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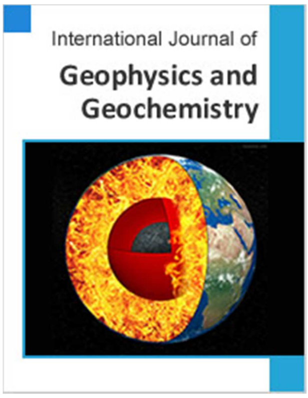

Acoustic Traces in the Upper Part of the Earth's Crust

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Abstract
Seism acoustic studies with high resolution in the pilot well of the SAFOD seismic testing site were launched in 2010 with the support of William Ellsworth (USGS). Together, Valery Korneev (LBNL), Andy Snyder (USGS) and Askold Belyakov (IPE RAS), the new Magnetoelastic Inertial Geophone (MIG-3W) measuring the orthogonal components of the acoustic impact vector is placed in the well at coordinates 35.974257N, -120.552076W to the depth 1000 m and pressed to the casing. Experiments on monitoring seism acoustic emission and earthquakes have been started. At the end of 2015, the MIG-3W geophone and the registration system were upgraded. Preliminary amplifiers installed earlier in the geophone housing were located on the surface and a new registration system was used, which allowed to continue monitoring and recording the geophone signals in digital form with a sampling frequency of up to 100 kHz. In August 2016, a similar geophone MIG-3W was installed in the Russian Federation in the Vorotilovskaya Deep Well (VDW) at coordinates 56.967017N and 43.720605E at a depth of 1400 m in rocks without casing for long-term monitoring. Test registration for a similar scheme began on August 16. Two sessions were conducted, lasting 14 seconds and 30 minutes. In both wells (SAFOD and VDW), in addition to seismic signals, acoustic traces similar to traces of neutrinos were found, which are given in publications on acoustic neutrino detectors. In particular, measurements in the Atlantic Ocean region of the Bahamas using a hydro acoustic antenna have detected and published characteristic signals with a frequency of 50 kHz, which because of their shape were called "diamond". In wells, analogous signals with a sampling frequency of 10 kHz have an apparent frequency of about 5 kHz. In both cases, this is basically 10 to 12 oscillations with smoothly increasing and smoothly falling amplitudes. But the results were unexpected after the extraction of the device in May 2017 from the SAFOD well, when it was installed for urban testing (the second floor of a residential building in San Francisco). Short monitoring showed that, in addition to events like "diamond", events of a different form appeared. Additional express check in the basement on the seismic pedestal of the Institute of Physics of the Earth also showed the presence of signals like "diamond".

Keywords
Well,
Continuous Acoustic Monitoring,
Magnetoelastic Inertial Geophone,
Frequency and Dynamic Ranges,
Acoustic Neutrino Detector,
Neutrinos,
"Diamond"

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1. Methods and Equipment for Registration

The amplitudes of the acceleration velocity in the enclosing medium are measured by a vector three-component inertial device MIG-3W [1] and a system for digital recording of the output voltage of the device in mV. These data can be converted into physical units: acceleration, speed and offset, using conversion factors that depend on the electromechanical coupling ratio of the MIG-3W sensor, the gain factor and the frequency. The conversion procedure is shown in the Appendix. The coefficients for the frequency 5 kHz are calculated for horizontal channels: 1 – 0.058×10^{-15}m×mV^{-1}, 2 – 58×10^{-15}m×mV^{-1} and for the vertical channel: 3 – 0.23×10^{-15}m×mV^{-1}. So for the events in Figure 12 and 13 on channel 1, the maximum amplitude is 0.46 fm, channel 2 is 580 fm and for vertical channel 3 is 920 fm. Here it is necessary to clarify that the calculations for the frequency of 5 kHz and more are not entirely correct, since after the resonant frequencies of the vertical (1250 Hz) and horizontal (350 Hz) channels of the MIG-3W geophone, the amplitude – frequency characteristics of the geophone channels change and the system registers not the acceleration speed, and speed, as an ordinary seismometer.

Unfortunately, the shortage of wires in the armored cable for launching the device into the well at the SAFOD range allowed using only one horizontal and vertical channels of the three-component device.

Surface observations in San Francisco used all three channels of the MIG-3W device at a sampling frequency of 100 kHz and at the Institute of Physics of the Earth – four channels with a sampling frequency of 25 kHz. In addition to the three channels of the MIG-3W, an exploration seismometer was installed.

2. Results of SAFOD

At the SAFOD range, monitoring with a modernized registration system was started in October 2015. It was intended to record close earthquakes and the preceding specific vibrations in the frequency range up to 1000 Hz. One of the closest earthquakes is shown in Figure 1. An earthquake with a magnitude of 3.5 occurred on May 17, 2016 at 22:58:06 UTC at a depth of 7.83 km 4 km south-east of SAFOD (35.97N, -120.53W). The maximum amplitudes of the horizontal component of the signal with a frequency of 38 Hz reach 480 mV, and the vertical component - 60 mV, which in terms of bias is 42 nm and 30 nm, respectively.

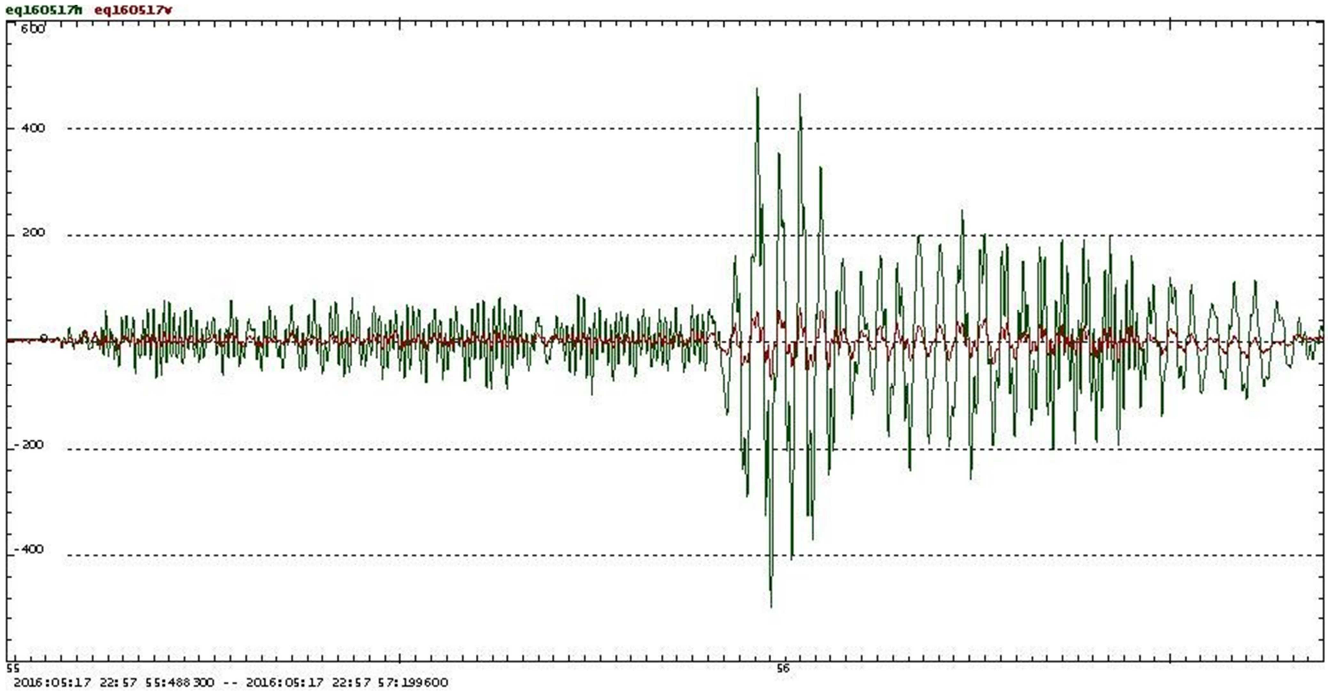

Figure 1. *Earthquake, horizontal direction – 1 (green) and vertical direction – 2 (red)*。

At 20:00 GMT on December 12, bipolar pulses, typical of an acoustic neutrino detector, began to appear in the vertical channel, but on December 20, the vertical channel registration ceased due to an inadmissible offset of the zero ADC value. In May 2016 registration was restored, but bipolar impulses were no longer observed. Analysis of the data showed that in a horizontal channel, in the period from 09 h 50 m to 21 h 32 m on January 31, 2016, pair pulses are recorded, the shape of which is mentioned in the works on acoustic detection of neutrinos. Also, numerous acoustic tracks with a frequency of 5 kHz and a wide range of amplitudes were found, whose wave form was surprisingly in line with the "diamond" forms described in the literature [2].

The fragment of registration of bipolar pulses of the vertical channel in the SAFOD pilot hole, whose steel casing opened at a depth of 1000 m thick granite and granodiorite, is shown in Figure 2.

