SAND2017-10182R

SAND20XX-XXXXR
**LDRD PROJECT NUMBER**: 206542
**LDRD PROJECT TITLE**: Evaluating the Capability of High-Altitude Infrasound Platforms to Cover Gaps in Existing Networks
**PROJECT TEAM MEMBERS**: Daniel C. Bowman, Steven J. Arrowsmith, Sarah A. Albert, and Neill P. Symons

## ABSTRACT

A variety of Earth surface and atmospheric sources generate low frequency sound waves that can travel great distances. Despite a rich history of ground-based sensor studies, very few experiments have investigated the prospects of free floating microphone arrays at high altitudes. However, recent initiatives have shown that such networks have very low background noise and may sample an acoustic wave field that is fundamentally different than that at the Earth's surface. The experiments have been limited to at most two stations at altitude, limiting their utility in acoustic event detection and localization. We describe the deployment of five drifting microphone stations at altitudes between 21 and 24 km above sea level. The stations detected one of two regional ground-based explosions as well as the ocean microbarom while traveling almost 500 km across the American Southwest. The explosion signal consisted of multiple arrivals; signal amplitudes did not correlate with sensor elevation or source range. A sparse network method that employed curved wave front corrections was able to determine the backazimuth from the free flying network to the acoustic source. Episodic broad band signals similar to those seen on previous flights in the same region were noted as well, but their source remains unclear. Background noise levels were commensurate with those on infrasound stations in the International Monitoring System (IMS) below 2 seconds, but sensor self noise appears to dominate at higher frequencies.

## INTRODUCTION

Forces imposed on the atmosphere produce acoustic waves that carry valuable information about their origin and the properties of the medium through which they travel. Acoustic signals in the “infrasound” range (below 20 Hz, the limit of human hearing) can travel hundreds to thousands of kilometers, sampling regions from the Earth's surface to the thermosphere. A variety of natural and human sources produce infrasound; these include volcanic explosions, meteors, earthquakes, ocean waves, thunderstorms, wind-mountain interactions, chemical and nuclear blasts, supersonic aircraft, rockets, and large structures such as buildings and dams.

The vast majority of infrasound studies to date have utilized ground-based detector networks; prior to 2014 no attempts to record low frequency sound above 8 km altitude had occurred for over half a century. Balloon campaigns in the 1950s and 1960s focused on long range detection of atmospheric nuclear blasts and the source of the acoustic background at altitude. The 2014 and 2015 High Altitude Student Platform (HASP) infrasound experiments discovered a variety of unusual signals in the stratosphere that likely originated from non-

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

acoustic interference. Design changes during the 2016 HASP flight resulted in a dramatic drop in the noise floor and lack of interfering signals; the ~6 second ocean microbarom infrasound peak was prominent throughout the stratospheric portion of the balloon's trajectory. A similar design was used on a long duration balloon flight in the Southern hemisphere, which also yielded relatively low noise levels and continuous ocean wave generated infrasound, along with sporadic discrete events of unknown origin.

The lack of ground truth during these flights motivated the 2016 Stratospheric Infrasound Sensitivity Experiment/UNC-Sandia Infrasound Experiment (SISE/USIE), in which several microphones were lofted into the stratosphere and ground explosions were detonated to generate low frequency acoustic waves. Simultaneously, an experimental solar hot air balloon with a lightweight infrasound microphone/logger combination was launched in the same region. Results from SISE/USIE indicated that high altitude stations were more sensitive than ground microphones, with all three explosions detected on the main balloon and one on the prototype. However, because the two balloons were very far apart and at different altitudes, the direction of arrival for the explosion signals could only be determined in a rudimentary fashion. The LDRD Express project described here is a first attempt at deploying a free flying infrasound microphone array capable of determining the direction of arrival of acoustic events. The experiment was named Heliotrope, a term inspired by the solar powered flight system that lifted the microphones into the stratosphere.

We fielded five drifting microphone stations at altitudes between 21 and 24 km above sea level. The stations detected one of two regional ground-based explosions as well as the ocean microbarom while traveling almost 500 km across the American Southwest. The explosion signal consisted of multiple arrivals; signal amplitudes did not correlate with sensor elevation or source range. A sparse network method that employed curved wave front corrections was able to determine the backazimuth from the free flying network to the acoustic source. Episodic broad band signals similar to those seen on previous flights in the same region were noted, but their source remains unclear. Background noise levels were commensurate with those on infrasound stations in the IMS network below 2 seconds, but sensor self noise appears to dominate at higher frequencies.

## METHOD

Four Arduino-based Gem infrasound sensor/logger combinations and one prototype Raspberry Pi infrasound sensor/logger combination were included in the free flying Heliotrope array. The four Gem infrasound payloads also included an Adafruit Ultimate GPS logger to determine the position of the payload throughout the flight. The Gem loggers were powered using one Ultimate Lithium 9 volt battery, which ground tests had indicated would last over 40 hours. The Adafruit Ultimate GPS shield was powered using 6 AA Ultimate Lithium batteries for a nominal lifetime of 14 hours. The Raspberry Pi based sensor was powered using a lithium ion portable cell phone charging battery with an estimated lifetime of 12 hours. The balloon landing site was transmitted using a SPOT Trace asset tracker, which was set to report horizontal position every 10 minutes via the Globalstar satellite network.

The flight systems consisted of approximately 19 ft. diameter solar powered hot air balloons. The envelope was constructed from 12 x 400 ft. sheets of 0.31 mil polyethylene sheeting (advertised as “light duty painter’s plastic” at hardware stores). Five 30 ft. gores were cut to produce a 60 ft. diameter sphere. The gores were joined together using heavy duty clear shipping tape. A hole approximately 6 ft. in diameter was constructed at one pole of the sphere, and a loop of 500 lb. test paracord was placed around the hole to provide a payload attachment point. The envelope was darkened using air float charcoal powder to increase solar absorption efficiency.

The payload consisted of one 20 lb. test fishing swivel (testing at Sandia determined that it had a <50 lb. breaking point per FAR 101 regulations), a Rocketman 6 ft. diameter parachute, one heavy duty foam medical shipping container holding the SPOT Trace, and another heavy duty foam medical shipping container holding the infrasound payload and GPS tracker. The total weight of the payload (parachute, tracker, instrumentation, etc.) was approximately 700 grams. The parachute and balloon envelope provided dual descent arrest mechanisms. All objects in the payload were secured to the parachute using 500 lb. test paracord.

