Listening for a Boom You Can't Hear

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Introduction

On the morning of July 16, 1945, seismic and acoustic signals were recorded across the southwestern United States from an excessively energetic event. These signals emanated from a location roughly 50 km south of Socorro, New Mexico. Microbarographs 45 km away near San Antonio, Texas, recorded a local overpressure from the event of more than 780 Pa (Manley et al., 1945). This overpressure exceeds 150 dB sound pressure level and is equivalent to being in the immediate vicinity of a shotgun blast or large firework explosion. Seismic and acoustic signals from this event were observed more than 1,000 km away near Mount Wilson in southern California and numerous other locations across the southwestern United States (Gutenberg, 1946).

The source of these observations was the test of an implosion-design plutonium bomb called Trinity (see bit.ly/Blom1) that was conducted as part of the Manhattan Project to develop a nuclear bomb. The bomb design was the product of years of research by J. Robert Oppenheimer and other scientists at Los Alamos Laboratory, Los Alamos, New Mexico. The device was nicknamed "the gadget" and released an explosive energy equivalent to 21,000 tons of TNT (US Department of Energy [DOE], 2015). The fireball produced by the explosion (**Figure 1**) was visible more than 100 km away. Trinity was the first of more than 2,000 nuclear tests that would be detected and characterized via seismoacoustic means over the following decades through the nuclear arms race and into the modern era.

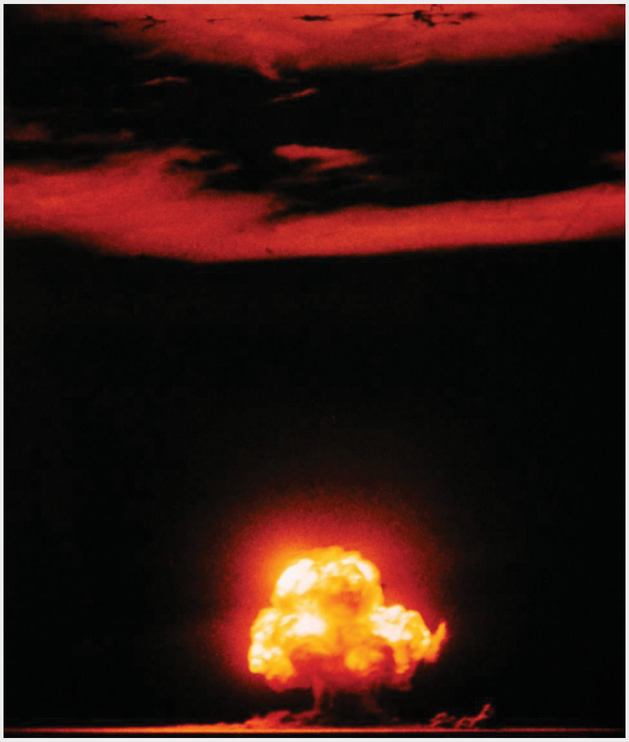

Figure 1. *The fireball produced by the Trinity nuclear test. Photo by Jack W. Aeby, captured as part of the Manhattan Project. Available at bit.ly/3ySMzMD.*

Subaudible Acoustic Waves

The acoustic signals produced by Trinity and other nuclear tests contained significant amounts of energy at subaudible frequencies (below 20 Hz). Such acoustic waves are termed "infrasound" and although they cannot be heard by the human ear, they are a remarkably useful means of passively monitoring energetic phenomena in the atmosphere. Any phenomena that displace a large volume of air in the atmosphere can produce these subaudible acoustic waves. Infrasound is generated by both natural and anthropogenic events, and many of these sources are of interest to natural hazard monitoring (e.g., volcanic eruptions, earthquakes, tornadic and maritime storms) as well as to national security interests (e.g., explosions, rocket launches, supersonic aircraft).

