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Application of vibroseismic oscillations for time synchronization of self-contained deep-water stations

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1. Introduction

It is well known that the self-contained deep-water stations (ADS) are widely accepted in the tasks of the World Ocean monitoring. Various information about physical fields is collected via the ADS network, distributed throughout the ocean floor. The information from each ADS is clocked with its internal clock having a relative temporary instability in the best case at a level of 10^{-8}. The absolute daily deviation on time ± 10 msec corresponds to it, and is accumulated in conditions of the long-term self-contained work of the station. Naturally, this is the reason of deviation of the internal clock of the ADS in relation to the global (world) time. In this connection, there is a problem of synchronization of the internal clock by signals from outside. The complexity of solution of the task thus consists in the fact that the conventional ways of transferring synchronization signals from outside with the help of electromagnetic oscillations are unacceptable because of their rapid damping in water with depth.

The usage of hydroacoustic waves is possible. The distance of their propagation, except for the cases of their propagation in the underwater sound channel, is limited by occurrence of refraction of waves resulting in appearance of shadow zones, which in turn, brings about failures in reception of signals. In addition, the state of the medium affects the characteristics of the trajectory of of hydroacoustic wave propagation causing additional errors in time synchronization of the ADS.

In the given work, an approach to solving the problem employing seismic oscillations excited in the ground by powerful vibrational sources (vibrators) as synchronization signals from outside is considered. Due to precision of controllability of signals of the global time such sources can be used as synchronization signals sources. Moreover, due to time invariance of the characteristics of a medium of seismic waves propagation and, also, due to the fixed position of the ADS, seismic signals at reception points have high recurrence of time parameters. This circumstance is prerequisite for possibilities of precision time synchronization on the basis of using seismic oscillations.

The vibrators can excite two types of signals: harmonic and frequency-modulated (sweep-signals), when propagating in the ground the harmonic signal has higher noise immunity by an order as compared to sweep-signals [1]. In view of this fact, the application of harmonic signals for the solution of the ADS synchronization problem is considered in the present paper.

2. Formulation of the problem

Vibrators excite simple harmonic motions with periods T_1, T_2, ..., T_N. Signals of the two types are, respectively, rewarded at the ADS:

$$S_{0k}(t) = A_0 \cos[\omega_{0k}(t - \Delta)], \qquad k = 1, 2, \dots, N,$$

are the inner reference signals with a constant amplitude A_0 and frequencies ω_{0k}, formed by the ADS timer (the parameter Δ is the value of deviation of the internal timer in relation to the global (world) time) and

$$u_k(t) = A_k \cos[\omega_{0k}(t - t_k) + \varphi_k^*] + n(t)$$

is a seismic signal corded at the ADS in the steady-state mode at $t \gg t_{\mathrm{st}}$, where t_{st} is the setting-up time of response of a medium.

Here A_k, ω_{0k}, and t_k are, respectively, amplitude, frequency, and time of propagation in environment of k-th signal; φ_k^* is the phase of a sounding signal at the point of radiation; and $n(t)$ is the ground noise at the point of the ADS installation.

The task is reduced to the measurement of deviation Δ using both types of signals.

3. Solution of the problem

First of all, in the expression for a seismic signal $u_k(t)$ let us estimate the initial phase of the steady-state oscillation $\varphi_k = \varphi_k^* - \omega_{0k} t_k$, measured in relation to the phase of a reference signal $S(t)$, equal to $\theta_k = \omega_{0k}\Delta$. The initial values φ_k $(k = 1, 2, \dots, N)$ are measured at the instant 0 according to the clocks of the server corresponding to $D = 0$, i.e., immediately after the ADS installation. Such a measurement is possible employing the quadrature algorithm of processing [2].

Based on the obtained values φ_k, the values x_1, x_2, ..., x_N are calculated, representing time slices between zero moment at clocks of the server and the beginning of the following (after zero moment) cycle of a recorded useful signal (Figure 1).

