SEISMIC AND INFRASOUND ENERGY GENERATION AND PROPAGATION AT LOCAL AND REGIONAL DISTANCES: PHASE 1 – DIVINE STRAKE EXPERIMENT

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ABSTRACT

There are unanswered critical questions on the phenomenology surrounding the generation and local-to-regional distance propagation of seismic and low frequency acoustic energy from shallow sources (industrial and mining explosions, chemical test explosions, underground mine related stress release, and earthquakes) that impact the use of observations for source identification, location and characterization in areas with little ground truth. While there have been extensive seismic and acoustic observations of shallow sources (McKenna, 2005; Mutschlecner and Whitaker, 2005; ReVelle, 2004; Patton et al., 2003; Yang et al., 1999, and Dighe et al., 1998) these have been limited in most cases to a moderate number of short-term stations for a single group of events or have focused on signals from one location into one possibly augmented array. Therefore, there is a need to extend the previous observational and theoretical studies using dense networks of simultaneous seismic and infrasound observations of a wide variety of sources at local and regional distances. The acquisition of a dense profile of observations along one or more profiles that characterize the wavefield transition from local to regional distances is a critical component needed to understand seismic and infrasound propagation. Ground truth provides source constraints that are necessary for unique interpretations.

The Defense Threat Reduction Agency (DTRA) planned detonation of approximately 700 tons of explosives in Area-16 of the Nevada Test Site (NTS) was to provide the opportunity to gather such a dataset. On February 22, 2007, DTRA announced the cancellation of the Divine Strake explosion. During the preparation for the Divine Strake experiment and as a result of a single infrasound array and seismic network across Utah, a number of large and consistent infrasound sources have been identified and characterized. These preliminary efforts have resulted in the identification of regular (21 recorded to date) and large (40,000–80,000 lb) surface explosions at the Utah Test and Training Range (UTTR) of the Hill AFB. These sources are producing excellent near-regional seismic and infrasound signals that are currently being stored at the Incorporated Research Institutions for Seismology (IRIS) Data Management Centre (DMC). Our group has cooperated with the group at Hill AFB and begun modeling these events and has used atmospheric profiles that are regularly taken by the Air Force in this modeling exercise (documented in our annual report). Additional sources of infrasound such as mining explosions are also documented in the report, and the regional earthquake database is being compiled.

Based upon this unexpected source of large, surface explosions and close cooperation between the Air Force and our group, the initial goals of our project can be reached by shifting our focus to these new sources now that Divine Strake has been canceled. The rocket motor explosions, unlike the single Divine Strake explosion, occur about every week providing an opportunity to develop seismic and infrasound recordings under a wide range of atmospheric conditions. Cooperation with the Air Force will provide the necessary atmospheric data needed for modeling. Our consortium is redesigning the regional experimental deployment to take advantage of the regular rocket motor explosions at UTTR and plans to implement the experiment in the summer of 2007.

OBJECTIVES

The initial objective of this project was to record regional seismic and infrasound signals from the planned Divine Strake explosion. On February 22, 2007, DTRA announced the cancellation of the Divine Strake explosion. During the preparation for the Divine Strake experiment and as a result of the infrasound array and seismic network across Utah (Figure 1), a number of large and consistent infrasound sources have been identified and characterized. These sources included large (40,000–80,000 lbs) surface explosions at the UTTR of the Hill AFB. These sources are producing excellent regional seismic and infrasound signals that are currently being stored at the IRIS DMC. Our group has cooperated with the group at Hill AFB and has begun modeling these events and has used atmospheric profiles that are regularly taken by the Air Force in this modeling exercise. Additional sources of infrasound such as mining explosions are also documented in the report and the regional earthquake database is being compiled.