Infrasound waves exhibit efficient long-range propagation that makes them ideal for remote sensing applications. Thermoviscous absorption of acoustic waves by the atmosphere decreases with frequency. This decreased loss of energy into the propagation medium, combined with the

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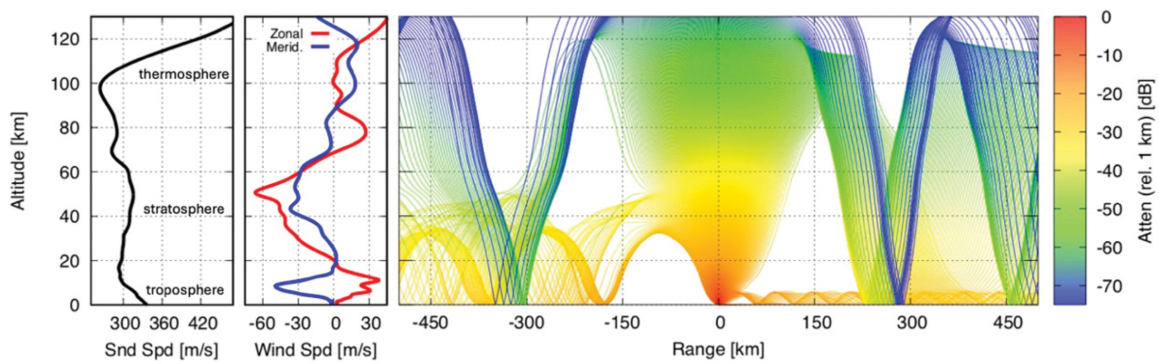

Figure 2. *Example of infrasound propagation including tropospheric, stratospheric, and thermospheric refractions. Tropospheric and stratospheric waveguides are driven by the atmospheric winds, whereas temperature gradients in the thermosphere produce refraction. Snd Spd, sound speed; Atten, Attenuation.*

energetic source mechanisms required to displace air volumes on the scale of infrasonic wavelengths, results in acoustic waves that can remain detectable hundreds or even thousands of kilometers from the source.

Infrasonic waves propagate through the atmosphere and are refracted by gradients in the wind and temperature as shown in **Figure 2**. Temperature gradients in the atmosphere (**Figure 2**, *left*) are relatively weak so wind gradients are typically needed to produce waveguides through which infrasound can efficiently propagate. The jet stream near the top of the troposphere (12 km altitude, where airplanes fly) can produce enough refraction to return infrasound waves to the ground surface. Further up, strong winds in the stratosphere (12-50 km altitude) are produced by the polar vortex (the same one often associated with sudden weather fluctuations during the winter).

In **Figure 2**, *middle*, the zonal (east and west component) and meridional (north and south component) winds are shown. Due to global circulation patterns, wind-driven waveguides are typically oriented east/west around the globe and are strongly dependent on the zonal winds. The propagation plane shown in **Figure 2**, *right*, is oriented east/west and shows a westward stratospheric waveguide (negative range values) and eastward tropospheric waveguide (positive range values).

In the thermosphere (above 85 km altitude), strong temperature gradients produce refraction of infrasound waves from the upper atmosphere. Thermospheric infrasound waves are particularly complicated as they extend beyond the Kármán line at 100 km, which astrophysical conventions define as the edge of space. Infrasonic refractions from the thermosphere can be thought of as sound waves that have been to outer space and back. At these altitudes, the atmospheric density decreases significantly, and linear acoustics does not fully capture the propagation physics.

Infrasound in Early Nuclear Nonproliferation

Following the conclusion of World War II, the United States held a monopoly on nuclear weapons, although that would only last a few years. Many of the scientists and engineers who had worked on the Manhattan Project speculated that the US nuclear monopoly would be short-lived and that "the fundamental physics of the bomb are well-known to all nations" (Marshak, 1946).

On August 29, 1949, the first Soviet nuclear test was conducted. This test was codenamed "Joe-1" in United States reports in reference to Joseph Stalin. Prior to Joe-1, in September 1947, General Dwight D. Eisenhower ordered the Army Air Forces to investigate technologies that would enable the United States to detect nuclear explosions across the globe. This effort to monitor and deter nuclear weapon development by foreign nations is termed "nuclear nonproliferation." The decision to assign this task to the Army Air Forces was based on the need to sample the atmosphere for radioactive debris that was indicative of a fission reaction that would identify a nuclear test. Initial deployments were targeted at the Soviet Union, and such debris was detected by a modified B-29 Superfortress aircraft when the first Soviet test was conducted in 1949 (Ziegler, 1988).

