

Experience in synchronous observation of seismic-strain oscillations of the Earth by the spaced laser interferometers

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Abstract. The first results of unique experiments on the synchronous registration of seismic-strain oscillations of the Earth's surface by three laser interferometers-deformographs (strainmeters) spaced 6740 km apart are presented. Two 100-meter laser interferometers at the Fryazino site (Moscow Region) and the 18-meter laser strainmeter at the observation point of Karymshina (Kamchatka Peninsula) were applied. The frequency-stabilized and thermally controlled lasers and the interferogram registration systems of compensation and modulation types providing an absolute instrumental resolution of 0.1-0.01 nm were used. The results of data analysis in sessions of synchronous operation of these instruments during 2016-2020 were obtained and discussed.

1 Introduction

The instrumental ability and software advance of geophysical tools to extract a weak useful signal on a natural and anthropogenic noise background is one of the important issues of the applied facilities. These issues are at the forefront when the problem of detecting and identifying seismic and acoustic processes, which can be qualifying as precursors or indicators of large earthquake preparation as well as its temporal development. Measurements of the Earth's deformations such as volumetric strains, tilts and shear deformations of the crust are the basic methods of study because of supplying a primary information about geological media motions [1]. These methods along with the classical seismic monitoring techniques provide the new possibilities of combined data processing of the Earth's surface motions in the field of seismic waves [2-4]. The research of nature and spatiotemporal dynamics of the seismic-strain geophysical wave fields becomes fruitful considerably when the spatially distanced and array instruments are used [5, 6].

In this paper, we present the preliminary results of our experiments on the synchronous registration of seismic-strain oscillations of the Earth's surface by three laser interferometers-deformographs (strainmeters) spaced 6740 km apart and installed in aseismic (Moscow Region) and active seismicity (Kamchatka Peninsula) zones.

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2 Observational sites and instruments for linear and shear deformation measurements

Two distant sites that used in the described measurement experiments differ in their seismic activity properties (Fig. 1). Aseismic zone, where laser strainmeters operate at the Fryazino Beam-Waveguide (underground testing site) [7], are placed within the Moscow Syncline (Fig. 1a).

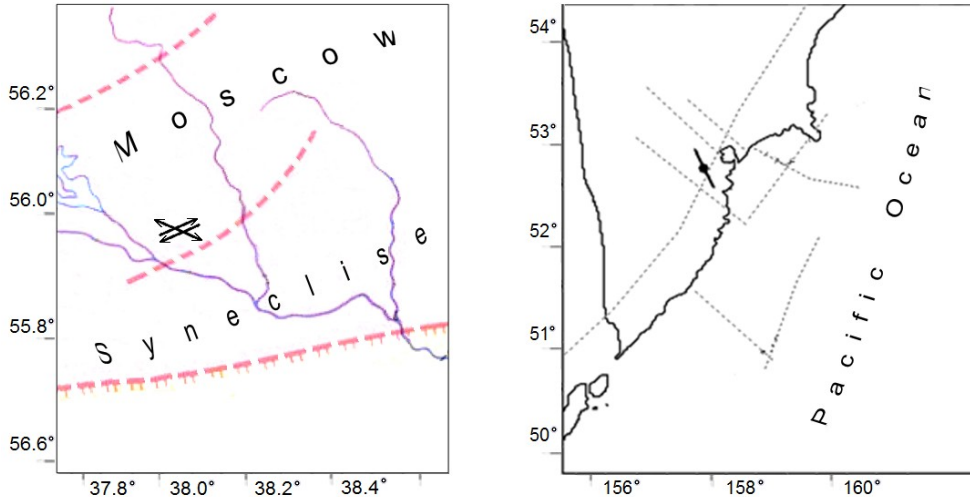


Fig. 1. Location and orientation of strainmeters in Moscow Region (a) and Kamchatka (b); arrows show the strainmeters orientation.