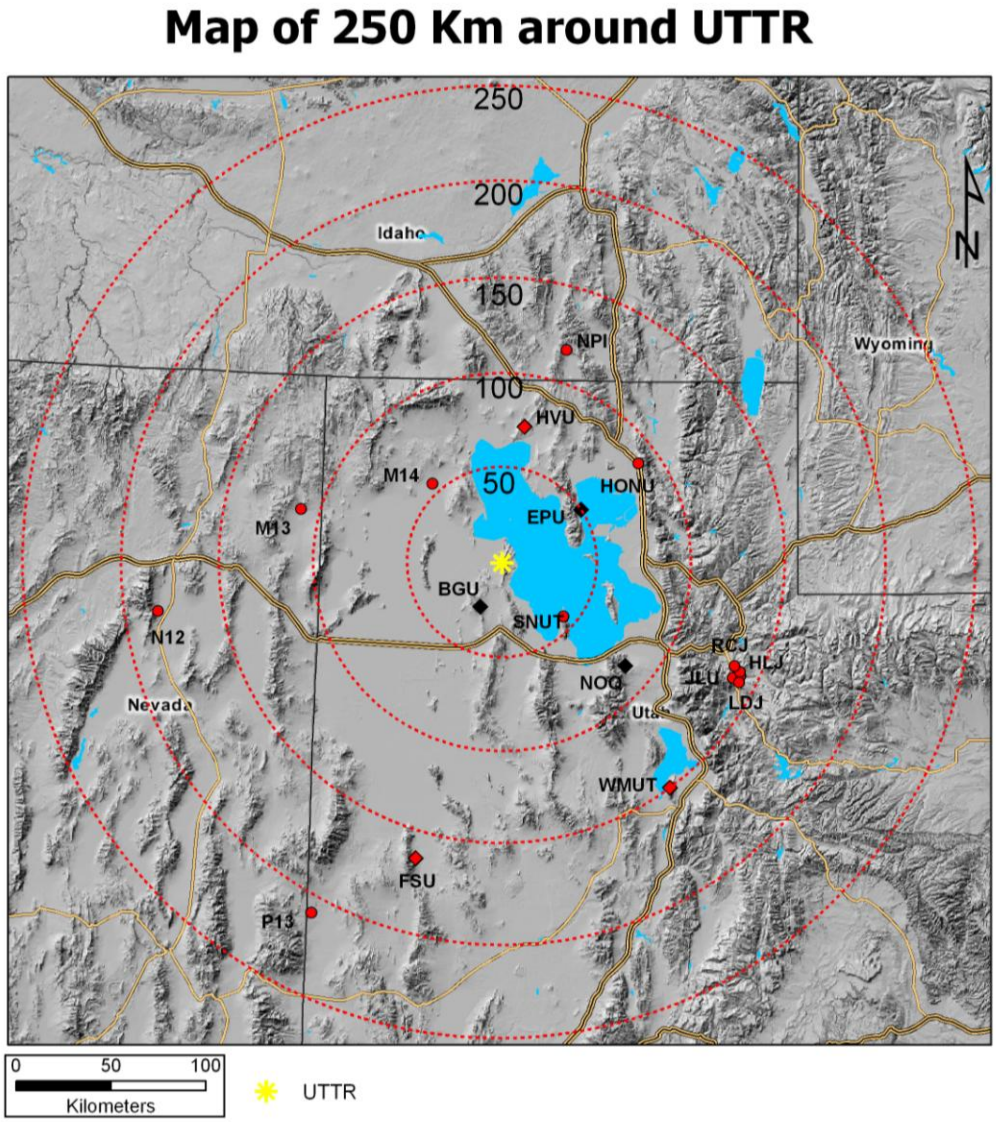

Figure 1: Existing and planned seismo-acoustic stations in Utah. The yellow star is UTTR, the site of the explosion. Solid black diamonds are permanent infrasound arrays, red diamonds are temporary infrasound arrays, and red circles are locations of single infrasound gauges.

