OPTIMUM FILTRATION OF ACOUSTIC PULSES CAUSED BY UNDERGROUND NUCLEAR AND ABOVE-GROUND CHEMICAL EXPLOSIONS

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ABSTRACT

For identification of acoustic pulses from explosions, we devised a method using optimum filtration of signals. As a reference signal we use the calculated form of an acoustic pulse. To describe the propagation of an acoustic pulse through the inhomogeneous atmosphere, we developed a new equation and corresponding computer simulation code. The model takes into account nonlinear effects, inhomogeneities of the atmosphere, absorption, expansion of a wave acoustic front, etc. At present the model is developed for the ascending part of a trajectory of an acoustic ray: from a ground surface up to the height of a reflection point (ionospheric height). Data from parachute measurements of acoustic pulses, and measurement of acoustic pulses at different heights in the ionosphere along with Doppler radio soundings were used to test the model.

The program includes the following subroutines:

1. Subroutine of the vertical movement of the earth’s surface during an underground nuclear explosion (we use an empirical model).
2. Subroutine of a calculation of atmospheric parameters (we use an MSIS model).
3. Subroutine of a calculation of wind profile along an acoustic ray trajectory (we use a HWM model).
4. Subroutine of an acoustic pulse generation by a spall zone.
5. Subroutine of acoustic pulse generation by an above-ground chemical explosion (we developed a new initial form of an acoustic pulse).
6. Subroutine of the propagation of an acoustic pulse from the earth’s surface up to the ionospheric height.
7. Subroutine of the calculation of the ionospheric profile (we use an IRI model and data of an ionogram).
8. Subroutine of acoustic wave influence on the ionospheric plasma.
9. Subroutine of the trajectory of radio wave propagation in the ionosphere (we account for the geomagnetic field).
10. Subroutine of the ionospheric perturbation influence on the Doppler frequency of a radio wave.
11. Subroutine of the optimum filtration.

We used data from the Mill Race experiment (an above-ground chemical calibration explosion for which the yield was 500 ton TNT) to test the model calculations simultaneously at eight different locations in the low atmosphere and ionosphere. The correlation coefficient between the calculated and the experimental form of the acoustic pulse was in the range of 0.85 to 0.98. The average mean yield of the explosion was 531 ton TNT with a standard error of ± 34 ton. We also estimated the yield of the Flixborough explosion using the data from six independent measurements of acoustic pulses at ionospheric heights. The reconstructed oblique radio soundings agree remarkably well with experimental results when a ground source explosion yield of 283 ± 38 tons of TNT is utilized. We used the data from the Soviet – US experiment (underground nuclear calibration explosion at the Semipalatinsk test site in 1988, the yield of which was about 150 kiloton TNT) to test the model calculations simultaneously at three different locations in the ionosphere. The correlation coefficients between the calculated and experimental forms of the acoustic pulse were 0.83, 0.8 and 0.68. The probability of detection of a signal was equal to one with the threshold of acceptance of the cross-correlation set equal to 0.4.

OBJECTIVE

The manner in which infrasound monitoring can aid in remote detection and identification of underground nuclear explosions has been the subject of some exploration. We propose the theory of optimum filtration as a way for infrasound to be applied to this problem. The optimum analysis should include: a correlation device and a reference signal such that:

$$R(\tau) = \int_0^T f_s(t) f_p(t-\tau)dt\ ;$$

where $f_s(t)$ input is the infrasonic signal and $f_p(t)$ is the reference signal – the infrasonic "portrait" or analysis of an explosion.

To produce analyses of explosions, we can use theoretical calculations. Obviously, the correlation between physical and numerical models and experimental results should be sufficiently high. The model should take into account the following factors:

- Process of generation of an acoustic impulse by an explosion.
- Oblique propagation of acoustic impulses in the real atmosphere.
- Reflection of an acoustic wave from the atmosphere.
- Propagation of acoustic impulses back down to the receiver.

Each of the four parts of this model should be experimentally verified. For long distances, acoustic pulses (infrasound) are propagated from the earth's surface to an altitude about 100-120 km (ionospheric heights). Thus, it is possible to use experiments on radio sounding in the ionosphere (for example, Doppler radio sounding) for testing a model at these heights. As a result we have developed new theoretical models and corresponding computer simulation codes that account for the entire range of atmospheric and ionospheric phenomena involved in the technique, from the generation of acoustic pulses by surface ground motions during underground nuclear explosions to the synthesis of radio frequency signatures recorded by ionospheric radar systems (Drobzheva and Krasnov, 2002). The model accounts for non-linear effects, atmospheric and ionospheric vertical inhomogeneity, absorption, diffraction effects, geomagnetic field, horizontal wind, etc.

The purpose of our work: to show the efficiency of the optimum filtration method for detection of acoustic impulses from chemical and underground nuclear explosions from the ionosphere.