A flight trajectory model was developed based on Global Forecast System outputs and ascent data from a solar hot air balloon flight in 2015. On July 25, 2017, the trajectory model indicated that the balloons would land in regions free of cities or inaccessible areas, so the decision was made to attempt launch. All five balloons were inflated using a box fan and launched between 7 and 8 AM MDT from Socorro, New Mexico. The balloons initially traveled north, turning sharply west south of Bernardo, New Mexico and continuing in that direction until the Flagstaff, Arizona area (see Figure 2). At that point, sunset terminated the flights. The balloons landed at approximately 9:30 PM MDT. Payload recovery took place August 7-8.

A ground network consisting of Hyperion infrasound microphones with high frequency wind shrouds was deployed in the area also (see Figure 3). Four stations were installed approximately 20 km from the balloon launch site: one on Magdalena Baldy (BLDY), one in San Acacia (ACIA), one south of San Antonio (ANTO), and one in the Quebradas to the east of Socorro (GRDY). An additional four element microphone subarray named GRAD was located between BLDY and the launch site.

The Energetic Materials Research and Testing Center (EMRTC) was employed to detonate three 800 kg TNT equivalent surface explosions to generate acoustic signals for the experiment. One blast occurred at 11 AM and another at 12:30 PM MDT. The third was canceled due to an approaching thunderstorm.

Several array processing methods were used to determine the backazimuth (azimuth angle from the center of the microphone cluster to the acoustic source) from the free flying infrasound network to the explosion epicenter. The first was based on an algorithm developed to find the direction of arrival of quasiperiodic signals using three dimensional acoustic arrays, and the second used minimum variance distortionless response (MVDR). Neither of these produced accurate backazimuths. A sparse array triangulation method using the Tau-P approximation was investigated, but it was too difficult to implement given the time frame of the project. A more promising technique designed for IMS stations was tried next. This method takes into account elevation differences between stations. The resulting backazimuths were still of poor quality compared to those reported at IMS stations. Finally, we employed a location grid search method

Built on LDRD Laboratory Directed Research and Development

that corrected for wavefront curvature. This resulted in reported backazimuths within one degree of the true backazimuth.

Built on
LDRD
Laboratory Directed Research
and Development

*Figure 1: Payloads (top left), one of the solar hot air balloon just after launch (top right), a photo taken on the Raspberry Pi during the flight (center) and recoveries (bottom). Flight photo courtesy Guide Star Engineering, LLC.*

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

Built on
LDRD
Laboratory Directed Research
and Development

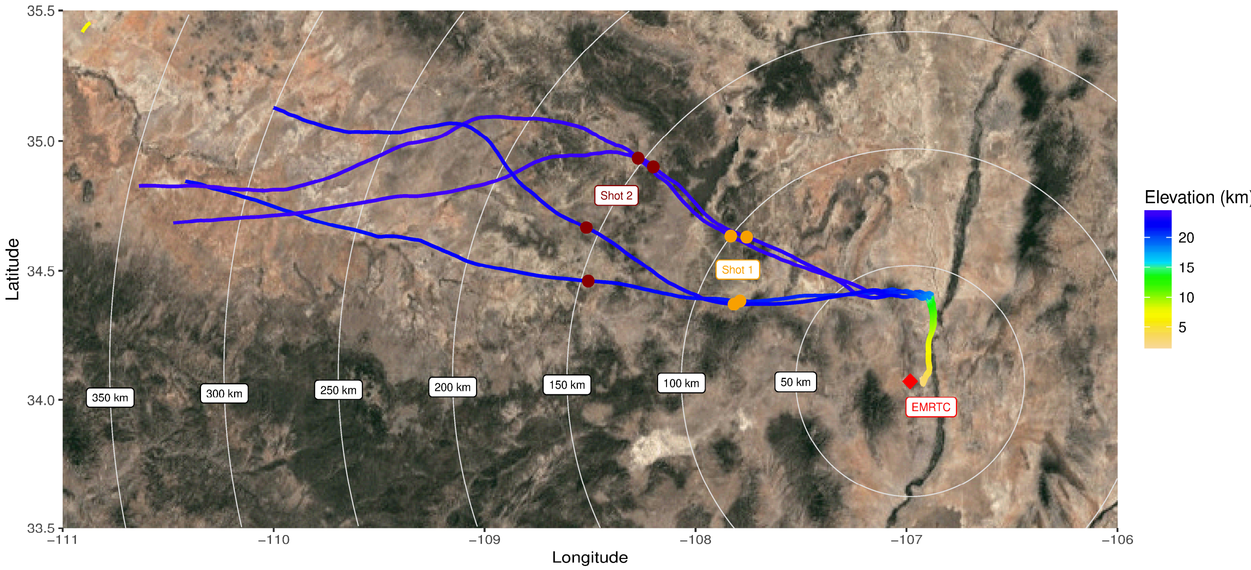


*Figure 2: Balloon flight paths with positions at the time of the two shots marked.*

