Registration of Hydroacoustic Signals by Coastal Laser Strainmeters

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***Abstract*—This study aims to investigate the possibility of registering a source of hydroacoustic radiation by a system of spatially spaced coastal laser strainmeters (LSs) or a two-coordinate LS. The experimental complex includes onshore LS of stationary and mobile versions and low-frequency sonar emitting systems. The method of conducting this experimental work is described, which allows for the investigation of the possibility of receiving a signal at different distances from receiving systems and a moving signal source. Based on the results of the experiment, LSs stably register signals from sources of hydroacoustic vibrations. The results obtained reveal the possibility of registering a source of hydroacoustic radiation as it moves through a controlled water area. In this case, the control can be conducted by combining two different measurement methods: (1) the method of spatially spaced LS and (2) the method of amplitude modulation of the signal of multidirectional components of LSs. The results obtained revealed the prospects of using a system of LS to register sources of low-frequency sonar radiation along the coast of offshore zones.**

Keywords—two-coordinate laser strainmeter, hydroacoustic radiator, amplitude modulation, transformation of acoustic signals

I. Introduction

Hydroacoustic, seismic, and infrasound waves are generated by various natural and anthropogenic radiation sources. To investigate various events, especially of a catastrophic nature, a wide range of vibrations and waves must be recorded. Various seismographic complexes on Earth are networked and track events recorded in the Earth's crust. As an example, we can mention such networks as the German Regional Seismic Network [1], which includes seismic exploration equipment, sonar, and infrasound sensors. The Global Seismographic Network records seismic data and provides information to the scientific community [2]. Moreover, the Russian Federation has the Federal Research Center (FIC) "Geophysical Survey of the Russian Academy of Sciences," which conducts continuous seismic monitoring, monitoring of slow geodynamic processes, tsunami warnings, and volcanic activity. Such networks are utilized to register and study large-scale events, allowing them to be recorded using a distributed sensor system.

Low-frequency hydroacoustic vibrations of various origins can propagate over considerable distances in the marine environment. Such vibrations are transformed in the geosphere transition zone into seismoacoustic vibrations. This behavior is dependent on the ratio of the length of the sonar wave to the depth of the sea. At depths less than half the length of the sonar wave, conditions arises under which almost all the sonar energy is transformed into elastic vibrations of the seabed. In [3], it was shown that in the low-frequency region, seismoacoustic surface waves become the dominant mechanism of acoustic energy transfer in the shallow shelf zone of the sea. As demonstrated by experimental studies on the transformation of hydroacoustic vibrations [4], in the offshore area of the sea, low-frequency hydroacoustic waves from depths less than half the wavelength mainly propagate in the form of Rayleigh-type surface waves along the boundaries between "water and Earth's crust" and "Earth's crust and air." Registration of such waves was conducted both by the authors of this work [5] and by other researchers [6]. At the same time, the polarization properties of Rayleigh-type waves enable the laser strainmeter system to determine the position of the radiation source in space. Further research has shown [7] that the coastal measurement complex of laser strainmeters can confidently detect sufficiently distant objects emitting sonar signals and also monitor the dynamics of their movement. The study of the characteristics of natural and anthropogenic events and phenomena, the interaction of signal generation mechanisms is becoming increasingly important, especially in the localization of events and the identification of the mechanisms of their occurrence.

Two acoustic experiments were conducted in the waters of Peter the Great Bay of Sea of Japan to study variations in the amplitude of the hydroacoustic signal recorded by coastal laser strainmeters. In the first experiment, the signal was recorded by two spatially spaced strainmeters, one of which is a mobile surface variant, and the other is a stationary two-coordinate laser strainmeter (TCLS). The second experiment consisted of recording the signal of a hydroacoustic radiator moving at the same speed across the water area at the same distance from a TCLS. The capabilities of a laser strainmeter for recording such a signal and its direction finding will be presented.

II. Experimental Complex and Methodology of Experiments

Two sonar radiators were used as radiating systems. The GI-2 hydroacoustic system was used at long distances [8], designed to generate long-term tonal and phase-manipulated signals in a frequency band of the order of 1 Hz at a central frequency of 22 Hz with an effective sound pressure of

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approximately 10 kPa. The radiator is quite massive equipment and weighs 260 kg. A system of series-connected car batteries is employed as the primary source of direct current. As a result of a series of test experiments, the number of power batteries amounted to 14 pieces. At short distances, a second radiator was utilized, which is an analog of the GI-2 system but was manufactured much earlier. The radiator has smaller geometric dimensions and a weight of approximately 50 kg. The effective sound pressure at a frequency of 33 Hz is approximately 3600 Pa. The radiator was adapted to work not only in conditions of anchorage and drift but also during the movement of the vessel, for which a hydrodynamic structure was created to stabilize the position of the radiator in space.