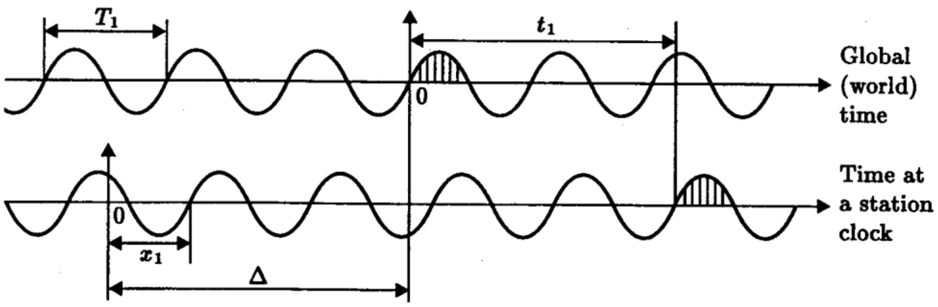

Figure 1

From Figure 1 it is seen that $\varphi_k + \omega_{0k} x_k = 2\pi$. Hence follows

$$x_k = T_k \cdot \left(1 - \frac{\varphi_k}{2\pi}\right). \tag{1}$$

With an error Δ present instead of the values $\{x_k\}$ there will be the values $x_k = \Delta + t_k$ (see Figure 1). This will bring about change of the estimations $\{\varphi_k\}$, by whose value deviation one can judge about the error Δ. An ambiguity, arising in this case of measurements Δ, caused by periodicity of sounding signals, can be removed using the relation

$$x_k = (\Delta + t_k) \bmod T_k. \tag{2}$$

The notation $a \bmod b = c$ means that $a = bn + c$, where n is integer, $0 \le c < b$ (i.e., mod means the operation of taking the residual).

As taking the residual is a linear operation (on a ring), relation (2) can successively be written down in the following forms:

$$\Delta \bmod T_k + t_k \bmod T_k = x_k, \qquad \Delta \bmod T_k = R_k, \tag{3}$$

where

$$R_k = x_k - t_k \bmod T_k = T_k \cdot \left(1 - \frac{\varphi_k}{2\pi}\right) - t_k \bmod T_k.$$

The values $t_k \bmod T_k$ can be calculated beforehand if we carry out sessions of radiation of harmonic signals with appropriate frequencies immediately after an automatic deep-water station was installed, i.e., at the instance when its clocks still work precisely ($\Delta = 0$). From the above-said it follows that the measurement of the phase of a useful harmonic signal at zero instant according to the clock of the station enables us to determine the residual from the division of Δ into the period of this harmonic signal T_k.

There arises a problem: how can Δ be restored using the residuals from the division of Δ into the values T_k?

For such a restoration be possible, the values T_k should satisfy the following condition:

$$T_k = p_k T, \qquad k = 1, 2 \ldots N, \tag{4}$$

where p_k are coprimes.

This is justified by the theorem of residuals: if the residuals from division of some number into coprime integers p_1, p_2, ..., p_N are known, then it is possible to calculate a residual from the division of this number into the product of numbers p_1, p_2, ..., p_N.

In this case, calculations are based on the standard method of solution of the Diophantine equations employing decomposition to a chain fraction.

If condition (4) is fulfilled, then on the basis of a set of equations (3) it is possible to calculate the value: $\Delta \bmod (p_1 p_2 \times \ldots \times p_N \cdot T)$. Selecting a set of the values p_k, it is possible to make so that the value $p_1 p_2 \times \ldots \times p_N \cdot T$ be rather large ($p_1 p_2 \times \ldots \times p_N \cdot T \gg \Delta$). In this case, $\Delta \bmod (p_1 p_2 \times \ldots \times p_N \cdot T) = \Delta$.

Let us remark that even in the event that there are no limitations on the greatest possible deviation of clocks, it is not a serious barrier, as in this case it is possible approximately to predetermine time with the help of any of known methods (for example, a method based on determination of the response arrival time of the matched filter [2]), and then to define it more precisely by calculation of a residual.

The possibility to restore Δ by a residual from its division by T_k is illustrated in Figure 2 for the following conditions: $N = 2$ (i.e., two sounding harmonic signals are used), $p_1 = 5$, $p_2 = 3$ (i.e., the periods of these harmonic signals are related to each other as 3/5).

Figure 2 represents the dependence of the residuals x_1 and x_2 as parametric function on Δ. Each point in the given figure represents a pair of values (x_1, x_2), unambiguously defined by phase values, obtained through the quadrature algorithm of processing. As x_1, x_2 represent residuals from the division of Δ into periods of harmonic signals, it is obvious, that a point, representing them, cannot be outside the limits of a rectangle represented in the figure. In the case, when (x_1, x_2) are recorded in conditions of the absence of noise the point, representing them, should lie on a bold line.

