NONSTANDARD APPLICATIONS OF THE INFRASONIC AND HYDROACOUSTIC COMPONENTS OF THE INTERNATIONAL MONITORING SYSTEM OF NUCLEAR EXPLOSIONS

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Abstract

The Comprehensive Nuclear-Test-Ban Treaty, which was ratified by the Republic of Bulgaria in 1999, prohibits nuclear tests in the atmosphere and outer space, underground and underwater. At present, the International Monitoring System collects data from inspections at the International Data Centre located in Vienna, using four modern technologies: seismic, underwater acoustic, infrasonic and radionuclide. This paper discusses the features, methods, equipment and capabilities of the infrasonic and hydroacoustic components of the monitoring system. It has been shown that such systems can be used to detect other phenomena of natural origin or caused by human intervention: volcanic eruptions, hurricanes and typhoons, quarry or mine explosions, firing from large-caliber gun systems, missing submarines and more. Some results of the ***in situ*** *study of the acoustic (sound and infrasound) characteristics of the truck-mounted 122 mm multiple rocket launcher BM-21 "Grad" are investigated.*

1. INTRODUCTION

A nuclear explosion releases a huge amount of energy into the atmosphere. A strong shock wave is formed, behind whose front in the initial period the temperature and pressure are extremely high. As it moves away from the epicentre of the explosion, this shock wave becomes acoustic. This is accompanied by a dissipation of its energy, as the short wave components of its spectrum attenuate faster than the long-wave. Only infrasonic waves remain over long distances, namely those in the ultra-low frequency range (far infrasound), i.e., with frequencies less than 1Hz [1,2,3]. The principle of further propagation of low-frequency components remains in underground and underwater nuclear explosions, where and other types of waves occur. If the nuclear explosions are under water, in the atmosphere above the surface of the world's oceans or underground near the shore, then the sound waves caused by the nuclear explosion can be detected through sonar monitoring stations. Due to the peculiarities of the propagation of sound waves in an aquatic environment (so-called SOFAR), the detection can take place over great distances. It has been proven that this can be done through only 11 stations [1]. They are of two main types: underwater hydrophone stations and so-called T-phase stations [2,7].

However, it should be emphasized that hydroacoustic stations are one of the most expensive and most difficult to maintain. This is because they are located in places with huge hydrostatic pressure, aggressive environment and temperature changes.

In the presented work the peculiarities, methods, equipment and possibilities of the infrasonic and hydroacoustic components of the system for monitoring of air and underground nuclear explosions are considered. It has been shown that these systems, or similar local ones, can be used to detect other phenomena of natural origin or caused by human intervention: volcanic eruptions, hurricanes and typhoons, quarry or mine explosions, firing from large-caliber gun systems and others.

For the first time in 1945, the American scientist Maurice Ewing proposed the use of an ionospheric waveguide channel for acoustic control of possible atomic experiments in the USSR. In the former Soviet Union on the idea of Academician I. K. Kikoin in 1953 created an infrasonic measuring station to detect atmospheric nuclear explosions. In the 1990s, this type of system received a new impetus for development in connection with the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

American scientists Maurice Ewing and J. Worzel discovered the existence of underwater sound channels SOFAR (SOund Fixing And Ranging) transmission in 1944. In the former Soviet Union in 1946, the same discovery was made by L. M. Brekhovskikh and L.D. Rosenberg [6,7].

2. INFRASOUND AND ITS PROPAGATION IN THE ATMOSPHERE

Detection and registration of infrasound waves is a complex task, as the wavelength reaches several kilometers (for example, infrasound with a frequency of 1Hz has a wavelength of 340 meters, and if the frequency is 0.1Hz, the length is already 3.4 kilometers) [4,5]. The sensors used should be protected from noise caused by other factors, such as wind, temperature anomalies, turbulence, etc. Resonant vibrators such as loudspeakers, pipes, strings, etc. could be used as sensors. Their main disadvantage is their large size (hundreds of meters and more) and narrow frequency range. On the other hand, they have high sensitivity and efficiency. At present, compact sensors are most commonly used, which convert acoustic oscillations into electrical signals. They are of two main types: low-frequency condenser microphones [5] (for near infrasound) and microbarometers (for far). This is necessary because the electromotive voltage of the microphones is proportional to the acceleration of the membrane, and in one oscillation for a few seconds or minutes practically no e.v. In the case of microbarometers, on the other hand, they perceive low-frequency infrasound well, while at higher frequencies they are very inert [3].