The distant laser strainmeter [8] operates in Kamchatka Region that characterized by high seismic activity. The dashed lines on the maps show the fractures of the crystalline basement (Fig. 1a) and the basic tectonic faults in the Earth's crust (Fig. 1b).

Two types of laser interferometers we applied for investigations (Fig. 2). An unequal-arm (asymmetric) Michelson interferometer (Fig. 2a) measures a linear strain, which is valued as variations of the interferometer long arm and expressed in fractions of the laser wavelength. A classical equal-arm Michelson interferometer measures a shear deformation along the axis, which is parallel to a hypotenuse of an interferometer arms triangle as shown in Fig. 2b.

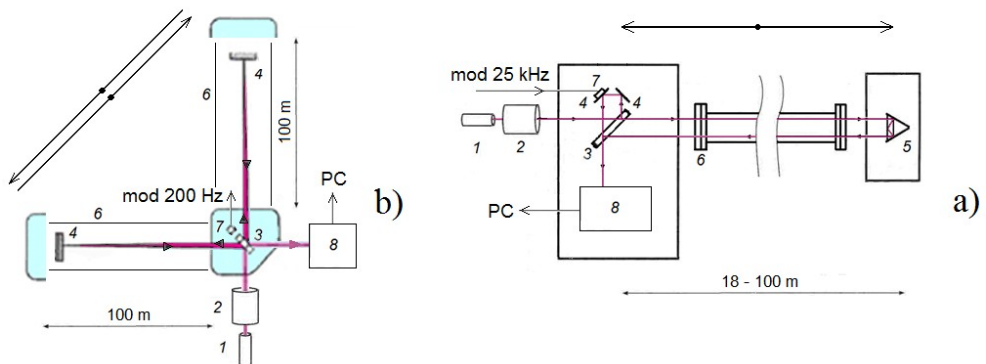


Fig. 2. The diagrams of unequal-arm (a) and equal-arm (b) interferometer-strainmeters: 1 – laser, 2 – collimator, 3 – beam-splitter, 4 – mirrors, 5 – triple prism reflector, 6 - enclosing pipes, 7 – modulating piezo or em-transducer, 8 – photo-electronic unit.

The 18-meter laser strainmeter is located at the Karymshina complex geophysical observation site [8] on the Kamchatka Peninsula. This strainmeter is a modified unequal-arms Michelson interferometer with a measuring arm length of 18 m, and the length of the reference arm is about 0.1 m (Fig. 2a). An interferometer is installed on the ground surface on case pipes of two 5m dry wells 18m spaced. Light path is protected by airtight enclosing pipe, which is covered by a special housing from precipitation and wind.

Two laser strainmeters at Fryazino underground testing site in the Moscow Region [7], which are considered in this paper, also are built according to the Michelson interferometer scheme. One of them is an unequal-arm (asymmetric) interferometer – the length of the measuring arm is 100 m, and the length of the reference one is about 10 cm (Fig. 2a), and another is an equal-arm interferometer, the lengths of each measuring arms are about 100 m (Fig. 2b). Distance between these interferometers-strainmeters is 400 m. The lasers, optics and pre-amplifying electronics are installed below a ground surface about at 1.5-2 m depth. Light beams pass through the underground steel pipe, which is partially connected with outer atmosphere. Frequency-stabilized and thermally controlled lasers with a wavelength $\lambda = 633$ nm are used in the strainmeter schemes as radiation sources.

Two versions of registration systems are applied to measure the interferometer fringes displacements in our strainmeters. The examples of typical records of the used registration systems are shown in Fig. 3. The 100-meter unequal-arm laser interferometer (Fryazino site) is equipped with a registration servo-system of compensation type [9]; its frequency range is limited near 100 Hz, and the highest resolution had been approved up to 0.01-0.001 nm in a 1 Hz band. The sharp and high ruptures in the recording data track (Fig. 3a) are the servo-system resets to its initial zero position with values $(5 \div 10) \times \lambda/2$ and are accounted during interferometer signal processing (Fig. 3 b).