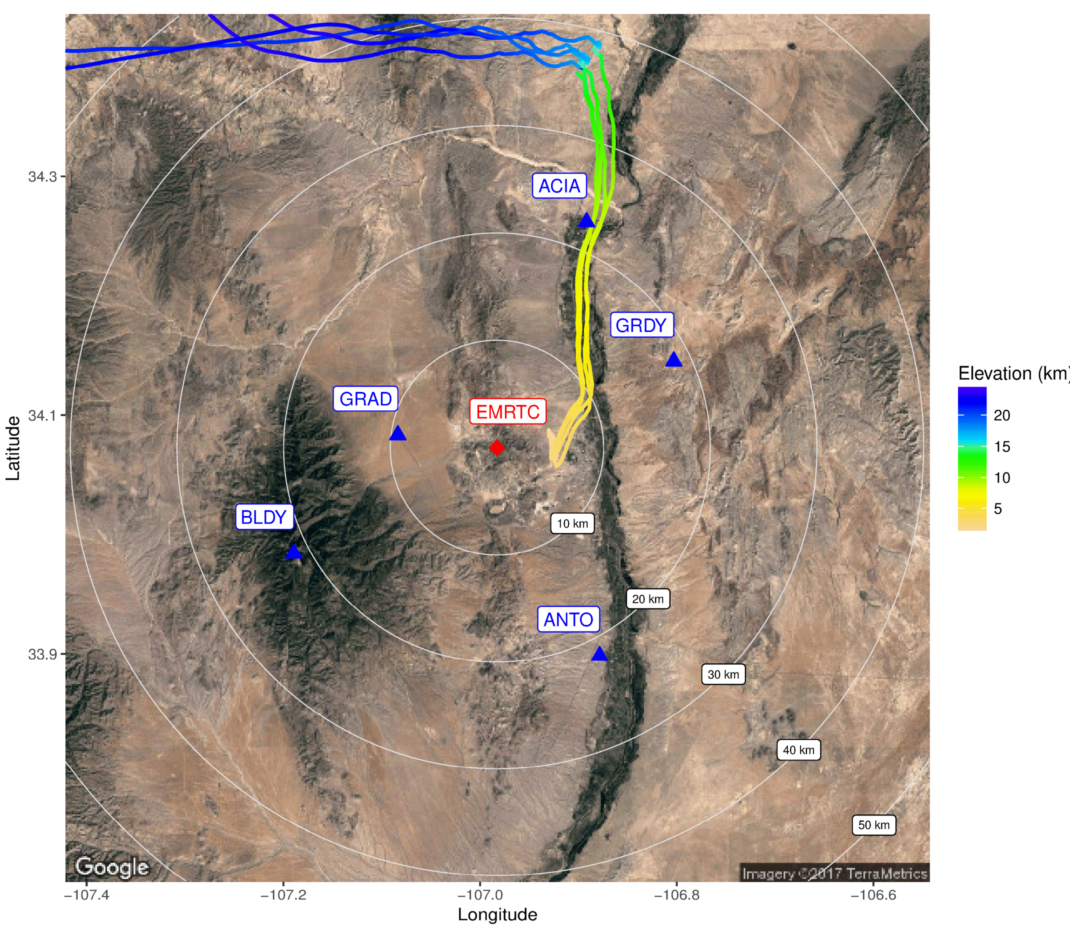


*Figure 3: Ground infrasound station network and balloon launch site.*


Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

## RESULTS

Each balloon reached neutral buoyancy, or "float" at about three hours after launch (between 10:00 and 11:00 AM local time, 1600 and 1700 UTC). Float altitudes were 21.7 +/- 0.3, 23.9 +/- 0.2, 23.9 +/- 0.2, and 23.0 +/- 0.2 km above sea level for the balloons with Gem loggers. The GPS on the prototype Raspberry Pi based logger did not record positions once it ascended above 13 km, but likely reached similar altitudes based on payload weight and envelope size. The first four balloons also lost GPS positions several hours before sunset. The SPOT Trace trackers worked continuously for some of the balloons, but ceased transmitting for others. All GPS and SPOT Trace units acquired payload positions just before landing. The cause of the GPS dropouts is likely due to extreme cold; the ambient air temperature was approximately -70 C at the balloon float altitude.

Because they floated at slightly different altitudes, the balloons were located in different wind fields. This resulted in the network drifting apart over time. Individual balloons oscillated up and down with amplitudes on the order of tens of meters and periods of around 200 seconds. This self-oscillation has been observed on helium balloons as well, where it tends to be slightly longer than the local Brunt Vaisala period. The result is a long period pressure signal that has much greater amplitude than far field infrasound arrivals.

Acoustic signals from the two EMRTC explosions were quite variable across the ground array (see Figure 4). The first shot was detected on ground station GRAD (9.4 km from blast site) and three of the four outer stations. Station BLDY, located to the west on a mountain ridge, does not have an arrival despite moderate background noise levels. Signals from the second shot appeared different than from the first one, despite being the same size and location and only 1.5 hours later. Infrasound arrivals were about 3.5 times higher amplitude at station GRAD on the second shot relative to the first, but they were still not detected on station BLDY (21 km to the west). In contrast, no arrival is evident at station ANTO (22 km to the south, noise levels about 1 Pa) despite a maximum amplitude of over 7 Pa for the first shot. Station GRDY (18 km to the east) had similar amplitudes for both shots, but station ACIA (23 km to the north) had about double the amplitude on the second shot compared to the first.