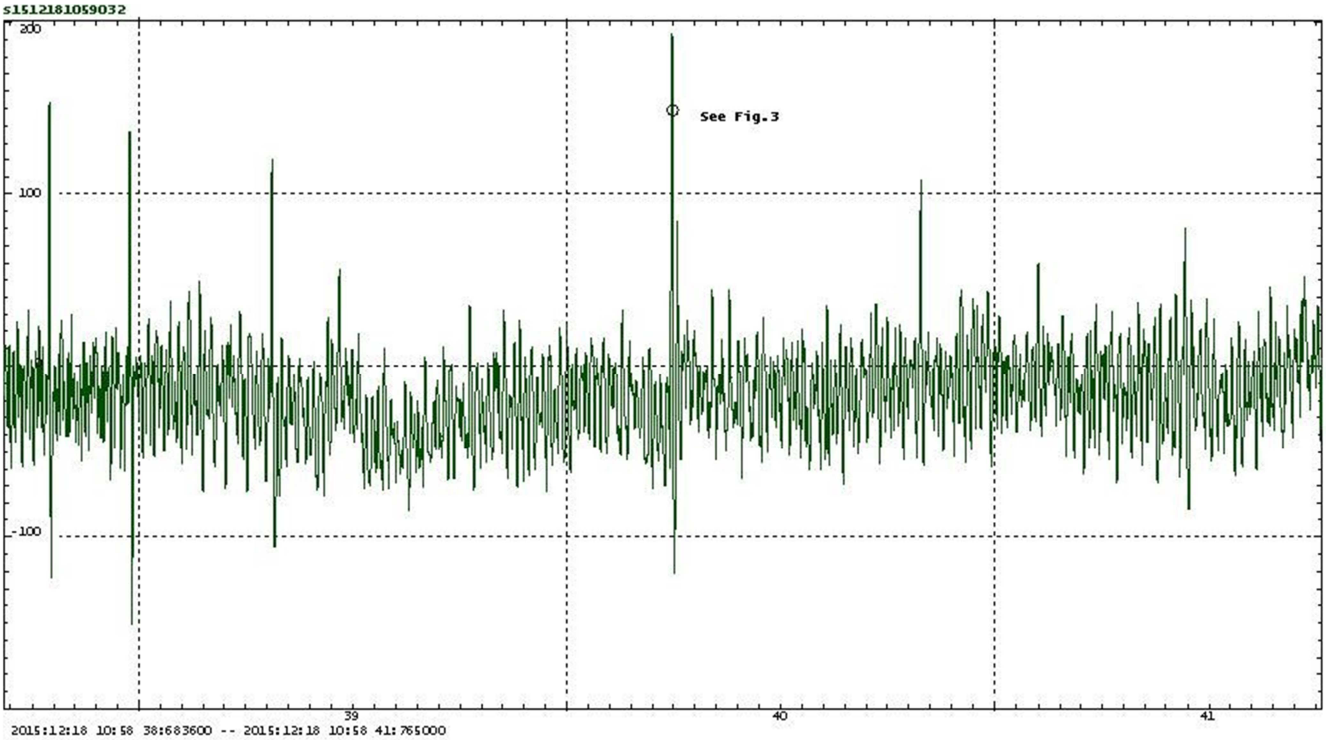

***Figure 2.** Bipolar pulses at a depth of 1000 m.*

In Figure 3 bipolar pulse, noted in the 14 second fragment in Figure 2, is shown in more detail. According to preliminary estimates, the average duration of the bipolar pulse is 12-13 ms (the visible frequency of the first half-wave is about 98 Hz, and the second half-wave is about 72 Hz), while the duration of the negative half-wave is greater than positive, and the amplitude of the positive half-wave is greater than negative. The observed repetition intervals vary over a wide range from 0.3 to 20 s longer repetition intervals were observed at the beginning of a series of pulses.

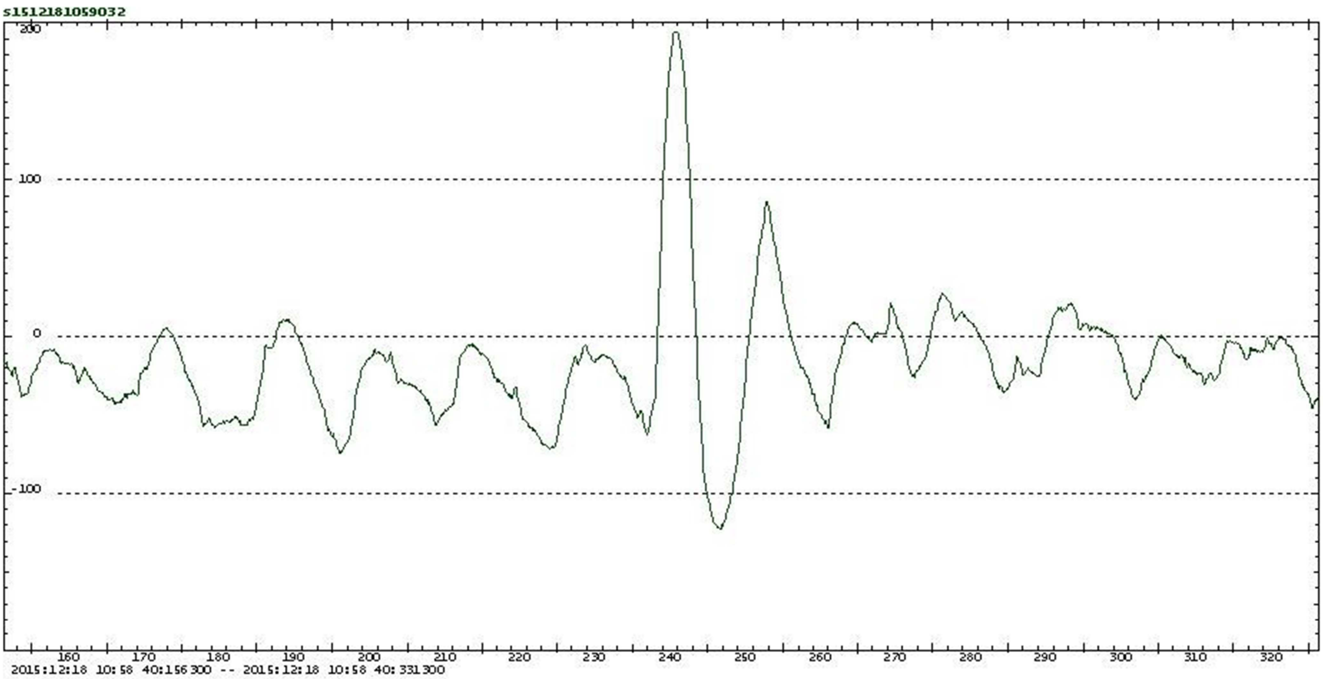

***Figure 3.** Bipolar pulse on a large scale.*

Another series of acoustic events in the horizontal channel, a fragment of which is shown in Figure 4, started at 09 h 50 m (GMT) and lasted until 21 h 32 m on January 31, 2016.

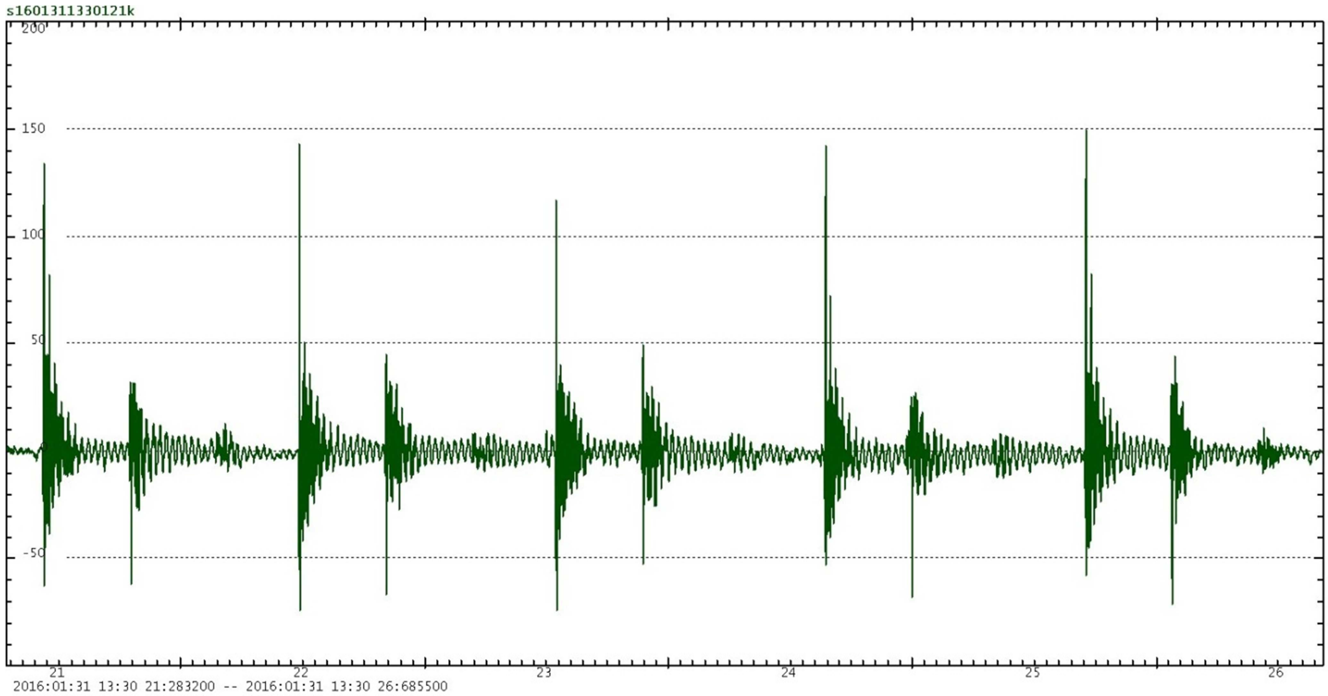

Figure 4. *Acoustic events in a horizontal channel.*

During this time, the intensity of paired events varied from 1 to 58 events per minute. Only those pair events were calculated, the amplitudes of which considerably exceeded the amplitude of the background. The time between the first and second pulses in the pair is about 0.35 sec permanently. The time between pairs varies from 1 to 60 sec. More time was observed at the beginning and at the end of the series. The initial amplitude of the first oscillation in the first pulse (Figure 5) reaches 200 mV at background amplitudes of about 6 mV. The amplitude of the first oscillation having an apparent frequency of about 250 Hz in terms of the offset is 60 pm. For a frequency of 250 Hz, the conversion factor is 0.3×10^{-12} m, and the sensitivity is 3.3×10^{9} V / m.