Registration systems of modulation types are used in schemas of 18-meter unequal-arm interferometer (Karymshina) and 100-meter equal-arm interferometer (Fryazino), which provide an absolute instrumental resolution near 1.0-0.1 nm (record examples in Fig. 3 c, d, e and f).

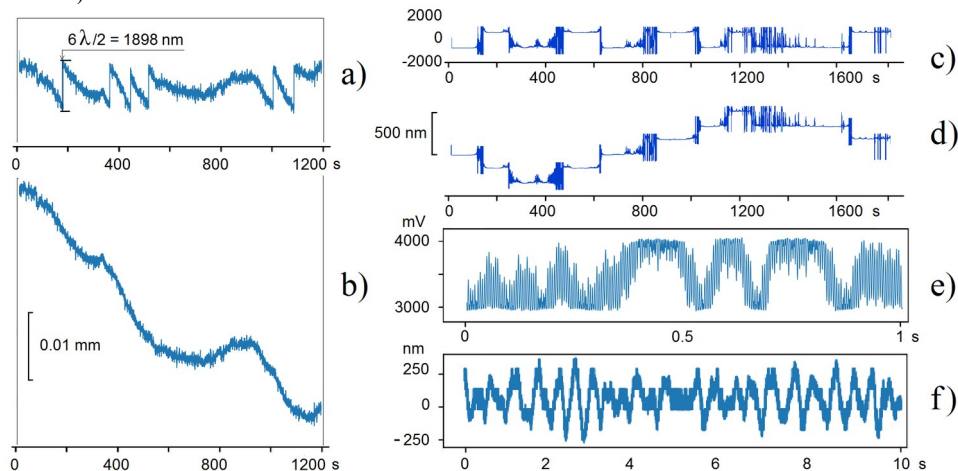


Fig. 3. The recording data tracks (a, c, e) and the results of data acquisition (b, d, f).

In the Karymshina strainmeter (Fig. 2 a), the electric signal corresponding to the change of light intensity in the interference pattern is formed on a photodiode in the photo-electronic unit 8, which is thereupon transformed into voltage and amplified on a transimpedance amplifier. A frequency range carrying the useful information is separated from the spectrum of the obtained electric signal by a band filter of the 8-th order. The pick of a pass band corresponds to the modulation frequency of 25 kHz. Then a signal is

transformed into a square signal, which comes to a pulse counter No1 and on the input of a phase detector. The reference signal modulating the phase shift between the reference and the measuring laser beams comes to the pulse counter No2 and on the second input of a phase detector. A phase detector generates a signal proportional to the phase difference within 2π between the reference and the interference signals. The number of phase shift transitions across 2π is determined by the difference of readings of pulse counters No1 and No2. To digitize a signal, which is formed by the phase detector, we use a 16-bit ADC together with LF filter of the 8-th order with the cut-off frequency of 500 Hz. The ADC sampling rate is 1 kHz and the result of digitization are formed and stored in a PC. The basic accuracy of the recording system is $\lambda/4 = 158$ nm (Fig. 3 c, d), while appropriate tuning parameters of the interferometer modulation and acquisition software allows the resolution to be improved up to 1.0-0.1 nm.

The registration system of modulation type applied in the equal-arm interferometer (Fryazino, Fig. 2 b) includes a modulating em-transducer (7) and a single photo-receiver in the electronic unit (8). The detecting an interference phase difference within 2π and phase shift transitions across 2π is performed by data acquisition system (Fig. 3 e, f). The modulation frequency is 200 Hz and a 14-bit ADC sampling rate is 2 kHz.

3 Analysis of synchronous seismic-strain observations

In this Section, we present the preliminary results of analysis of a few sets from synchronous seismic-strain observational series carried out by means of described instruments during 2016–2020. The used technique and amounted results are original and first obtained according to up today publications.

The number of major seismic events $M_w=7-8$ happened in this period and part of them have been recorded by laser strainmeters in Moscow Region and Kamchatka. Three of the recorded earthquakes, which are presented in the Table 1, have been analyzed and the obtained results are discussed below.

