

Infrasound as a tool for CTBT verification

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During the 1994–1996 negotiations on the Comprehensive Nuclear Test Ban Treaty (CTBT), it was decided that infrasound was one of four techniques that would be used to verify it. Infrasound is very low-frequency sound that is inaudible to humans. The term ‘infrasound’ is analogous to ‘infrared’, the part of the visible light electromagnetic spectrum with lower frequencies than the red part. Infrasound monitoring is directed towards the atmosphere where the sounds of nuclear explosions propagate. The other technologies used are seismology for the verification of nuclear explosions in the earth; hydroacoustics for ocean basins; and the measurement of airborne radionuclides to detect atmospheric fallout.

Three media and four techniques might at first sight seem to be overkill. However, for the atmosphere there is no single earth-based technique that is able to locate and identify nuclear explosions. Satellite technology was considered at the time of the CTBT negotiations, but was judged to be too expensive. The measurement of radionuclides can provide the ‘smoking gun’ that identifies a nuclear explosion but is not well suited to locating the event. Infrasound complements the radionuclide measurements because it enables analysts to locate the events faster in time and space.

This chapter considers various aspects of infrasound as a tool for CTBT verification. As a young and relatively unknown technique compared with the other technologies, it needs some technical explanation if we are to understand its role and contribution to the verification system. While the infrasound technique could be considered to be the equivalent of seismology for the atmosphere, in fact, the atmosphere has a complicated dynamic structure that is unlike the solid earth. This adds to the complexity of the technique.

The CTBT system is the first worldwide network of infrasound stations that has been built. Even experience with regional infrasound networks is very limited. This is a challenge for scientists and might lead to unexpected contributions by infrasound to the verification system, especially when integrated with the other techniques. It could also lead to new applications of infrasound for civil use.

A brief history of the infrasound technique

The infrasound technique did not simply emerge during negotiations on the CTBT. Efforts had been undertaken since 1920 to measure pressure variations from large explosions, such as those from exploding meteors. Two well-known American seismologists at the California Institute of Technology at Pasadena, Hugo Benioff and Beno Gutenberg, in 1939 developed both instrumentation and applications for the detection of infrasound.¹ The primitive instrumentation consisted of a wooden box with a low-frequency loudspeaker mounted on top. Being seismologists, they connected their instrumentation to earthquake recording equipment. Even today this primitive detector is very effective, having low mechanical and electronic noise and a response which naturally adapts to existing wind noise.

The problem Benioff and Gutenberg needed to solve is still a problem—to study the temperature structure of the atmosphere to heights over 50 kilometres (km).² One of their objectives was to study the detonation of 5000 kilograms (kg) of buried ammunition near Berlin, Germany, in 1939. Surprisingly, they found that the explosion was heard in a relatively small area, less than 100 km in diameter. The sound of the explosion was not observed immediately outside this region, which they called the ‘zone of silence’. At larger distances, the sounds were noticed again in an asymmetric ring at distances averaging 160 km, as well as in other rings at 400 and 600 km. A zone of silence separated each ring from the next. The asymmetry of the rings was caused by the influence of the wind. Finally, they concluded that sound waves had their highest point of reflection in the stratosphere at a height of 50 km. Today all of this is underpinned with solid theory.

For over 20 years after World War II, infrasound was mainly developed and used to monitor nuclear explosions. During that period the concept of wind noise reducers was developed; it is still used today. One development was initiated by Fred Daniels, who patented a directional microphone. It was recognised that

these directional microphones, scaled up to accommodate longer wavelengths, were very effective in suppressing the pressure variations caused by wind from all directions.³ Tapered tubes were designed, which could easily reach 100 metres or more, fitted with over 30 capillary inlets, to reduce the noise by a factor larger than 10. At high frequencies, however, they showed the features for which they were originally designed—a high degree of directionality, which is not desired in a system that should have the same response in all directions. These types of problem, especially under high wind conditions, still play an important role in infrasound research. Later, porous hoses were applied which are the same as those used to water the garden. These were very effective but were vulnerable under various environmental conditions—for instance, to pores clogging with moisture or dust—and to small animals. Today complicated tree-like structures are used to make many individual inlets.