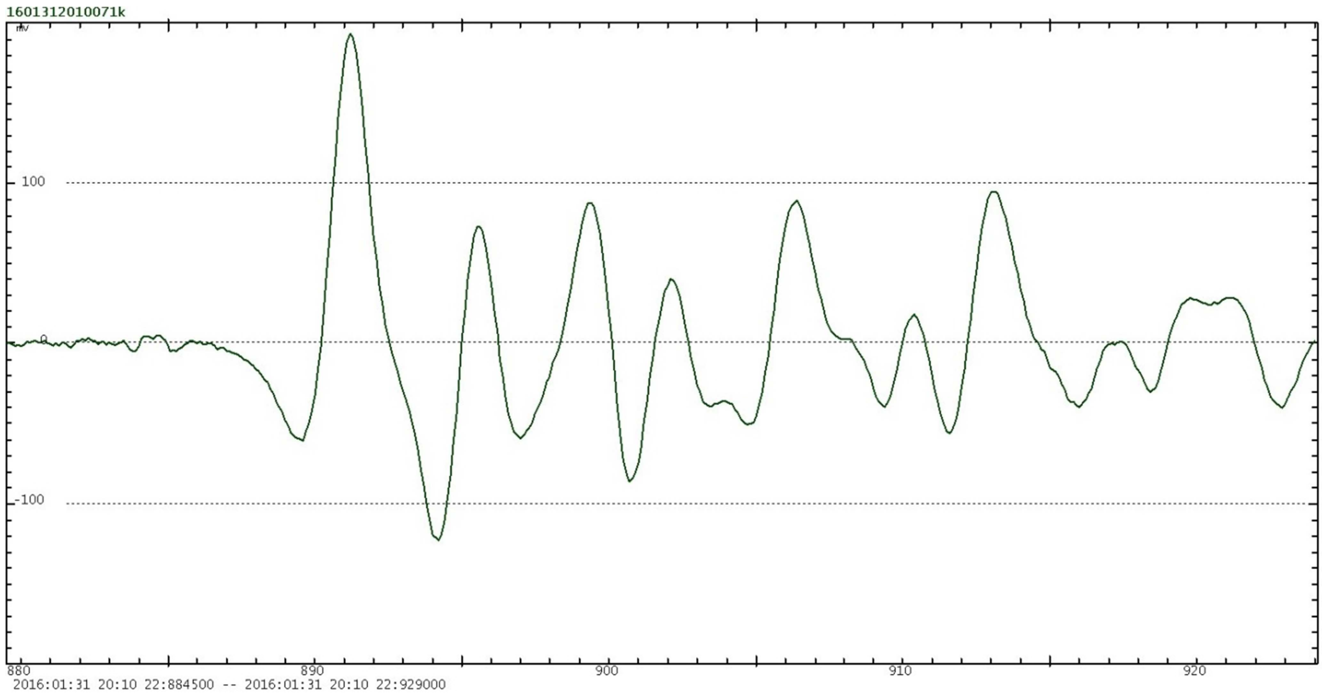

Figure 5. *The first package of oscillations from a pair.*

It should be noted that the background level at the measurement site is about 6 mV. The background is large, and is determined, in the main, not by microseisms, but by an interference of 60 Hz. The same hindrance makes it difficult to allocate a third packet, possibly associated with the first two. The time between the second and third pulses is the same as between the first and second pulses. In addition, it seems that the initial stage of all these oscillations is a bipolar pulse.

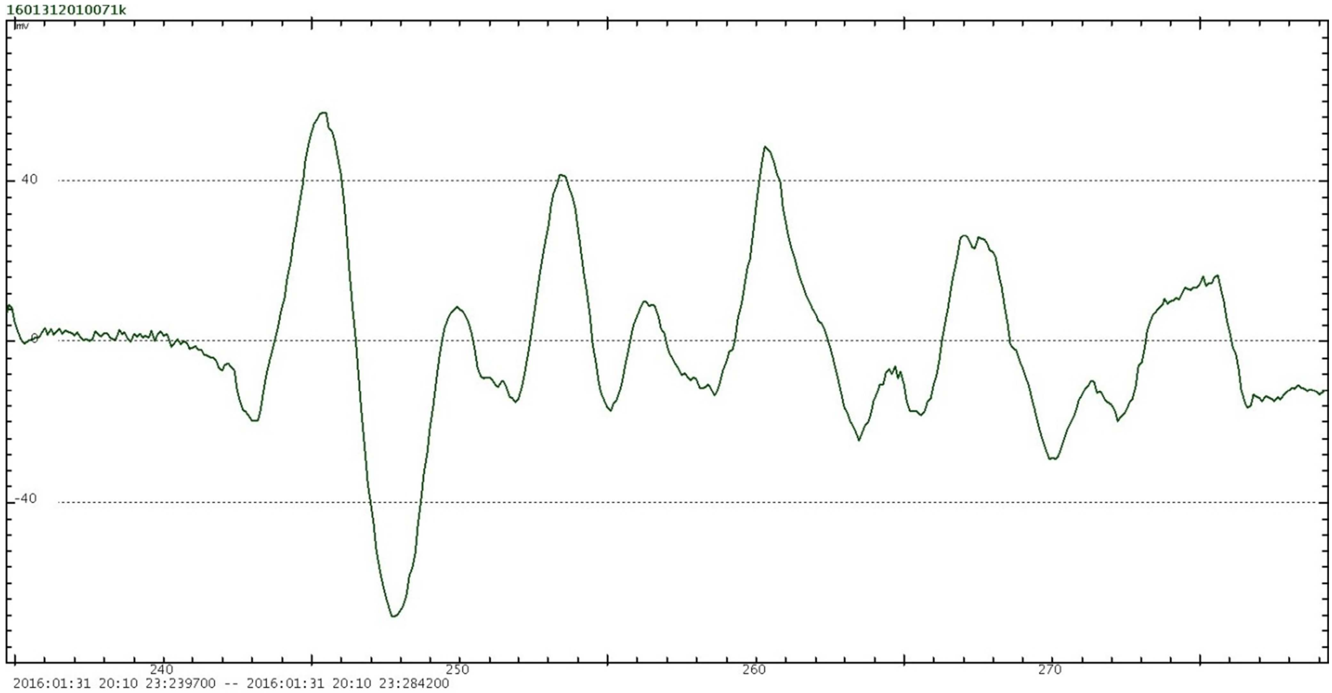

Figure 6. *The second packet of oscillations from the pair.*

The initial amplitude of the first oscillation in the second pulse is about 65 mV at a frequency of 192 Hz. For this frequency, the maximum displacement amplitude is 44 pm at a conversion factor of 0.68×10^{-12} m and a sensitivity of 1.47×10^{9} V / m.

In the data obtained, events with waveforms of the "diamond" type and a visible frequency of about 5 kHz are often encountered, as shown in Figure 7. High level of seismic and network (60 Hz) noise allows detecting only events with relatively large amplitudes.