Table 1. The major earthquakes $M_w = 7.7-8.2$ in 2016–2020 considered in present paper (USGS - US Geological Survey web-data from //earthquake.usgs.gov/earthquakes/)

No	Date yy-mm-dd	Time (UTC) hh:mm:ss	Lati- tude	Longi- tude	Magni- tude M_w	Region
1	2016-03-02	12:49:48	4.95°S	94.3°E	7.8	Southwest of Sumatra, Indonesia
2	2017-09-08	04:49:19	15.0°N	93.9°W	8.2	SSW of Tres Picos, Mexico
3	2020-01-28	19:10:24	19.4°N	78.8°W	7.7	Caribbean Sea (NNW of Lucea, Jamaica)

2.1 Sumatra M_w 7.8 earthquake (2 March 2016)

The Southwest of Sumatra, Indonesia M_w 7.8 earthquake (No 1 in the Table 1) occurred in March 2, 2016 and was considered in our recent publication [10]. Let us analyze the obtained data of seismic-strain registrations in more detail. Four fragments of this earthquake recordings performed by Karymshina and Fryazino laser strainmeters are shown in Fig. 4.

The main difficulty in recording the earthquake by any strainmeter is the small value of primary (P) and secondary (S) body seismic waves. The slow Raleigh (R) and Love (L) surface waves have big amplitudes and are recorded with sufficient accuracy (see the right of Fig. 4). It was unexpected, although the accuracy of the Karymshina digital system is lower than that of the compensation servo-system in Fryazino, it allows the fast P and S signals to be isolated with high sensitivity. The record fragments in the left of Fig. 4 a, b show this effect, which occurring due to non-linear characteristics of the used digital registration system. The time-frequency processing these data yields the arriving times and frequency bands of the isolated body waves (Fig. 5).

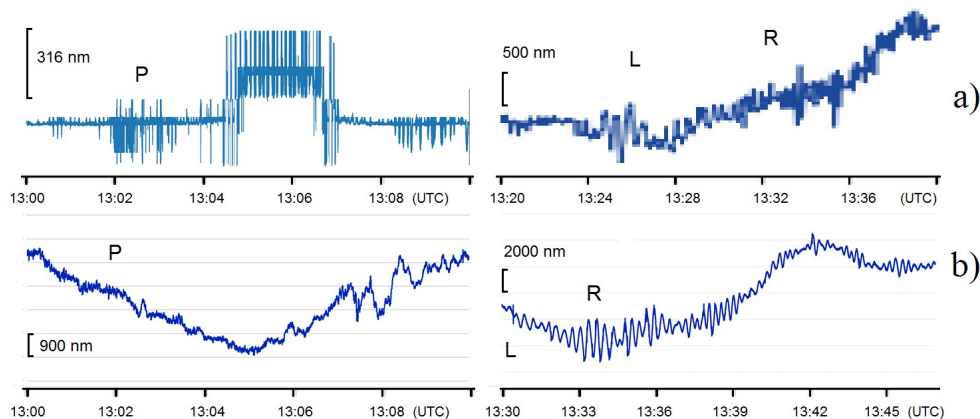


Fig.4. The fragments of 2016 Sumatra Mw 7.8 earthquake recordings performed by Karymshina (a) and Fryazino (b) unequal-arm laser strainmeters.

