

Some Aspects of the Registration of Low-Frequency Impulse Signals in Air Using a Complex Receiving System

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Abstract—The specific features of the formation of impulse acoustic and seismic signals, as well as their propagation to relatively short distances under various conditions of their excitation, based on the registration of consistent data on a pressure field and an oscillation speed field are discussed. It is shown that the “delayed” character of the signals, especially at low exit angles of projectiles, is due to the intense interaction of a wave excited by a shot with the ground and to multiple reflections of the signals. The use of signals registered by the channels of a vector receiver makes it possible to obtain information on the spatial distribution of the signals. When a projectile bursts in air, the sound wave that is incident on the land surface induces a seismoacoustic wave that is first registered by channels of a combined receiving unit (CRU).

Keywords: pulse sound sources, combined receiving unit, muzzle blast, ballistic wave, sound-pressure level, burst of projectile, seismoacoustic wave, vector receiver.

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INTRODUCTION

The problem of the registration and determining the location of low-frequency impulse land sound sources is largely governed by conditions of the formation and propagation of acoustic signals in the atmosphere of the Earth [1, 2]. At relatively short distances to a source (a few kilometers or a few tens of kilometers), the acoustic bearing to a source of power impulse signals is, as a rule, determined by measuring the difference in times of the registration of the leading edge of the wave or, for sources of continuous signals, by measuring the difference of phases between the signals recorded by different split-site microphones [3–7]. However, peculiarities of the topographical relief, the interaction of the sound wave with the land surface, variations in the wind speed and direction, as well as the existence of a vertical gradient of temperature and, therefore, the sound velocity in the atmosphere, commonly lead to fairly high fluctuations of the signal phase and amplitude, as well as the arrival time of the wave’s leading edge [2]. This makes the solution of applied problems (e.g., problems of the determining the location of low-frequency impulse land sources) difficult.

The aim of this work was to determine the specific features of the formation of impulse acoustic and seismic signals and their propagation to fairly short distances based on the registration of consistent data on the pressure field and oscillation speed field.

1. MATERIALS AND METHODS

In recent decades, information registered by a combined receiving unit (CRU) has found increasing use for finding the direction of impulse signal sources in the low-frequency band [8, 9]; the CRU includes a three-component vector receiver (VR) [10, 11] and a sound-pressure receiver, for which the above-mentioned fluctuations are insignificant in many cases. Analysis of the literature shows that in a number of countries direction finding and determining the location of impulse-signal sources are carried out using oscillation-velocity sound detectors [12]. For example, Microflown Avisa Co. (the Netherlands) developed innovative acoustic vector sensors (AVSs) for finding and determining the location of shots from small arms, guns, aircrafts, and vehicles [13, 14].

For level ground covered with greenery and for “good” weather such as that described in our earlier work [15], the advantages of the CRU in solving problems of the determining the location of guns and projectile impact points are clear.

However, in the hot season, as well as on a rolling or mountainous terrain, the character of the propagation of sound changes strongly due to the intense interaction of a sound wave excited by the shot with the ground and to multiple reflections of the signals. Signal events can often be of “delayed” character, especially at low jump angles of projectiles.

To determine the specific features of the propagation of acoustic and seismic signals to fairly short distances and the possibility of determining the locations

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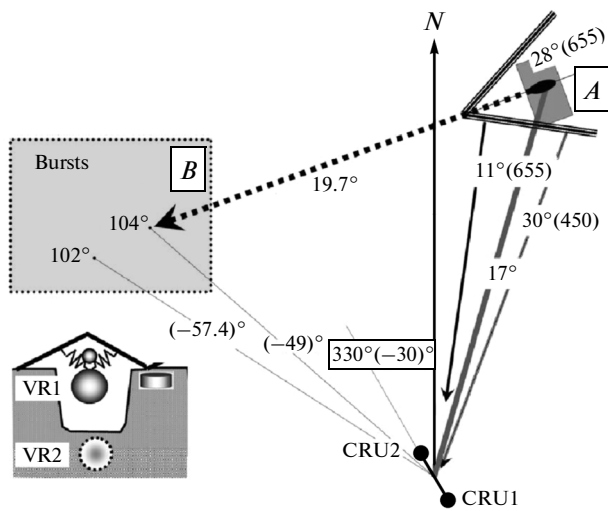


Fig. 1. Field-experiment arrangement and the layout of sound detectors.

of guns and projectile impact points based on the registration of consistent data on the pressure field and oscillation speed field, an experiment was carried out on one of the testing areas in the European region of the Russian Federation during the summer season.

