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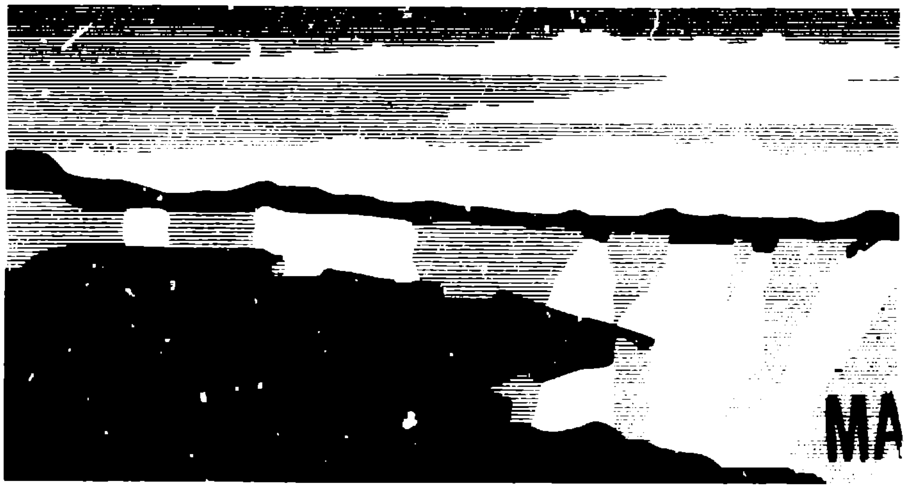

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Nuclear Test Monitoring/ Infrasound/atmospheric explosions/ underground explosions/ ionospheric perturbations/ ionospheric hf sounding/ U.S. Department of Energy/ infrasound duct/

The U.S. DOE sponsored research investigating atmospheric infrasound as a means of detecting both atmospheric and underground nuclear tests. Various detection schemes were examined and were found to be effective for different situations. It has been discovered that an enhanced sensitivity is realizable for the very lowest frequency disturbances by detecting the infrasound at the top of the atmosphere using radio sound techniques. These techniques are compared to more traditional measurement schemes.

Atmospheric Methods for Nuclear Test Monitoring

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1. History of Infrasound/Acoustic Monitoring

Since 1979 the United States Department of Energy (DOE) has carried out a research and development program examining the utility of various "atmospheric methods" for the detection and monitoring of nuclear explosions. "Atmospheric methods" are detection technologies which sense the disturbances in the air which result from an atmospheric explosion and/or the ground motion above a nuclear explosion buried in the ground. This work was motivated by the understanding in 1979 that, for a comprehensive test ban, there would be many problems that seismic monitoring alone would not be able to address (in particular various evasion scenarios). There was also the desire to seek out other detection methodologies to fulfill the generally accepted idea that dual phenomenology should yield more information than any single phenomena.

From 1979 to 1989 the DOE followed two lines of research for underground nuclear explosions each developing a somewhat different detection scheme with sensitivity to different aspects of essentially the same phenomenon, that is the atmospheric pressure perturbations arising from the motion of the ground surface above a contained explosion. The ***Near Infrasound Technique*** concentrated on the detection of signals in the frequency range of 10 to 0.1 Hertz at distances of several hundred kilometers away from ground zero, while the ***Ionospheric Monitoring Technique*** utilized radio wave sounding methods to detect disturbances in the ionosphere 100 to 150 kilometers in the atmosphere above an underground nuclear explosion. Over this ten year period the DOE demonstrated a capability to utilize these methods to detect and discriminate underground nuclear explosions. From 1990 through 1994, the DOE executed a program looking at a detection scheme which emphasized very distant detection of atmospheric explosions in anticipation of a CTB/NPT monitoring regime. This technique called **ROSTER** (for Remotely Observed Signatures of Thermospheric Energy Releases) looks at the ***Far Infrasound*** (0.001 Hz to 0.1 Hz) utilizing transionospheric vhf radio waves to probe the high-altitude side of the atmospheric infrasound duct.