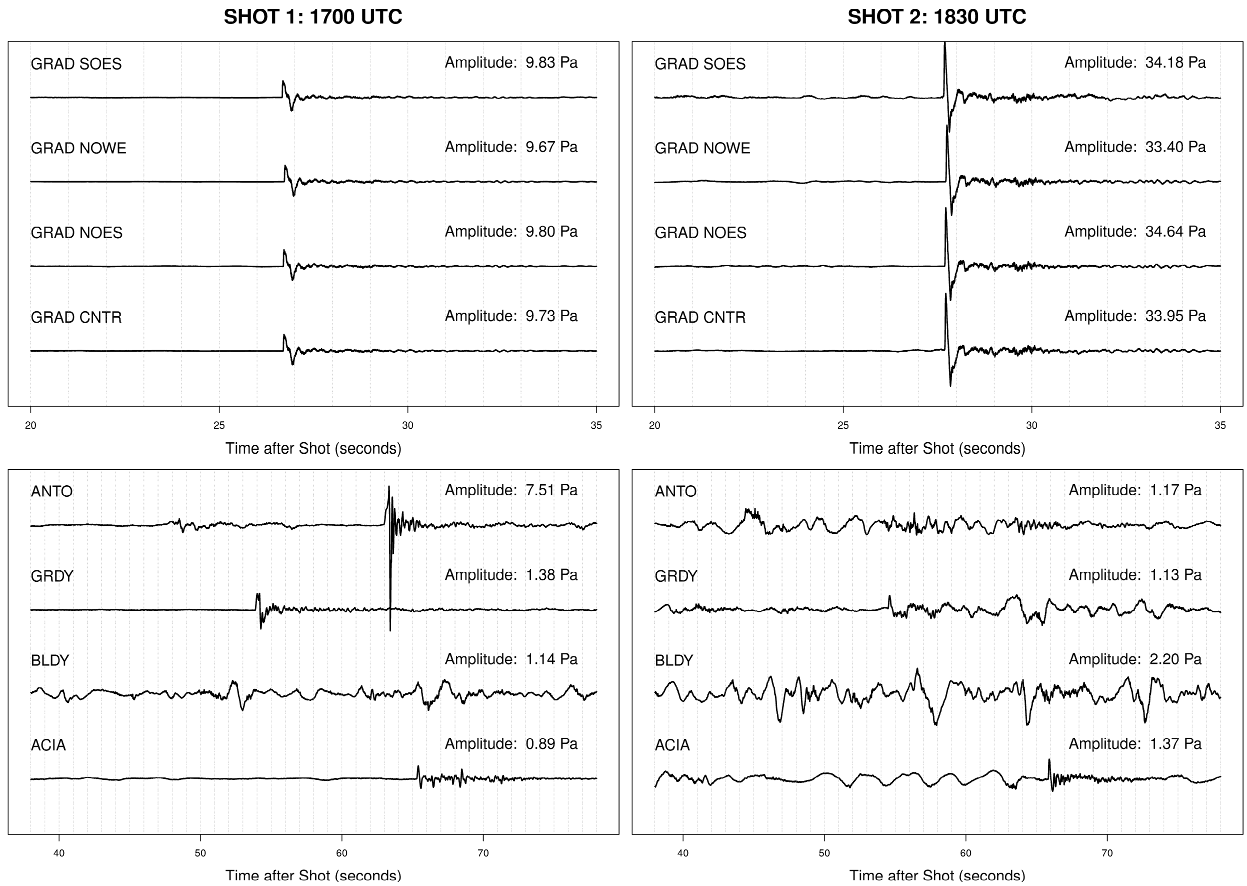


*Figure 4: Acoustic signals from EMRTC blasts recorded on ground infrasound microphones.*

The balloon borne stations were between 82 and 100 km away from the blast site at the time of the the first shot. At this range, acoustic waves from the explosion should have arrived between 240 and 300 seconds for the closest balloon and between 290 and 360 seconds at the furthest balloon. This celerity range (280 to 350 m/s) includes direct arrivals from the troposphere as well as refractions from the stratosphere. However, no arrivals are evident during this time period.

The balloon borne stations were between 145 and 156 km away at the time of the second shot. All five balloons detected arrivals between 505 and 532 seconds after the shot, by which point the stations had drifted several kilometers further west. However, only arrivals on the balloons carrying Gem loggers will be discussed here due to data quality issues on the Raspberry Pi. In contrast to the ground stations, three of the four airborne sensors carrying Gem loggers detected several acoustic arrivals over about ten seconds (see Figure 5). On three of these balloons, one to several lower amplitude initial arrivals precede a higher amplitude main phase. In two of the three cases, a lower amplitude trailing arrival is present as well. The celerity of the first arrival was 302, 304, and 302 m/s, respectively, with an uncertainty of about +/- 1 m/s. Interference

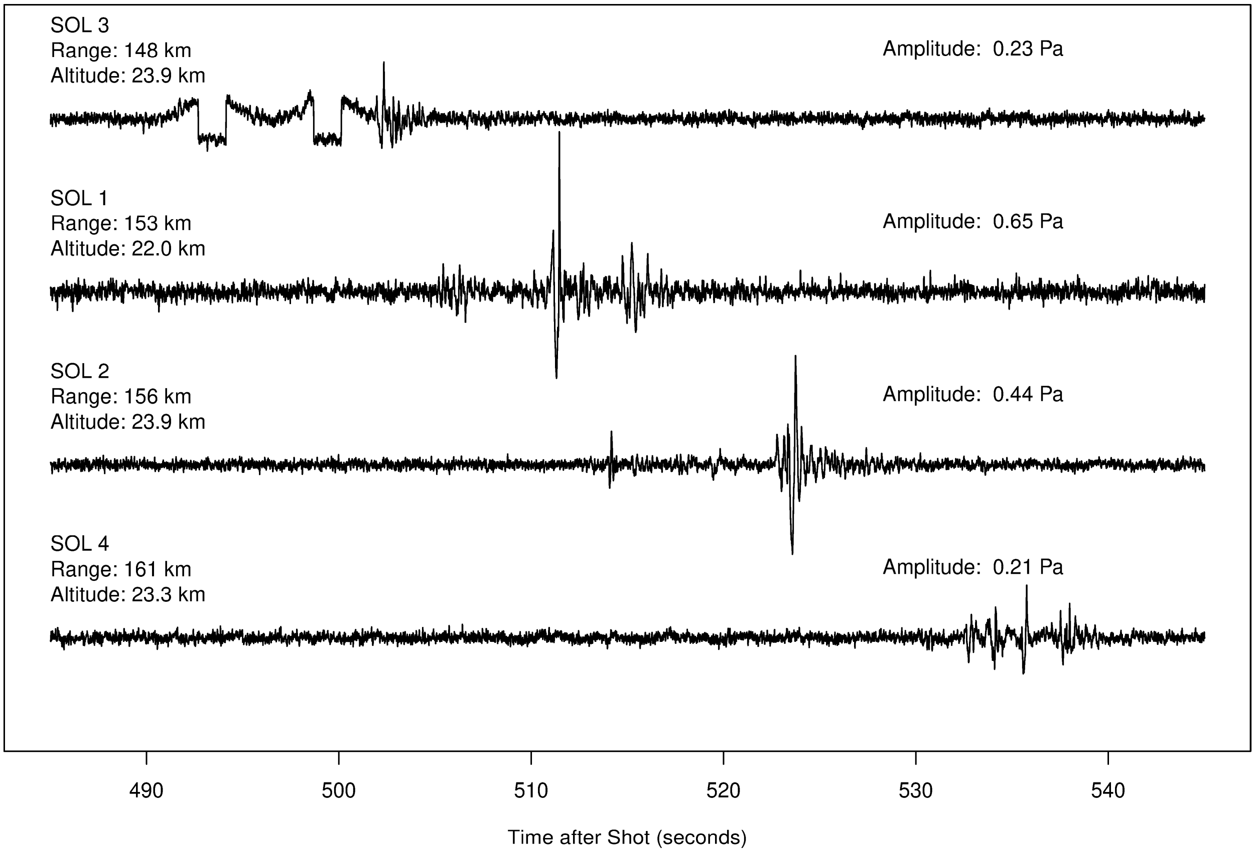


*Figure 5: Infrasound signal from Shot 2 recorded on the free flying Gem loggers.*

from the SPOT Trace tracker may have prevented the detection of a low amplitude first arrival on the fourth balloon.