The detection of fission debris from Joe-1 demonstrated the capability of the Air Force Office of Atomic Testing (AFOAT-1) to detect foreign nuclear tests; however, the aim to monitor the entire globe for nuclear tests was more challenging than focusing on a single region. Aerial sampling for radioactive debris across the entire globe was simply not an option.

Thus, additional signatures were needed that could detect explosive events and inform aerial sampling. Seismic and infrasonic monitoring methods were identified as candidates for detecting the explosive waves from nuclear tests. Any belowground or near-surface explosion would couple energy into both the seismic and infrasonic wavefields, and airbursts would produce infrasonic signatures observable at significant standoff distances.

The need to consider these and other emplacement scenarios, as well as the need to discriminate conventional chemical explosives from those of nuclear origin, led to a multiphenomenological capability development. A combination of mechanical sensing modalities (seismic, infrasonic, and underwater acoustic) alongside radiochemical sampling was developed to detect explosions and then discriminate whether the explosion was conventional or nuclear.

AFOAT-1 evolved through the subsequent decades into its current form as the Air Force Technical Applications Center (AFTAC). AFTAC is based at Patrick Space Force Base near Satellite Beach, Florida, roughly 40 km south of Cape Canaveral. AFTAC maintains and utilizes a network of sensors across the globe, called the United States Atomic Energy Detection Systems, that enable its mission to monitor the globe for nuclear explosions.

Changing Nuclear Nonproliferation Challenges

The landscape of nuclear explosion monitoring shifted notably in August 1963 when the Partial Test Ban Treaty (PTBT), also known as the Limited Test Ban Treaty (LTBT), was signed by the United States, the United Kingdom, and the Soviet Union. The PTBT prohibited nuclear test detonations except those conducted underground, which limited the usefulness of infrasound as a sensing modality.

Infrasound was still utilized in monitoring applications to ensure no aboveground tests were conducted that would violate the PTBT. However, its primarily day-to-day use shifted to that of a supplement to seismic methods. When a possible explosion was identified, the presence of infrasound signatures was used to aid in discrimination between deep and shallow belowground sources. Deep sources were likely earthquakes, but shallower sources that coupled energy into the atmosphere could be explosions.

Around this same period, the US Defense Advanced Research Projects Agency (DARPA) initiated Project Vela in September 1959. Project Vela was aimed at monitoring compliance of foreign nations with the in-development PTBT. It included seismic monitoring capabilities (Vela Uniform) as well as satellite-borne sensors monitoring the atmosphere and space (Vela Sierra and Vela Hotel, respectively) (Penman, 1999).

Thus, following significant use of infrasound as a sensing modality for more than 450 atmospheric nuclear tests conducted from the late 1940s to the 1960s, the introduction of satellite sensing platforms and the shift of nuclear tests to exclusively below ground limited how useful infrasound would be in future nuclear explosion monitoring. With few other applications in the greater scientific community, infrasound research diminished in the early 1970s, and the field went relatively dormant for several decades.

An Infrasound Renaissance

During the 1990s and early 2000s, the field of infrasound underwent what some have referred to as a "renaissance" (Garces, 2008; Evers and Siegmund, 2009). This renewed interest in infrasound was due to a combination of newly identified applications of infrasound monitoring, newly available data, improvements in atmospheric specification accuracy, and advances in computational capabilities.

Infrasound Applications

Infrasound studies of volcanic eruptions became more frequent in the 1980s following subaudible recordings of the eruptions of Mt. Saint Helens, Mt. Tokachi, and Sakurajima volcanos among others (Johnson and Ripepe, 2011). The ground motion produced by earthquakes was shown to couple into the atmosphere and produce infrasonic waves that aid in magnitude estimation and other characterizations (Mutschlecner and Whitaker, 2005).

Studies have also identified infrasound signals produced by tornadic (Frazier et al., 2014) and maritime (Hetzer et al., 2008) storms that can potentially be leveraged for early warning and monitoring for such natural hazards. Planetary science researchers have leveraged infrasound in analyses of exceptionally bright and energetic meteors that produce fireballs in the sky, termed bolides. The resulting studies have provided information about the distribution of such objects in the solar system (Ens et al., 2012).