The **Near Infrasound Technique** for detecting **underground nuclear explosions** grew out of the U.S. experience with infrasound detection of atmospheric explosions utilized during the 1960s and 1970s. This method was very successful at detecting large (megaton class) explosions at great distances. Over this twenty year period, several infrasound networks were in operation. At one time the U.S. Department of Defense operated 20 infrasound stations worldwide. As a result of this experience there is a significant data base of detections. Theoretical relations for determining yield as a function of amplitude, distance and period have also been developed, and backgrounds and noise have been thoroughly studied.

The **Ionospheric Monitoring Technique** for detecting **underground nuclear explosions** was first suggested by Louis Wouters (a staff scientist at Lawrence Livermore National Laboratory), who performed some initial first-look calculations in 1977. He was motivated by some very poorly understood but very dramatic measurements of ionospheric disturbances resulting from atmospheric nuclear explosions in the late 1950s and early 1960s. A DOE-sponsored joint Los Alamos, Livermore, and Sandia research program investigating ionospheric disturbances from underground nuclear explosions was undertaken as a result of Wouters' investigation. This program investigated the various methods of detecting and measuring ionospheric disturbances resulting from earthquakes, atmospheric explosions and underground nuclear explosions. Data was gathered from more than 50 underground explosions, several atmospheric kiloton class conventional explosive tests and a number of earthquakes over a period of ten years from 1979 to 1989.

The **ROSTER** program grew out of the realization that enhanced sensitivity methods for detecting atmospheric explosions would be useful for a CTB regime. Our experience with the Ionospheric Monitoring taught us that the upper atmosphere was extremely quiet in the far infrasound region which, coupled with the amplification of signals from the ground, should yield an extremely good signal-to-noise ratio. Several years of measuring various sources of acoustic signals with the method has demonstrated a sensitivity threshold of a hundred or so (100-150) tons HE equivalent at 3000 km.

2. Basic Phenomenology

2.1. UNDERGROUND NUCLEAR TESTS

Atmospheric signals from underground nuclear explosions result from the movement of the ground surface immediately above a buried explosion when the initial shockwave arrives at the surface. The most coherent part of this surface ground motion occurs within a few seconds of the underground explosion when the compressional shockwave generated in the ground arrives at the ground-air interface. The ground surface is moved upwards violently as the shockwave attempts to carry energy into the air across this ground-air interface. The extreme difference in density between the two media presents a very large effective impedance mismatch to this wave motion. The wave is therefore primarily reflected back into the ground giving rise to the reflected seismic wave (the Pp wave so often observed in seismic signals from underground nuclear explosions.) The interaction of the reflected wave and the incident wave causes a rupturing of the ground freeing a significant piece of earth to fly freely upward accelerated by the trapped wave energy within this so-called spalled region. This spalled earth can travel upwards on the order of a meter or so (at accelerations in excess of 1 G) before falling backward under the force of gravity to come crashing down upon the earth. The ground motion and the induced air pressure perturbations have a relatively complex time behavior. The phasing of the initial spall surface motion results in a well-focused, weak air shock wave directed straight up into the atmosphere. The half power points of this focused beam are about 27 degrees apart (each side 13.5 degrees away from the vertical). There are weaker side-lobes which permit energy to be directed at much shallower angles away from the vertical direction. The slap-down of the spalled region also causes significant reverberations in the ground surface leading to less coherent rumblings in the air which are radiated more or less isotropically.

