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Seismoacoustic waves from powerful seismic vibrators

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The phenomenon of intensive acoustic wave excitation by surface explosion sources is known in seismology and seismic prospecting geophysics [1–3]. The sound impulse from explosion propagating along the Earth's surface induces elastic surface waves. They are recorded on seismograms with arrival times equal to the travel time of acoustic wave from the explosion point to the recording point. Experimental data show that the amplitude of elastic surface wave induced by acoustic impulse at distances of 0.5–3 km is 1–2 orders of magnitude larger than the amplitudes of longitudinal and transverse seismic waves from explosion [1]. These waves are identified by arrival times and are excluded from processing by special methods [2]. Modeling of the propagation process of acoustic impulse from explosion and induction of surface waves are considered in [3]. The results of experimental investigations of the radiation processes and interaction of the acoustic and seismic fields generated from powerful vibroseismic sources of the low-frequency range are presented.

The authors of the present paper were first to detect experimentally the excitation effect of acoustic waves and subsequent induction of surface waves from powerful vibration sources at large distances between a radiator and a receiver [6]. The following powerful vibroseismic sources of the Bystrovka vibroseismic test site of SB RAS were used in the experiments: the centrifugal CV-100 vibrator (the force amplitude is 100 tons, the frequency range is 5–9 Hz), the hydroresonant HRV-50 vibrator (the force amplitude is 50 tons; the frequency range is 2–8 Hz), the CV-40 centrifugal vibrator (the force amplitude is 40 tons; the frequency range is 6–12 Hz) [4–5]. A first series of experiments on recording of monochromatic and sweep-signals and measurement of some of their parameters was performed with the HRV-50 vibrator in September–October, 1993. The distance between the radiator and receiver was 20 km. A 15-channel measurement system was used at the recording point. A profile consisting of 5 three-component low-frequency SK1-P seismic receivers was arranged at a spacing of 100 m. The profile and all components of the X seismic receivers were oriented to the vibrator. The frequency range of the channel amplitude was 1–10 Hz.

The velocity cross-section of the area is typical for the south of Western Siberia. The upper layer (0–15 m) is a zone of small velocities (clay, sand) with $V_p = 400$, $V_s = 300$ m/s. The layer (15–50 m) is a weathering zone of sedimentary rocks with $V_p = 2400$, $V_s = 1800$ m/s, and the layer lower than 50 m consists of consolidated sedimentary rocks (limestone, shale) with $V_p = 4500$, $V_s = 3000$ m/s.

In experiments from 24.09.93 to 2.10.93, radiation sessions were repeated every 3 hours at night time. A series of vibrational correlograms obtained by convolution of recorded signals with the reference sweep-signal radiated by the vibrator at 3–7 Hz and 6–7 Hz is presented [6].

All correlograms contain a train of oscillations with arrival times of 4–10 s. The first arrivals correspond to refracted P-waves with characteristic velocities of 4–6 km/s, intensive arrivals of transverse SV- and SH-waves and surface waves are observed at a 6–7th second. The duration of the impulse response of the medium is 10–15 s. The character of the seismogram is in good agreement with the velocity cross-section of the region. The amplitudes and phases of this train of waves (4–10 s) are kept constant in all experiments. Oscillations of the X, Y, Z components in the whole train have similar amplitudes and have complex three-dimensional polarization.

Beginning on 30.09.93, correlograms show the second train of oscillations with an arrival time of 57–60 s, which corresponds to velocities of 330–340 m/s at a basis of 20 km. The group velocity determined by 5 seismic receivers along the line, also corresponds to this value. In the second train of oscillations, the X and Z components dominate, and the amplitudes of the Y component are by a factor of 5–10 lower. Polarization in this train of oscillations is elliptic, typical for surface waves. A peculiarity of the second train of oscillations is considerable (by a factor of 3–5) variation of the amplitude from session to session (the characteristics of the first train of oscillations being constant) and sometimes it disappears. Variation in the arrival time, the group velocity and polarization is up to 5%.