The early period of development came slowly to an end when the Limited (Partial) Test Ban Treaty (LTBT or PTBT) was signed in 1963 by the Soviet Union, the United States and the United Kingdom, confining nuclear test explosions to underground. To mark the development, a series of articles on infrasound was published in the *Geophysical Journal of the Royal Astronomical Society* in 1971.⁴ This series was taken as a point of departure when in 1995–96 the CTBT was negotiated and when it became gradually clear that infrasound monitoring should become one of the four techniques used by the treaty's verification system. Between 1971 and 1995 much of the existing knowledge had been lost, and only a handful of researchers were working on infrasound. Australia, Sweden, the US, the Netherlands and France were among the countries that had some activity in the field.

In recent years, since the signing of the CTBT, infrasound research has been expanding again. The almost yearly informal infrasound conferences play an important role in keeping the research community up-to-date. Although this is a positive development, the conferences are only attended by a group of around 50–70 scientists who represent almost 90 percent of the world's knowledge in the field.

How does the infrasound technique work?

The infrasound technique in the context of the CTBT is based on a global network of 60 stations. Each station is an infrasound array, which consists of between four

and eight infrasound detectors. The detectors are highly sensitive barometers, also called microbarometers, and have separations between 1 and 3 km. The operating principle of an array is as follows: when a signal crosses the array, small differences in the arrival times of the signal at the individual array elements are used to calculate the velocity and direction of the signal.⁵

The accuracy of the velocity and direction determinations increases with the diameter of the array. On the other hand, the diameter of the array cannot be made larger than 3 km since the shape of the signal must not significantly change from one array element to the other; the signal should be coherent. This coherence limits the size of the array, called the 'aperture'. The shape of the signal slowly changes, while travelling over the array, due to changes in velocity structure of the atmosphere. The coherence of the noise must also be taken into account. Coherent noise will make the array less effective. Fortunately, most of the noise is exceptionally incoherent in infrasound, in contrast to seismology. Although in practice the apertures of infrasound arrays are limited to diameters of 3 km, it is still an open question what the optimum diameter of an infrasound array is under given circumstances. However, in a large number of cases, local circumstances such as the availability of land and existing infrastructure strongly influence the array layout.

The array technology is not the only factor that determines the quality of an array station. The method of reducing wind noise, which is a hindrance at every station, is perhaps most important.⁶ For that purpose, every array element is equipped with a noise reducer. This is a structure of pressure inlets designed to average out the atmospheric pressure fluctuations over a considerable area in order to reduce pressure fluctuation due to wind. The signals are not affected by the noise reducer since their wavelength is larger than the diameter of the wind-reducing structure. The noise reducer is in almost all cases located just above the earth's surface, where the wind velocity is lowest. As an extension of these noise-reducing structures one might even think of using natural conditions, such as a wooded area, to reduce the noise. In fact, one of the CTBT system's infrasound stations, in French Guiana, is built in the rainforest and is one of the quietest stations in the network because of the natural noise-reducing qualities of its surroundings.

The products from the 60 arrays in the CTBT network are the waveform of the signals, which is the acoustic fingerprint, the direction of the coherent signals and

their apparent velocity. The apparent velocity is dependent on the angle of incidence of the signal. The angle is usually close to the horizontal plane due to the structure of the atmosphere. The small differences in apparent velocity can help to identify the height at which the wave is reflected back to the earth's surface. The other product is the time of arrival of the signal. In seismology this is one of the main products, but the nature of infrasound arrivals is such that the onset of the signals is hard to identify. Equally hard to identify are the secondary arrivals, which are caused by different atmospheric trajectories of the signals, for example, a higher reflection. More study could lead to improvements in this respect. Usually the low velocity of sound will compensate for this shortcoming in the technique.

With respect to analysis of the waveforms, the situation in infrasound is even more complicated than that in seismology. In seismology a trained analyst can, on the basis of the fingerprint of the waveform, identify a large number of signals. In infrasound this is not yet possible and it is not clear if the influence of the medium is such that it will ever be possible. There are research challenges.

The signals from the CTBT network of infrasound stations will be transmitted continuously to the International Data Centre (IDC) in Vienna for processing. The detection parameters will be extracted from all stations. The result is essentially a list of arrival times and directions of detected signals for each station. In the subsequent process, that of association, the list of arrival times is converted to a list of events that are detected by two or more stations. The location of the event is determined by the point where the directions cross and that is consistent with the arrival times.