The two detection methodologies utilizing these low frequencies disturbance in the atmosphere as stated above have come to be known as ***Near Infrasound*** and ***Ionospheric Monitoring.***

The **Near Infrasound** technique detects the signal which is projected into the side-lobes of the primary acoustic disturbance created by the ground motion. Early experiences from utilizing very large atmospheric nuclear explosions as a source for infrasound demonstrated that near tidal acoustic gravity modes were excited by such explosions (figure 1). These ultra low frequency waves traveled all the way around the world. The explosion also generated a nearly isotropic shockwave which was detectable at many hundreds to many thousands of kilometers from the explosion. Figure 2 shows the sound paths followed by these waves as they propagated up into the high atmosphere and were returned to the ground only to be reflected back upwards and continue around the world. These waves are ducted between the earth's surface and the high-altitude thermocline where the atmospheric temperature rises very rapidly yielding a corresponding increase in the sound speed. The explosion produces a nearly isotropic disturbance which propagates into all possible inclination angles; the entire space in the duct was, in fact, filled with the signal as it bounced between the ground and the thermocline. Unlike the atmospheric explosion generated wave the ground motion signal is not isotropically generated. With the wave focused vertically only a small portion of the air pressure perturbations travel out at lower elevation angles eventually moving up into the atmosphere as shown in figure 2 and returning to the ground in a like manner. As they are weaker than the atmospheric explosion case, the low elevation angle waves experience less period stretching to lower frequency, and will therefore not be as easily detected at many bounces from the source region. The refraction occurs in any region in which the effective sound speed exceeds the sound speed on the ground. This can be caused by winds aloft in the 50 to 60 kilometer altitude region of the atmosphere or, if there are no such winds, when the waves arrive at the thermocline 100 kilometers in altitude. The perturbation travels back to the ground and fills the duct in a similar manner to that described above for the case of an atmospheric explosion.

The **Ionospheric Monitoring** research has concentrated on detecting the weak air shockwave (over pressure of 0.01%)which is launched straight up above the underground explosion. This disturbance travels upwards into an increasingly more rarefied atmosphere. Conservation of energy leads to an ever increasing wave amplitude as less and less material is moved by the same amount of energy. This amplification is more than sufficient to compensate for the minor frictional dissipation. By the time this disturbance arrives at the ionosphere, some eight minutes after slapdown, it has become a 10% pressure perturbation and spreads some 100 kilometers across the sky. The detection scheme for this physically large disturbance involves sending radio waves through the disturbed ionosphere with transmitters and receivers on the ground and/or in space. Standard radar analysis yields easily interpretable signals. The pressure perturbation in the air coupling to the ionospheric electrons results in phase changes in the radiowaves

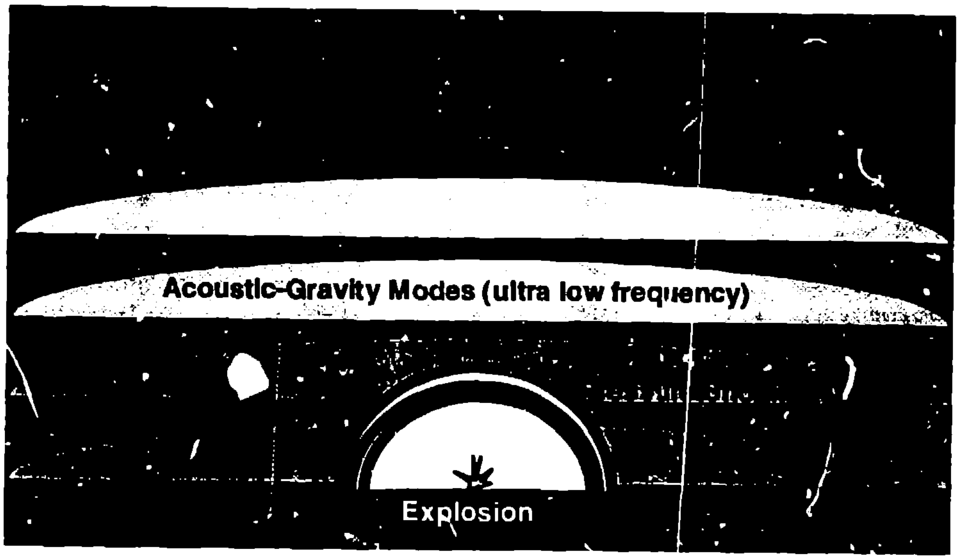

Figure 1. Atmospheric nuclear explosions in excess of several hundred kilotons produce sufficient lift of the atmosphere to excite buoyancy or acoustic gravity modes throughout the depth of the atmosphere.