Based upon this unexpected source of large surface explosions and close cooperation between the AF and our group, the initial goals of our project are being addressed by focusing our experimental work on these new sources. Preliminary data collected and analyzed in this report illustrate that both seismic and infrasound signals are observed at the distances of interest to our proposal as it was funded. The rocket motor explosions, unlike the single Divine Strake explosion, occur about every week providing an opportunity to develop seismic and infrasound recordings with a range of atmospheric conditions. Cooperation with the AF together with our own planned atmospheric profiling will provide the necessary atmospheric data needed for modeling.

As a result of preparations for Divine Strake two, four-element infrasound arrays are deployed at seismic sites BGU and NOQ both part of the University of Utah Seismograph Stations (UUSS) regional network (Figure 1). One additional array is planned at a third site, EPU. These three arrays are all telemetered in real-time to the University of Utah. NOQ has operated for over one year and regularly records seismic and infrasound signals from UTTR rocket motor detonations as well as numerous explosions from nearby mining operations.

UTTR explosions are planned weekly during the summer of 2007, and so a four-week equipment deployment to supplement the two current and one planned infrasound arrays has been planned. The planned four-week campaign will provide the opportunity to record 3 to 4 UTTR explosions as well as numerous other events that occur during the time period. The experiment has the following components as illustrated in Figure 1:

- 3 close-in acoustic plus seismic stations to document the source in the 100–1000 m range.
- Supplementation of the existing three-infrasound arrays to bring the total number to six. The three additional arrays will be deployed at distances beyond 100 km and may be expanded to five elements each.
- Addition of a single infrasound sensor at 4 Earthscope US Array and 7 UUSS sites in order to quantify infrasound to seismic coupling as well as to expand the number of azimuths and ranges recorded.

In preparation for the planned experiment a visit was made to UTTR on 4 June 2007 to observe the detonation of a rocket motor. The explosion was observed from a distance of about 1 mile as illustrated in Figure 2.

Figure 2: Images documenting the rocket motor detonation (explosive weight 39,000 lb) on June 4, 2007, at UTTR.

RESEARCH ACCOMPLISHED

Research in the last year has focused on three areas. In order to deploy a substantial number of infrasound gauges to document the regional propagation path effects, it was necessary to acquire and characterize a new and cost effective acoustic gauge. Second, while waiting for the Divine Strake experiment to occur two (soon to be three) infrasound arrays were deployed in Utah. Preliminary analysis and modeling of data recorded at one of these arrays identified a number of interesting infrasound sources. Finally, as a result of the cancellation of Divine Strake and the identification of the large surface explosions at UTTR, an experiment was designed to document UTTR detonations in the summer of 2007. A visit to UTTR for the June 4, 2007, rocket motor explosion (Figure 2) provided preliminary data used to complete the planning for the experiment.

New Infrasound Gauges

Twenty-five, new cost-effective infrasound gauges were ordered and received from Inter Mountain Laboratory (IML) (Figure 3). The lower cost of these gauges provided the opportunity to purchase enough gauges (25) to instrument a number of infrasound sites. These gauges, as illustrated in Figure 3, are composed of 20 individual microphones whose output is summed to improve the instrument signal to noise. The instruments were designed for the purpose of avalanche monitoring. However, no data sheets or instrument response tests were published for the gauges. As our application is different, we needed to quantify the gauge response.

The electronics pictured in Figure 3 include a variety of filtering and signal conditioning components. Each gauge has eight ports for connection to porous hoses for noise reduction purposes. As a result of the filtering and signal conditioning capabilities built into each gauge, two different outputs, with different frequency responses, are available from each gauge.