In scenarios where source information is known, infrasound propagation effects can be analyzed and used to estimate wind speeds in the atmosphere. Infrasound paths extend into the middle and upper atmospheres, which can be challenging to probe using ground- or space-based radar and similar platforms due to atmospheric opacity (Blom and Marcillo, 2017).

The Comprehensive Nuclear-Test-Ban Treaty and the International Monitoring System

Innovative applications of infrasound monitoring helped renew interest in the field, but a global source of high-quality infrasound data supported and enabled many of these new research areas. Ongoing security concerns drove additional nuclear treaty negotiations following the success of the PTBT, including the 1968 Nuclear Non-Proliferation Treaty that prohibited nonnuclear nations from developing such capabilities and the 1974 Threshold Test Ban Treaty that banned nuclear tests with yields greater than 150-kilotons equivalent TNT.

Additional negotiations continued intermittently through the 1980s and 1990s, leading to the eventual drafting of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The CTBT bans all nuclear weapons tests in any environment and was adopted by the United Nations in September 1996; however, it has not entered into force due to several nations having not yet ratified the treaty. A more detailed discussion of the history and nuances of the CTBT can be found in Dahlman et al. (2009).

The International Monitoring System (IMS) is a global network of geophysical and radionuclide sensing platforms that monitor for signatures of nuclear tests and is operated by the Preparatory Commission for the CTBT Organization. This organization is tasked with developing the capability and verification regimen for enforcing the CTBT once it has entered into force. The IMS is a global network of seismic, infrasonic, and hydroacoustic and radionuclide particulate and noble gas sensors and laboratories that monitor the globe looking for signatures of a nuclear explosion. It is also frequently leveraged for more general scientific studies.

The IMS includes 60 planned infrasound stations distributed across the globe (Christie and Campus, 2010). Global security infrasound research resumed at US DOE laboratories in the 1980s, including analysis of infrasonic signals from belowground nuclear explosions and their capability to aid in characterization of such sources. Part of the work at the DOE laboratories included construction of a prototype IMS infrasound array to test and evaluate the performance of the sensing platform in 1997, jointly undertaken by the Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, and the Sandia National Laboratories (SNL), Albuquerque, New Mexico. In recent years, the IMS has become a treasure trove of useful infrasound data with signals captured from the Chelyabinsk superbolide (Pilger et al., 2015), the Hunga Tonga-Hunga Ha'apai volcanic eruption (Matoza et al., 2023), and numerous other energetic events in the atmosphere.

Improved Atmospheric Data

Simulating and understanding infrasound propagation effects requires knowledge of the atmospheric structure through which waves propagate. Infrasound paths extend into the middle and upper atmospheres so that temperature, pressure, and density as well as the ambient wind fields from the ground into the stratosphere and thermosphere are needed to accurately predict and model propagation. During the early decades of nuclear explosion monitoring, atmospheric data were limited, and idealized atmospheric models were used to understand infrasound observations. A series of atmospheric models were developed and refined by the US National Oceanic and Atmospheric Administration (NOAA) through the 1950s and 1960s and culminated in the US Standard Atmosphere 1976. The model was moderately useful for modeling infrasonic propagation but did not include any seasonal variations and the altitude resolution was overly coarse.

Atmospheric measurements improved over the subsequent decades and by the 1990s and 2000s, atmospheric specifications could be obtained for specific locations and times to simulate and understand infrasonic propagation effects more accurately. A comparison of the US Standard Atmosphere 1976 and a modern Ground-to-Space (G2S) atmospheric specification (Drob et al., 2003) is shown in **Figure 3**. **Figure 3**, *gray line*, shows the sound speed profile in the US Standard Atmosphere, and **Figure 3**, *black line*, shows the sound speed as well as the zonal (**Figure 3**, blue line) and meridional (**Figure 3**, *red line*) wind fields, respectively, as specified in the sample from G2S. The US Standard Atmosphere captures the general trends of the atmospheric sound speed but has less than 10 reference altitudes and assumes linear variations between them. In comparison, available G2S atmospheric data has 100 m-altitude resolution and includes wind information in addition to sound speed. The more detailed atmospheric data result in significantly improved prediction capability. G2S atmospheric data, useful for infrasound propagation analysis, is openly available through a University of Mississippi National Center for Physical Acoustics (NCPA), Oxford, web service (see bit.ly/4ch59vZ).