RESEARCH ACCOMPLISHED

The first and second parts of the model were tested with experimental data obtained during the Mill Race experiment (Banister and Hereford, 1991; Warshaw and Dubois, 1981) and the Soviet – US experiment (09/14/88). In the Mill Race experiment, data collected during the surface burst of a 500-ton TNT equivalent chemical explosion represented a unique opportunity to assess the credibility of calculations used to evaluate the yield of surface explosions from atmospheric and ionospheric measurements. The evaluation of the model used the results of atmospheric pressure variation measured by probes suspended by four parachutes at an altitude of about 10 km at horizontal distances of 1.9 to 16.3 km from a vertical line through the explosion point. Doppler shift records (f_d), made when radio waves were reflected from the altitudes of about 151, 222, 242 (vertical sounding) and 263 km (oblique sounding) were also used. It was therefore possible to test the model calculations simultaneously at eight different locations in the atmosphere and ionosphere. To estimate the yield of the explosion, the forms of the calculated and experimental acoustic and Doppler disturbances for a variety of explosion yields were compared. This comparison took the form of determining the correlation coefficient (K) between calculated and experimental values and choosing the value of the explosion yield when the correlation coefficient achieved its maximum value. Figure 1 and Table 1 indicate the results of these comparisons.

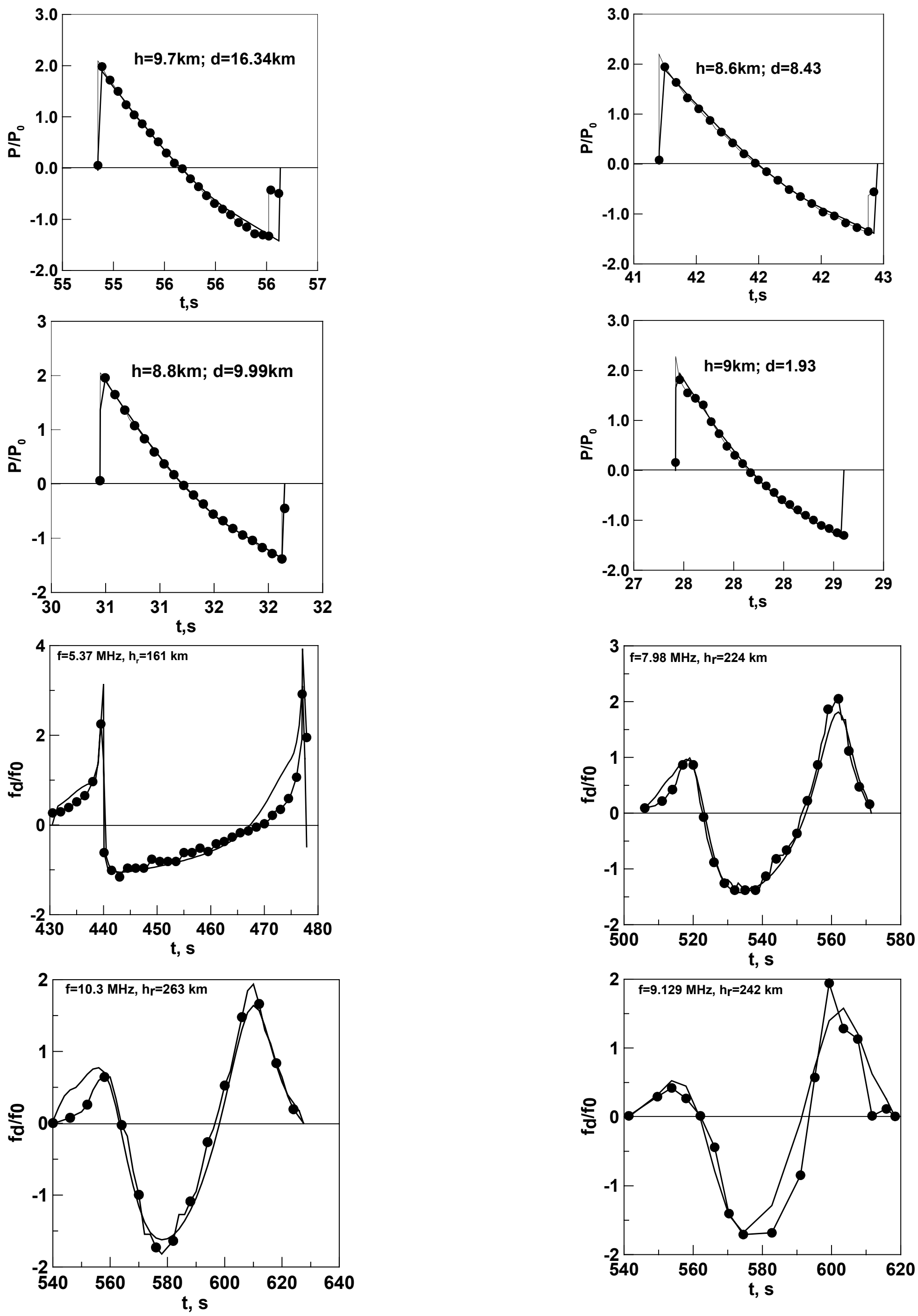

Figure 1. Comparison of calculation results of acoustic and ionospheric perturbations for the Mill Race experiment. Calculations are represented by solid lines and experimental results by dots; h – altitude of observation, d – horizontal distance from the site of explosion, f - frequency of radio sounding.