The time and velocity characteristics of the second train of oscillations made it possible to assume that it is caused by the arrival of acoustic wave from the vibrator at the recording point. A highly sensitive infrasound microphone was developed to check this hypothesis. This allowed recording of acoustic oscillations together with the seismic oscillations of the ground at the location point of the seismic profile. Signals were recorded at a distance of 20 km from the source. Regular polarization of seismic oscillations along the X–Z components in the second train, as well as the absence of the first train of waves (with the arrival times of the P- and S-waves) in the acoustic channel are clearly seen. A time shift of approximately 1.5 s in the acoustic channel is also observed in the second train of waves, because the microphone is at a distance of 500 m from the seismic receiver in the direction opposite to the vibrator.

The second series of experiments on recording of seismic and acoustic oscillations on the base of 20 km was made using the CV-100 and HRV-50

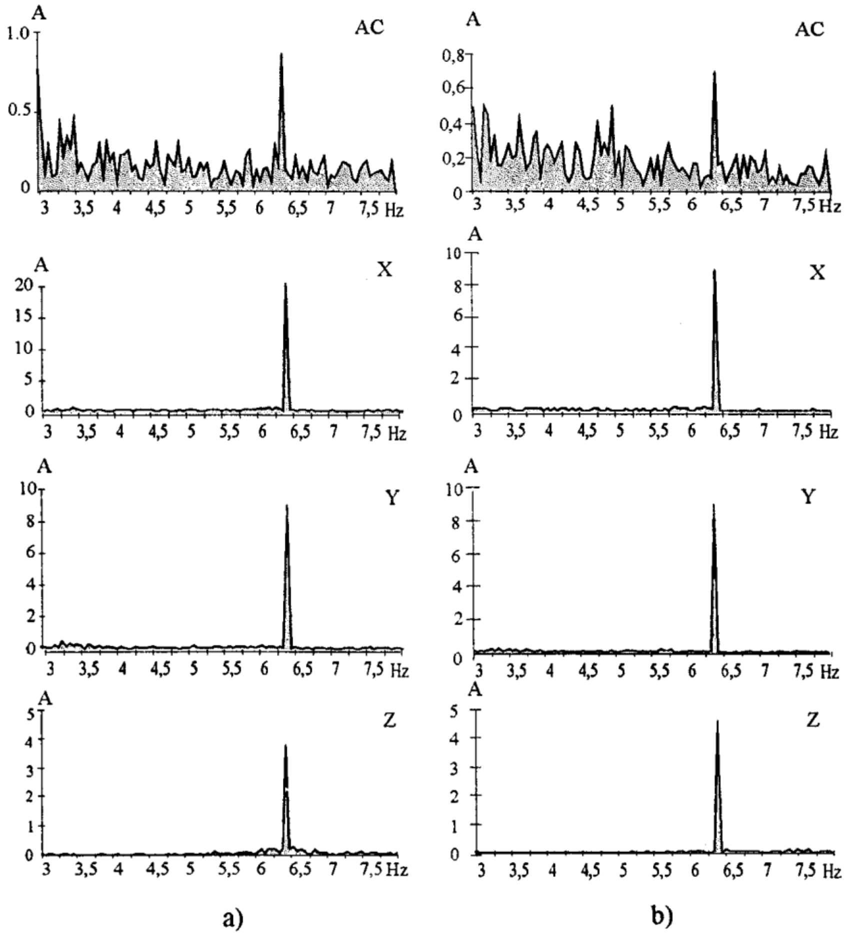

Figure 1. Spectrums of seismic and acoustic signals of vibrators (a) CV-100 and (b) HRV-50 at the distance 20 km

vibrators and harmonic signals. Radiation sessions of 15 minutes at a constant frequency of 6.4 Hz allowed synchronous accumulation of harmonic oscillations at a recording point with spectral resolution of approximately 0.001 Hz. The spectra of seismic oscillations for three components of seismic receiver and acoustic oscillations recorded by the infrasound microphone (Figure 1) have narrow peaks of the radiation frequency.

A probable mechanism of radiation of acoustic waves by the both types of vibrators is as follows. During the work of the vibrators, the ground surface around the source of an area of 200–500 m^2 oscillates as a large membrane of infrasound acoustic radiator with an amplitude of 1–5 mm. Besides, a pneumatic drive used as an energetic unit for a compressor of power of 150 kW with the compressed air pressure of 6 atm and consumption of 20 m^3/s is the second source of acoustic oscillations for the HRV-50 vibrator.