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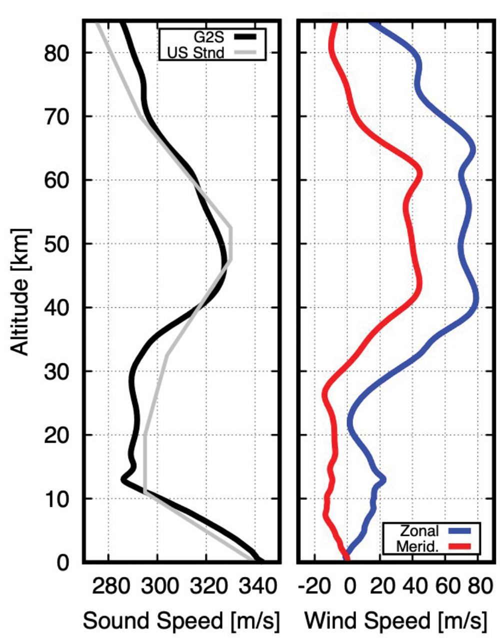
Figure 3. *Comparison of historical US Standard (Std;* ***gray line****) with modern Ground-to-Space (G2S;* ***black line****) atmospheric model resolution. Year-round averaged pressure, density, and temperature were specified in the US Std atmosphere, whereas G2S specifies such information as well as zonal (****blue line****) and meridional (****red line****) winds (east/west and north/south, respectively) on a nearly hourly basis using data from weather prediction tools (****red and blue lines****).*



Complicated Physics Requires Advanced Computational Tools

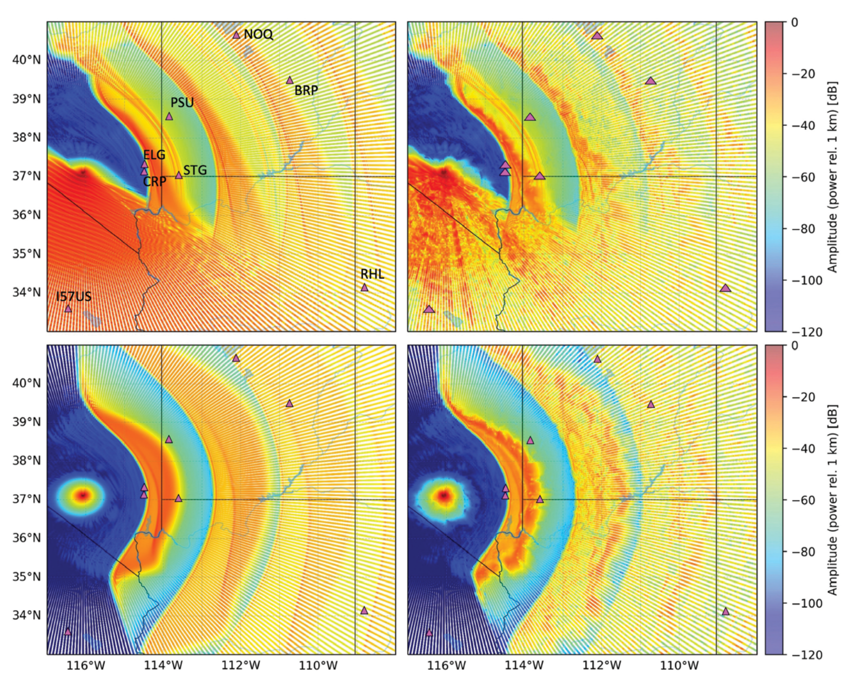
Simulations of infrasonic waves as they propagate through the atmosphere are computationally intensive partially due to the sheer spatial scale of the problem. Although some applications can deploy sensors in the immediate vicinity of sources of interest (e.g., a network of sensors around an active volcano), remote sensing applications of infrasound, such as nuclear explosion monitoring, leverage a network of stations covering a region extending hundreds or even thousands of kilometers from the individual stations. Infrasonic wavelengths range from a few tens of meters to a few kilometers and simulating all the complicated interactions of infrasonic waves with atmospheric structure and terrain over relevant spatial scales requires advanced numerical capabilities.