The arrival with the highest amplitude has a similar form across the four stations. This inverted "N" shaped wavelet has a celerity of 299, 298, 295, and 300 m/s, respectively, with an uncertainty of about +/- 1 m/s. Acoustic amplitudes do not correlate with range: the closest and furthest stations had similar values, whereas a balloon about midway between the two was higher by nearly a factor of three. The stations' altitude did not seem to account for amplitude differences either: two balloons were at the same elevation yet recorded a twofold difference in amplitude.

The pressure spectra recorded during the experiment is shown in Figure 6. They show a prominent ocean microbarom peak at a period of about 6 seconds. Wind noise typically obscures this peak during the day on ground sensors. In contrast, the presence of the ocean microbarom peak on the balloon-borne stations during the experiment underscores the lack of wind noise on free floating microphones.

Acoustic impedance variation must be taken into account when comparing pressure wave amplitudes and power spectra for sensors at different altitudes. When the stations are adjusted for acoustic impedance, the traces collapse together across the microbarom peak. This is to be expected since the ocean microbarom arrives from thousands of kilometers away, and thus its intensity is probably uniform over the network aperture. Although care must be taken when

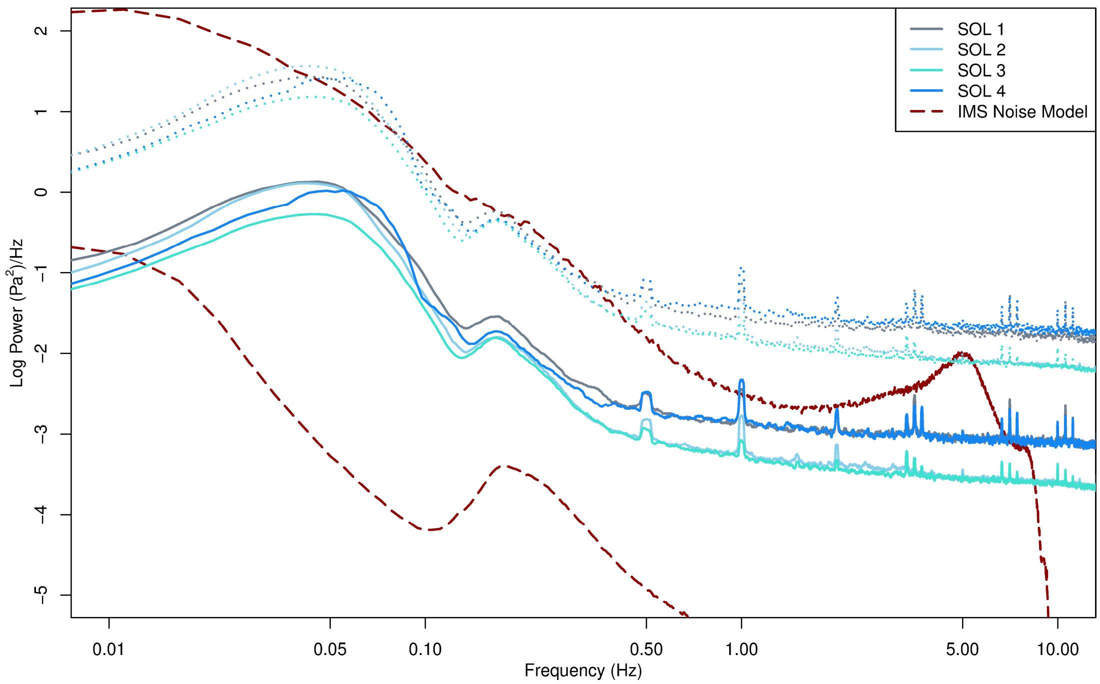


*Figure 6: Infrasound spectra on the four Gem stations. Solid lines are as-recorded, dotted lines are adjusted for acoustic impedance relative to standard atmospheric conditions at sea level. The IMS noise model is shown for comparison.*

interpreting the ordinate distance between lines on a logarithmic scale, simply multiplying each trace by a factor of 5 (the approximate impedance contrast between sea level and the balloons' collective mean float altitude) does not provide as close a fit. Therefore, the agreement across the microbarom peak does reflect a correct impedance adjustment across the approximately 3 km elevation difference between array elements.

A comparison with the IMS infrasound array noise model shows that the balloon borne sensors performed well in the 20 to 2 second band. However, the adjusted spectrum above 0.5 Hz has higher noise levels than the IMS noise model. In addition, peaks at integer multiples of 0.5 Hz are present. The harmonics are probably due to electronic interference from the status LED on the Gem sensor, which flashes at 1 Hz during normal acquisition and 2 Hz when the GPS is active. The spectrum above 0.5 Hz is probably also due to the digitizer itself rather than the ambient acoustic wave field.

Flight spectrograms (Figure 7) illustrate the sporadic occurrence of the harmonics described above as well as times when the SPOT Trace tracker was transmitting at ten minute intervals. While the complex narrow band signals shown on spectrograms during the HASP flight over the same region in 2014 are absent, similar periods of broad band activity occur. During the Heliotrope experiment, the broad band episodes are present between 1900 and 2200 UTC on SOL 1 and SOL 4 but do not appear on the higher altitude stations SOL 2 and SOL 3. Three individual bands between 1930 and 2100 UTC appear to have a time delay of about 720-740 seconds between SOL 4 and SOL 1, suggesting a possible link between them. Given the distance between the balloons (40 to 79 km during that time period), the signals are clearly traveling much too slow to be acoustic waves.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