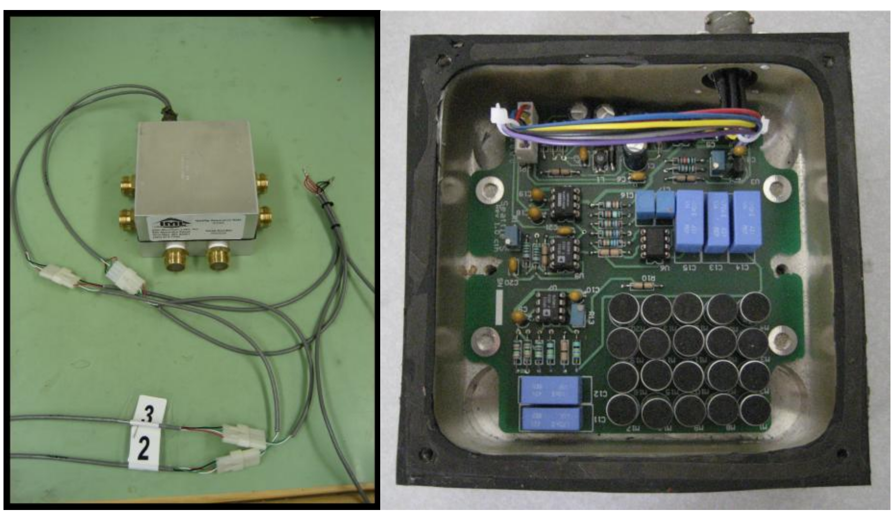

Figure 3: The IML infrasound gauge is pictured above. The exterior view is illustrated to the left with six of the eight ports for hose connections. The interior view of the gauge is illustrated to the right with the 20 microphone cartridges in the lower right and the accompanying signal conditioning and filtering electronics.

Laboratory tests were conducted on all 25 IML gauges. For calibration purposes, each IML gauge was run along side a reference gauge, a Chaparral 2. Three-hour data segments were recorded and used to determine the frequency response of the filtered and unfiltered output of the IML gauge as well as the response of the Chaparral 2 for comparison (Figure 4, left). The data were also used to compute the coherence of the IML filtered and unfiltered outputs with the reference Chaparral 2 output (Figure 4, right). The Chaparral 2 has a broader band response (Figure 4) but there is great similarity between the IML and the Chaparral 2 in the important band of 1–10 Hz. The high coherence between the Chaparral 2 and the unfiltered IML to nearly

50 s and to below 10 s with the filtered IML output suggests that, despite the difference in responses, the IML gauge can be utilized to retrieve signals below 1 Hz.

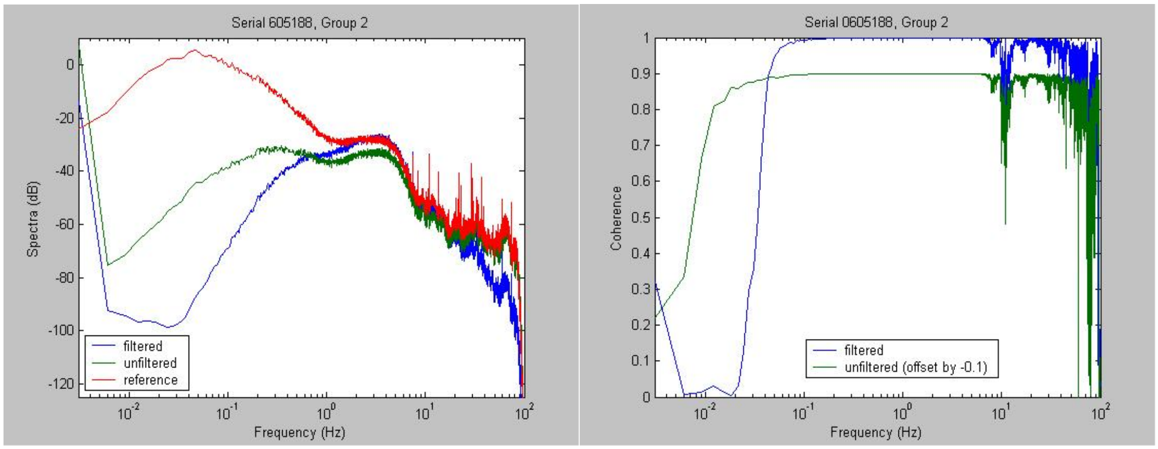

Figure 4: Response of the Chaparral 2 (red), unfiltered IML (green), and filtered IML (blue) from the calibration tests (left). Coherence between the Chaparral 2 and the filtered IML output (blue) and the Chaparral 2 and the unfiltered IML output (green, offset by 0.1 units for display) is displayed to the right.