Even numerically efficient simulation methods such as ray tracing can be challenging when considering infrasound scenarios. The atmosphere is a dynamic, inhomogeneous moving medium. The geometry of the atmosphere is a spherical layer surrounding the globe in comparison to a Cartesian geometry that can be used for small-scale simulations. Infrasound waves interact with mountains, valleys, and other large-scale terrain structures as they propagate. Furthermore, when energy propagates into the thermosphere, the atmospheric density decreases so much that simple linear acoustic physics is no longer accurate. Despite this, several infrasonic propagation tools have been developed using ray-tracing algorithms. Additionally, several methods utilized in underwater acoustics have been adapted to infrasound applications including parabolic equation and horizontal wave number (modal) methods.

Current Infrasound Simulation Capabilities

The improved accuracy of atmospheric data combined with the advanced propagation simulation capabilities discussed in ***Complicated Physics Requires Advanced Computational Tools*** have provided continued momentum to the so-called renaissance of infrasound research and development (R&D). **Figure 4** shows propagation simulations for a pair of conventional chemical explosions conducted at the Nevada National Security Site (NNSS) (formerly the Nevada Test Site) in the fall of 2020. These explosions were part of the Large Surface Explosion Coupling Experiment (LSECE) and were conducted less than 72 hours apart. The first explosion, Artemis, occurred just after 6:30 a.m. local time on October 27, 2020, and the second, Apollo, just after 3:30 p.m. on October 29, 2020. In the relatively short time between the two explosions, the jet stream winds changed from strongly southward to much weaker so that the infrasonic waveguide dissipated and propagation to the south became inefficient. A definite infrasonic signature was observed at the I57US IMS station to the south for the first explosion but not for the second. Propagation simulations for these two events are shown in **Figure 4**, *top and bottom rows*, and capture this difference in propagation due to the temporal variations

Figure 4. *Propagation simulations using a parabolic equation method for two surface explosions conducted 2 days apart during the Large Surface Explosion Coupling Experiment (LSECE). The LSECE-Artemis (**top row**) and –Apollo (**bottom row**) events are shown. The differences when considering flat ground (**left column**) and realistic terrain (**right column**) simulations are shown. From Blom (2023, Figure 9).*



in the atmospheric structure, thus explaining the observed signal during Artemis and lack of signal from Apollo.

At several stations, infrasonic signals that required higher fidelity propagation simulation methods were identified. **Figure 4**, *left and right columns*, shows the difference in predicted propagation effects when considering flat ground and realistic terrain, respectively, using a parabolic equation algorithm. The impact is most notable for the tropospheric waveguide to the south because those propagation paths interact with the ground surface more extensively than those refracted in the middle atmosphere. Following several ground reflections, however, the propagation of energy to the east also exhibits notable focusing and defocusing of energy due to the interaction with the terrain. As noted in Blom (2023), the focusing and defocusing are impacted by both the static terrain structure and dynamic atmospheric state. Thus, high-resolution atmospheric data as well as advanced numerical methods are required to fully understand the infrasonic signals observed in remote-sensing applications. The availability and continuous improvement of both atmospheric data and numerical simulation capabilities have enabled infrasound to become a useful remote-sensing capability for natural-hazard monitoring, global security, and other applications.

Modern Infrasound Research and Development for Global Security

AFTAC continues to conduct the operational monitoring and reporting aspects of treaty and nuclear nonproliferation verification for the United States. R&D supporting that mission is conducted both by subject matter experts at AFTAC and across multiple fronts outside AFTAC. This includes significant efforts by the US DOE that supports work nationwide at US DOE laboratories, other government facilities, and through various industry and academic partners. US DOE programs maintain the scientific and technical base needed to advance nuclear threat reduction via detection and monitoring of foreign nuclear weapons development activities.

Infrasound research sponsored by the US DOE improves AFTAC's explosion monitoring mission and other aspects of nuclear nonproliferation and global security. These efforts support a combination of analysis and software development as well as experiment-driven efforts at the NNSS. Software and method development includes the tools mentioned in ***Complicated Physics Requires Advanced Computational Tools*** as well as development and evaluation of signal-analysis tools. Both traditional and machine-learning frameworks are being considered for identifying and understanding infrasonic signatures.