The depth of immersion of each radiator was determined based on the ratio of the relative radiating power of the near-surface source from its depth:

$$\frac{Pa}{P0} = 1 - \frac{Sin\left(\frac{4\pi h}{\lambda}\right)}{\frac{4\pi h}{\lambda}}, \qquad (1)$$

where P_a is the radiation power, λ is the wavelength, and h is the depth of immersion.

It follows from this correspondence that with a small depth of the source, its field matches the field of the dipole; therefore, the amplitude of the sound pressure decreases considerably with a small depth of the radiator. Following the ratio, the immersion depths of the radiator with a radiation frequency of 33 Hz–15 m and the radiator with a radiation frequency of 22 Hz–18 m were selected.

The coastal TCLS is located at the Marine Experimental Station "Schultz cape" of the Pacific Oceanological Institute of Far Eastern Branch of the Russian Academy of Sciences in the area with central coordinates 42°34′48″N and 131°9′24″E. The TCLS is located in underground rooms and consists of two almost orthogonal laser strainmeters of unequal type, one of which has a measuring arm length of 52.5 meters (South–North) oriented at an angle of 18° relative to the meridian, and the second strainmeter with a measuring arm length of 17.5 m (West–East) oriented at an angle of 110° relative to the meridian. A mobile laser strainmeter (MLS) was established in the coastal region on Rock Foundation at the extreme point of Cape Gamow having coordinates 42°33′17″N and 131°13′3″E at a distance of 5.74 km from the TCLS. The orientation of the shoulder of the MLS was 40° to the meridian line.

A diagram of both experiments, in which the radiation stations of the first experiment are shown in circles with green edging and the trajectory of the radiator in the second experiment is shown in circles with red edging from 1 to 13 points is presented in Fig. 1. The arrows indicate the directions to the corresponding radiation point, revealed as a result of processing the amplitudes of the signal received by TCLS.