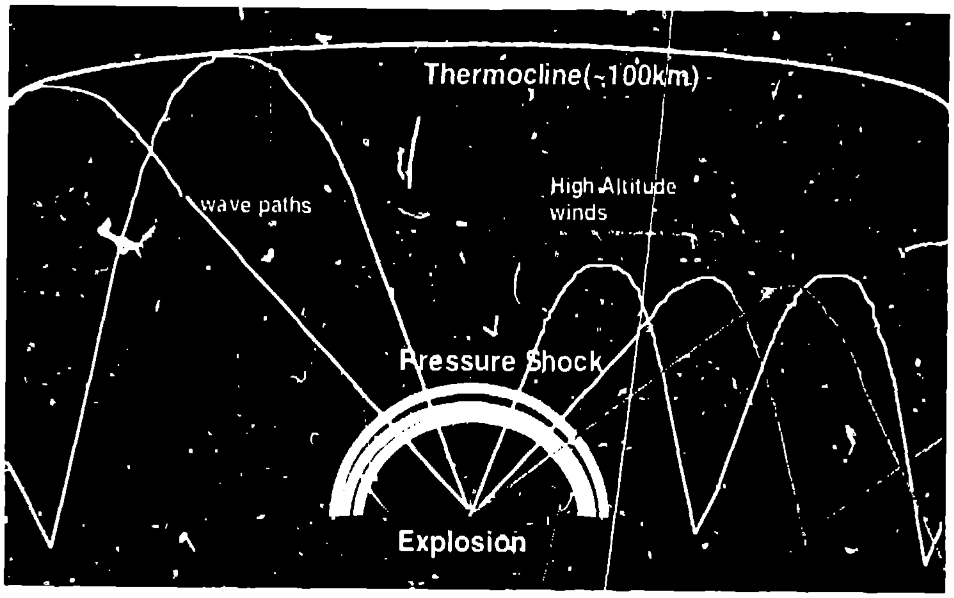

Figure 2. The air shock from large and small explosions produces infrasonic acoustic waves which are trapped in the earth-thermosphere wave guide.

Doppler in radar parlance) which are directly interpretable in terms of the original source at the ground.

2.2. ATMOSPHERIC NUCLEAR TESTS AND FAR INFRASOUND

A relatively low-yield atmospheric nuclear test (less than 20 kilotons) does not create an appreciable atmospheric tidal disturbance but does generate a strong atmospheric shockwave. As this shockwave travels away from the source, it experiences a nonlinear stretching which results in the signal moving to lower and lower frequency. This infrasonic disturbance, at sufficient distance from the source, fills the acoustic duct between the surface of the earth and the high altitude (100-150 km) thermocline. At distances greater than 1000 km, it becomes a far infrasound signal typically in the range of 0.001 to 0.1 Hz. The standard method of detecting this signal is shown schematically in figure 3. An array of several microbaragraphs (sensitive to far infrasound) is appropriately spaced on the ground (at the vertices of a square approximately 1 km on a side) to detect the amplitude and trace velocity of the disturbance. Combining the information from three stations yields a location by triangulation. This monitoring scheme is currently being considered by the Conference on Disarmament for inclusion in an International Monitoring System. Commercially-available instrumentation combined with the noise backgrounds at the earth's surface due to winds permits a detection threshold of 1 kiloton HE equivalent at a distance between 2000-3000 km which will be dependent on the immediate noise environment of specific stations. The limiting factor is signal-to-noise rather than detector sensitivity. Some careful consideration will be required when placing these sensors in a windy marine environment. As we emphasize above there has been significant experience detecting high-yield atmospheric tests with this detection method.