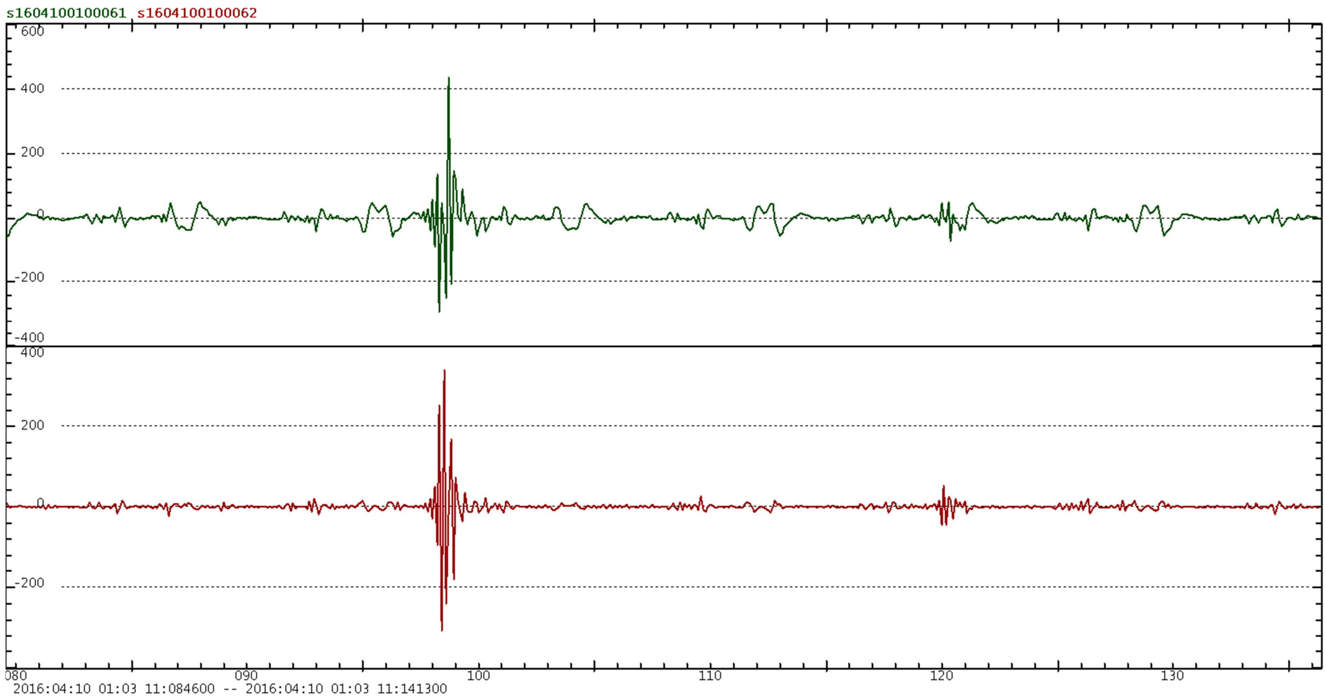

Figure 7. *Events like "diamond".*

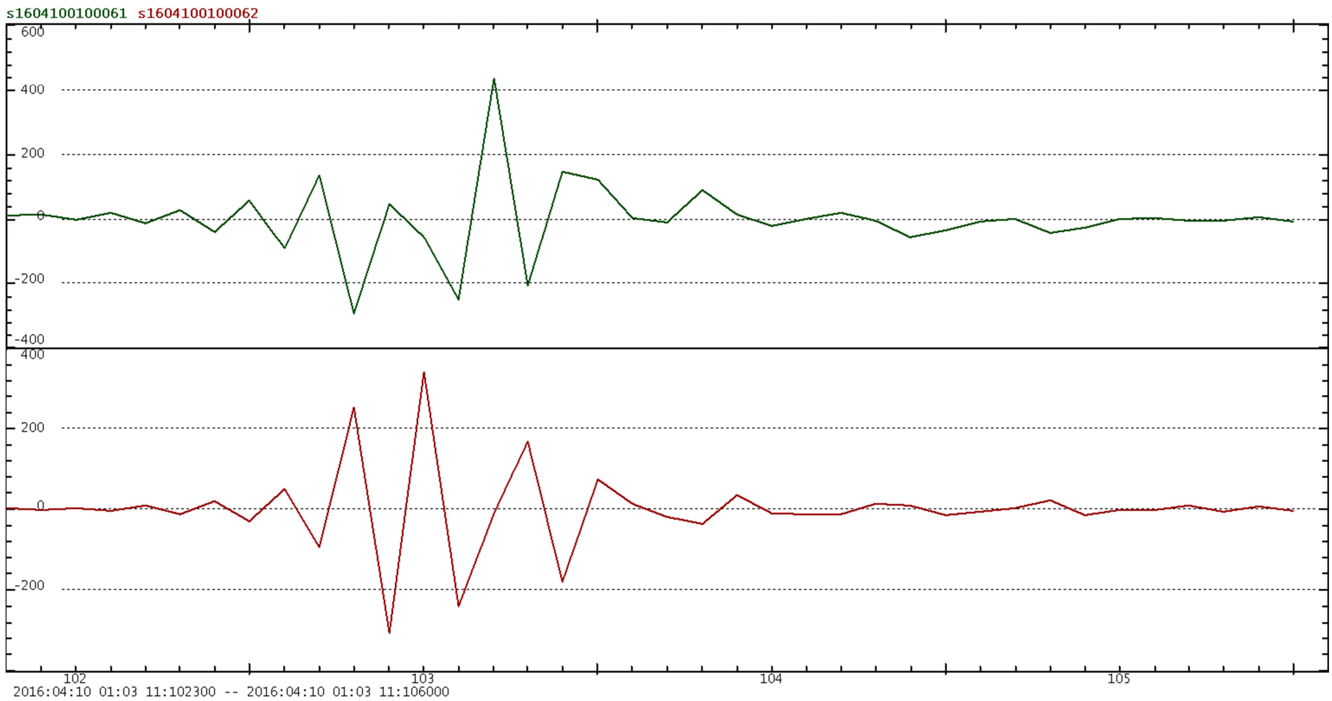

Figure 8. *A "diamond" event on a larger scale.*

The "clean" background shown in Figure 9, on which all significant events occur, does not exceed 0.1 mV.

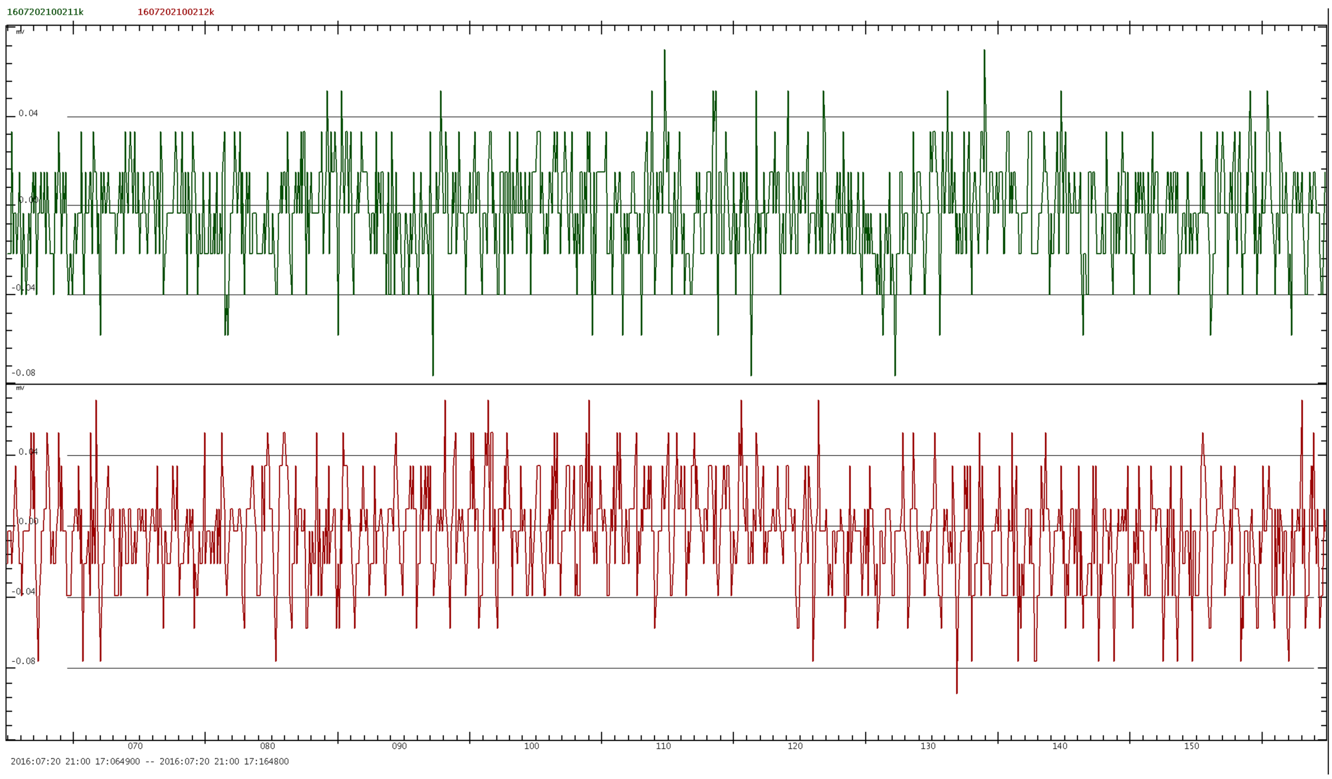

Figure 9. *"Clean" background.*

3. Results of VDW

In the VGS, a similar geophone MIG-3W was installed in August 2016 at a depth of 1400 m. At this depth, the development of koptoblastolites, intensively injected with veins of tagamites, is observed. Secondary minerals are mainly represented by smectites and zeolites. Well with open barrel without casing. The geophone is pressed directly to the wall of the well. The first test recording session lasted 14 sec. At 19.15 (MSK) on August 16, for 14 sec, not only the micro seismic event was recorded, but more than 175 acoustic events with the waveforms "diamond", which, with a high probability, can be traces of neutrinos [3].