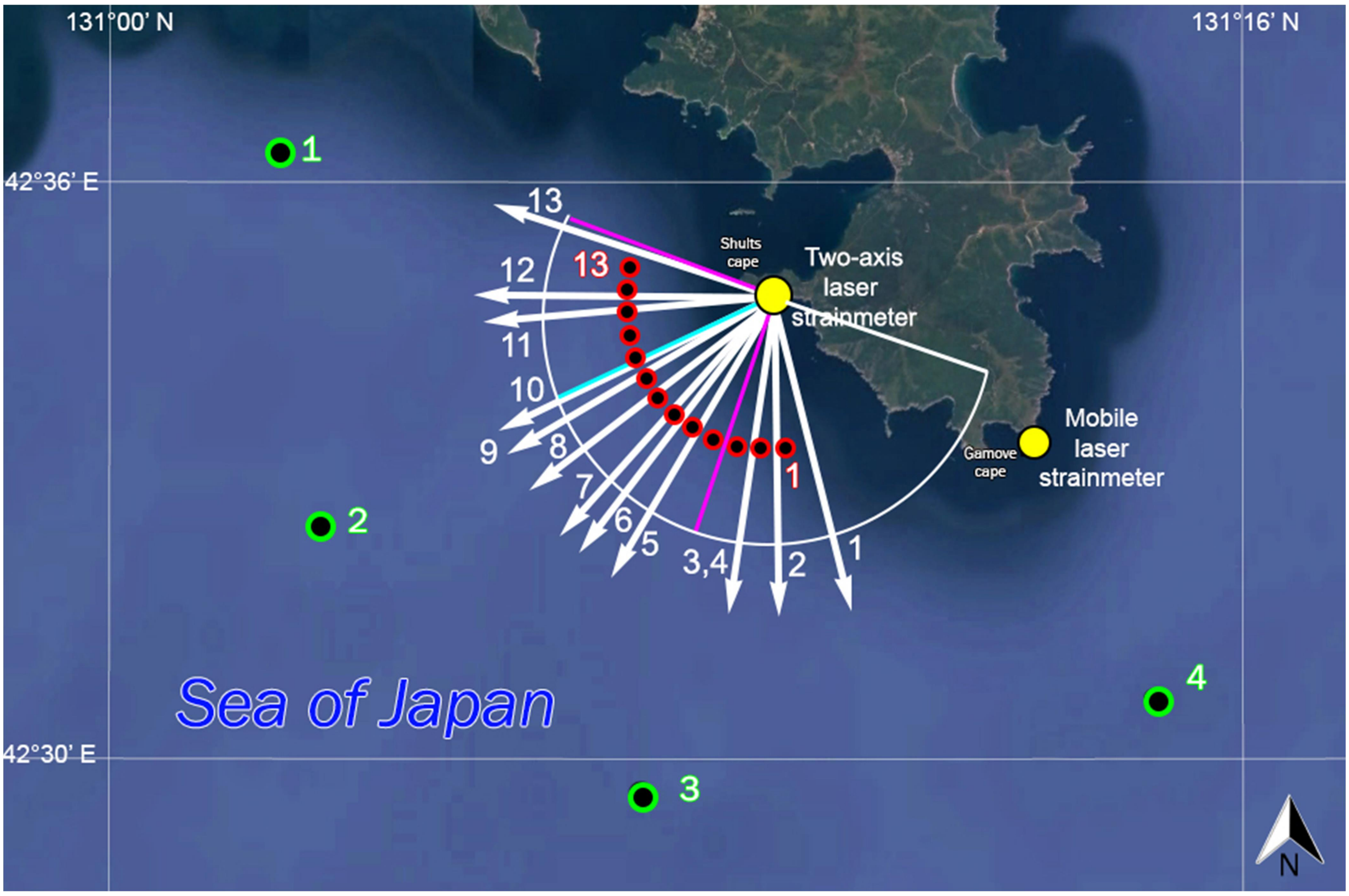

Fig. 1. Scheme of experiments.

The radiation technique in the first experiment was to mount the ship to the anchorage and stationary radiation of the signal. Four radiation stations were selected, each of which was located at a distance of 10 km from the TCLS according to the radiation pattern of its main measuring components, the direction of which is indicated in Fig. 1 in magenta. The radiation stations are indicated by green dots, and Table I presents their coordinates and distance from the measuring systems are shown in.

The methodology of the second experiment consisted of immersing the 33 Hz radiator to a predetermined depth of 15 m and gradually moving at the same speed at the same distance from the coastal measuring complex, over 3 km. The radiation was performed when moving from points 1 to 13 at a speed of 3 km/h.

TABLE I. CHARACTERISTICS OF THE RADIATION STATIONS

Station number	Coordinates of the radiation station	Distance from TCLS, km	Distance from MLS, km
1	42°36′20″N; 131°02′25″E	10	16,5
2	42°32′26″N; 131°02′59″E	10	13,5
3	42°29′39″N; 131°07′31″E	10	10
4	42°30′37″N; 131°14′47″E	10	5,5

The radiation signal in both experiments was cyclic in nature. Initially, tonal radiation was conducted for 300 s and after a pause of 30 s, an M-sequence was emitted with a duration of 155 s. After a pause of 30 s, the radiation cycle was repeated. As part of this work, the analysis of the tonal radiation signal is carried out to determine the possibility of determining the direction of the radiation source located in the water area.

III. PROCESSING AND ANALYSIS OF THE OBTAINED EXPERIMENTAL DATA

Fig. 2 presents the dynamic spectrograms of the signal received by TCLS located on the Schultz cape and MLS on the Gamov cape during the operation of the hydroacoustic radiator at station 1. All generated signals, both tonal and phase-manipulated with pauses between them, are present on the spectrograms of both strainmeters.