The signal sources were shots of land-based guns and projectile bursts.

The geometry of the field experiment and the layout of the arrangement of the sound detectors are shown in Fig. 1.

The receiving system (RS) was made up of two CRUs arranged 300 m apart.

The gun site (A) was located on an elevation so that the direction to the guns was 17° – 19° relative to the north line. The burst area (B) was located at angles of from -45° to -60° .

Each split-site CRU consisted of two VRs developed at the Moscow State University [11] and a microphone (pressure sensor). In addition, a Vektor-2N standard receiving unit was used, whose signal was proportional to the sound pressure.

One of the VRs in each CRU was placed in the air, while the other one was covered with soil. The protection of each CRU against wind noise was provided by using a radome.

Signals were simultaneously recorded in all channels and then successively transferred to the computer memory.

When the VRs are used, the simultaneous registration of signals is crucial for eliminating phase delays between the channels, which lead to misinterpretation of the character of the movement of medium particles in the wave and to the incorrect determination of the direction to a sound source [15].

2. RESULTS AND DISCUSSION

It is known that a gunshot induces a shock wave [16]; subsequently, three types of signals should be registered. At the moment when a projectile leaves the gun tube, an impulse wave (“muzzle” wave) arises, which propagates over the horizontal plane almost isotropically. A projectile that leaves a gun tube with ultrasonic speed induces a “ballistic” wave. An impulse signal of the third type arises in the projectile burst area after a fairly long time [17, 18].

In the field experiment, the number of registered pulses was substantially higher because of the multi-beam character of the propagation of the signals due to the vertical stratification of the atmosphere, the presence of wind, uneven surface topography, etc.

A specific feature of shooting on one of the days was the low height of the projectile trajectory and, therefore, the possible interaction of waves the projectile induced with the land surface, as well as the excitation of seismoacoustic waves [19, 20]. The wind speed at the site of the CRU was ~ 2.5 m/s, the wind direction varied in a range of 300° – 330° , the shade temperature was 22°C , and the humidity was 36%.

Let us analyze the time dependence of the signals recorded in various CRU channels, which correspond to the moment of shooting, as shown in Fig. 2 on an enlarged scale. This figure also presents the result of finding the direction of the arrival of the signal in the vertical and horizontal planes, as well as the energy of the signal.

The index “a” indicates the VP1 placed in air. The designation P-a corresponds to the signal taken from the standard sensor of the Vektor-2N receiving unit. If the signal registered by this sensor is considered as a reference signal, it can be assumed that the onset of the shot (the muzzle blast, almost immediately followed by a ballistic wave) corresponds to the moment of time shown by the second on the right dashed line.

However, an analysis of the energy propagating in the space using the CRU shows that there are several peaks of this energy.

The first peak, which is located ~ 7.8 s after the beginning of the recording (Fig. 2, the first on the left dashed line) and is interpreted as the local plane wave found from the direction of 11° – 15° corresponds, to all appearances, to a muzzle blast that arrives at an angle of 35° – 40° to the horizon in the vertical plane. The second dashed line corresponds in all likelihood to the onset of the ballistic wave that arrives at an angle of 35° – 40° to the north line, which, according to the estimates, corresponds to a jump speed of a projectile of ~ 440 – 450 m/s.

The “tail” of the signal from the shot, which lasts for the next 3 s, is characterized by the periodic appearance of pulses registered by VR2 (covered with soil) and, in the vertical plane, by the surface propagation of the signal.