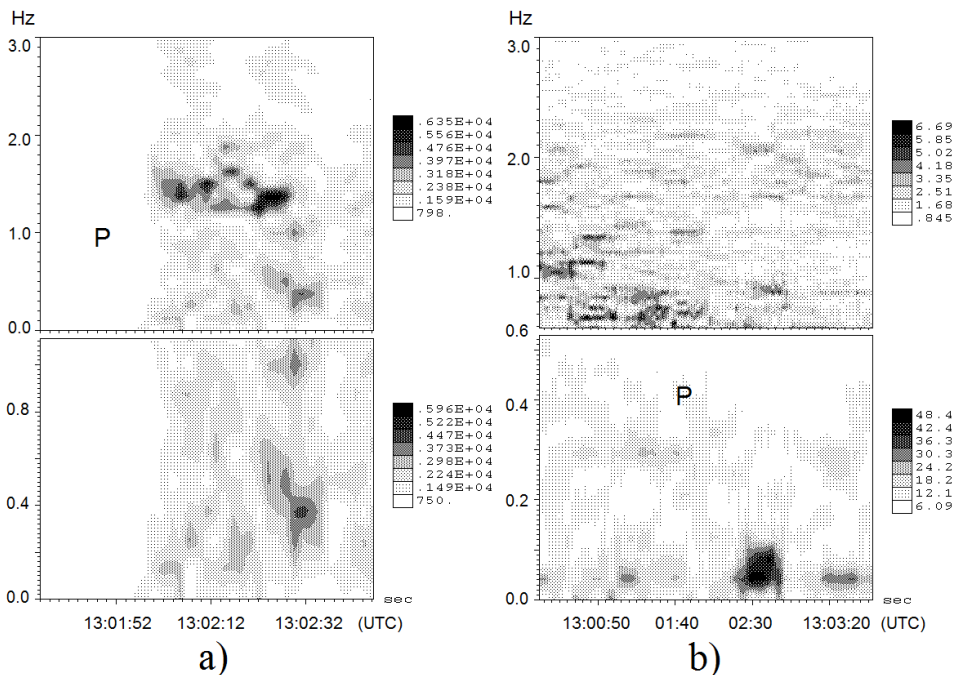


Fig. 5. Time-frequency diagrams shows the arriving times and frequency bands of body P-waves recorded in Karymshina (a) and Fryazino (b) sites.

Temporal synchronization of the operated distant instruments was performed by broadcast time signals with accuracy 1 second. The comparison the obtained results with data of neighbor seismic stations: Petropavlovsk-Kamchatsky (PET) and Obninsk (OBN) according to Geophysical Survey of Russian Academy of Sciences (www.ceme.gsras.ru/) is presented in Table 2.

Table 2. Arrival time of P-waves from Sumatra Mw = 7.8 earthquake on 02 March 2016 according to Fryazino (FRZ), Karymshina (KRM) laser strainmeter data and Petropavlovsk-Kamchatsky (PET) and Obninsk (OBN) seismic stations (www.ceme.gsras.ru/)

Station Name	FRZ	OBN	PET	KRM
Arrival time (UTC) hh:mm:ss	13:01:25	13:01:35.8	13:01:50.4	13:01:58

2.2 Mexico Mw 8.2 earthquake (8 September 2017)

The major 2017 Mexico (SSW of Tres Picos) Mw 8.2 seismic event was recorded by two 100-meter laser interferometers located at a distance of 0.4 km from each other at Fryazino testing site. Fragments of registration data and the results of their processing are shown in Fig. 6.