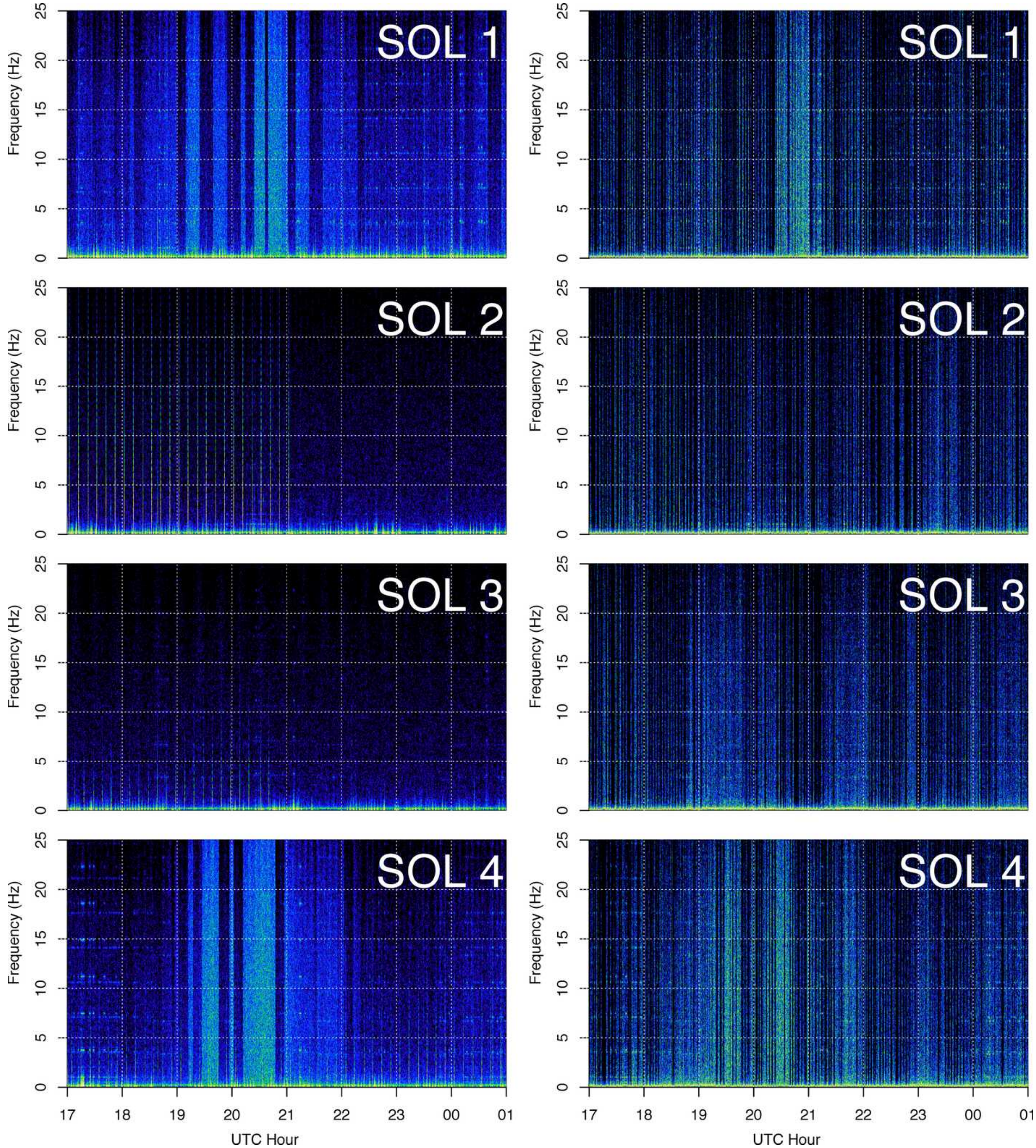


*Figure 7: Spectrograms recorded during the flights. The left panel is on a global scale, the right panel has each spectrum self-scaled between 0 and 1.*

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

## DISCUSSION

Arrivals on ground stations were remarkably variable despite the shots having taken place only 90 minutes apart. The ANSI range/overpressure model predicts acoustic amplitudes of about 40 Pa for an 800 kg TNT equivalent shot detonated at 10 km range, but the maximum overpressure at station GRAD was less than 10 Pa for the first shot. The atmospheric defocusing effect was less severe on the second shot, which had close to the predicted amplitude. Acoustic amplitudes recorded at Station GRDY (east) and ACIA (north) were less variable between the two shots. However, a very strong arrival was recorded at station ANTO (south) for the first shot, whereas the second shot is obscured by wind noise. Balloon trajectories indicate that winds from near the ground surface to several thousand meters above the ground surface were blowing to the south, creating an acoustic wave guide that could explain the amplification observed at ANTO. The large amplitude variations on ground stations between the two shots indicates that the wind and temperature structure of the lower atmosphere was very dynamic during the experiment.

The first shot was not visible on the balloon borne network despite it being at lesser range. It is likely that the network was located in an acoustic "shadow zone" produced by the sound velocity structure of the troposphere and stratosphere. This is often observed on the ground as well.

The balloons were no longer in the shadow zone when the second shot was detonated. Indeed, the distinctive inverted "N" shape of the highest amplitude Shot 2 wavelet on the high altitude stations gives clues to the infrasound propagation path from the blast site to the balloons. The celerity of the wave form indicates that it was trapped in the stratospheric duct. Caustics occur as part of this refraction/ground bounce mediated duct. When acoustic signals encounter a caustic, the waveform undergoes a 90-degree phase shift. Two successive caustics can take the direct wave (overpressure followed by rarefaction, an "N" wave), and flip it (rarefaction followed by overpressure, an inverted "N" wave). Simple caustics occur after each ground reflection but below the turning point for infrasound propagating in an acoustic duct. If the signal recorded on the Heliotrope balloons is a result of these successive transforms, the array either captured the wave after the second bounce but before the third bounce, or below the caustic after the third bounce.

Acoustic ducting in the troposphere and stratosphere is controlled primarily by the wind. On the day of the experiment, the balloon trajectories indicate that tropospheric winds were going north, and stratospheric winds were going west. Thus, infrasound from the EMRTC blasts could have been ducted northward in the troposphere and westward in the stratosphere. Stratospheric propagation models suggest that caustics will be separated by well over 100 km, which is too great a range for the observed signals. It is possible that the signals originate in the tropospheric duct and "leak" into the stratosphere; the smaller length scale of tropospheric bounces may permit the necessary number of caustics. However, celerities in the range of 300 m/s are indicative of waves propagating in the stratospheric duct instead of the tropospheric duct.