Similar tests were conducted on all 25 gauges. Results from these tests indicate that the response and coherence estimates for the one gauge in Figure 4 are similar for all 25 gauges. A theoretical transfer function for the IML gauge was developed as part of the analysis. The IML response was removed from the data taken during the laboratory tests and the resulting output convolved with the known Chaparral response. As illustrated in Figure 5, the observed Chaparral data (high pass filtered at 10 s) are reproduced by this deconvolution followed by convolution procedure.

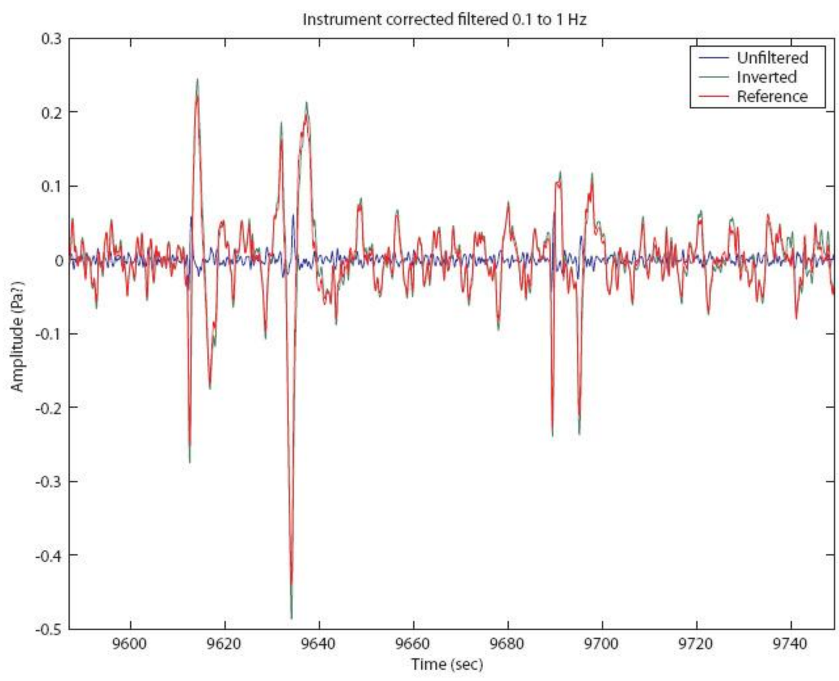

Figure 5: Comparison of IML output (unfiltered), Chaparral output (reference, high pass filtered at 10 s) and IML output corrected for IML response and convolved with known Chaparral response (inverted, high pass filtered at 10 s). The instrument corrected IML data closely match the Chaparral output for the same time window.

Preliminary Seismo-Acoustic Observations and Modeling

The infrasound array deployed at NOQ has regularly recorded signals from two locations since its installation in May 2006. The first source is mining explosions from the Bingham Canyon Mine operated by Kennecott Utah Copper. The mine is located to the south of the station (Figure 6) and blasts almost daily.

Figure 6: Location of two sources of infrasound signal observed at the NOQ. Bingham Canyon Mine is to the south of the station and the Utah Test and Training Range is to the northwest. Image generated by Google Earth.

Figure 7 shows a seismic and infrasound signals recorded from a Bingham blast on May 5, 2006, at NOQ. This event had an M_L of 1.8 and was observed at 15 stations of the UUSS regional network. Clear infrasound signals accompany this event.