Figure 4 is a schematic representation of the **ROSTER** technique for detecting far infrasound from atmospheric nuclear explosions. This scheme utilizes very high frequency radio waves to probe the upper side of the acoustic duct rather than microbaragraphs on the ground. At first look this may seem very complicated but it yields a significant enhancement in sensitivity because the natural noise background in the far infrasound frequency region is so much less relative to the signal strength. The infrasound signal in the air modulates the density of electrons in the ionosphere as it modulates the air density. A radio wave passing through the region experiences a phase-shift which is directly proportional to the change in electron density integrated along the path of the radiowave. Several radiowaves passing through the region can sample the wave properties just as a microbaragraph array on the ground samples the wave properties. The DOE program has performed experiments to demonstrate the sensitivity of this technique by placing an array of four radio receivers on the ground with spacings of several kilometers. Satellites such as ATS-5 and GOES have steady vhf beacons which serve as the transmitter source. One four-station pod on the ground can track two satellites at different locations in the sky and create effectively two four-element arrays in the upper atmosphere as shown in figure 4. The sensitivity of this technique is such that 18 appropriately placed stations could monitor the world with a 1 kiloton threshold.

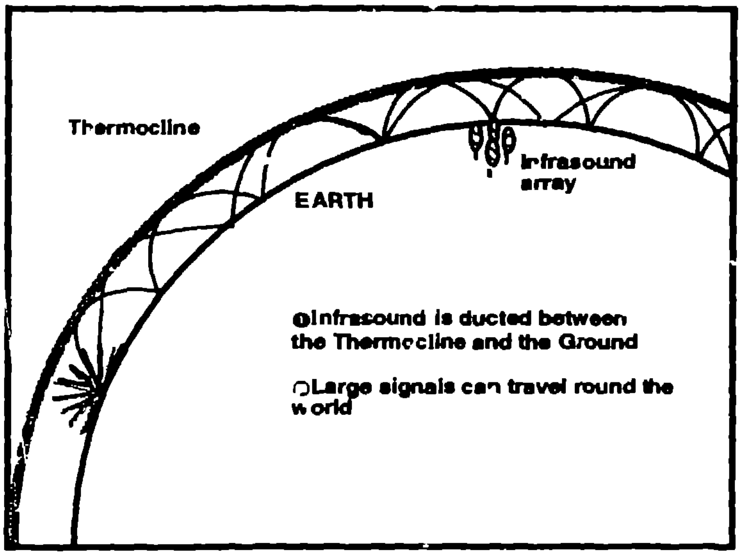

Figure 3. The earth and thermocline provide the wave guide which allows infrasound to propagate out to many thousands of kilometers from a source.

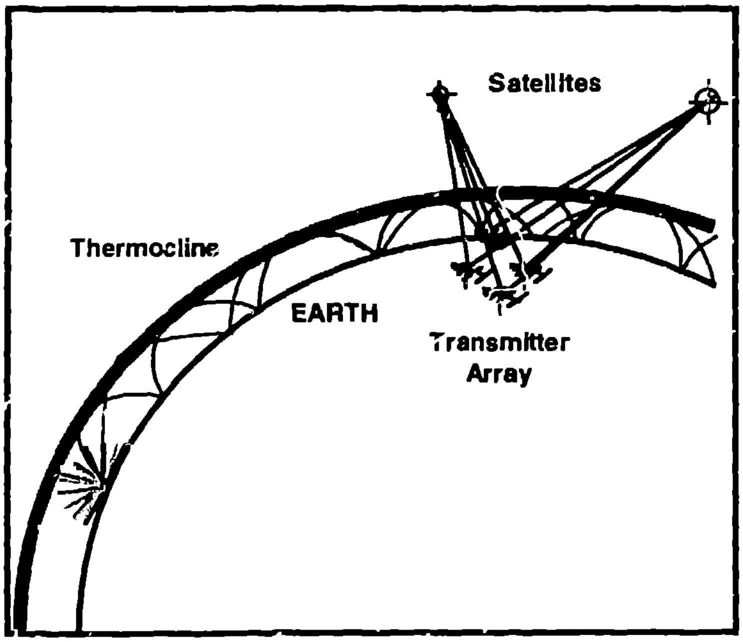

Figure 4. A schematic representation of the ROSTER scheme for detecting far infrasound at the top of the waveguide.