Compressed air is thrown from the vibrator into the atmosphere periodically, in phase with the vibrator oscillations, creating an acoustic signal, which is synchronous with the seismic signal.

The propagation of acoustic waves of infrasonic frequencies (6–7 Hz) to a distance of several tens of kilometers is possible owing to the phenomenon of refraction of sonic waves in the atmosphere. Two mechanisms of this phenomenon are known. They are temperature inversion in the air layer near the Earth's surface and the presence of wind with the velocity profile increasing with height.

In two series of experiments in windless weather, rapid and considerable decrease in the temperature at night time was observed. It resulted in the appearance of a wave near-surface channel. In contrast to the seismic channel, which determines the first train of waves in the seismogram, the acoustic channel is much more variable. This is responsible for considerable variations in the amplitude of the second train of waves, up to its disappearance when the channel vanishes.

The excitation mechanism of the surface seismic wave caused by the acoustic wave arrival at the recording point (acoustoseismic induction) was validated in mathematical simulation of the process [7]. It was shown that as the atmospheric acoustic wave propagates along the boundary of the elastic half-space, a surface wave is induced. This surface wave propagates at a velocity equal to the sound velocity in the atmosphere. If the velocity of Rayleigh waves in the ground coincides with the velocity of the acoustic wave, resonant increase in the amplitude of surface waves takes place.

A series of experiments was performed from April to December, 1996 to determine the influence of temperature and wind processes in the atmosphere on the effects of interaction of acoustic and seismic fields from vibrational sources. The centrifugal CV-40 and CV-100 vibrators of the Bystrovka test site were used in the experiments. Sounding sessions with the duration of 47 min 32 s were performed at night time using sweep-signals in a frequency range of 6.25–9.57 Hz. The meteorological situation along the wave propagation path was fixed by a nearby meteostation.

Signals were recorded by a three-component SK1-P seismic receiver in the seismic observatory of the Klyuchi settlement at a distance of 50 km from the source. It was isolated acoustically from the environment, and a special temperature was kept. The works were performed at night time from 22.00 p.m. to 5.00 a.m. two hours apart. At the stage of processing long seismic signals were convoluted with the reference signal reconstructed at the recording point in accordance with the scanning law of sounding signals from vibrators. As a result, a set of vibrational correlograms was obtained.

A part of such correlograms obtained in the Klyuchi settlement at a distance of 50 km in the periods from 25 to 26.04.96 and from 28 to 29.05.96 is shown in Figure 2. The figure contains additional information on the file