The ability to detect useful infrasonic signals from the pressure sensors described above is usually determined not by their sensitivity but by the fluctuations in the atmosphere at their location caused by other causes. As an example, the pressure of a typical useful infrasonic signal from a remote source at the point of detection is of the order of 0,1 Pascals, which is equivalent to a barometric pressure caused by a change in height of 1 cm and is not a problem. in the absence of noise to be registered. That is, modern sensor designs provide sufficient sensitivity, but noise filtering is required. At low frequencies, they are caused mainly by changes in weather on a synoptic scale, tides, the effect of sunshine during the day, the breeze circulation in the atmosphere. At higher frequencies they are caused mostly by convection and turbulence.

The energy dissipation of acoustic waves is proportional to the square of their frequency. This means that sound with a frequency of 1000 Hz loses 90% of its energy at a distance of 7 kilometers at sea level, if the frequency is 1 Hz this distance is 3,000 kilometers, and at a frequency of 0,01 Hz it is comparable to the circumference of the globe. (This includes losses from the expansion of the wavefront).

Since the Earth's atmosphere is layered and randomly inhomogeneous, as a result of refraction and other physical phenomena in it, the so-called sound channels in which infrasound propagates over great distances - Fig.1 [2].

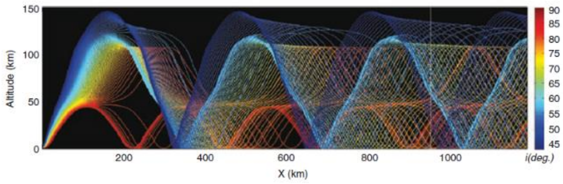

Fig. 1. The propagation of the infrasonic wave (stratosphere and thermosphere)

As emphasized above, in order to detect the useful signal, filtering, spatial and frequency, is required. In spatial filtering, it is important that the correlation radii of the useful signal and the noise are different. The radius of spatial correlation of useful infrasound is much larger. This makes it possible to build spatial filters that average and greatly minimize the energy of noise. Fig.2 shows a picture of a real infrasonic station, in which a similar spider filter is realized [1].

Fig. 2. Acoustic group from infrasound station IS18 in Greenland [1]

The analysis of the function of the cross-correlation or of the mutual spectra between the signals from different noise-protected sensors from one acoustic group or from several groups makes it possible to determine the speed and direction (azimuth) of the source by the signal delays. This analysis can be used in the whole frequency range, and the analysis of the mutual spectra allows to identify signals with different frequencies, but having the same speed and coming from one direction.

A minimum of three infrasonic acoustic groups are required to determine the direction of the source. Typically, an infrasound station contains between 4 and 8 such groups. At present, the International

Monitoring System (IMS) consists of 60 infrasound monitoring stations located around the globe in suitable places (low noise, etc.), [1,2].

Data are collected in quasi-real time in Vienna. An interesting fact is that an electronic signature is used for security of the transmitted information in the stations. Communication links are required to operate with 99.5% availability and its terrestrial communication links with 99.95% availability [1].

2. UNDERWATER SOUND CHANNEL SOFAR. HYDROACOUSTIC DETECTION SUBSYSTEM

The underwater sound channel is formed at a certain profile of the gradient of the speed of sound under water [6,7]. Usually, the axis of the channel is at a depth of about 1 kilometer. On it the sound can travel huge distances almost without attenuation. This is shown in Fig.3.