3. The DOE Atmospheric Monitoring Research Program

The Department of Energy developed very sensitive detection schemes for both **Near Infrasound** and **Ionospheric Monitoring** over several years of research using underground tests at the Nevada Test Site as the source of the disturbances. In the case of **Ionospheric Monitoring** this research effort developed an inherently active technique and demonstrated conclusively that kiloton class and larger underground nuclear explosions could be routinely detected by ionospheric techniques at distances up to 3000 kilometers. The phenomenology is well documented and could be utilized for monitoring if the appropriate circumstances arise. While we do not believe that it is economically justifiable to utilize this technique in a worldwide monitoring regime, there are circumstances in which important and unique data may be obtained utilizing the method. The DOE has supported a small research program, EDIT (Explosion Discrimination with Ionospheric Techniques) over the last two years to determine if the vast experience gained from this ionospheric research program might be applied to the special problem of discriminating quarry blasts from underground explosions in particularly troublesome areas. Figure 5 illustrates the various ionospheric radar sounding methods that were utilized for the research program. These included vertical ionosondes, vertical and bistatics phase sounding and Over-the-Horizon radars. Table 1 summarizes the results of the research program.

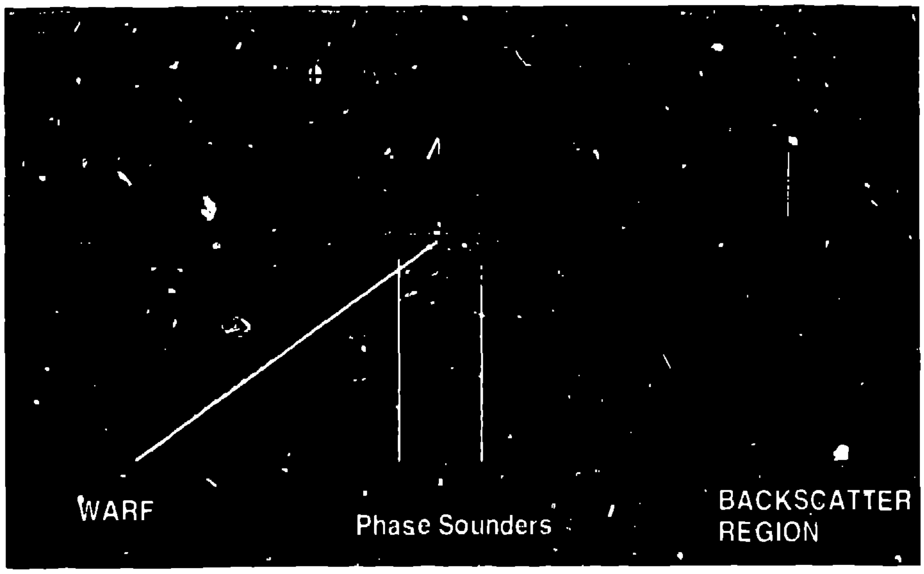

Figure 5. A schematic presentation of the various radar and radio experiments performed by the DOE to develop the detection of the ionospheric prompt disturbance from underground nuclear explosions. The Wide Aperture Radar Facility (WARF) and the White House Radar Facility demonstrated detection of underground explosions at the Nevada Test Site from regional (>2000 km) distances.