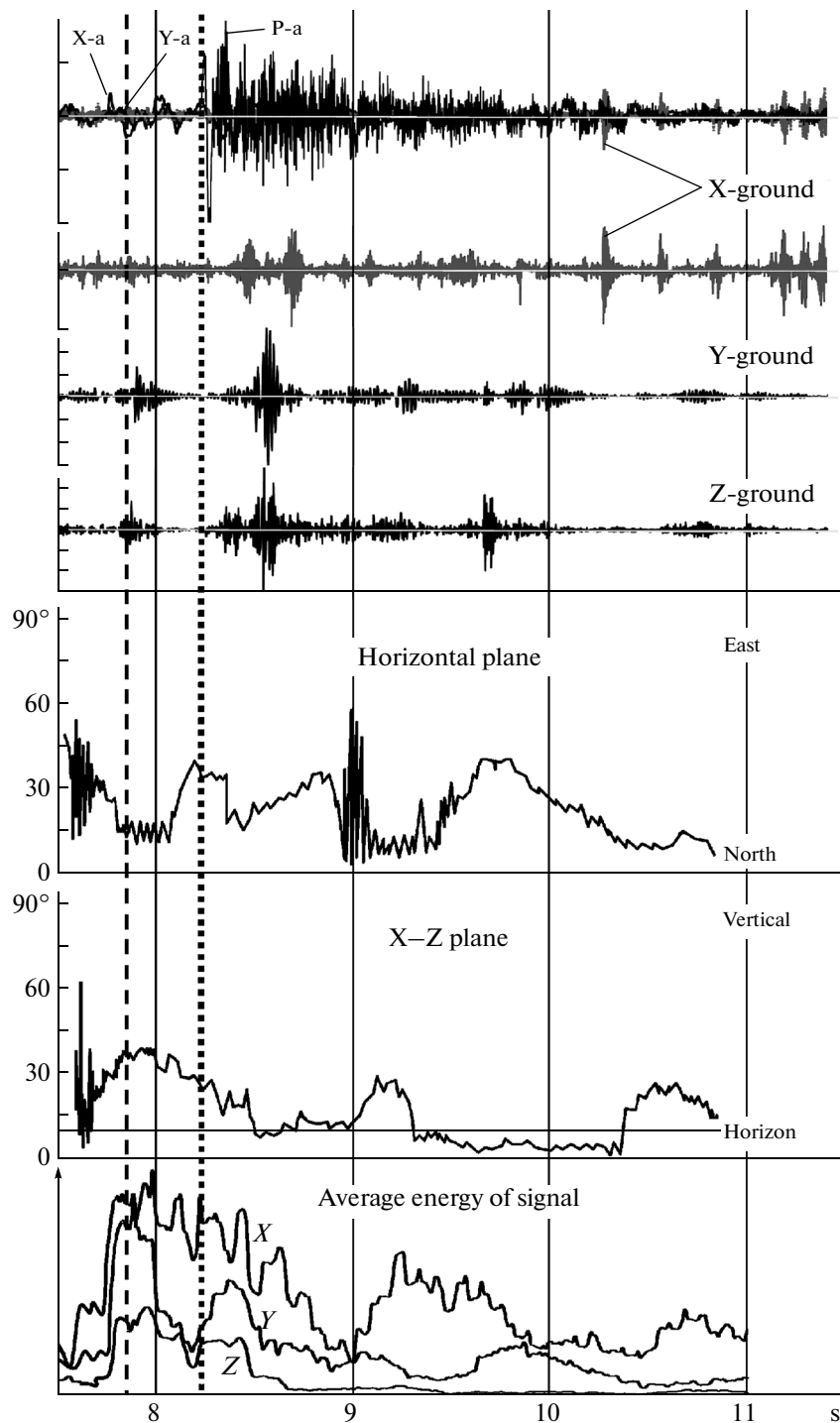


Fig. 2. The analysis of a "shot" signal.

We suppose that the long "tail" of the signal from the shot is related to specific features of the terrain relief and to the intense interaction of the ballistic wave with the ground.

Figure 3 shows the fragment of the spatial distribution of the energy of this shot, which corresponds to the moment of the projectile burst. In the channels of the

VR1, the signal is clearly detected at an angle of 55° – 57° , which approximately corresponds to point 102 in the burst area (B) (Fig. 1). Since the signal is fairly powerful, it is clearly detected in the channels of the single CRU. The bearing that was determined based on registering the delay time of the arrival of the burst signal to the split-site CRU1 and CRU2 was $\sim 59^\circ$.

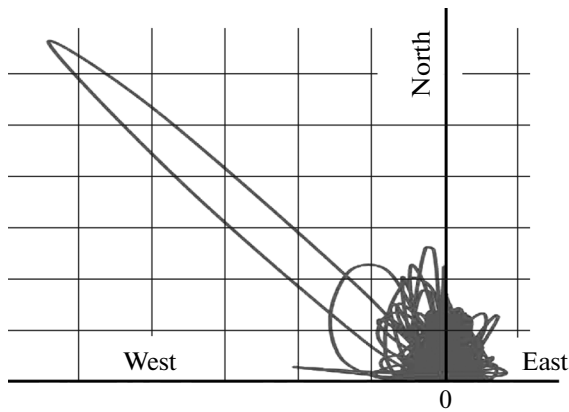


Fig. 3. The bearing of a "burst" signal.