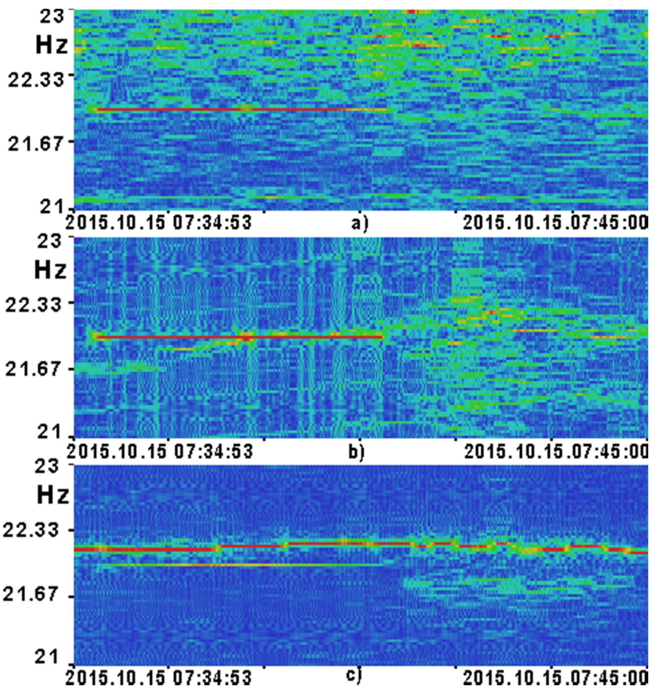

Fig. 2. Dynamic spectrograms of TCLS during operation of a hydroacoustic radiator at station 1 (green in Fig. 1): a) NS TCLS 52.5 m; b) WE TCLS 17.5 m; c) MLS.

Table II shows the summary results of the amplitude of the seismic acoustic signal recorded by laser strainmeters as a result of operation at stations of a low-frequency hydroacoustic radiation source.

TABLE II. AMPLITUDE OF THE SIGNAL OF LASER STRAINMETERS DURING OPERATION OF THE GI-2 RADIATOR AT STATIONS 1–4.

Station number	Amplitude SN TCLS, nm	Amplitude WE TCLS, nm	Amplitude MLS, nm
1	0.713	0.246	0.463
2	0.872	0.218	0.761
3	1.36	0.132	1.429
4	1.00	0.194	2.84

The first experiment shows that the method of registering a source of hydroacoustic radiation by a system of spatially spaced coastal laser strainmeters is feasible and has considerable prospects. Table II shows that the magnitude of the signal amplitude recorded by the MLS increases as the radiation stations approach the location of the MLS. At the same time, the radiation stations were at the same distance from the TCLS. Variations in the amplitude of the received signal in this case depend on the spatial position of the measuring axes of laser strainmeters, characterized by different radiation patterns. Measurement by TCLS uses the principle of polarization of seismoacoustic signals transformed from hydroacoustic signals. The amplitude values of the received signal indicated in Table II also confirm the change in the location of the source of the hydroacoustic signal following this theory.

The second experiment consisted of conducting a continuous series of sonar signal emissions when the vessel was moving along a circular trajectory relative to the coastal receiving system at the same distance from it by 3000 m (shown by red circles in Fig. 1) and registration of the seismoacoustic signal with the TCLS. The vessel started moving along a given trajectory at a constant speed of about 3 km/h. The initial radiation point was offset by an angle of about 30 degrees relative to the axis of the 52.5-m component SN of the TCLS. Then, the trajectory of the radiator crossed the axis of this component and spread up to the intersection of the axis of the component of the 17.5-m component WE of the TCLS.

The second experiment shows that a continuous recording of the hydroacoustic signal by a TCLS was obtained when moving the emitter around a circle with the same distance from the radiating system. The dynamic spectrograms of synchronous recording sections of a control hydrophone and components of a TCLS are presented in Fig. 3.

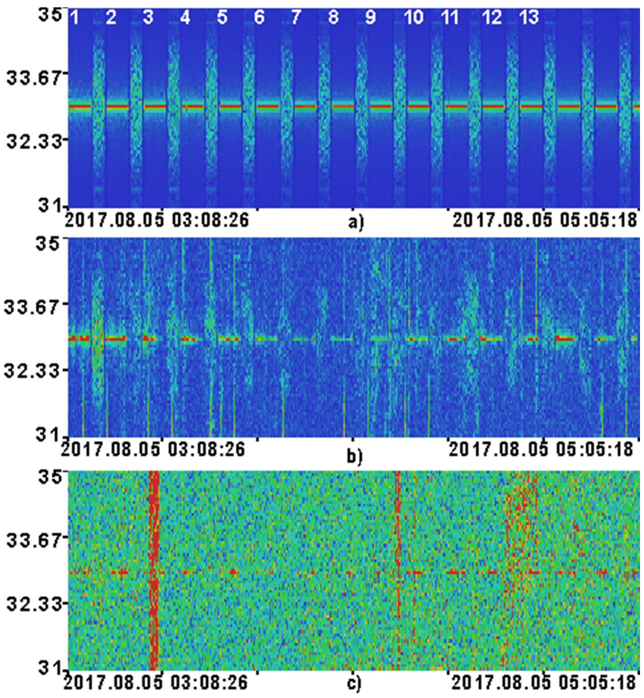

Fig. 3. Dynamic spectrograms of synchronous recording sections (red on Fig 1): a) Control hydrophone, the numbers indicate the time of the beginning of the radiation of the next signal packet. b) NS TCLS 52.5 m. c) WE TCLS 17.5 m.