Table 1. Mill Race Explosion Yield; comparison of experiment to theory.

h (km)	K (correlation coefficient)	Q (ton TNT)	Error in Q (%)
8.6	0.95	450	10
8.8	0.973	550	10
9.0	0.964	550	10
9.7	0.943	450	10
161	0.85	700	40
224	0.989	600	20
242	0.952	400	20
263	0.982	550	10
mean	-	531	6.4

It is necessary to note that there are some differences between the experimental and calculated arrival times of the disturbances. However, to show the agreement between the experimental and calculated waveforms, these were matched by arrival time; any error in the calculation of the arrival time does not exceed 5%.

The average mean of the explosion determined in this manner is 531 ton TNT with a standard error of the mean of ±34 ton. The calculated result agrees well with the experimental value. It is important to note that in spite of using numerous input data (profiles of atmospheric pressure, density, sound speed, ionosphere, etc.), the calculation results show only a small spread in values of yield; ±6.4%. The reason for this is that the parameters of acoustic disturbances depend critically on explosion yield and the altitude profile of atmospheric density (Drobzheva and Krasnov, 2001; Drobzheva and Krasnov, 2002). In turn, any error in the determination of the model of atmospheric density is small – about a few per cent.

In the Soviet – US experiment, data collected during the calibrated underground nuclear explosion of 150 kiloton TNT equivalent represented a unique opportunity to assess the credibility of calculations from ionospheric measurements. Doppler shift records were recorded when radio waves were reflected from the altitudes of about 179, 210-213, 221 km (oblique sounding). It was therefore possible to test the model calculations simultaneously at three different locations in the ionosphere. Figure 2 indicates the results of the comparisons.

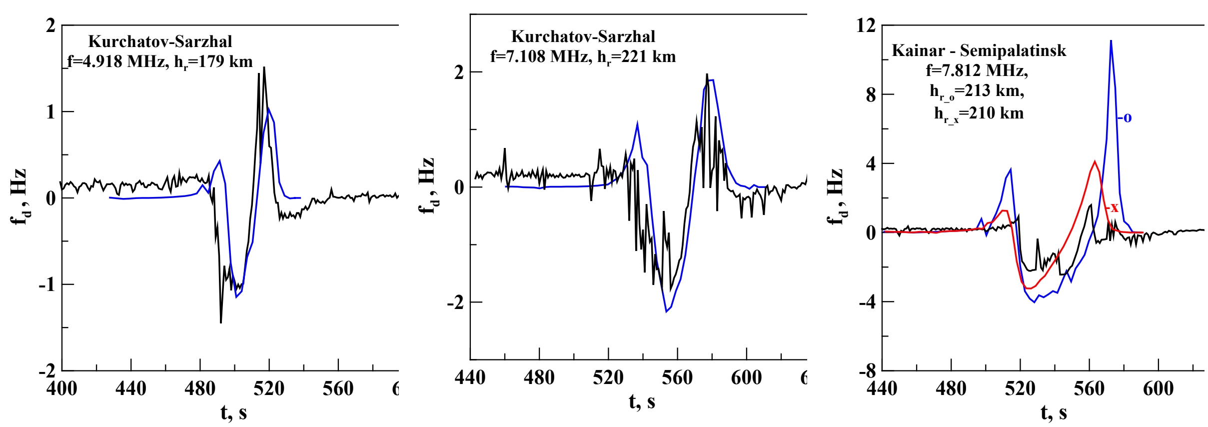

Figure 2. Comparison of calculation results of ionospheric perturbations for the Soviet - US experiment. Black line = experiment, dark blue line = calculation for an ordinary radio wave and red line = calculation for an extraordinary radio wave. h = altitude of observation, f = frequency of radio sounding.

A coefficient of cross-correlation between calculated and experimental curves produced the following results: 0.83 (for Fig. 2a), 0.8 (for Fig. 2b), 0.61 (for Fig.2c - for an ordinary radio wave), 0.68 (for Fig. 2c - for an extraordinary radio wave). The smaller coefficient of correlation for the case in Figure 2c is caused by the fact that the heights of a reflection of ordinary and extraordinary radio waves only differed slightly. As a result, perturbations on the Doppler record were almost simultaneous for both types of waves. This caused an interference in the Doppler record. The model developed does not take into account interference effects.