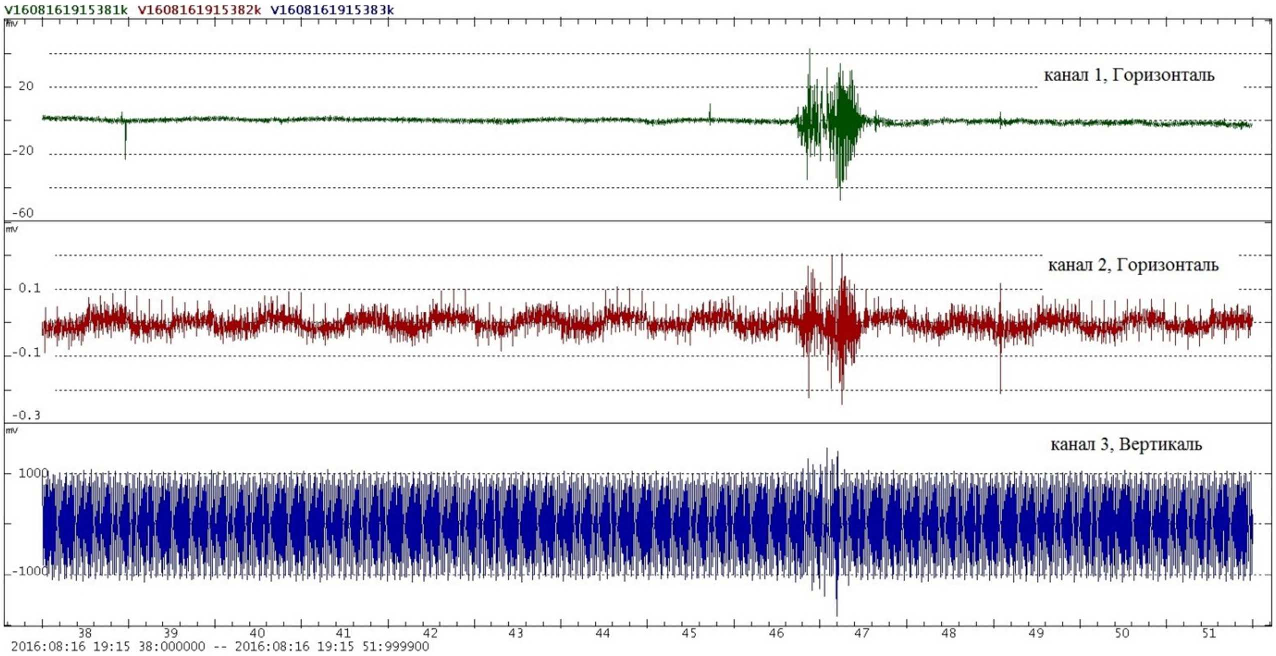

Figure 10. *Tracks, 14 s at a depth of 1400 m.*

In Figure 10 shows the data of three channels: 1, 2 – horizontal and 3 – vertical channel. At the initial stage, the amplification was used for channels 1 and 3 – 60 dB, and for channel 2 – 0 dB. The exact orientation of the horizontal channels 1 and 2 is not known, but it can be assumed that channel 2 has the East-West direction. This assumption is based on oscillations with a frequency of 1 Hz corresponding to the global frequency of the hydro generators of the HPP, which is located in the West from the observation point. Vertical channel 3 has no protection from electromagnetic fields, so the network interference of 50 Hz in Figure 10 masks almost all acoustic events. An exception is a micro event with a visible frequency of about 80 Hz, which is more a tremor than an earthquake. The apparent maximum amplitudes of this event on channel 1 are 70 mV, on channel 2 – 0.2 mV, and on channel 3 – 1820 mV.

Another picture is observed when considering fragments of the same graphs in reduced time intervals. In Figure 11 shows a record of 0.2 sec. On its tracks, you can consider 8 or more acoustic events of the "diamond" type with different amplitudes.

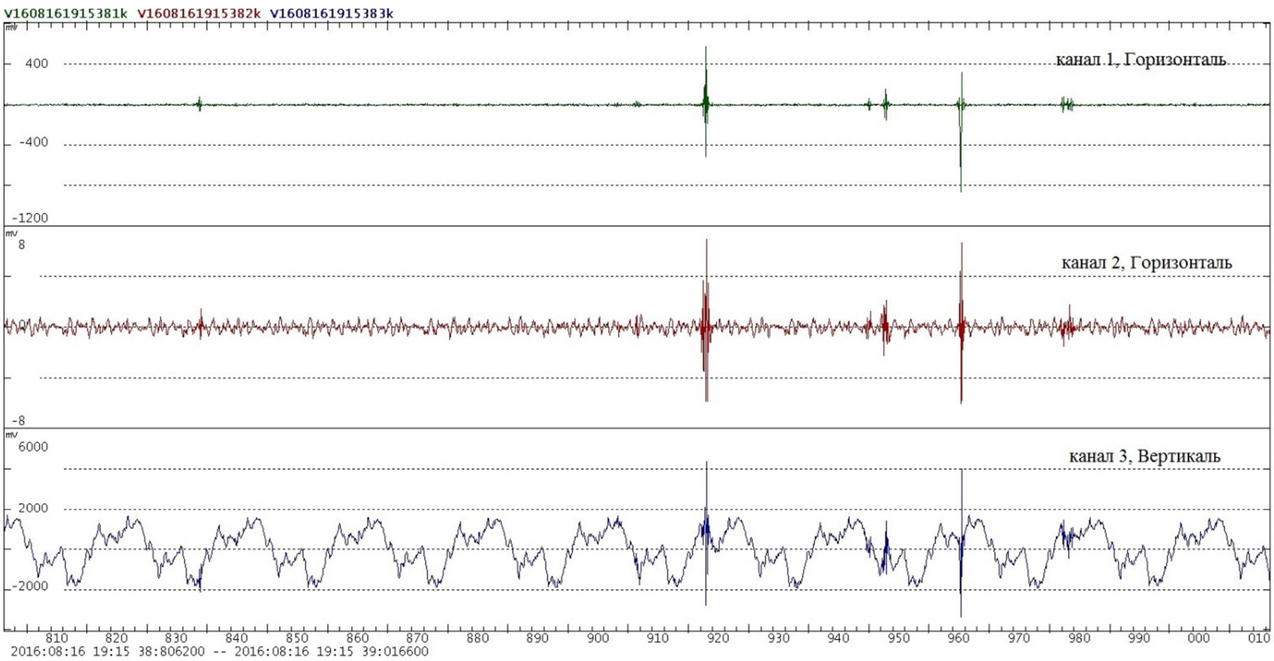

Figure 11. *Tracks, 0.2 s.*

More than 175 similar events were registered in just 14 sec. Three components of one of them are shown in the tracks of Figure 12. This event lasts about 0.002 s, has 8 to 12 oscillations with an apparent frequency of about 5 kHz, the amplitudes of which smoothly increase from the conventionally background amplitudes of 10 mV to a maximum of 800 mV, and then also smoothly decrease to the background level.

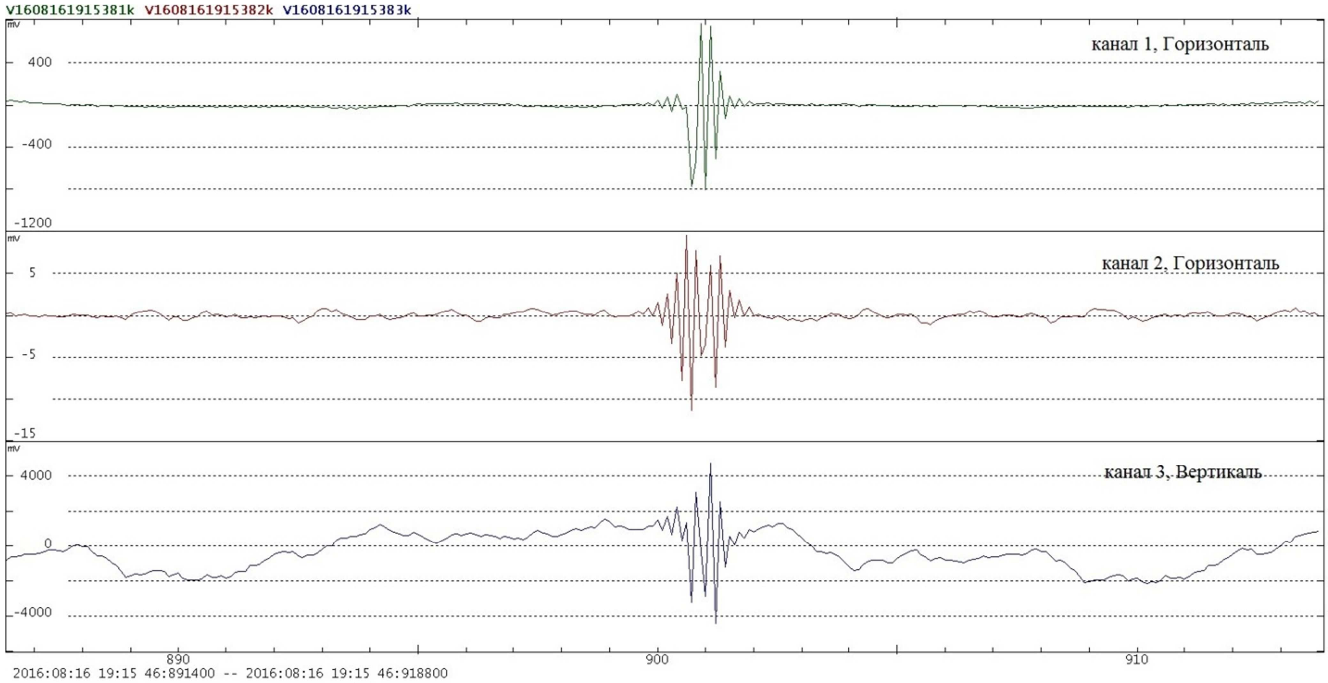

Figure 12. *Tracks, 0.027 s.*

The following analogous event, which occurred through 2.18 s is shown in Figure 13.