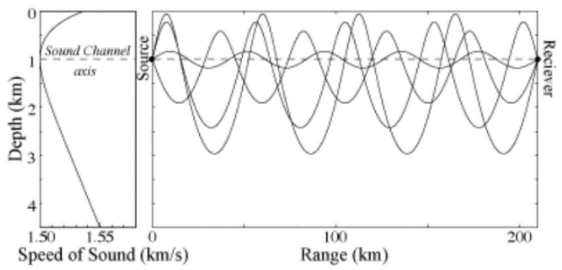

Fig. 3. Example of underwater sound channels SOFAR [6,7]

The hydroacoustic subsystem consists of two types of stations, all 11 in number. They have been shown to cover all important areas of the world's oceans. Six of the 11 stations use low frequency sensitive hydrophones [8] are deployed on the ocean floor, their signals sent by cable to a nearby island for transmission to the International Data Center. For security, two triples of low-frequency hydrophones are located on opposite sides of well-chosen islands.

In addition, five so-called T-phase (from *terrestrial*) seismic stations are deployed on oceanic islands. Hydroacoustic wave travels horizontally from an ocean source, converting to a seismic wave when it meets land. The hydroacoustic and seismic networks are complementary in verification terms: hydroacoustic stations are more sensitive than seismic ones in regard to monitoring the southern oceans, while the reverse is true for the northern oceans [10]. The schematics is shown on Fig.4 and Fig.5 respectively.

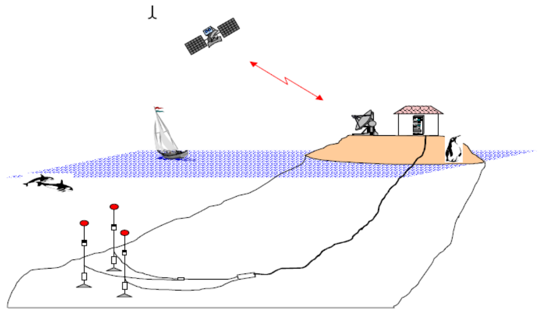

Fig. 4. Hydroacoustic station

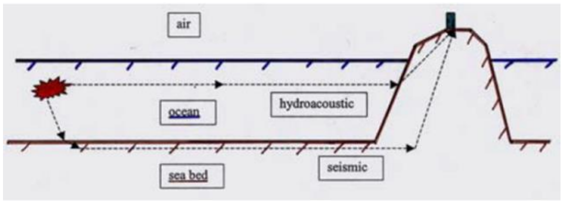

Fig. 5. T-phase station

It should be noted that hydrophone triples are used to applicate triangulation methods in the localization of underwater events [9].

3. SOME EXAMPLES OF APPLICATION OF THE INFRASONIC AND HYDROACOUSTIC METHODS

In addition to their direct purpose (detection of above-ground and underground nuclear explosions), infrasound stations can be used for other useful activities. For the first time, without the necessary equipment, humanity discovered events generating infrasonic waves of enormous power in 1883, the eruption of Krakatoa volcano and in 1909, the fall of the Tunguska meteorite in eastern Siberia. In both cases, infrasonic waves orbit the globe several times and are detected as anomalies in the recordings of ordinary barometers. At present, it is considered that modern infrasonic equipment can be used for the following events of natural and anthropogenic origin (the list is not complete):

- volcanic eruptions;
- occurrence of hurricanes and typhoons;
- quarry or mine explosions;
- rocket launches;
- shock waves when crossing the sound barrier from aircraft;
- falling meteorites;
- infrasound emitted by animals such as elephants;
- shooting from large-caliber gun systems, etc.

Figure 6 shows the spectrum of the noise from the launch of a Scud missile [3]. The distance to the source is 27 km. It can be seen that the event is about 150 seconds from the recording, and the infrasound is from 1Hz to about 25Hz.