The United States conducted more than a thousand nuclear tests between 1945 and 1992, ceasing nuclear explosive testing activities prior to the start of negotiations for the CTBT in 1993. This has led to a need to leverage historical or "legacy" nuclear data for empirical nuclear nonproliferation research or to investigate and develop chemical-to-nuclear source relationships to continue R&D supporting nuclear explosions monitoring without conducting nuclear explosive tests.

A similar challenge exists in US DOE efforts to ensure that the existing US nuclear weapon stockpile is safe, secure, and reliable (a mission often referred to as "stockpile stewardship"). Advanced materials science and computational analyses are utilized to provide confidence in the US nuclear stockpile. A significant effort has been made between the 1990s and today to maintain the stockpile and conduct nuclear nonproliferation research that ensures treaties are enforceable, all without the need to conduct nuclear explosive tests.

Nuclear Nonproliferation Field Experiments

Several campaigns of large-scale field experiments have been undertaken using conventional chemical-explosive sources to continue development of source models for above- and belowground explosions in support of nuclear nonproliferation and related global security applications. Two large-scale and enduring efforts aimed at such investigations are currently supported by the US DOE.

The Source Physics Experiment

The first of these programs is the Source Physics Experiment (SPE) that has completed two series of conventional explosions at the NNSS (Snelson et al., 2014). Phase I of the SPE was conducted in a hard-rock granite geology between 2010 and 2016, whereas the second was conducted in a softer dry alluvium geology (DAG) between 2017 and 2019.

The first two phases of the SPE focused on understanding the generation of seismic shear energy by explosive

Figure 5. *Workers at the Nevada National Security Site (NNSS) emplacing the DAG-2 explosive during the Source Physics Experiment (SPE). DAG-2 was a 50-ton equivalent TNT explosion at a depth of 385 m below the ground surface. Photo from US Department of Energy, taken by a representative of the Nevada National Security Site.*

sources (in theory, a purely compressional source) as well as various other investigations related to the seismoacoustic wavefield produced by such sources. Phase III of the SPE is ongoing, and the focus has shifted to a direct comparison of seismoacoustic signatures from several shallow earthquakes and colocated explosions to evaluate models for discrimination of earthquakes and explosion sources.

A significant amount of R&D has been conducted as part of SPE investigating how seismic energy propagates from the explosion to the ground surface and couples into the acoustic wavefield (Blom et al., 2020; Kim et al., 2022). This research has shown that acoustic signals produced by belowground explosions are strongly dependent on the scaled depth of burial (SDOB; the physical depth divided by the cubic root of the explosive yield). A similar trend is known for aboveground explosions where blastwaves from different explosions are found to be similar at corresponding scaled propagation ranges.

Figure 5 shows the emplacement of the canister for the DAG-2 explosion by the high-explosives team at NNSS. This chemical explosion was 50-ton TNT equivalent at a depth of 385 m below ground level. Despite the relatively large 50-ton equivalent TNT yield of DAG-2, ground-based microbarometers within 2 km of surface ground zero did not detect an acoustic signal from the explosion. In contrast, Phase I experiments SPE-2 and SPE-3 were shallower and smaller explosions at depths of just over 45 m and yields of 1-ton equivalent TNT. Both events produced infrasonic signatures observable more than 5 km from surface ground zero.

As discussed in Blom et al. (2020), DAG-2 produced significant ground motion, but the spatial extent of the motion (i.e., the radius of the effective speaker cone or piston in an acoustic analysis of the ground motion) is much larger than the radiated acoustic wavelengths. In such a case, radiated energy is highly directional and focused perpendicular to the ground surface. This dependence of the seismoacoustic coupling of energy from a belowground explosion on the SDOB implies that information contained in the infrasound signal from such a source could be used beyond a simple shallow versus deep discriminate.

Low Yield Nuclear Monitoring and Multi-Phenomenological Explosion Monitoring

The second ongoing experimental effort sponsored by the US DOE is the Low-Yield Nuclear Monitoring (LYNM) program. LYNM looks to extend a multiphenomenology approach to better detect and characterize smaller nuclear explosions at shorter distances. **Figure 6** shows an idealized realization of such multi-phenomenological explosion monitoring (often referred to as "multi-PEM").