One specific feature of the next signal to be analyzed is the power of the projectile, which exceeded that in the previous case by a factor of approximately 1.5, as well as the high parabolic trajectory of the projectile ($H_{\max} \sim 95$ m). The wind speed on the site of the CRU was ~ 3 m/s, the wind direction was 300° , the air temperature was 19°C , and the humidity was 32%.

For the pulse being analyzed, the record of the shot signal has a more complex structure compared to that of the above-described records of the signals. Two or three "predecessors" are the first to appear, which are clearly registered by the VR2 covered with soil and more poorly by the VR1 placed in air.

It is quite problematic to determine the exact arrival of the muzzle blast using the signals taken from the pressure sensors.

This problem was partially solved by using the processing of the signals registered by the channels of VR1. Figure 4 shows the signal registered by the channels of VR1, as well as the time dependence of the energy of this signal on the same time scale and the direction of the spatial propagation of this energy in the horizontal plane.

Based on the known geometry of the mutual arrangement of the gun site and the CRU, it should be assumed that the first "peak" of the energy in Fig. 4, which is found at an angle of 14° – 17° , corresponds to the muzzle blast. The next maxima of the energy correspond, in all likelihood, to the ballistic wave, which repeatedly interacted with the ground.

If it is assumed that the next peaks are indeed related to the ballistic wave, which was reflected from land objects at different moments of time, the first pulse corresponds to a projectile speed of 467 m/s, the second pulse corresponds to a speed of 440 m/s, and the third pulse corresponds to a speed of 433 m/s (Fig. 4); i.e., the reflected signals are formed successively, as the projectile speed decreases, rather than simultaneously.

An additional series of shots was carried out. An increased power and a high parabolic trajectory

($H_{\max} \sim 95$ m) of projectiles were used, as in the previous case. The wind speed on the site of the CRU was ~ 3 m/s, the wind direction was 300° , the air temperature was 19°C , and the humidity was 32%.

A specific feature of this series of shots was that the projectiles burst in air at some height above the ground.

In this case, the record of the shot signal for the pulse that was being analyzed is not considered, since the typical indicators of this pulse differ only slightly from those of the corresponding shot signal, which was considered above.

Let us consider the signal that corresponds to the moment of the burst. Figure 5 shows the typical time dependence of the signals simultaneously recorded in the channels of the VR1 and the sound-pressure channel P, which correspond to the moment of the burst. The abscissa is the time (s) and the ordinate is the amplitude (arb. units).

Let us consider specific features of the registered signals at the moment of the burst.

Two types of pulses are recorded in the V_x and V_z channels of the VR, while single pulses are recorded in the V_y and P channels. At the time of registration, the pulse recorded in the V_y channel corresponds to the first pulse recorded in the V_x and V_z channels of the VR, while the pulse recorded in the P channel corresponds to the second pulse recorded in the V_x and V_z channels of the VR.

Let us assume that the following events occur during the burst of a projectile in the air.

First, the burst of the projectile in the air at a fairly low height (according to the conditions of shooting, this height should not exceed 95 m) induces a sound wave, which propagates in air.

Second, the burst of the projectile in the air causes the sound wave to hit the ground surface to produce a seismoacoustic wave in it.

Third, the sound wave induced by the burst of the projectile in the air reflects from the ground surface and also propagates in the air.

The pulse of the signal registered in the P channel corresponds to the sound wave induced by the burst of the projectile in the air, since this sound detector responds to only sound waves; therefore, the second pulses, which are registered in the V_x and V_z channels of the VR and correspond to this pulse in time, also correspond to the sound wave. The sound wave induced by the burst of a projectile in air and reflected from the ground surface was not registered by either the VR or the sound–pressure sensor; therefore, it is not considered.

Thus, it can be assumed that the first pulses registered in the V_x and V_z channels, as well as in the V_y channel, of the VR correspond to the seismoacoustic wave that was a result of the sound wave that was induced by the bursting of the projectile in the air,