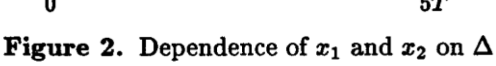

Figure 2. Dependence of x_1 and x_2 on Δ

The location of the point (x_1, x_2) depends on Δ as follows: at $\Delta = 0$ the point (x_1, x_2) is in the left lower corner, with Δ increasing by 1 it is shifted along the bold line to the right and upwards by unit (unit is understood as length of the diagonal of one small square in the diagram). Such, indeed, is the case the point reaches the boundary of a rectangle, then it "skips" along the dotted line and continues its move along the next segment of the bold line. After the point reaches the right upper corner of the rectangle, it "skips" into the left lower corner and starts moving again.

The summarized length of all the segments of the bold line is equal to $P_1 \times P_2$ units (i.e., in our case 15 units). It is easy to notice, that in the case known beforehand, Δ is less, than $P_1 \times P_2$, a pair of the coordinates (x_1, x_2) enables us to unambiguously determine Δ (it is supposed, that the noise is absent). Really, it is possible to calculate Δ as distance, to be passed by the point starting with the origin of coordinates, moving along bold line to hit into the preset point. For example, the point A in Figure 2 corresponds to Δ equal to $3 \times 6 \times T$.

In the case when due to the presence of noise the phases of signals are determined with certain errors, the point (x_1, x_2) will not locate on the bold line. For example, the point B in Figure 2 is the point A, shifted under the influence of an error to the right and downwards.

With the help of Figure 2 it is possible to illustrate the requirements to the accuracy of definition of a phase needed for the method working. The absolute error of definition of the values x_1, x_2 should not exceed $T/2$ (i.e., half a side of a cell in Figure 2). With allowance for (1) and (4), the absolute error of definition of a phase of each of N harmonic signals should not exceed p/p_k. The given sort of an error determines necessary conditions of usage of the method.

Generally, the accuracy of definition of the phases φ_k at the expense of the influence of external factors can be described by a meansquare error, which is summarized from the following components:

$$\delta_\varphi^2 = \delta_1^2 + \delta_2^2 + \delta_3^2.$$

Here the following notations are used:

- δ_1 defines the accuracy of maintaining the phase of a sounding signal at the radiation point. Its value for modern types of vibrators is within 1–1.5°;
- δ_2 appears in connection with fluctuations of travel times of the waves tk in a medium under the World Ocean bottom caused by geodynamic and tectonic processes such as earthquakes, earth blocks shifts, etc. The resulting phase errors make about 1–2° [3];
- δ_3 is the error of measurements due to the ground noise. Its value is of order $1/\gamma$, where γ is the signal/noise ratio on the output of the device of processing. This sort of an error can be up to the level of no more than 1° at the expense of the choice of the energy of a sounding signal.

In view of the indicated components the summarized error δ_φ is attained up to the level 3°. The error of measurements of a temporary discrepancy Δ is expressed through the error δ_φ as the relation $\delta_\Delta = (T_k/2\pi)\delta_\varphi$. In this connection for the sounding frequency equal to 5 Hz, the error of measurements of a phase equal to 3°, in the time domain an error about 1.6 msec will correspond. Such an error corresponds to the requirements of the temporary synchronization to the ADS.

Limitations on the usage of the proposed method are the following:

1. The originally measured phase of a recorded signal on the ADS should be be repeated from session to session. This means the phase of repeated sounding signals in relation to the global (world) time should be constant as well as the velocity of seismic waves propagation on a given source-receiver trace.
2. Signals should not be weakened up to zero as a result of interference. This problem can be overcomed by the proper choice of sounding signals of different frequencies.

4. Conclusion

The method of temporary synchronization of self-contained deep-water stations (ADS) in relation to the global time by means of vibroseismic signals, emitted by high-powered vibrational sources in the monochromatic mode is offered and analyzed. The influence of a different types of external interference and errors originating in the system of synchronization on the accuracy of binding the internal timer ADS to the global time is estimated. It is shown that the accuracy of synchronization at a level of not worse than 1.5–2 m/s is accessible.

References

[1] Khairetdinov M.S., Krivoputcki V.S., Senin A.G. On noise stability of vibroseismic signals at depth exploration of the Earth // Problemno-Orientirovannye Vychislitel'nye Kompleksy. – Novosibirsk, 1991. – P. 42–53 (in Russian).

[2] Khairetdinov M.S., Dvoretckaja L.G., Rodionov Yu.I. Software and hardware means of processing of vibroseismic signals and analysis of microseisms. – Novosibirsk, 1998. – (Preprint / RAN. Sib. Branch. of Comp. Math. and Math. Geoph.; 969) (in Russian).

[3] Glinsky B.M., Kovalevsky V.V., Khairetdinov M.S., Vibroseismic monitoring of seismic-danger zones // Volcanology and Seismology. – 1999. – № 6. – P. 60–64.