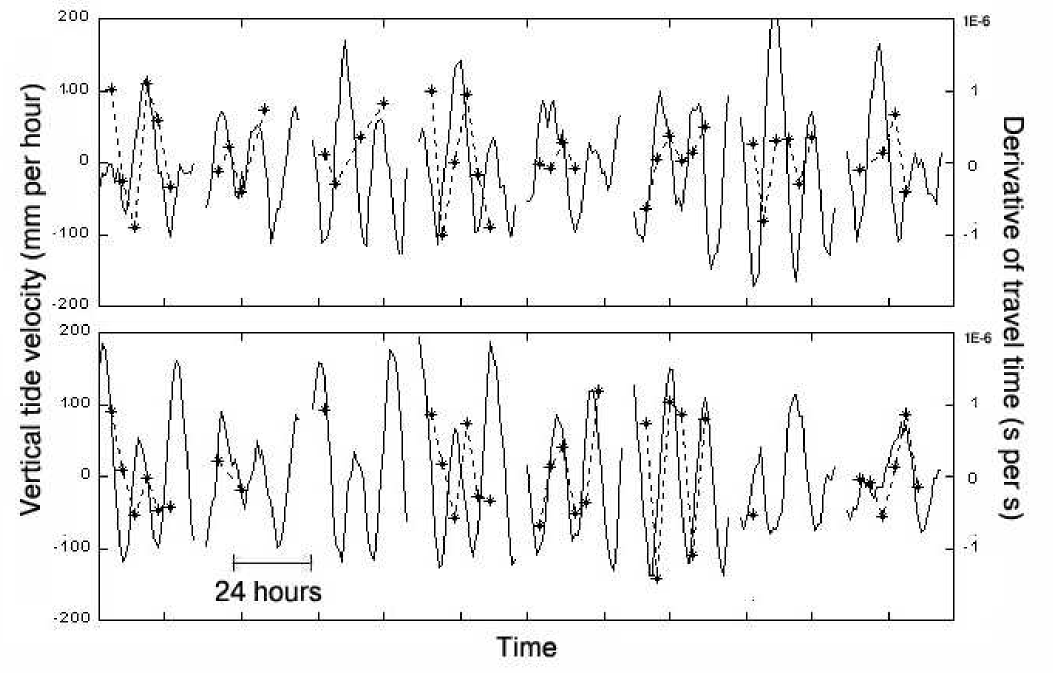

Figure 4. The rates of sea level changes near Hawaii (solid line and the left vertical scale) and the acoustic signal travel time (dotted line with crosses and the right vertical scale) for several days of 1998. The bottom plot is the continuation of the upper plot.

[1] The data were kindly given by the University of Hawaii Sea Level Center.

travel time is about 0.2 sec. Data presented in Figure 4 show the correlation between fluctuations of the travel time and the rate of the sea level change.

THEORETICAL MODEL

The major factor causing fluctuations of the travel time of acoustic signals are tidal currents. Sea level changes are too small (less than 10^{-3}) to cause noticeable changes of the thickness of the acoustic waveguide. To identify the ray arrivals, which are seen in Figure 3, we calculated the travel time for the given acoustic path for various seasons. In these calculations we used a model for the sound speed variations with depth, obtained by the empirical orthogonal function method (EOF). EOFs for each of the seasons and sites along the acoustic path were calculated using the climatological data (Levitus's Atlas). This allowed us to obtain the smoothed decomposition coefficients of the vertical sound speed profiles along the path and for different seasons. These coefficients were used to restore the vertical profiles of the sound speed for calculations of the travel times for different rays.

It is possible to select several sections of the acoustic path with approximately homogeneous sound speed profiles, which were used in the numerical calculations. These sound profiles produced a significant error in the absolute travel time but relatively small error for travel time differences corresponding to the different rays. This enabled us to tune the calculated and observed groups of time arrivals (Figure 3) and, therefore, to identify the groups of the rays having specific number of ray cycles along the path. A simple model of interaction of sound waves with the moving ocean medium was used. Variations of the travel time were calculated for one ray along the axis of the acoustic waveguide. The sound speed for this ray is the sum of the sound speeds in the ocean without any motion and the projection of the tidal currents on the path:

$$t = \sum_{m=1}^{M} \frac{r_m}{c_m + v_m} , \qquad (7)$$

where c_m is the sound speed at the m-th interval of the path, r_m is the length of this interval, v_m is the projection of the tidal vector on the path at the m-th interval of the path, M is the number of such intervals. The derivative of the travel time was calculated discretely as the deviation of the travel time in a short interval of time.