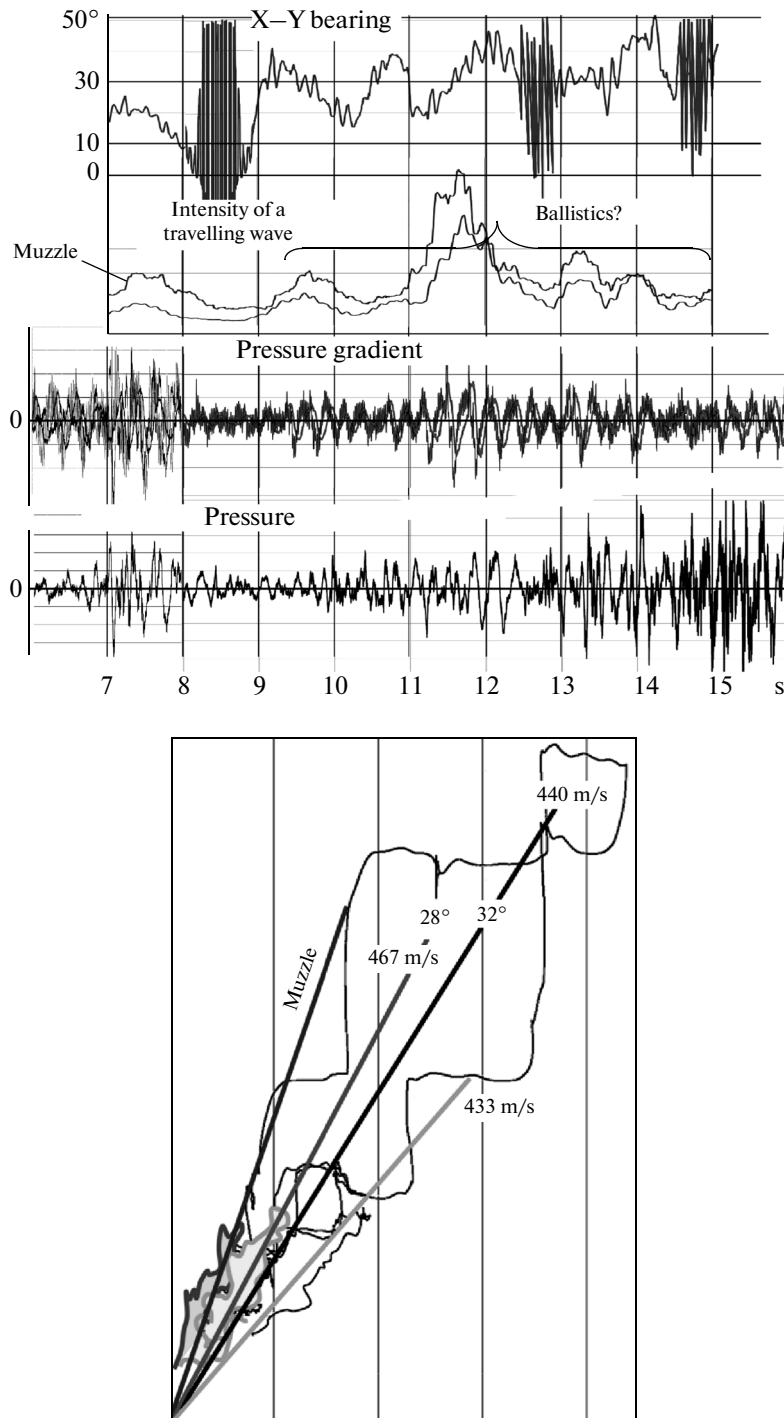


Fig. 4. Analysis of a “shot” signal. The spatial distribution of the arrival direction of the energy of the waves in the horizontal plane and the directions that correspond to the centers of gravity of these waves for the “shot” signal are shown on the right.

which hit the ground surface. The processing of all shot signals from double bursts has shown that the time difference between the first and second signals of the pulse is 0.68–0.69. This time is the sum of the time of the propagation of the sound wave induced by the burst of the projectile in the air to the ground surface

and the time of the propagation of the arising seismoacoustic wave to the receiving system.

It follows from the parameters of the projectile flight that the maximum height at which the projectile can burst in the air is ~95 m. Therefore, the time of the propagation of the sound wave induced by the projec-