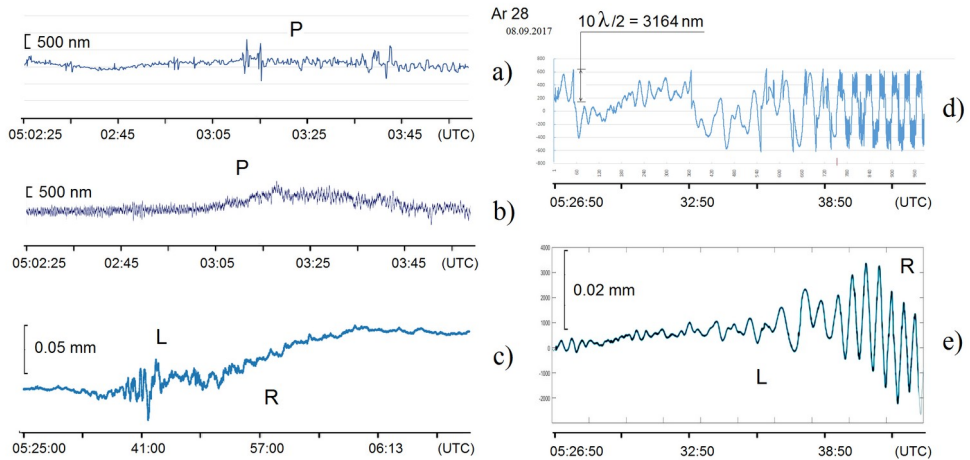


Fig. 6. The fragments of 2017 Mexico Mw 8.2 earthquake recorded by unequal-arm (a, d, e) and equal-arm (b, c) laser strainmeters in Fryazino site: a, b – arriving body P-waves, c, d, e – surface waves records.

Maximum amplitudes of shear L surface waves reach the values of 0.03-0.04 mm and are more than the R-waves amplitudes for shear equal-arm strainmeters (Fig. 6 c). After R-waves decay, ultra-long period disturbance starts – it can be explained by a process of the very beginning of the Earth’s free oscillation exciting [11, 12].

2.3 Caribbean Sea Mw 7.7 earthquake (28 January 2020)

The strong interplate earthquake (Mw 7.7, 19:10 UTC) occurred in Caribbean Sea 123km NNW of Lucea, Jamaica. The synchronous records obtained by the Fryazino and Karymshina unequal-arm laser strainmeters are shown in Fig. 7. Distances from this earthquake epicenter to the Fryazino and Karymshina sites are 1300-1600 km more than those for 2016 Sumatra Mw 7.8 earthquake (Section 2.1). The body P and S seismic waves arrival is almost imperceptible in the Fryazino strainmeter track (Fig. 7 a) and is completely missing on the Karymshina strainmeter record (Fig. 7 b).

Surface seismic waves (L and R) are recorded by two strainmeters: the oscillation tracks are quite distinct at 19:30-20:00 UTC. The comparison of recorded surface waves in the period of their maximum amplitudes during 19:55-19:58 UTC is shown in Fig. 8.

Two obtained synchronous records are different from each other although the distance difference from this earthquake epicenter to the Fryazino and Karymshina sites is only a few percent. The main periods of the isolated surface waves are 30 and 35 seconds in Fryazino and Karymshina respectively. This is explained not only by the difference in phase velocities of these waves [13], but also by the different structure of the geological medium under the surface wave's paths. Indeed, the signal from Caribbean Sea goes to Fryazino site through the Atlantics and the West side of Eurasian tectonic plate, while the path of seismic wave's propagation to Karymshina site lies through the Pacific tectonic plate.

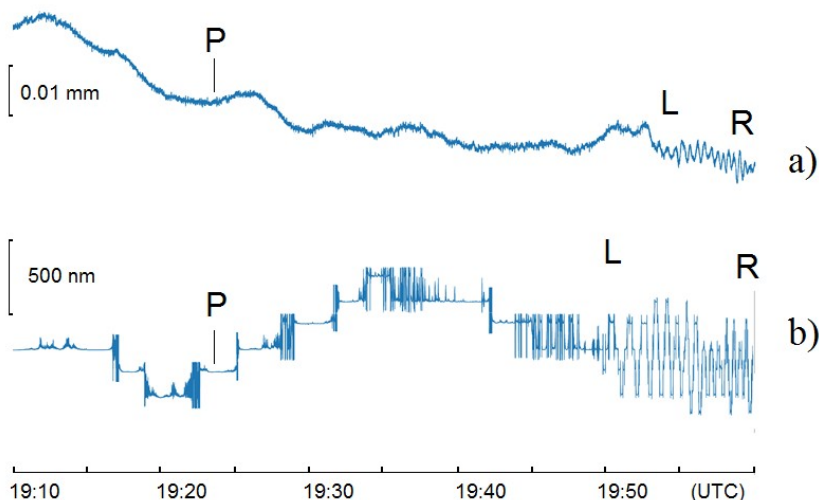


Fig. 7. The synchronous records of the 2020 Caribbean Sea Mw 7.7 earthquake performed by unequal-arm laser strainmeters in Fryazino (a) and Karymshina (b) observational sites.