For calculation of the tidal velocities we applied the model TPXO 5,0 [**http://www.oce.orst.edu/po/research/tide**], which allows one to calculate the tidal currents at any point of the ocean. The step along the path was chosen to be 100 km, i.e. $M = 50$. Figure 5 compares the calculated and observed travel time variations. The theoretical and experimental data are in good agreement. An advanced ray propagation model can be used to improve the results.

The suggested method of measurements of the travel time fluctuations can be used to detect tsunamis in the open ocean. The basic physical reason causing changes of the travel time both for tides and for tsunami are the corresponding currents produced by these long-wave processes. Since the tidal fluctuations are quite strong it is important to calculate them precisely to eliminate their influence and detect tsunami waves.

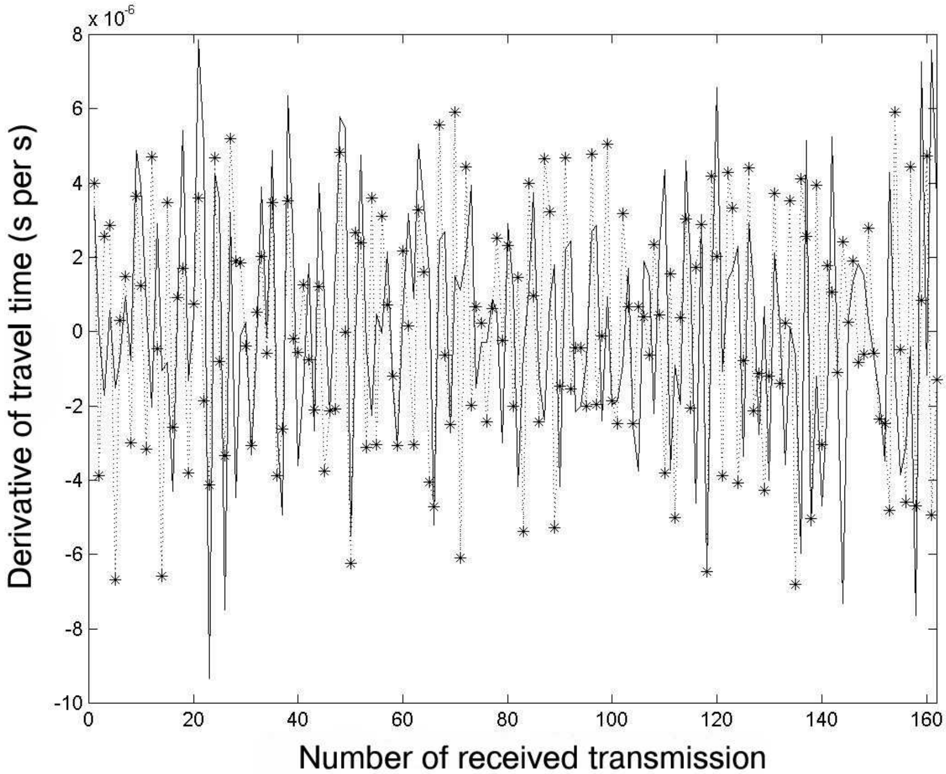

Figure 5. The rate of the travel time variations obtained from the observational data (dotted line and crosses) and from numerical calculations (solid line).

CONCLUSIONS

The results of the present work show that carrier signals modulated by the M-sequence can be used to identify and monitor small (0.02 radians per period of the carrier) fluctuations of the travel time at the stationary acoustic paths in the ocean. The simplified model, considered in this paper, allows the estimation of fluctuations of the travel time caused by the currents. One may believe in the possibility of tsunami detection by the measurement of travel time fluctuations caused by the currents produced by tsunami wave passing the acoustic path. Further works in this direction should be directed to improve the theoretical models of the fluctuations caused by tides to eliminate their effect and hence record a possible tsunami event.

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