During the Soviet-US experiment, the ratio of the signal to noise on Doppler records was more than one. Thus, it was not a problem to detect the signal. A more difficult task was encountered during an underground nuclear explosion on 12/27/87. Figure 3a, b represents initial Doppler records for two radio waves. Figure 3c, d represents the corresponding records after the optimum filtration; the signal considerably exceeds noise. If we determine the threshold of decision-making as a correlation coefficient of 0.4, then the probability of correct detection of the signal is equal to 100 %.

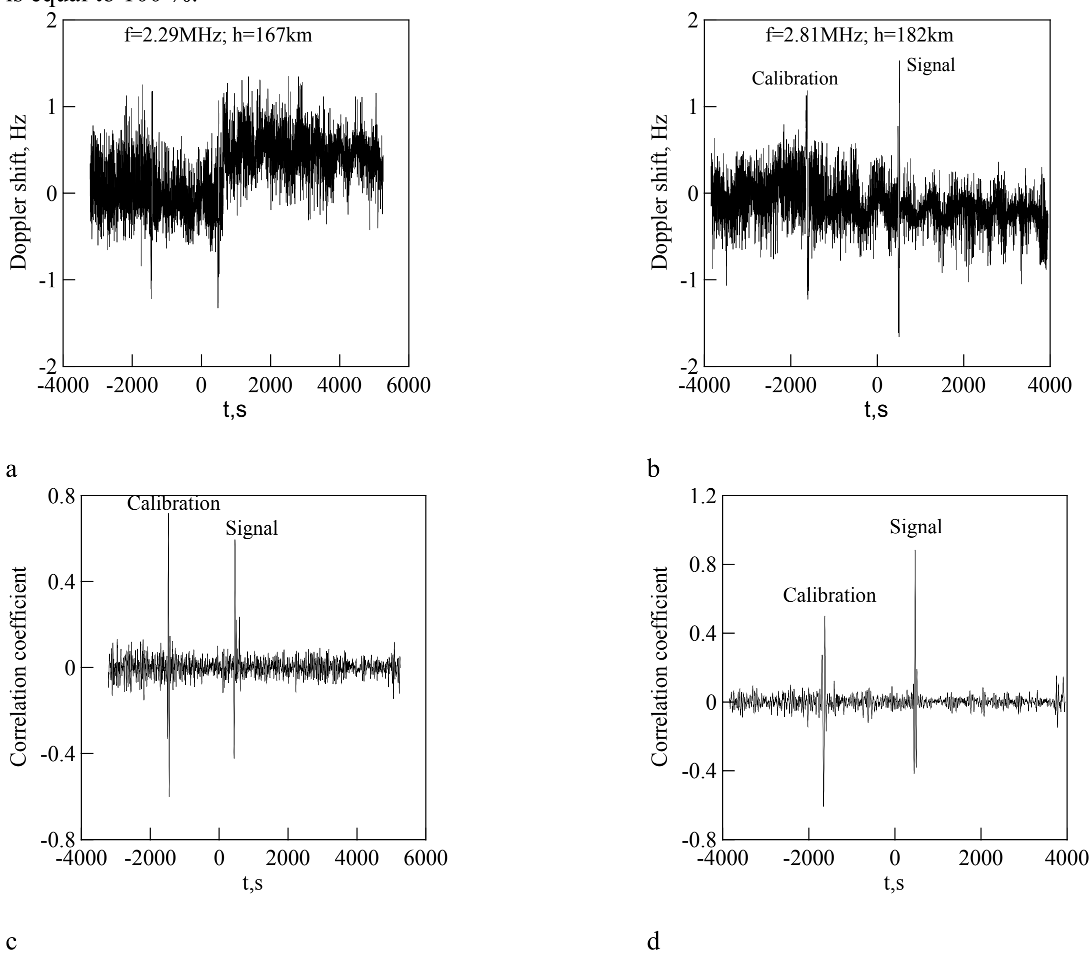

Figure 3. Doppler records before (a,b) and after (c,d) the optimum filtration for two radio trace.

Because the physical model agrees well with experimental results, it allows us to investigate the dependence of the form and magnitude of the Doppler response on the length of a radio trace during an underground nuclear explosion. The result of calculations for an approximately 210-km height of a radio sounding is represented in Figure 4 where it is shown that the form and magnitude of the Doppler response practically do not depend on the length of a radio trace. At the same time, these parameters are highly dependent on the height of radio wave reflection and horizontal distance between the radio wave reflection point and the explosion site. Because radio waves of short wave range can propagate all around the globe, the ionospheric method of detecting acoustic impulses due to explosions has no distance restrictions.