Perhaps the most likely explanation is that the balloons were located in a caustic surface that forms after the infrasound has refracted off of the stratosphere for the first time; this provides the best match for celerity, range, and altitude. In this case, the origin of the specific

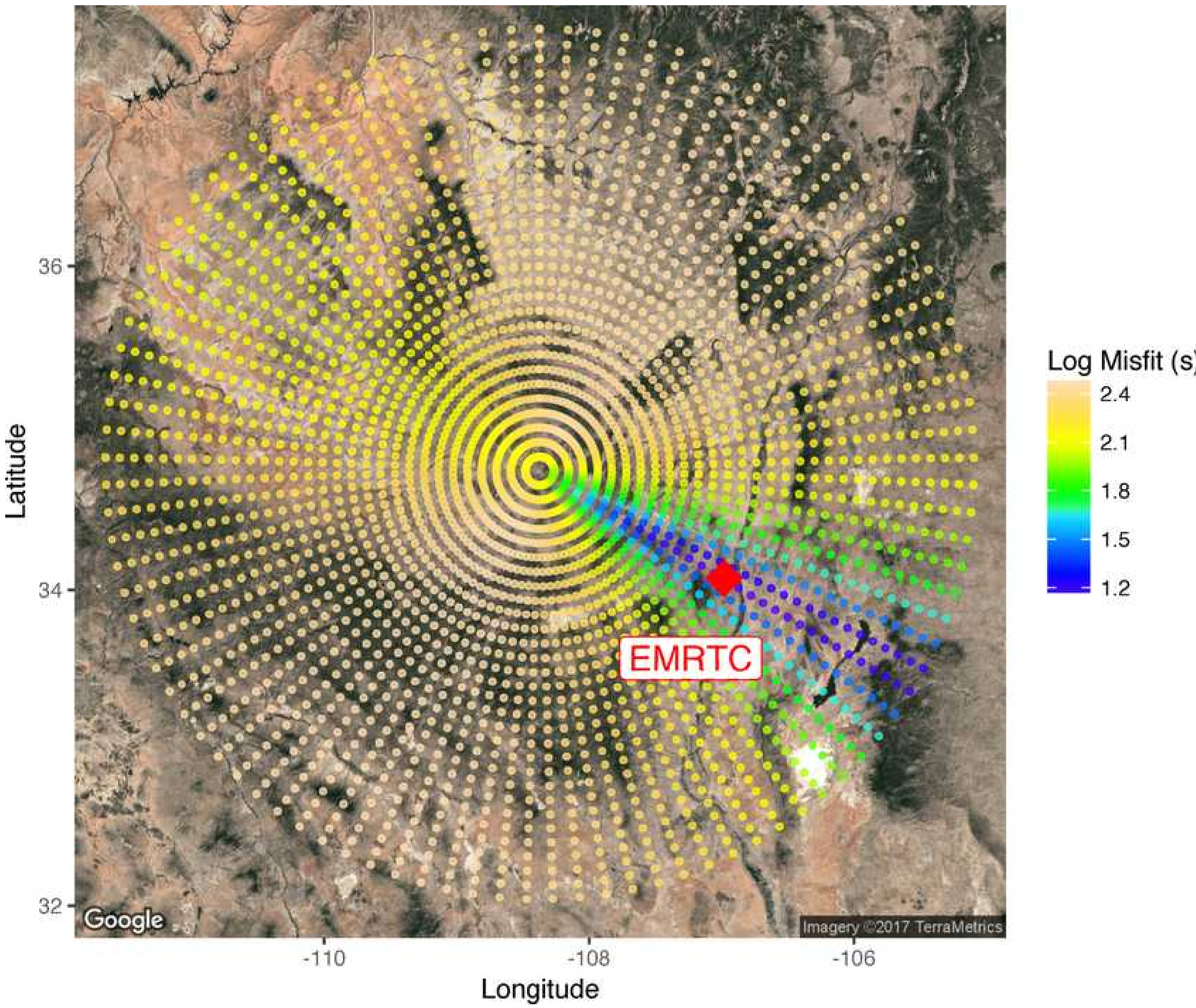


*Figure 8: Backazimuth determination using a curved wave front correction. The best solutions lie on the line between the source and the array centroid.*

wave form is less clear since geometrical acoustics assumptions do not hold near caustics. The modeling required to definitively resolve these questions is beyond the scope of the present work, but provides fruitful avenues for future study.

One of the goals of the study was to determine the backazimuths of the explosion signals. The balloon-borne array differed from a typical ground-based deployment in that the sensors were much further apart (tens of kilometers as opposed to 1-4 km for IMS stations). The balloons were at substantially different elevations as well, which reduces the effectiveness of 2D beamforming techniques.

Although the plane wave assumption fails for the network aperture/source distance ratio for Shot 2, the circular wave front geometry correction provided an accurate backazimuth estimation (see Figure 8). In principle, the method yields source location and celerity as well. However, we found that these values are very unstable with respect to the choice of arrival sets and even the density of the azimuth grid. Indeed, previous literature notes that localization capability is compromised when the source-receiver distance is greater than about two times the network aperture. At the range in which it was employed, therefore, the circular wave front geometry method is best regarded as a correction to plane wave based backazimuth estimators rather than a standalone location technique.

## ANTICIPATED OUTCOMES AND IMPACTS

The last three years have seen the first high altitude infrasound microphone deployments in half a century. The advantages and disadvantages of free flying stations are now becoming clear. They are entirely free of the wind noise that plagues even the most well engineered ground infrasound station. They can cross inaccessible areas, such as the open ocean, and detect signals at greater ranges than co-located surface microphones. However, they are susceptible to noise sources such as electromagnetic interference; this becomes more severe with altitude due to decreased pressure wave amplitudes at lower air densities. It is difficult to control their position. Finally, the extreme environment in the upper troposphere and lower stratosphere bring unique challenges, primarily in regards to temperature control.

The high altitude infrasound program progressed from pilot testing in 2014 and 2015 (demonstration of infrasound acquisition at altitude) through proof of concept in 2016 (detection of a known ground source). The Heliotrope experiment was the next logical step: an attempt to field a free flying infrasound array that was able to accomplish the same direction-of-arrival operations as a ground network. This project was a success: it accomplished the primary objective (record and determine backazimuth to a known acoustic source using a network of free flying stations) and the secondary objective (utilize a solar hot air balloon flight system to loft payloads for multi hour missions.