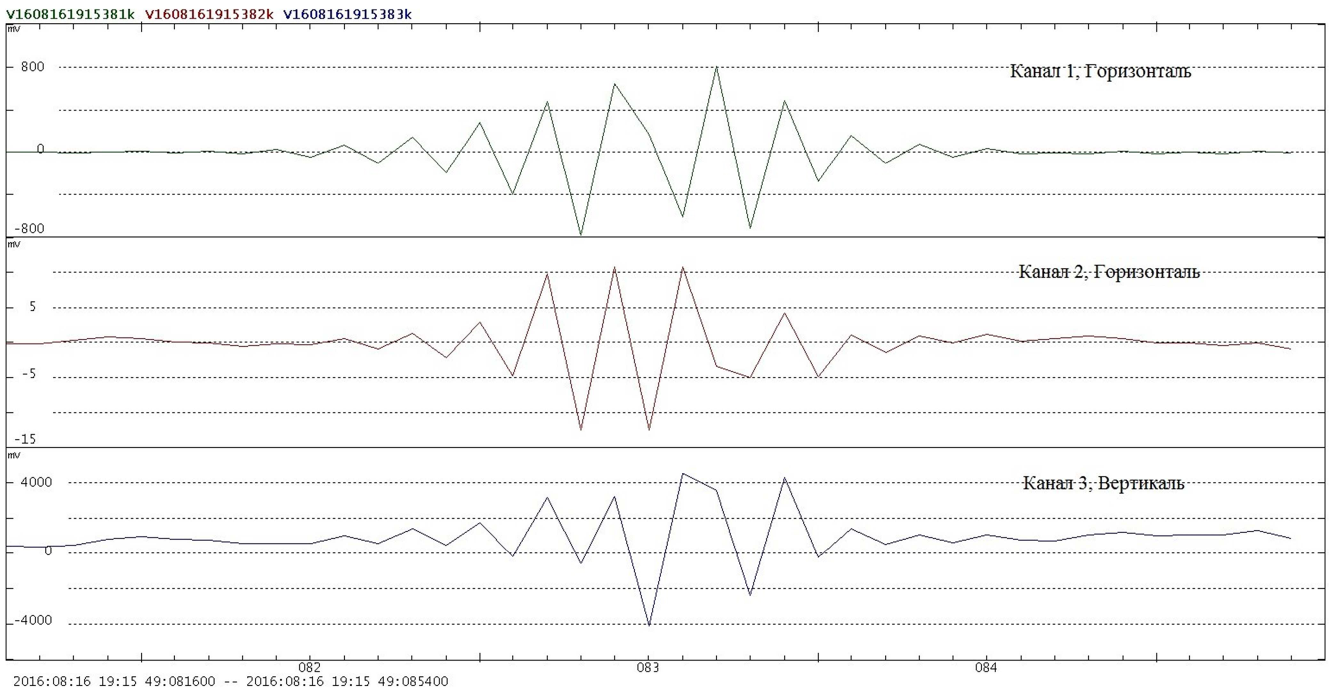

Figure 13. *Tracks, 0.0038 s.*

In fact, the total number of events of the "diamond" type is much larger than that shown, since only those events whose amplitudes were twice or more than the background amplitudes (10 mV in the first channel) were calculated to simplify the procedure. Of these, with events ranging from 20 to 100 mV, 154 events occurred, from 100 to 200 mV - 12 events and with the amplitudes from 200 to 1000 mV - 9 events.

The largest oscillation amplitudes in the diamond event were observed during the second 30-minute trial period and exceeded 92 pm for horizontal North-South, 10 pm West-East and 5.5 nm for vertical oscillations. The tracks of this event are shown in Figure 14.

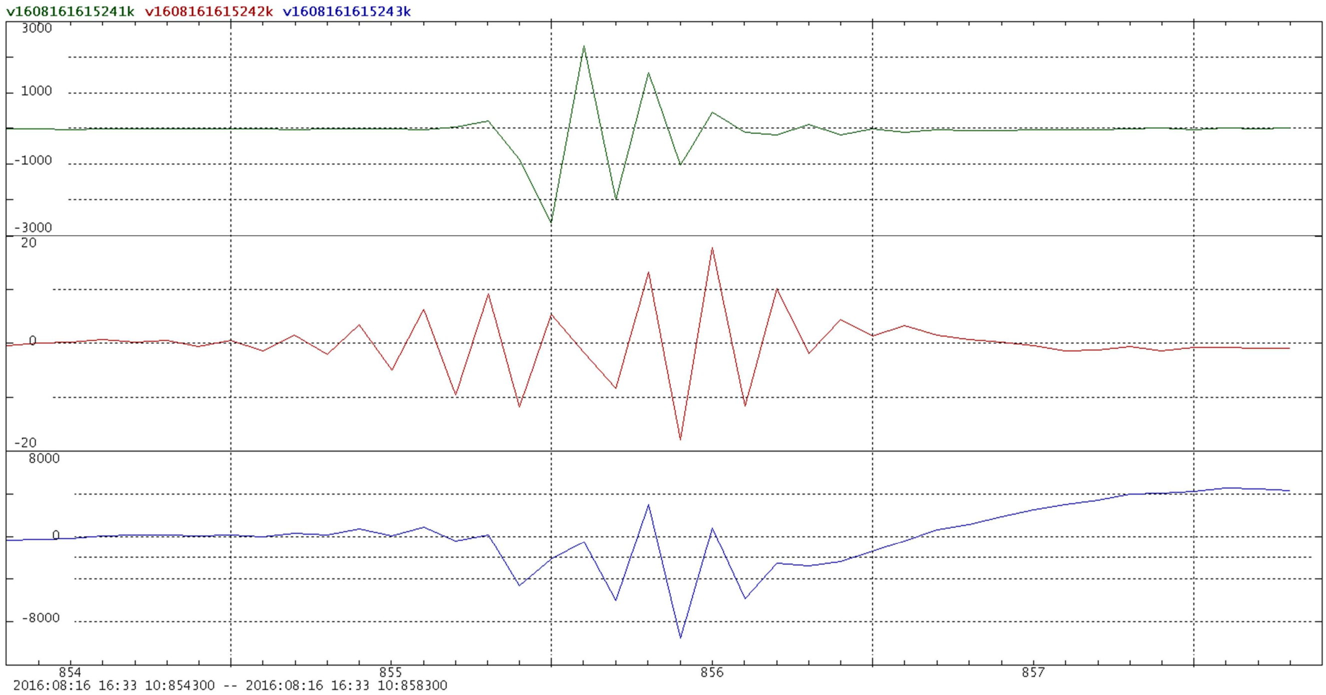

Figure 14. *Tracks, 0.004 s.*

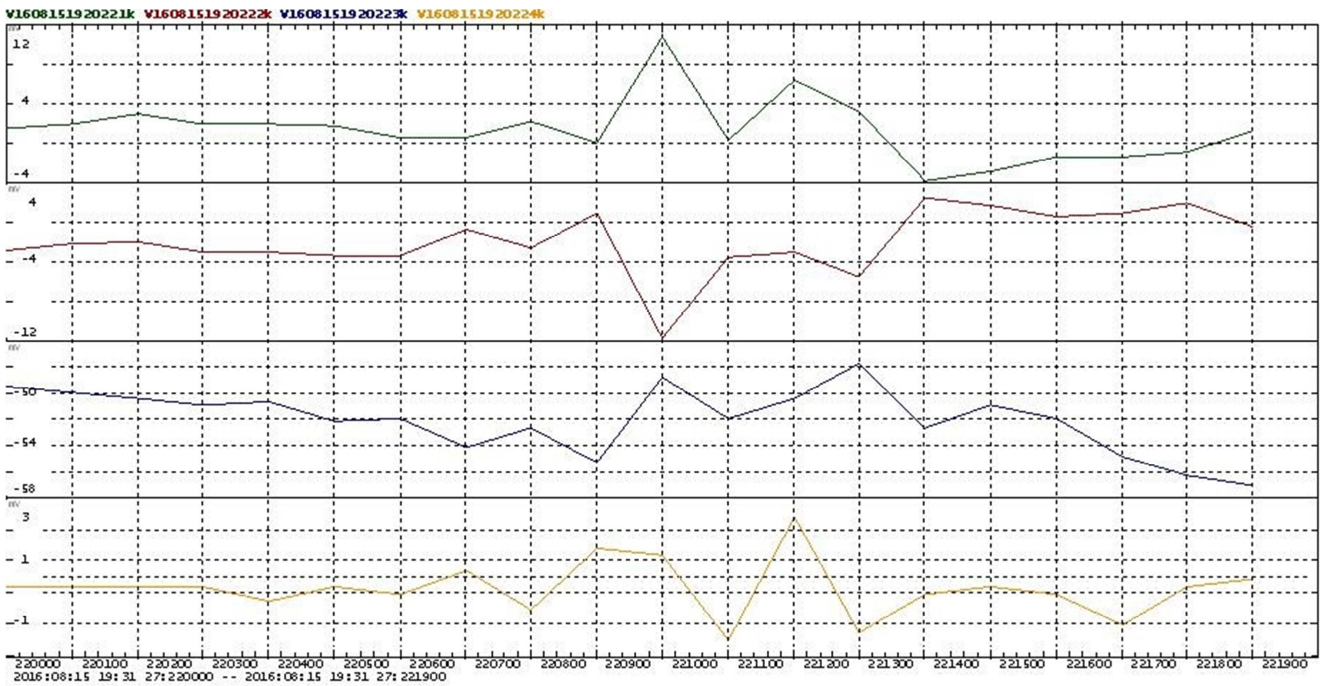

Figure 15. *Tracks, 0.0019 s.*

In Figure 15, a fourth track of the vertical channel of a similar device was added to three tracks from a depth of 1400 m of the VDW that was previously installed in the well at a depth of 553 m and 100 m to the South of the VDW.