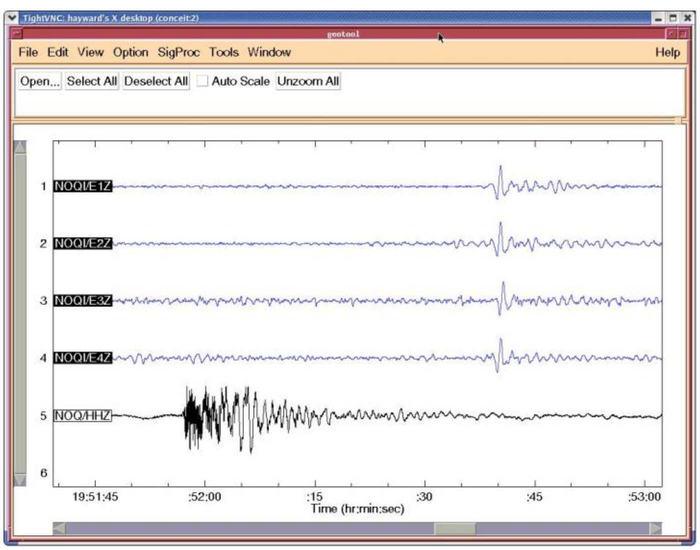

Figure 7: This signal is from a mining blast detonated at Bingham open-pit copper mine on May 5, 2006. The event had an M_L=1.8 and was observed by 15 stations of the UUSS regional network.

The second set of sources that have been recorded on a regular basis at NOQ are a result of the explosive disposal of Trident rocket motors to the northwest of the station (Figure 6). These detonations are conducted at the Thermal Treatment Unit (TTU) of the UTTR of the Hill AFB. Two events recorded to date at NOQ from these detonations are illustrated in Figure 8. These figures illustrate the signal coherence, phase velocity and azimuth estimates for events on May 9 and August 21 using the InfraTool (Hart and Young, 2005). Coherence across the array is good for both events and produced stable azimuth estimates. One interesting thing to note in this example is the marked difference in both amplitude and signal duration for these two signals. The signal from the May 9 detonation is nearly 40 times larger in amplitude than that from August 21 and much shorter in duration.