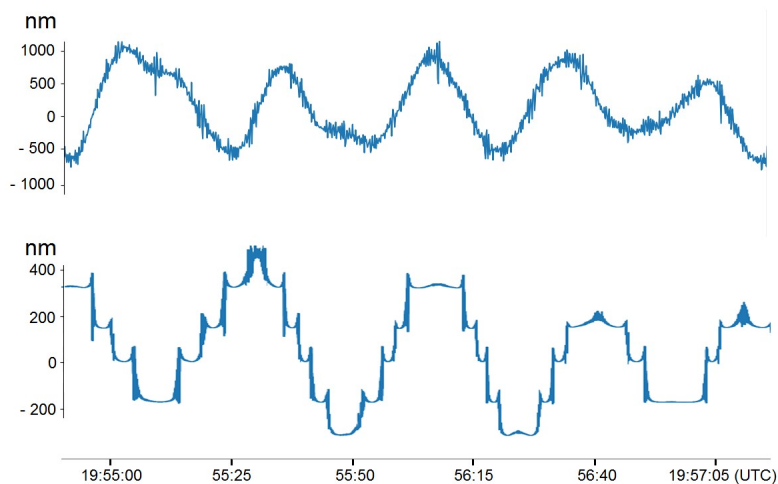


Fig. 8. The synchronous records of the L surface waves excited by 2020 Mw 7.7 earthquake: a – registration servo-system of 100-meter unequal-arm laser strainmeter (Fryazino), b – registration systems of modulation type (18-meter laser strainmeter in Karymshina).

4 Study of synchronous records of micro-seismic strains

Microseisms are worldwide geophysical processes that continuously force the Earth's crust every-where. They occupy the wide frequency range (10^{-2} - 10^2 Hz) and have as a rule natural origin. These kind of microseisms are presented in general by earth surface waves of Love and Rayleigh type and are generated by various ocean waves, which call force ground motions at the seafloor. Microseisms in the period range of 1–5 sec are excited by effect of ocean surf and wind while microseisms with periods of more than 3–5 sec are usually caused by large meteorological disturbances above oceans. Microseisms in a frequency band higher than 1 Hz are usually excited by artificial sources and form the spatially distributed coherent seismic field. Investigations of properties and behavior of wideband micro-seismic oscillations were considered as possible method of earthquake precursors studies [14, 15].

Laser strainmeter allow us to investigate the characteristics of microseism in wide frequency and accuracy ranges. From the other hand, the system of spaced laser interferometers will be able to determine the coherency of detected micro-seismic fields including those of extra-terrestrial origin [16].

A number of synchronous series of micro-seismic strain measurements were carried out by means of the laser strainmeters at Fryazino and Karymshina observational sites during 2016-2020. The examples of analysis of two strainmeters data recorded 18 hour before the 2020 Caribbean Sea Mw 7.7 earthquake (Section 3.3) are shown in Fig. 9.