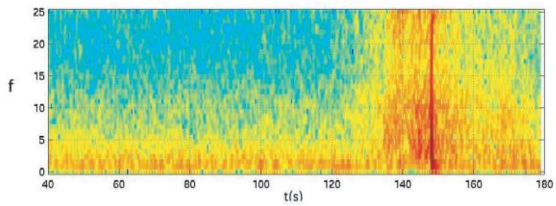

Fig. 6. Launch of an operational tactical missile SS-1 Scud B (8K14 Elbrus). Source: S. Tenney, ARL.

Fig. 7 shows the scalogram of a recording of firing with a rocket-propelled grenade launcher system "BM-21" - flight of 7 122 mm projectiles from a package of volley fire of AP Markovo, Bulgaria, 05 Oct. 2017. It allows for a detailed analysis of the event and to obtain the so-called sound signature of the system.

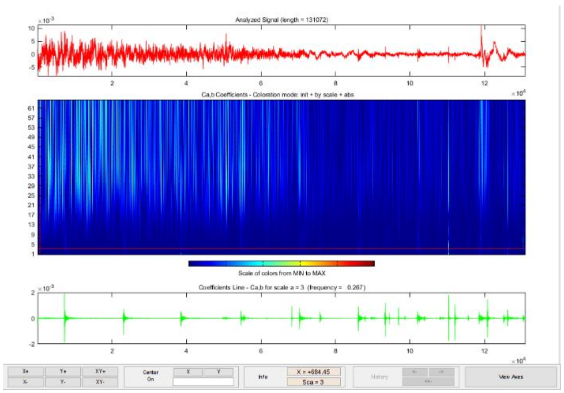

Fig. 7. The scalogram of the recording of firing with a rocket-propelled grenade launcher "BM-21"

The recording was made by the authors with the participation of doctoral students and cadets from Vasil Levski National University, with the integrated PULSE 12 platform of Brüel&Kjær and a low-frequency measuring microphone of the same company [5].

The study of acoustic effects caused by infrasound is a relatively new field, which is an expensive and time-consuming study, which, however, gives very useful results [4].

In Fig. 8 is shown the localization of the crash of the Argentine submarine San Juan. The analysis is performed by specialists from the Center in Vienna [1]. The signal processing is from the north triplet hydroacoustic station H10 in temporary interval from 14:58 to 15:16 on November 15, 2017. The method of progressive multichannel correlation is used. The graph shows the main arrival of the signal at 14:59:07 and subsequent introductions. It can be seen that although the system is designed for other purposes, it must be accurate enough even in non-standard use.

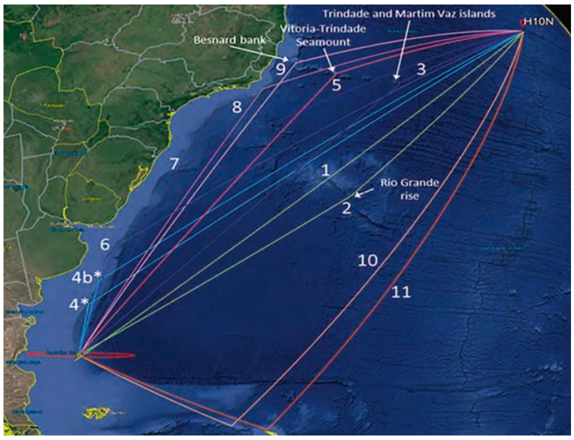

Fig. 8. Localization of the crash of the Argentine submarine San Juan

CONCLUSION

Infrasonic and hydroacoustic monitoring stations, in addition to detecting and locating nuclear experiments in the atmosphere, underground, and underwater, can be used to detect and study other anthropogenic or natural phenomena: volcanic eruptions, the formation of hurricanes and typhoons, quarry or mine explosions, firing from large-caliber gun systems, missile launches, detection of damaged submarines, etc.

The main advantage of this method is that near and far infrasounds propagate over extremely long distances in the air and underwater. Of course, in its implementation there are important features and difficulties, which, however, in the current state of the art are completely surmountable.

In the present work, it is shown by real *in situ* measurements that the method can also be used to collect data on the acoustics of the battlefield, i.e., to monitor tactical infrasound. The created database can be used for civil and military purposes.

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