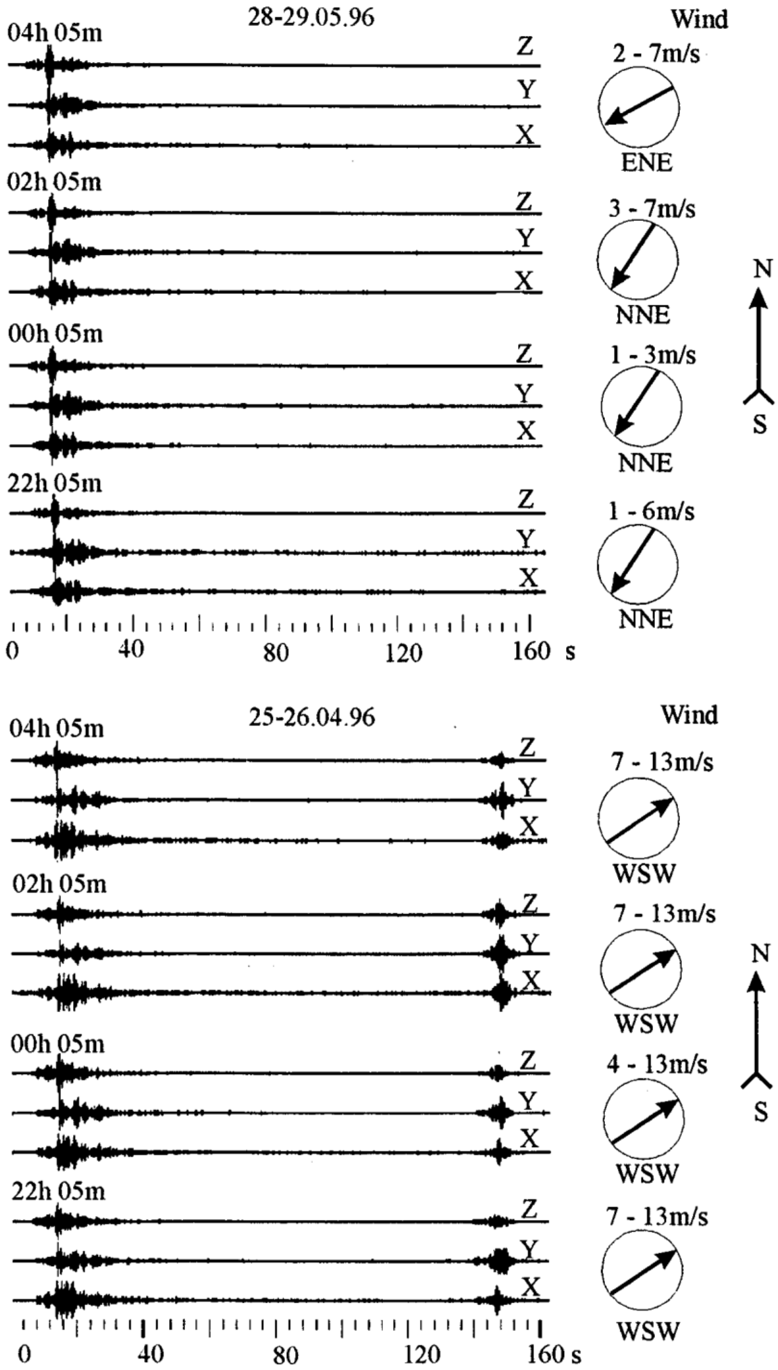

Figure 2. The results of recording of seismic and acoustic waves (distance 50 km)

the component types (X, Y, Z), the time of the beginning of work of the sources and the meteorological parameters, such as the wind direction and velocity in the period of works.

Two trains of waves are present in the correlograms. The first train of waves is observed in all correlograms. It is characterized by almost similar recurrence from session to session. It has the seismic P- and S-waves for the X, Y, and Z components with the arrival times of 8.1–8.3 and 14.5 s. The velocities $V_p = 6.0$ and $V_s = 3.5$ km/s correspond to these waves. Besides the P- and S-waves, surface waves are clearly seen.

The second train of waves is recorded in the part of correlograms with arrival times of 146–150 s. The propagation velocities of 333–342 m/s which coincide with the propagation velocities of acoustic waves in the air correspond to these arrival times. In contrast to the experiments on the basis of 20 km, the appearance of a train of waves is observed in all the three components. Besides, in the X and Y components the amplitudes of the second train of waves have close values, and in the Z component they are by a factor of 3–5 smaller. Additional appearance of signals in the Y component is due to the complex relief of the acoustic wave propagation path. This leads to the appearance of lateral waves in the Y component.

The experiments have shown that the appearance of the second train of waves is correlated with the wind direction. The figure shows that this train of waves is clearly seen when the direction of the wind coincides with the direction from the source to the receiver, i.e., west-south-west (WSW). It is known that in this case acoustic rays deviate to the Earth's surface, and a near-surface wave channel is formed. This favors sound propagation to large distances. Otherwise, when the direction of the wind is opposite to the direction to the recording point, rays deviate upwards, and the appearance of the second train of waves is not observed, although such a dependence is not so unambiguous due to the complexity of the considered effect.

The manifestation of the acoustoseismic effect was supported by the results of subsequent experiments performed from 26.10 to 11.12.96.

In contrast to seismic waves, the surface wave induced in each session is characterized by one arrival time for all the X, Y, Z components. This indicates that there is one reason for its occurrence. This time fluctuation from session to session is, however, up to 13 s, which is approximately 8% in comparison to 0.1% for seismic waves. Fluctuations of the induced wave arrival times are correlated with the wind direction: the arrival time increases at contrary wind and decreases at fair wind.