The mathematics of detection is highly sophisticated. Signals can be detected with much lower amplitude than the ambient noise. The quality of the arrays will be greatly improved when the number of elements is raised from four, as in the original specifications, to eight. All of this will lead to a large number of infrasound detections and increase the detectability of small events. On the other hand, the large number of detections makes the association of individual arrivals more difficult. The propagation velocity of sound is only 300 metres per second (m/s), unlike in seismology where 2000–5000 m/s is reached, and the long travel time of infrasound has a negative affect on the identification of associated arrivals at different stations. It takes an infrasound wave almost two hours to travel 2000 km

from the source to the station. If in that period a substantial number of events has occurred in the region of interest, different events can be assumed from the association of various combinations of data detected. To sort out this kind of puzzle and separate real from erroneous events is one of the challenges for the IDC.

Pressure

What are the pressure changes relevant to the detection of infrasound events? To answer this question, reference should be made to the ambient pressure at sea level measured in pressure units of one bar or one atmosphere. This pressure originates from the mass of air pressing down and corresponds approximately to a column of water 10 metres high. The unit of pressure accepted in science and technology today is not the atmosphere, but a unit 100,000 times smaller, the pascal (Pa) named in honour of French mathematician and physicist Blaise Pascal (1623–62).

To get a feeling for this unit of one pascal, imagine that the pressure measuring instrument is lifted up slowly from the surface. The absolute pressure that the instrument shows will slowly become smaller, since the column of air pressing down on the instrument is also diminishing. When the instrument has been lifted only 10 centimetres (cm) it corresponds to 1 Pa. Although the atmosphere is approximately 100 km thick, the air gets thinner and thinner as the height increases. Therefore, most of the atmospheric pressure at sea level is due to the first 10 km of air. A signal with a pressure change of 1 Pa already constitutes a large infrasonic signal. More likely is a regular signal that is one-hundredth of 1 Pa. This pressure change corresponds to lifting the measuring instrument by 1 millimetre (mm). The precision of the pressure measurements corresponds to changes in height equivalent to the thickness of a sheet of paper.

The atmosphere: the medium of transport

The medium of transport for infrasonic signals is the atmosphere. The atmosphere is complex in many ways, both in space and in time. Temperature, wind and pressure conditions influence the propagation of infrasound.

The pressure in the atmosphere, as has already been noted, decreases exponentially with height. At 30 km the pressure is reduced by a factor of 100 relative to that at the earth's surface, and at 100 km the pressure is one-millionth—almost a vacuum.

We all are familiar with outdoor audible sound propagation and know that an aeroplane flying overhead at a cruising altitude of 10 km is barely audible. How can it be that large explosions in the atmosphere are detected over a distance of 2000 km, the typical distance between stations in the 60-station worldwide network?

The explanation consists of two elements. First, the energy dissipation of infrasound is very low compared to that of audible frequencies, so the transformation of the elastic energy to heat is not very efficient. Moist air has even lower attenuation than dry air. As a rule of thumb, for the same attenuation, a 10-hertz (Hz) signal can travel 100 times further than a 100-Hz signal, and a 1-Hz signal can travel 10,000 times further. The other factor of importance is the way signals are bent back to the earth's surface by the atmosphere. This is mainly caused by the vertical temperature profile of the atmosphere.

The absorption of solar radiation shapes the temperature profile of the atmosphere. Most of the transfer from radiation to heat takes place at the earth's surface, so the atmosphere is heated from below. Therefore the temperature of the atmosphere decreases with height in the lower atmosphere. This affects the propagation of sound by bending the sound path away from the surface. This explains why it is relatively quiet at the earth's surface where audible sounds are concerned. Occasionally this situation changes. For instance, over cool water surfaces the temperature near the surface can be lower than the temperature higher up in the atmosphere, in which case exceptionally good sound transmission may occur. This is called a temperature inversion.