4. Surface Observations

Brief surface observations were conducted on the second floor of an apartment building in San Francisco. A 30-second monitoring fragment with a sampling frequency of 100 kHz is shown in Figure 16.

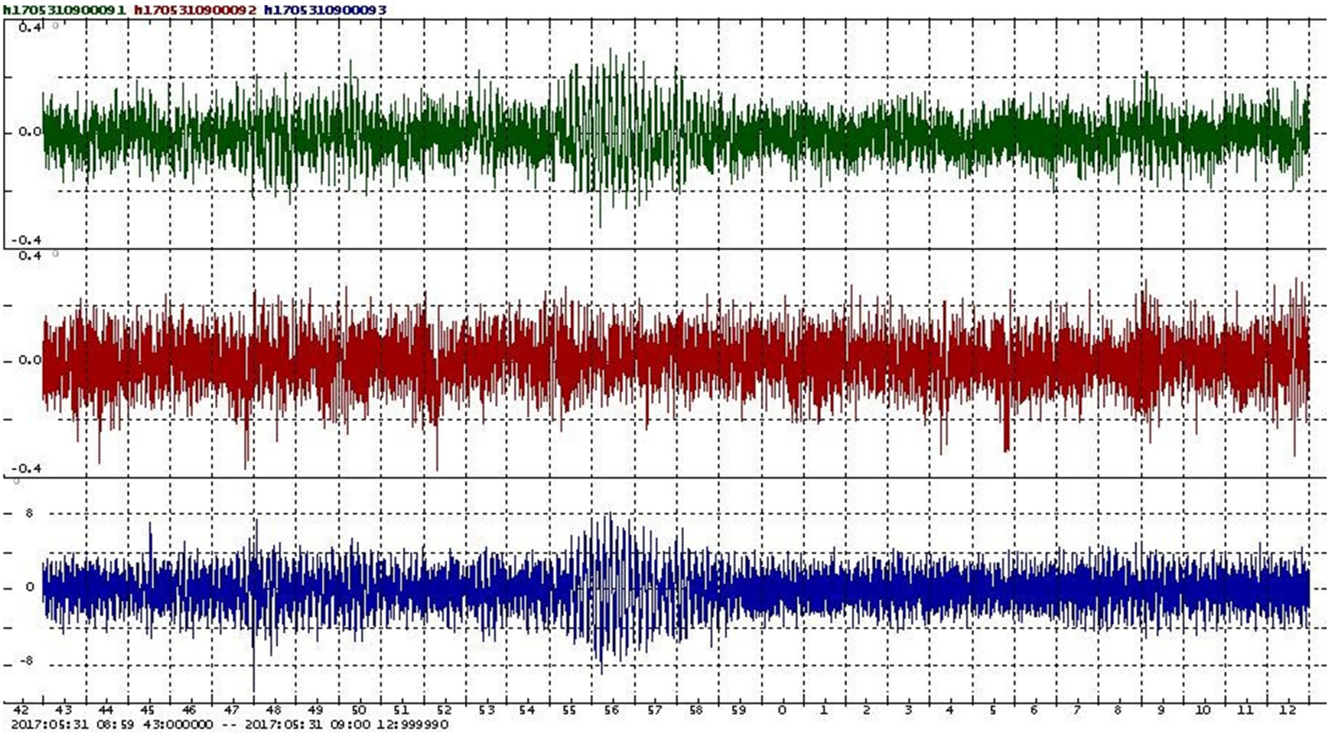

Figure 16. *30-second monitoring fragment in the city.*

At first glance it may seem that this is "just noise", but if you reduce the time interval to 0.0045 sec and less, the picture will change dramatically, Figure 17.

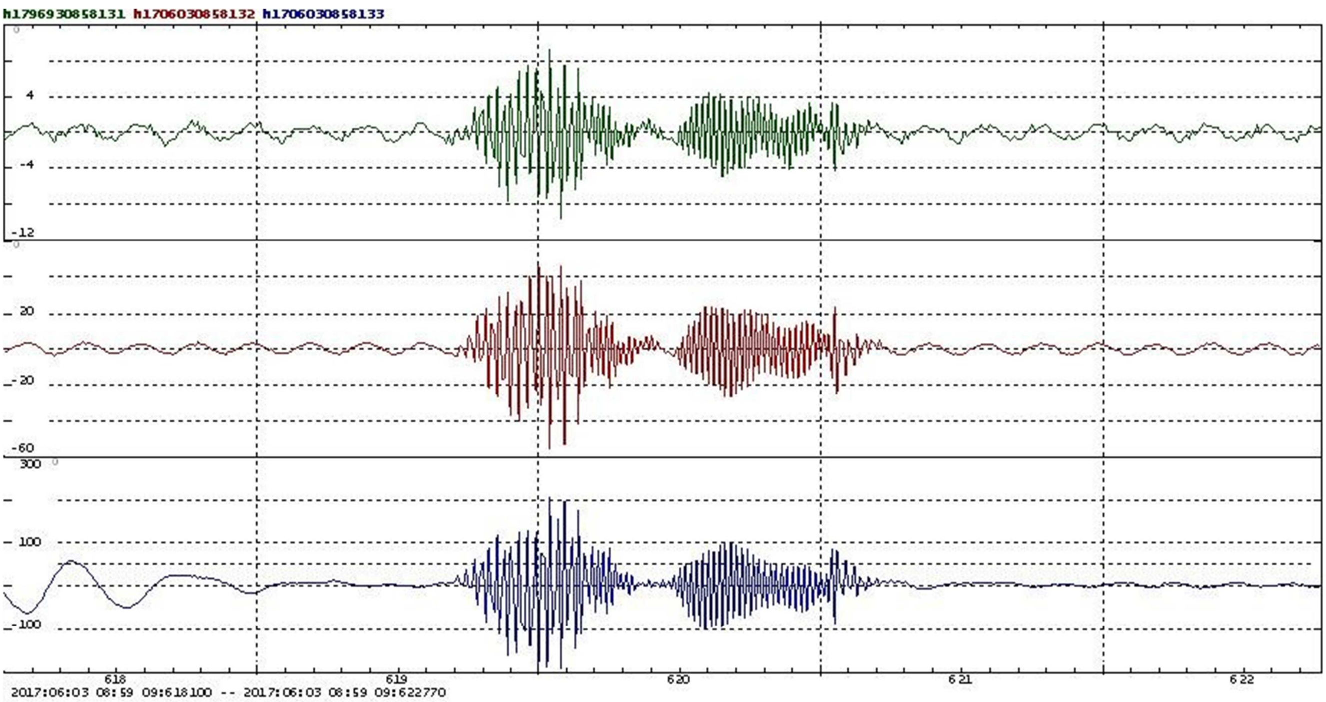

Figure 17. *Fragment of city noise.*

There are events that were not observed during underground registration. The characteristic forms of these events, whose visible frequencies are in the range from 37 to 50 kHz; do not give grounds to consider them seismic (acoustic). There are also numerous events of the "diamond" type, Figure 18.