Future work on high altitude infrasound stations must focus in improving the microphone's sensitivity, eliminating spurious noise sources, increasing temperature resistance, and developing a data telemetry system. Although the aperture of the Heliotrope array remained relatively constant throughout flight, it likely could have been tighter had the balloons been ballasted to exactly match each other's mass and thus float altitude. While solar hot air balloons are ideal for short duration campaigns, they cannot fly past sunset; small superpressure helium balloons can stay aloft for over two years. Finally, data analysis methods adapted for drifting (rather than static) stations must be further investigated. Currently, the influx of data from successive balloon-borne microphone experiments is outstripping the development of signal processing expertise to properly analyze the signals that are recorded.

A balloon-borne infrasound acquisition system is a secondary diagnostic on the Dry Alluvium Geology project taking place in 2018. During this experiment, a series of buried explosions will be detonated and the resulting seismic and acoustic signals analyzed. Since buried explosions radiate most of their acoustic energy upward, a high altitude network is the only viable means of measuring their full infrasound wave field. The balloons will carry more sensitive microphones with mechanical high pass filters that have corner frequencies above the Brunt-Vaisala cutoff. This will eliminate the high amplitude, long period pressure signal from balloon oscillation, allowing the microphones to operate at much higher gain. This should greatly improve the signal to noise level. During test flights in preparation for this experiment, we will paint the payload boxes black to raise their internal temperature. This simple fix may be sufficient to prevent the cold-induced GPS issues experienced during Heliotrope and other flights. The scope of the DAG experiment is similar to that Heliotrope: detect a known acoustic source occurring at a predictable time. In this case, however, the scientific yield will be greater because the acoustic signal is believed to be directional.

Now that the capability of targeting a known signal occurring at a specified place and time has been realized, two new avenues present themselves. The first is to demonstrate the ability to overfly a specific region and acquire signals directly above it, and the second is to create a long duration free flying infrasound station that remains in the air for months to years. A natural target for the first objective is a volcano that erupts several times a day. Reventador Volcano in Ecuador creates exceptionally powerful explosions every few hours, and flight models suggest that a Heliotrope-like array launched from the Quito region could pass overhead. The scientific dividend of such a project would be an accurate characterization of the 3D wave field from volcanic explosions. This is currently a very active research area in volcano acoustics.

A balloon-borne sensor that stays aloft for years at a time is also within our technical means. The flight system is already proven: a university group recently launched a small balloon that has circled the Earth multiple times. In fact, it has traveled nearly as far as the Moon in terms of total distance. A balloon carrying a lightweight infrasound payload consisting of a photovoltaic system, microphone, digitizer, and telemetry would be able to characterize signals and background noise on a global scale. The most challenging aspect of this proposal is designing a robust power system and telemetry apparatus. One idea is to to store data locally, then transmit it via APRS whenever a ground station comes into range. Both the volcano overflight and the persistent station are appropriate for a full LDRD proposal. We will be reaching out to potential team members shortly.

Our increasing expertise in high altitude infrasound has led to two NASA proposals with Sandians as PI. The first is to use balloon-borne microphones to detect meter and submeter scale bolides. The Earth-impacting population in this size range is poorly characterized, but ground based studies suggest that a sensitive microphone network can detect one event per week. Given the sensitivity advantages at altitude, we believe we could achieve even higher rates. Our proposal was submitted to the Solar System Observations Near Earth Object Observations solicitation in June 2017. Our second Sandia-led proposal was to the NASA Innovative Advanced Concepts (NIAC) program. It aims to demonstrate long duration flight with a hot air balloon that absorbs sunlight during the day and infrared radiation from the Earth's surface at night. Such balloons were demonstrated in the 1990s, but we aim to make them much smaller and cheaper. This would not only enable low cost, long duration scientific ballooning campaigns on Earth but also missions to planets such as Jupiter or Venus. Experience gained when fielding solar hot air balloons during the Heliotrope project directly led to the NIAC proposal. Finally, Jet Propulsion Laboratory has proposed to hire Sandia to perform two solar hot air balloon flights with infrasound sensors on board as part of a NASA proposal they will submit this October.

## CONCLUSION

A five element, free flying infrasound network was deployed over New Mexico and Arizona to capture acoustic signals in the lower stratosphere and evaluate the capabilities of balloon borne arrays. The network was able to detect and determine the backazimuth to one of two explosions performed near the launch site. The signal recorded at altitude was complex and showed multiple refractions from the troposphere or the stratosphere. The other explosion was not detected, although the noise floor of the sensors used on the balloons may have obscured it.

The presence of the ocean microbarom peak throughout the flight suggested that the network was not susceptible to wind noise, although interference from the payload tracker may have caused loss of signal for one of the shots. The balloon borne microphones' noise level compared favorably to the International Monitoring System ground station noise model in the 50 to 2 second band. However, the self-noise of the Gem logger probably dominated the spectra above 0.5 Hz. The complex signals present on previous flights in the same region were not observed, although similar episodes of sporadic broadband activity was noted.

The Heliotrope experiment has shown that it is possible to deploy a network of free floating microphones to perform observations in regions inaccessible to ground based instruments. These stations can directly observe infrasound that seldom reaches the ground, such as waves from supersonic aircraft trapped in elevated ducts. They are able to intercept elevated caustics and other phenomena that have rarely been observed directly. Event location techniques applicable to sparse networks on the ground can be employed at altitude as well, although elevation differences tend to be much greater and thus must be accounted for. Free flying networks also have unique advantages. For example, a continuously moving network may permit precise location of a source that repeats itself at least once; in effect the multiple events generate an equal number of unique sensor configurations.

Expertise gained during the Heliotrope experiment has led to a high altitude infrasound component during the DAG campaign. It has contributed to two NASA proposals and is relevant to the work outlined in a third one. Two follow up proposal concepts to the full LDRD program are being considered: one to target an exploding volcano and another to field a globe-crossing infrasound station. Finally, the results outlined in this report are largely taken from a submission to the peer-reviewed journal *Geophysical Journal International* titled “Infrasound Event Location and Background Noise on a Free Flying Microphone Network in the Lower Stratosphere”.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.