At higher altitudes—between 20 and 50 km—there is a warmer zone because of the absorption of ultraviolet radiation by oxygen and ozone. In fact this warm zone is the main reflector of infrasound back to the surface. At approximately 100 km the situation changes again, as here the direct ultraviolet radiation of the sun heats the atmosphere to the highest values. This high-temperature region may also reflect infrasound rays. As a result of this complicated temperature structure, signals may travel long distances by being bounced up and down in several 'hops' between the surface and one of the two reflectors.

The effects of wind also have to be taken into account when the propagation of sound through the atmosphere is considered. Especially important is the wind shear. In general the winds increase with altitude. Therefore, in a situation where

the signal travels in the direction of the wind and the wind is stronger at a higher altitude, the signal is bent back to the earth. In contrast, when the signal travels against the wind the signal leaves the surface. We all know that it is harder to hear audible sound upwind than downwind. Winds in the atmosphere are highly variable: the surface wind may be westerly and at a height of 50 km the winds may be easterly, turning to westerly again at 100 km. At high altitudes high wind speeds of over 50 m/s are common.

Infrasound propagation in the atmosphere is a complex matter, but by studying infrasound much may be learned from this medium. This may be one contribution to civil society of the CTBT infrasound network.

Noise is a complication

As with the other CTBT monitoring techniques, infrasound monitoring is not without its complications. Ambient wind and other atmospheric noise are a severe problem for the detection of infrasound. A considerable number of infrasound stations are on small oceanic islands due to the relative large amount of ocean surface compared to land mass. Here, the weather conditions with strong winds are far from ideal for infrasound detection.

The atmosphere is in a constant state of turbulence, in contrast to the solid earth. The turbulence is present at every level and on every length scale, and the noise in the frequency regime is therefore spread over a wide frequency range. As a rule of thumb, the amplitude of the noise will increase by a factor of 10 when the frequency is lowered by the same factor. This type of noise is called $1/f$ noise and is notoriously difficult to suppress.

Better noise reduction is achieved with more array elements, as is necessary on oceanic island sites. On the most optimistic estimates, the ratio of the signal detected to the apparent noise amplitude will be proportional to the square root of the number of elements. One needs nine times more instruments in order to gain a factor of 3 in detection level under the same noise conditions.

As a verification technique, infrasound detection has to deal with the dynamics of the atmosphere; this is apparent in the estimation of the noise as well as in the propagation of the signal. Air has two distinct properties: it can flow in often irregular patterns, like the movements of smoke from a cigarette or a chimney, or it can behave elastically, as is apparent from a rubber balloon or a soap bubble.

The noise associated with the wind follows from the flow property of air. This noise is apparent over a broad frequency range, over the whole band of interest, from periods of 50 seconds to a fraction of a second. In general the amplitude of the noise will be roughly proportional to the period. Therefore, the noise is lower at high frequencies and high at low frequencies. This is a sign of the complex nature of the noise. The noise is of the order of a few pascals at the highest frequencies of interest for infrasound. Fluctuations on a daily scale are of the order of 10,000 pa, as we know from the weather service.

To counteract the wind noise, special noise reducers are designed in a variety of shapes and forms. The basic principle is that the fluctuations of the air pressure are summed over a large area, perhaps 100 square metres or more, to average out the incoherent wind-induced pressure changes. These systems are difficult to design in such a way as to produce a satisfactory response at higher frequencies.

The optimum solution to the noise reducer problem is currently being researched. Much more research is needed on the improvement of noise reduction systems, where every small gain in signal-to-noise ratio is a significant contribution to the infrasound network of the verification system.

Signals and false alarms

The infrasound network is set up to detect atmospheric nuclear explosions in the context of the CTBT. These explosions may originate thousands of kilometres away and the signals may be small. The basic problem, as with so many problems in science and technology, is that of detecting signals in a background of ever-present noise. Most of us will interpret the term 'noise' as the continuous sound coming from a radio that is tuned in between two radio stations. This kind of continuous noise is taken care of in infrasound detection with the wind-noise reducers in front of every instrument.

However, in connection with the detection of specific explosions, one may think of another kind of noise—unwanted signals. These may lead to false alarms in the detection process. In the seismology part of the International Monitoring System (IMS) network, these unwanted signals are the natural earthquakes which can hinder the detection of explosions. So what are the unwanted signals in infrasound, how often do they occur and do they also prevent the detection of nuclear explosions?