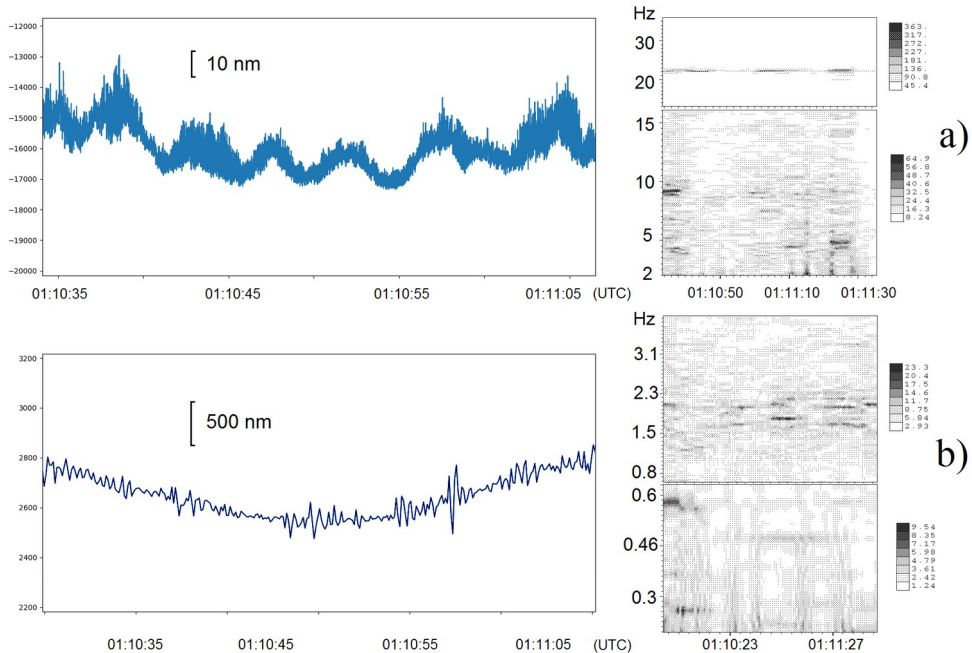


Fig. 9. The synchronous records of micro-seismic strains and their time-frequency diagrams, obtained at Karymshina (a) and Fryazino (b) sites on 28 January 2020.

The registration system of the Karymshina 18-m laser strainmeter being in linear mode operation is able to record the storm 4-6 s microseisms (Fig. 9 a). The relatively large value of the microseism amplitude (10-20 nm) is explained by the small distance (30-40 km) to the Pacific surf coastline. The most usual amplitudes of storm 4-6 s microseisms from Atlantic recorded in Moscow Region (1000-1200 km to the ocean coastline) is in units of nanometer for strainmeter of the same length installed in deep gallery [1].

The synchronously operating 100-m unequal-arm strainmeter at Fryazino site records 0.3-0.4 s microseisms of industrial origin (Fig. 9 b). Their amplitudes arise to 200-300 nm in daytime and decrease several times at night period.

Results of time-frequency analysis of these data are shown in right column of Fig. 9. High frequency micro-seismic signals are observed on the Karymshina diagrams. The isolated peak frequencies are 4.5 Hz, 9.1 Hz and 14 Hz. The narrow and high intensity peak with frequency 22 Hz (Fig. 9 a) is sufficiently coherent and probably have artificial origin.

Time-frequency diagrams of the Fryazino strainmeter reveals the next isolated peaks: 0.27 Hz, 0.49 Hz, 0.59 Hz in the lower diagram (Fig. 9 b). The split spectral peak with frequency near 1.9 Hz is distinguished in the upper part of this diagram. This peak exhibits moderate coherency properties. It should be noted that strong splitting of this spectral peak we observed before the major Chile Mw 8.3 earthquake on 16 September 2015 using the same laser strainmeter [10].

4 Conclusion

The preliminary results of unique experiments on the synchronous registration of seismic-strain oscillations of the Earth's surface by three laser strainmeters spaced 6740 km apart are presented and analyzed. The used technique and amounted results are original and first obtained according to up today publications.

The frequency-stabilized and thermally controlled lasers, which used in the deformograph schemes as radiation sources, as well as the registration systems of compensation and modulation types, which are applied to measure the interferogram shifts, provide an absolute instrumental resolution of 0.1-0.01 nm for 18-100 meter basis of interferometers.

The effectiveness of the proposed methods is shown on the examples of the registration of remote signals from Mw 7.7-8.2 earthquakes. The results of spectral analysis of data obtained during 2016-2020 in sessions of synchronous operation of the applied instruments are presented. The results are compared with regional and global seismic services. The development of the presented methods can be useful for the detection and identification of precursors of large seismic events and other dangerous natural phenomena.

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