TABLE 1. Results of the DOE Ionospheric Disturbance Program

- Demonstrated detection of Underground tests at regional and continental distances.
- Developed discrimination techniques between earthquakes, surface explosions and UGTs.
- Developed effective discrimination techniques between signals and noise
- Proved too expensive for general utilization at regional distances, although application to the special problem of detecting quarry blasts may be feasible.

In a like manner the DOE **Near Infrasound** research program demonstrated detection of underground nuclear explosions at regional distances by examining the signals from more than 60 underground tests at the Nevada Test Site. It also gathered data of near infrasound signals at regional distances from large earthquakes. The program pursued background and noise reduction studies as well as examining the impact of high altitude winds on signal strength. It was discovered that the signal amplitude could be corrected or normalized from standard high altitude wind models to achieve a reproducible signal amplitude which then made it possible to not only detect signals from underground nuclear explosions but to extract a measure of explosive yield from this data. The complex ducting of the signals between the thermocline and the earth required the use of signal propagation models to properly deduce the origin of the signals. These propagation models were developed and their utility was demonstrated for the case of Nevada Test Site explosions. The results of the research effort are summarized in table 2. If an infrasound system should be deployed by an international monitoring system for purposes of detecting atmospheric nuclear explosions we feel that there will be some dual phenomenology gain from monitoring underground tests as well.

TABLE 2. Results of the DOE Near Infrasound Program

- Demonstrated detection of underground explosions at regional distances on more that 60 tests.
- Carried out background and noise reduction studies.
- Derived wind normalization for amplitude correction.
- Demonstrated appropriate propagation models.
- Collected data sets of signals from large Earthquakes.

The DOE Far Infrasound research program has examined the utility of the ROSTER technique for application to the CTB monitoring problem. Although large scale impulsive energy releases in the atmosphere with sufficient size to test the ideas are uncommon, we have had very encouraging results on a few near-kiloton-size, high explosive effects tests performed at White Sands, New Mexico. We have taken many hours of background data for characterization of noise during both daytime and nighttime. We have had no opportunity to gather empirical data for nighttime operation but can scale the sensitivity from daytime data. History may have overtaken this research in the sense that the CD negotiations are currently underway and there remain many open questions of operational feasibility as well as overall sensitivity of a potential global monitoring system. Worldwide coverage would require either a system of satellite transmitters or receivers as well. As a result, the DOE is currently turning its research to the immediate problems concerning the configuration of an international infrasound monitoring system utilizing arrays of microphones and microbarographs. We are developing system models which will aid in the design and eventual testing of such a system. Our capabilities will include infrasound propagation models with amplitude and frequency scaling for distance and size of source, and we will determine the effectiveness of various systems configurations against potential evasion scenarios. We are also investigating the proposed potential of existing seismic arrays as infrasound detection systems. The DOE will also be examining its existing experimental infrasound stations for eventual incorporation into an international monitoring system.

4. Implications for a Comprehensive Test Ban regime

Far infrasound (0.1 Hz to 0.001 Hz) in contrast to near infrasound (10 Hz to 0.1 Hz) has demonstrated applicability for monitoring for atmospheric nuclear explosions at distances in excess of 1000 kilometers. The near infrasound is more effective within 1000 kilometers. The dependence of frequency upon distance from the source results from the nonlinear stretching of strong acoustic signals. Combining both near and far infrasound detection within a single system provides better spatial coverage and extends infrasound utility to underground tests as well as atmospheric tests giving such a system broader monitoring scope. As a part of an International Monitoring System, infrasound could provide a completely independent indication of the occurrence of an explosion. When compared to radionuclide monitoring, it provides detection rapidly and it is capable of reporting within hours rather than days. This may allow selected radionuclide sensors to be integrated in real time after an infrasound detection. It also provides a moderate location accuracy. In addition it also provides a detection technology which is complimentary to seismic and hydroacoustic systems for a number of evasion scenarios. This emphasizes the utility of infrasound measurements within the context of a CTBT The cost and simplicity of such a detection system makes it appropriate for any country to build, field and operate as distributed parts of a worldwide regime.