At the moment we do not exactly know, and this is therefore a subject of research. However, we do know that a larger number of unwanted signals are detected than the treaty negotiators expected, even with the rudimentary network operating today. Moreover, certain classes of these signals may lead to false alarms, such as signals generated by the explosion of meteorites high in the atmosphere. Fortunately, these false alarms may not be of long duration. The other technique that focuses on the atmosphere, the detection of traces of radionuclides attached to small particles in the atmosphere, will give the final answer, generally within a week, as to whether there has been a nuclear explosion or not. It is clearly beneficial to have synergy among various techniques.

All sources of infrasound involve the movement of large masses of air. Infrasound sources can be divided into two groups—impulsive, which create a pulse, and those with a more continuous character. The former consists of a variety of explosions—chemical, nuclear, volcanic and meteors. The continuous signal group includes phenomena such as the infrasound produced by the interaction of air and interfering ocean waves in an atmospheric depression. These waves are called microbaroms and are present in almost all recordings in low-noise sites. Other more continuous sources are helicopters, aeroplanes (both supersonic and subsonic), rocket launches or even aurora, the majestic lights in the north and south polar regions caused by the interaction of energetic particles from the sun and the atmosphere in the presence of a magnetic field. Much experience will be gained in the coming years from analysing this suite of signals.

During the days of atmospheric nuclear testing, many recordings were made of infrasonic waves from nuclear explosions, and these will serve as study material in the years to come. The largest of these explosions, in the megaton range, produced waves of very low frequencies, with periods of minutes. The atmosphere as a whole started slowly to vibrate. The wavelength of these waves can be 50 km or more, of the same order of magnitude as the thickness of the atmosphere as a whole. Similar explosions can have a natural cause, such as the explosion of Mount St Helens in Washington state, US, in May 1980 or the impact of the Tunguska meteorite in Siberia in June 1908. The waves of such explosions travel around the globe several times. There is only a small chance that these large events will be mistaken for nuclear explosions.

On the other hand, smaller events—in the kiloton range—are more difficult to deal with. The number of detections at individual array stations will be smaller, while the events are far more numerous. It is estimated that at least 10 meteor events per year occur in the kiloton range. Most of these will take place over the large ocean basins, leaving no traces but infrasound waves and a flash of light that may be detected by satellite surveillance as a part of national technical means (NTM).

Finally, there is a class of signals of yet unknown origin. Some of these signals are impulsive, while others are more or less continuous and can last many hours.

Contribution of the infrasound network to CTBT verifiability

The question how much the infrasound technique will contribute to the verifiability of the CTBT can be answered briefly: when we demand a 90 percent probability that an event will be detected by at least two infrasound stations, the detection threshold is 0.5 kiloton (kt) for most of the globe; the threshold is 0.1 kt at its lowest, and 0.3 kt in large parts of all the continents except Antarctica. These are the results of model calculations made by the Center for Monitoring Research (CMR) in Arlington, Virginia, US. Because of wind patterns the thresholds can be different for a substantial part of the year; moreover, the numbers are based on model calculations, so the reality may be slightly different once the complete network is in place. At this point it is too early to tell, but the limited current experience shows promising results.

Detection is the easy part. Identification and attribution are generally more difficult. In atmospheric monitoring we have the luxury (which we do not have with the other media—the solid earth and the ocean basins) of two techniques. Infrasound is used to detect and locate the explosion. If we rely on the radionuclide network to identify the explosion, then the question is not whether it is identified as a nuclear explosion but when a positive identification can be made.

Wave propagation in infrasound and the transport of particles in the radionuclide detection are two distinct aspects of the atmosphere, with a large difference in signal propagation speed. For a 1-kt explosion there is a chance of detection of 50 percent within five days by one of the planned stations in the 80-station radionuclide network of the IMS over most of the continents. This will increase to 90 percent within 10 days. Over the southern oceans it is somewhat less. The possibility

of tracking the signal back to its origin accurately is far smaller when longer periods are considered. The detection probability therefore increases with time, whereas the location capability diminishes with time for the radionuclide technique.

In detecting and identifying nuclear explosions, the performance of the combination of the two techniques directed to the atmosphere is probably comparable to the performance of the techniques for the other two media. In a few years experience will tell. The infrasound technique is therefore an essential element of the global verification system, and its detection and localisation capabilities are somewhat better than the detection and identification capabilities of the radionuclide technique in short time frames. This rule applies also to the techniques used for the other media; detection thresholds are usually lower than identification thresholds.