Leveraging these various phenomenologies to detect and characterize nuclear explosions is challenging due to the huge range of timescales. Electromagnetic signals propagate at the speed of light, mechanical signals at a few kilometers per second to a few hundred meters per second, and radionuclide signals at the speed of atmospheric advection. Despite this challenge, there are numerous advantages and information gains available through combinations of phenomenologies such as utilizing acoustic observations to constrain the boundary layer winds that impact the diffusion and transport of radionuclides. Furthermore, when considering small nuclear explosions, the number of sensors close enough to detect signals is often limited. In such scenarios, the ability to combine small numbers of signatures from disparate phenomenologies can mean the difference between identifying and missing an event of interest.

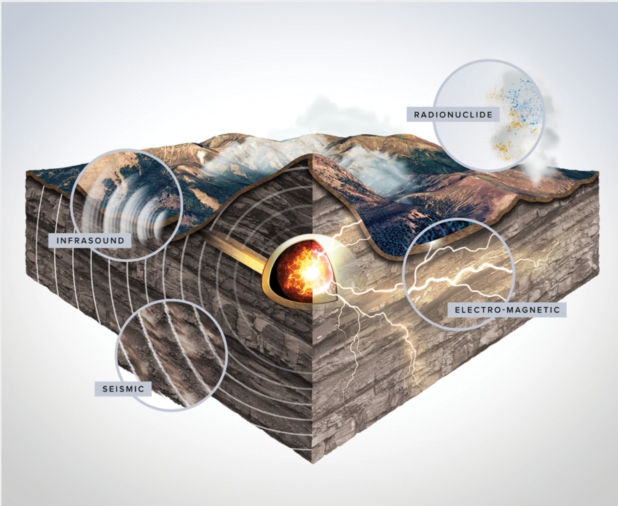


Figure 6. *Multi-phenomenology explosion monitoring (multi-PEM) is a growing focus of Department of Energy-supported Defense Nuclear Non-Proliferation Research and Development. In addition to the mechanical (seismoacoustic) and atmospheric radionuclide signatures historically leveraged to identify a nuclear explosion, electromagnetic signatures are being investigated to provide additional means of discriminating conventional and nuclear explosions. Figure created by Los Alamos National Laboratory.*

In addition to a significant amount of scientific work supported by the LYNM program, a series of experiments have been undertaken to generate data for testing in-development physical models and data-analysis methods. The LYNM Physics Experiment One (PE1) is an ongoing effort at the NNSS including testing of an electromagnetic source, various atmospheric releases of tracers for radionuclide transport model development, and a recent chemical explosion including radiotracers (Myers et al., 2024). These experiments are expected to provide additional data useful in developing and validating predictive models for multi-PEM research.

A Community Effort

Throughout the so-called infrasonic renaissance and into the current research landscape, infrasound experts have made increasing efforts to share the products of their work not only through peer-reviewed journal publications but also through sharing of datasets and software. The US DOE nuclear nonproliferation field experiments (e.g., SPE and LYNM-PE) have a policy of holding data for 2 years while US DOE scientists complete their work and then upload the data for others to utilize via platforms like EarthScope (see earthscope.org).

Several universities include infrasound in their regional networks for earthquake- and volcano-hazard monitoring (e.g., University of Utah, Salt Lake City; University of Alaska, Fairbanks) and make that data available to others. In addition to such institutional sources of infrasound data, "citizen scientist" data are a growing resource following the introduction of cheap seismoacoustic sensors built from Raspberry Pi platforms (Raspberry Shake, 2016).

Similarly, many scientists within the infrasound community have taken steps to establish open-source software licenses for algorithms and tools they have developed to share such methods more easily with the community. GitHub and similar software-sharing and-collaborative development platforms have been increasingly used to host R&D products.

A number of software tools for infrasound propagation simulation and data analysis are available through GitHub channels supported by LANL (see bit.ly/3XmeDlq), LLNL (see github.com/LLNL/AC2Dr), the University of Mississippi NCPA (see bit.ly/4b0MVOv), the University of Alaska (see bit.ly/4cgiBAr), and others.

The broader scientific community has been moving toward an "open science" mindset, and the infrasound community has adopted such an approach as well. Whether it's natural-hazard monitoring to keep communities safe or global security applications to protect the nation, the infrasound research community is providing needed data as well as tools and software to identify and understand signatures of interest.

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