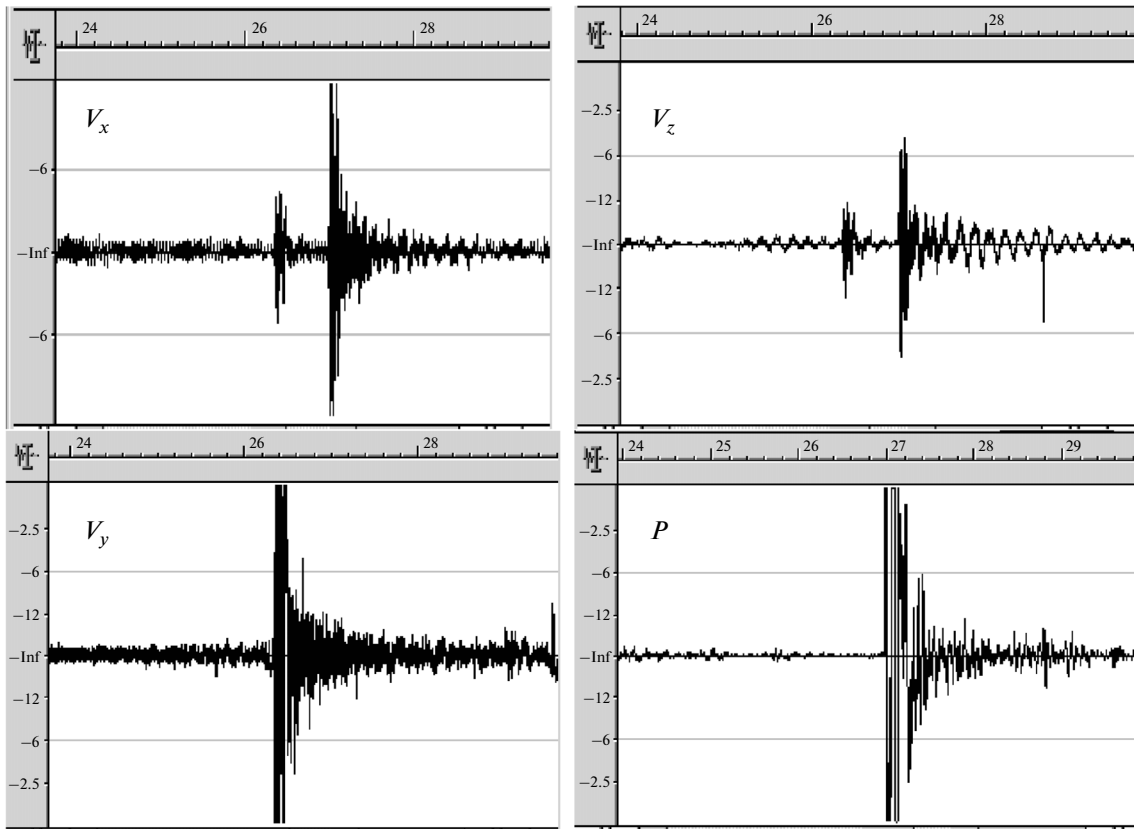


Fig. 5. The time dependence of a signal at the moment of the burst.

tile bursting in the air to the ground surface is ~ 0.29 s provided that the speed of the propagation of this wave is 330 m/s. Thus, it can be assumed that the remaining time (0.4 s) was spent for the propagation of the seismoacoustic signal from the site of the incidence of the sound wave induced by the bursting of the projectile in the air to the receiving system. Taking the fact into account that the speed of the propagation of the seismoacoustic signal is 2100–2500 m/s, the distance from the site of the incidence of the sound wave on the ground surface to the receiving system is estimated at ~ 1000 m.

The direction of the arrival of the registered seismoacoustic signal can also be estimated. The processing of all signals induced by the shots that produced double bursts showed that the seismoacoustic signal registered by the VR2 channels has a sufficiently high amplitude and is accurately found at an angle of 83° – 86° . It should be noted that when impulse signals induced by the burst of a projectile in air recorded by the VP1 channels exist, the location of the burst, which can substantially differ from the site at which the sound wave falls, can be found without any difficulty.

Thus, in the case where a projectile bursts in air, the existence of double impulses (the first impulse corresponds to the seismoacoustic wave to be induced) con-

siderably complicates the problem of the registration and determination of the location of the burst site.

CONCLUSIONS

The experimental results show that signals registered by the channels of the VR covered with soil contain a larger number of high-frequency components than signals registered by a similar VR placed in the air; the amplitudes of these signals induced by a shot and a burst are often substantially higher than those of signals registered by the VR placed in the air, especially for “delayed” signals. The latter fact indicates that in many cases the “delayed” character of the signals, especially at low jump angles of projectiles, is due to the intense interaction of a wave excited by the shot with the ground, multiple reflections of signals, and the excitation of seismoinduced acoustic waves.

For complex “delayed” signals, the data registered by the VR channels make it possible to obtain information on the spatial distribution of the signals. The possibility of determining the location of a signal source by triangulation methods using signals registered by site-split CRUs has been shown.

We also note that when a projectile bursts in air the CRU channels register double impulses; the first impulse corresponds to the seismoacoustic wave being

induced and the second impulse results from the sound wave induced by the projectile burst in air, which complicates the problem of the determining the location of the burst site.

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