The values of maximal variations in the induced wave arrival times make it possible to estimate the characteristic wind velocity in the near-surface wave channel. Since $dv/v = -dt/t$, the characteristic wind velocity is ± 15 m/s. The largest travel times for this wave are observed at contrary wind. The sessions 147–153 (Figure 3) clearly show this. The values

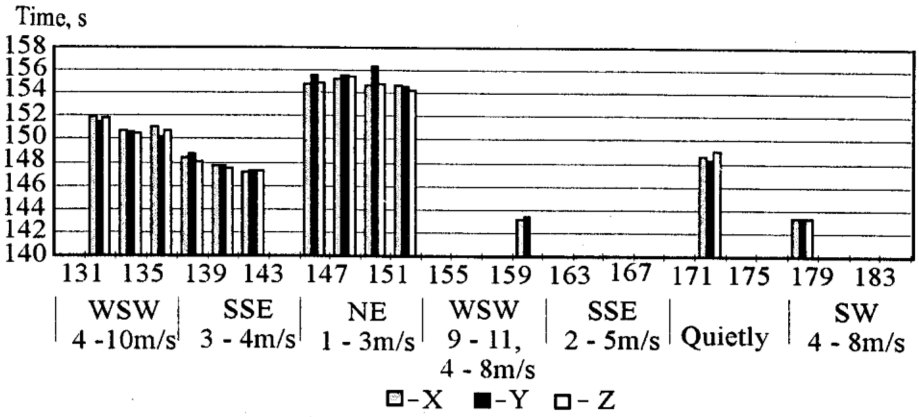

Figure 3. Acoustic wave times

obtained are similar to each other and, on the whole, exceed the values in sessions at fair wind (the sessions 131–143, 160, 179) and in quiet weather (the session 173).

As the distance and the meteorological situation change, the duration of the induced wave impulse also changes. The impulse duration at a distance of 20 km in quiet weather was approximately 2 seconds, and the single maximum was clearly defined. As the distance between the radiator and the receiver was increased to 50 km and in the presence of wind the impulse was up to 8–10 s and could have several maxima. This indicates that the velocity characteristics of the acoustic channel during the session of vibrational sounding are unstable and variable.

Variations in the amplitudes of the induced wave are to a larger extent connected with changes in the meteorological conditions than variations in the arrival times. When the meteorological conditions are similar, the amplitudes vary by a factor of 3–5, and when the meteorological conditions vary, disappearance of the wave is observed.

Spectral analysis shows that the form of amplitude spectrograms of seismic waves is highly stable from session to session, although variations here also occur during a long observation time, in which the ground freezes. In contrast to this, the spectra of acoustic oscillations are characterized by large variability of form due to variability of the acoustic channel depending on the meteorological conditions.

Conclusion

1. The detected effect of acoustoseismic induction has been investigated experimentally. During the work of powerful seismic vibrators, an infrasound acoustic wave is radiated simultaneously with seismic waves. In the presence of the near-surface sound channel, this wave can prop-

agate to a distance of tens of kilometers and induce surface seismic waves. These waves are recorded by seismic receivers together with radiated seismic waves from vibrators.

2. The influence of meteorological conditions on the appearance of induced surface wave at distances of 20 and 50 km from the source has been investigated. Variations in the travel times and amplitudes of the acoustic wave taking into account the meteorological factors, such as the temperature of the surrounding air, the direction and force of the wind, have been estimated. Variations in the arrival times of the induced wave constitute 8–10% in comparison to 0.1% for the seismic wave. This indicates that the dependence of the acoustic channel on the meteorological situation along the wave propagation path is strong.
3. Simultaneous recording of seismic and acoustic waves from powerful seismic vibrators with the help of seismic receivers isolated acoustically from the surrounding atmosphere shows that the wave phenomena in the atmosphere and the Earth are interrelated. Both types of waves give additional unique information, that can be used to solve some scientific and practical problems by the method of vibrational sounding of the Earth.

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