A separate problem is that of the capability to locate an event. In the solid earth component (seismology) of the verification system, the situation is clear. The location precision should correspond to the area that is felt to be realistic for an on-site inspection—1000 km². This corresponds to an area with a diameter of 35 km. For both the atmosphere and the ocean basins the situation with respect to location accuracy is less clear. When a nuclear explosion has occurred in one of the large ocean basins the central question is not that of localisation but one of attribution—which nation has detonated the explosion. The ship or aeroplane from which the explosion is triggered has probably disappeared, and the evidence could be destroyed in the explosion. What might be retrieved is some radioactive debris from the explosion that could give some insight into the technical sophistication of the device used in the explosion.

For an atmospheric explosion over land, at least, the exact geographical location may be an important factor. The question that remains is: is there enough reason to launch an on-site inspection to collect whatever evidence still remains, for instance, in border regions of several states, or are the data collected by the radionuclide technique already conclusive?

Suppose that the location accuracy needed is comparable to that of seismology. This means that the accuracy of location of the infrasound network should be of the order of 50 km. The detection of a series of volcanic explosions in July 2001 at Mount Etna in Sicily, Italy, has shown that such accuracies are possible for distances of 1800 km between source and receiver. In order to obtain such

results the direction of the signals was corrected for wind along the entire path through the atmosphere.

The performance of the infrasound network, judging from preliminary results, seems to be in line with the estimates that formed the basis of the network design by the small Infrasound Expert Group. This group reported as early as December 1995 to the Conference on Disarmament's Ad Hoc Committee on a Nuclear Test Ban, which was negotiating the treaty.⁷ Although they were right in their estimation of performance of the network, they were wrong in their estimates of its cost and the time needed to build it. The current cost estimates are higher by at least a factor of two, while the original estimate that the infrasound system could be built in three years was out by a factor of three.

Civil and scientific uses of infrasound

The infrasound technology as used in the context of the CTBT is a small niche where outdoor sound propagation, atmospheric sciences and a number of other disciplines come together. Up-to-date instrumentation is now largely preceding the research, although some research was carried out in recent times and prior to 1971. Wide application of the infrasound technology to cover the entire globe will become possible in the near future. As a result the discovery of many new phenomena should be expected. Especially in the field of meteorology and its many applications in our society, progress could be expected.

Two examples where society as a whole can benefit directly from the CTBT infrasound network are the detection of volcanic explosions, which can assist in the rerouting of aviation to avoid volcanic ash in jet engines, and the detection and characterisation of major disastrous chemical explosions, such as those at Enschede in the Netherlands on 13 May 2000 and Toulouse in France on 21 September 2001.

Focusing on the scientific use of infrasound technology, it should be noted that infrasound sources long escaped detection. Many sources, both impulsive and continuous, man-made and natural, are known today—chemical and nuclear explosions, helicopters and aeroplanes, rockets, city hum, meteors, volcanoes, earthquakes, microbaroms, severe storm systems, auroras, sprites, the sounds associated with mountains and even elephants. Infrasound can be used to study the characteristics of these events. After a number of years the archive of the IDC in Vienna

will contain a reliable high-quality worldwide database of infrasound data. This can be of special value when long data sets or data on specific events are needed for a variety of studies of yet unknown phenomena.

Conclusion

In conclusion, the infrasound technique has many unique features and cannot be seen as a simple extrapolation of what are called waveform technologies, such as seismology and hydroacoustics. Our current knowledge of the fundamentals is good enough to enable the infrasound monitoring system envisioned in the treaty to be built. At the same time it is clear that much work still has to be done in order for the technique to reach the same mature status as the other waveform technologies. Examples are the need to identify nuclear explosions and distinguish them from an abundance of other sources, and the need to quantify the dynamic atmosphere with respect to wind and temperature profiles and noise generation. When the network comes to life in the coming two to three years it will offer an unprecedented amount of high-quality data, which will help scientists worldwide in their future research. Since many of the applications of this research are connected to natural disasters and meteorology, civil society as a whole could eventually benefit.

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