The spectrogram of the control hydrophone recording shows digital marks that indicate the beginning of the next radiation packet. When evaluating spectrograms, it can be concluded that the amplitude level of the received signal decreases when the radiation source passes a section of the trajectory close to an angle of 45° with respect to the direction of the axes of the laser strainmeter, which is associated with their directional pattern.

The direction of the radiation source was determined according to the data of the 52.5-m SN and 17.5-m WE axes of the TCLS. A time interval of 50,000 samples was selected, which at a sampling frequency of 1000 Hz has a duration of 51 s. For each 300-s time interval, the amplitudes of the radiator signals were determined in the measurement data of NS and WE TCLS. From the ratio of the measuring arms of the 52.5-m and 17.5-m components of the laser strainmeter with the same external load on them, the ratio of the displacement values of the components of the laser strainmeter to each other should be as 52.5:17.5 = 3.0. This condition should usually be fulfilled when installing laser strainmeters on surfaces with exactly the same elastic characteristics. The surfaces on which the strainmeter components are mounted differ. However, this ratio can be estimated with the same effect of atmospheric pressure variations on the areas of the Earth's crust occupied by the considered components of the laser strainmeter. Such work was previously performed; as a result, it was found that with the same external force acting on the Earth's crust by Schultz cape at the locations of the components of the laser strainmeter, this ratio is not 3.0 but 2.8. We employed this ratio when determining the direction to sources of various signals—hydroacoustic, seismoacoustic, geophysical, and so on. In our case, the bearing was determined by the tangent:

$$tg\alpha = 2.8 * \frac{a_{17.5}}{a_{52.5}}, \qquad (2)$$

where α is the angle between the direction of the signal source and the axis of the 52.5-m laser strainmeter NS, $a_{17.5}$ – amplitude of the spectral component of the 17.5-m laser strainmeter (WE), $a_{52.5}$ is the amplitude of the spectral component of the 52.5-m laser strainmeter (NS).

Table III is compiled based on the results of the analysis of the amplitude of each component of the laser strainmeter during the movement of the sonar emitter. The table shows the amplitudes of the acoustic signal recorded by the laser strainmeter and the direction to the source determined by the results of the data obtained and reflected in Fig. 1.

TABLE III. THE AMPLITUDE OF THE LASER STRAIN GAUGE SIGNAL DURING OPERATION OF THE MOVING GI-1 RADIATOR AT STATIONS 1–13

Station number	Amplitude SN TCLS, nm	Amplitude WE TCLS, nm	Direction Angle, degrees
1	0.20	0.046	32.11
2	0.21	0.028	19.91
3	0.23	0.028	11.39
4	0.23	0.013	8.93
5	0.22	0.015	10.97
6	0.18	0.021	18.24
7	0.18	0.025	21.78
8	0.18	0.038	30.00
9	0.056	0.016	39.6
10	0.11	0.037	43.01
11	0.13	0.09	63.39
12	0.083	0.075	68.49
13	0.037	0.20	86.26

Analyzing the results of the experiment, it can be concluded that the error in determining the direction of the source of hydroacoustic radiation moving in the shelf area ranges from 0.2% to 10.5%. In this case, at a sea depth of approximately 40 m, the length of the sonar wave at a frequency of 33 Hz is approximately 45 m. Therefore, a considerable contribution to the error is made by the peculiarities of the transformation of hydroacoustic waves at the water-bottom boundary and the conversion of their energy into the energy of Rayleigh-type waves propagating along the water-bottom boundary, as well as various other waves (longitudinal and transverse, Stoneley and Love waves). Considering all the features is possible only with accurate knowledge of the structure of the seabed and the characteristics of the rocks of the seabed, the angle of inclination of the seabed, and so forth.

IV. CONCLUSIONS

Packages of hydroacoustic signals excited by sources of low-frequency hydroacoustic radiation in the offshore area of the Sea of Japan were isolated on synchronous recordings of laser strainmeters spaced along the coast. Experimental values of the amplitudes of seismoacoustic signals generated at different frequencies recorded via laser strainmeters have been attained. These results reveal the possibility of controlling the source of hydroacoustic radiation as it moves through the nearby water area. In this case, the control can be conducted by combining two different measurement methods: 1) the method of spatially spaced laser strainmeters and 2) the method of amplitude modulation of the signal of multidirectional components of laser strainmeters. The results obtained have shown the prospects of utilizing a system of laser strainmeters to register sources of low-frequency hydroacoustic radiation on the coasts of offshore zones.

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