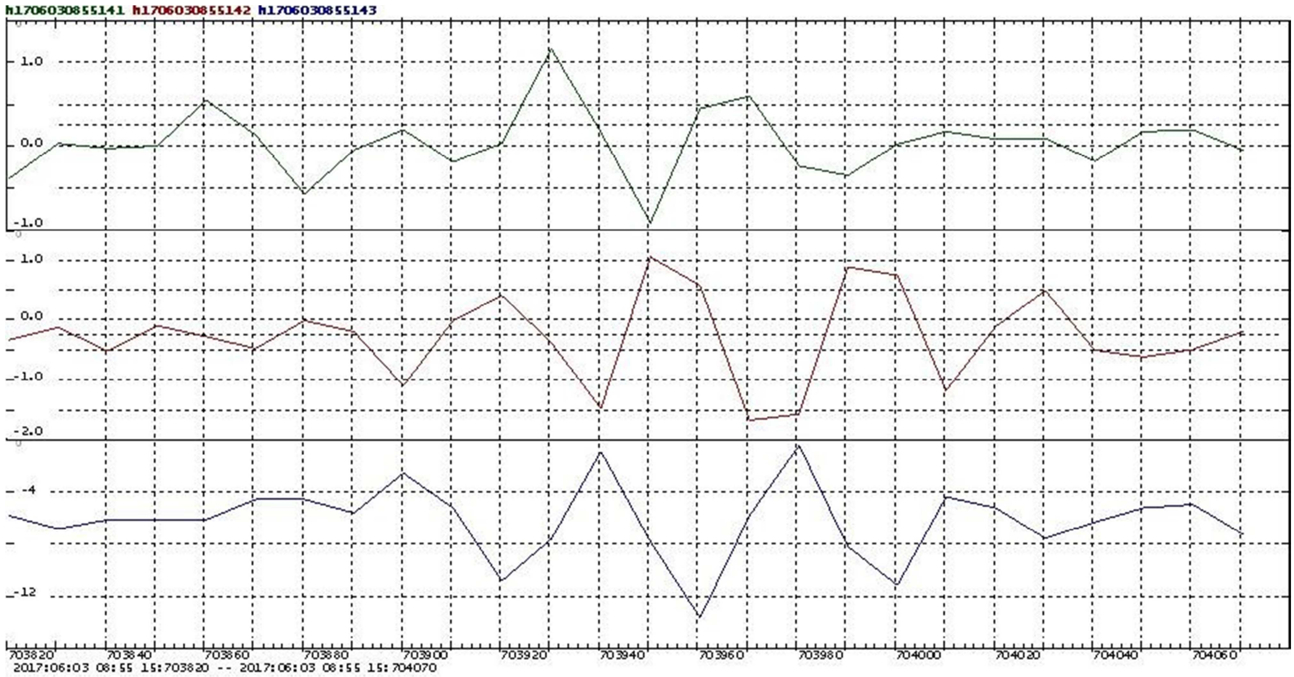

Figure 18. *Events like "diamond" in the city noise.*

5. Discussion

For acoustic monitoring, a new geophone MIG-3W is used. This is a highly sensitive, autonomous, inertial generator-type device equipped with three balanced outputs for each of the three orthogonal components that connect to the measuring system with three pairs of symmetrical wires (twisted pair). This solution significantly increases the interference protection and reliability of the entire system, and also allows, if necessary, to change the gain in the channels using preamp amplifiers with adjustable coefficients. The design of the instrument used is a compromise, adapted to work in wells; therefore the characteristics of the vertical channel (frequency range, sensitivity and protection from electromagnetic fields) differ from the characteristics of horizontal channels.

In the active time of day in the city with a dense building and a large number of electrical household appliances (perhaps there are other sources) there are impulse noises with a repetition frequency of 60 Hz, which penetrate and into the protected channels.

To optimize the monitoring system, oriented to acoustic registration of neutrinos, first of all it is necessary:

1. Maximize the upper limits of the frequency ranges of the channels of the geophone MIG-3W, calculated for seism acoustic signals;
2. To normalize the sensitivity and characteristics of the vertical channel and horizontal channels of the MIG-3W, and for surface observations (in mines, galleries, caves, in water areas and in ice), use the MIG-3S;
3. When registering, use a sampling frequency of at least 100 kHz;
4. In the monitoring mode, set equal transmission factors for all channels;
5. To monitor the acoustic traces of neutrinos, select areas with minimal seismic and industrial interference.

6. Conclusion

Acoustic monitoring in the upper part of the earth's crust by new high-sensitivity geophones with high resolution in amplitude and frequency and vector characteristics that are installed in wells (open or with casing pipes) makes it possible to register not only earthquakes and seism acoustic events but also acoustic tracks of events, Connected, presumably, with flying particles of high energy.

Surprising results have been obtained which, if confirmed, have broad prospects, as the World Science Community makes great efforts to obtain information on high-energy particles. In many countries polygons with detectors of various types are being created: in the Pacific and Atlantic Oceans, in the Mediterranean, Lake Baikal, Antarctica, the North Caucasus, and many other places on land, underground and under ice. Created polygons, at relatively low costs, can be equipped with proven high-resolution acoustic amplitude and frequency monitoring systems that will provide additional independent data and increase the reliability of event identification of the phenomena being studied.

The MIG-3W (MIG-3S) can also be used in water, losing about 30% of its sensitivity. Even in this case, the MIG-3S can be a good alternative to a hydrophone, having new qualities: vector characteristics, large dynamic range (more than 240 dB), unlimited immersion depth, energy independence, mechanical strength and service life of more than 25 years.

The MIG-3W (MIG-3S), as an acoustic neutrino detector, can be tested in an experiment with a controlled flux of neutrinos, for example: "The Deep Underground Neutrino

Experiment (DUNE)".
http://www.dunescience.org/

Application

Determination of Physical Characteristics of Acoustic Vibrations

(Place SAFOD and VDW, type of sensor MIG-3W)

Measuring channels of the system of geoacoustic monitoring use: a sensor, a preamplifier, and an ADC

The total coefficient of the measuring channel is K = K1 × K2 × K3, where:

K1 - coefficient of electromechanical connection of the sensor:

On SAFOD: 0.15 $mV \cdot s^3 \cdot m^{-1}$ vertical channel (2) and 0.85 $mV \cdot s^3 \cdot m^{-1}$ horizontal channel (1).

On the VDW: 0.15 $mV \cdot s^3 \cdot m^{-1}$ vertical channel (3) and 0.6 $mV \cdot s^3 \cdot m^{-1}$ horizontal channel (1.2).

K2 - the coefficients of the preamplifier: 1, 10, 100 or 1000.

K3 - the transfer coefficient of the ADC Zet 230 – 1

For example: $K_{0.85} = 0.85 \cdot 10^3 \cdot 1\ mV \cdot s^3 \cdot m^{-1} = 0.85 \cdot 10^3\ mV \cdot s^3 \cdot m^{-1}$. $R_1 = 1.18 \cdot 10^{-3}\ m \cdot s^{-3}$.

$K_{0.15} = 0.15 \cdot 10^3 \cdot 1\ mV \cdot s^3 \cdot m^{-1} = 0.15 \cdot 10^3\ mV \cdot s^3 \cdot m^{-1}$. $R_1 = 6.7 \cdot 10^{-3}\ m \cdot s^{-3}$.

$K_{0.6(1)} = 0.60 \cdot 10^3 \cdot 1\ mV \cdot s^3 \cdot m^{-1} = 0.60 \cdot 10^3\ mV \cdot s^3 \cdot m^{-1}$. $R_1 = 1.7 \cdot 10^{-3}\ m \cdot s^{-3}$.

$K_{0.6(2)} = 0.60 \cdot 10^0 \cdot 1\ mV \cdot s^3 \cdot m^{-1} = 0.60 \cdot 10^0\ mV \cdot s^3 \cdot m^{-1}$. $R_1 = 1.7\ m \cdot s^{-3}$.

The measured parameter (speed of acceleration in a longitudinal acoustic wave) - R [$m \cdot s^{-3}$] is determined by the formula R = N / K, where N is the quantity mV at the output of the Zet 230 ADC.

For example, with N = 1 mV: $R_1 = 1\ mV / 0.85 \cdot 10^3\ mV \cdot m \cdot s^{-3} = 1.18 \cdot 10^{-3}\ m \cdot s^{-3}$.

Table A1

f, Hz	2πf	$(2\pi f)^2$	$(2\pi f)^3$
38	239	57×10^3	13.6×10^6
80	502	252×10^3	127×10^6
192	1.2×10^3	1.44×10^6	1.73×10^9
250	1.57×10^3	2.46×10^6	3.86×10^9
5000	31×10^3	961×10^6	30×10^{12}

Determine the acceleration amplitude - a_1, speed - v_1 or displacement - L_1 at N = 1 mV is possible only for the set frequency (Table A1). For this, the calculated parameter R_1 must be divided into 2πf in the first, second or third degree, respectively, where f - Set frequency, (1, 2, 3) - channel numbers (Table A2).

Table A2

f, Hz	R_1, $m \cdot s^{-3}$	a_1, $m \cdot s^{-2}$	v_1, $m \cdot s^{-1}$	L_1, m
38(1)	1.18×10^{-3}	4.9×10^{-6}	21×10^{-9}	87×10^{-12}
38(2)	6.7×10^{-3}	28×10^{-6}	118×10^{-9}	493×10^{-12}
80(2)	6.7×10^{-3}	13×10^{-6}	26×10^{-9}	52×10^{-12}
192(1)	1.18×10^{-3}	0.98×10^{-6}	0.82×10^{-9}	0.68×10^{-12}
250(1)	1.18×10^{-3}	0.75×10^{-6}	0.47×10^{-9}	0.30×10^{-12}
5000(1)	1.7×10^{-3}	55×10^{-9}	1.8×10^{-12}	0.058×10^{-15}
5000(2)	1.7	55×10^{-6}	1.8×10^{-9}	58×10^{-15}
5000(3)	6.7×10^{-3}	216×10^{-9}	7×10^{-12}	0.23×10^{-15}

To determine R, a, v and L, the coefficients R_1, a_1, v_1 and L_1 must be multiplied by N (Table A3).

Table A3

f, Hz	R, $m \cdot s^{-3}$	a, $m \cdot s^{-2}$	v, $m \cdot s^{-1}$	L, m
38(1)	0.566	2.4×10^{-3}	10×10^{-6}	42×10^{-9}
38(2)	0.402	1.7×10^{-3}	7.1×10^{-6}	30×10^{-9}
80(2)	0.777	1.5×10^{-3}	3×10^{-6}	6×10^{-9}
192(1)	0.077	64×10^{-6}	53×10^{-9}	44×10^{-12}
250(1)	0.236	0.15×10^{-3}	94×10^{-9}	60×10^{-12}
5000 (1)	1.4×10^3	44×10^{-6}	1.44×10^{-9}	46×10^{-15}
5000 (2)	17	0.55×10^{-3}	1.44×10^{-6}	580×10^{-15}
5000 (3)	2.7×10^3	0.86×10^{-3}	28×10^{-9}	920×10^{-15}

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