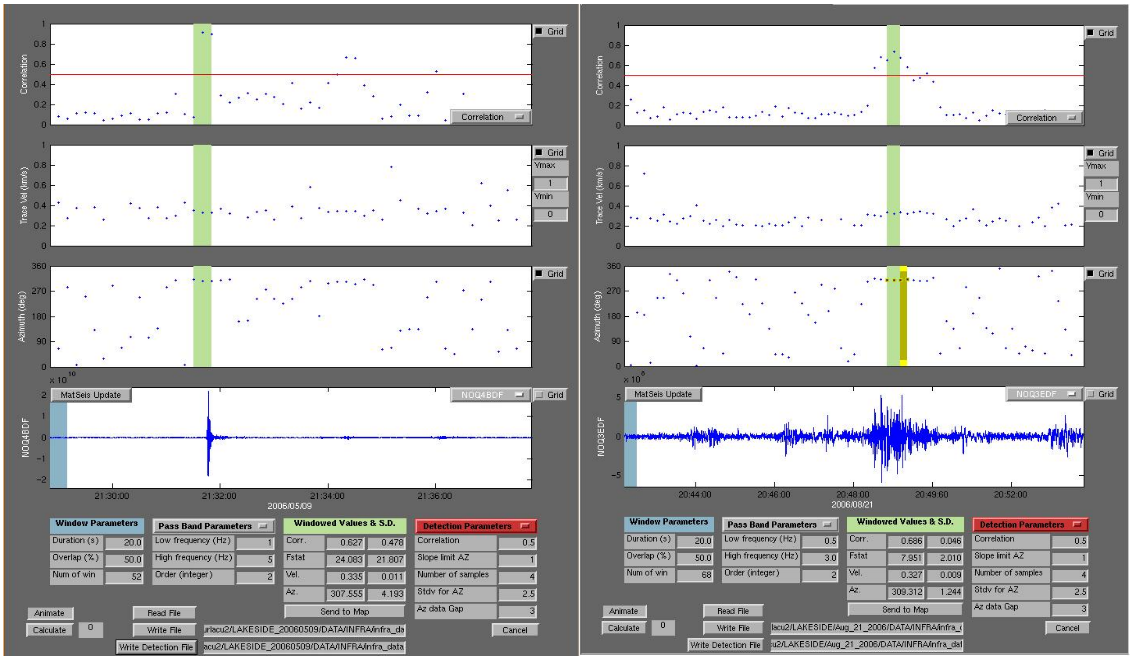

Figure 8: Infrasound signals recorded at NOQ from Trident rocket motor disposal explosions conducted at the UTTR. Processing results using InfraTool for a detonation on May 9 (left) and August 21 (right) are displayed.

It is interesting to note that infrasound signals from these rocket motor detonations are observed on some of the seismic stations of the UUSS regional network (Figure 9). These additional data, possibly calibrated for seismic to acoustic coupling, may prove useful in our infrasound studies.

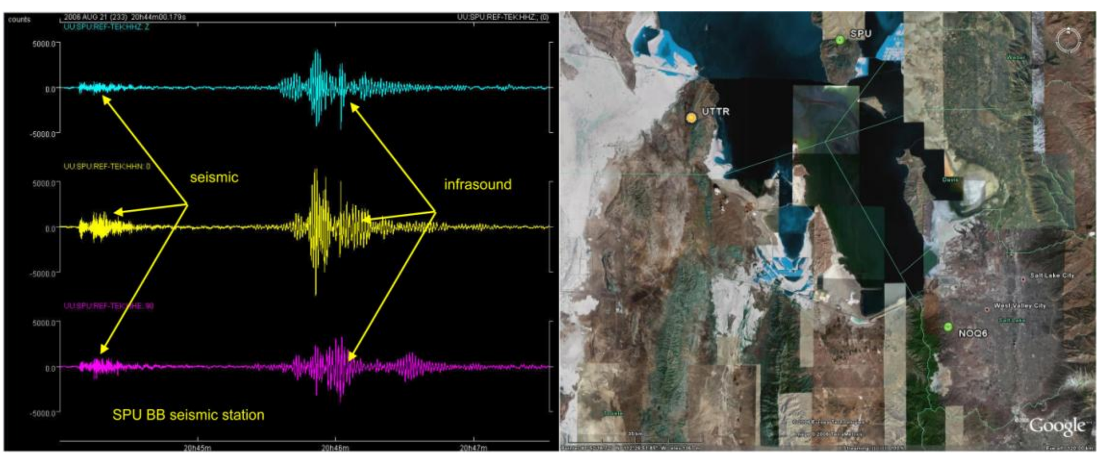

Figure 9: Infrasound signals observed on the seismic channels at the station SPU from UTTR rocket motor detonation (left) on August 21. The location of SPU relative to the source at UTTR and the infrasound array at NOQ is illustrated to the right. Overhead image generated by Google Earth.

The relatively large number of infrasound signals recorded at NOQ from repeated sources such as the rocket motor detonations at UTTR motivated a preliminary look at some simple modeling of the signals. As noted in Figure 8, large variations in amplitudes and wave characteristics have been observed. The explosions from UTTR are in the zone of silence and so some understanding of the path effects was of interest as well. The modeling package InfraMap written and maintained by BBN (Gibson and Norris, 2006) was utilized in this preliminary work. Figure 10 illustrates some early results comparing ray tracing using the MSIS/HWM model to a local model based on actual tropospheric soundings taken prior to the rocket motor detonation. The MSIS/HWM model predicts no ray arrivals inside of 300 km while the data based model predicts rays that turn in the troposphere and arrive at distances comparable to where we have infrasonic observations of the explosions.

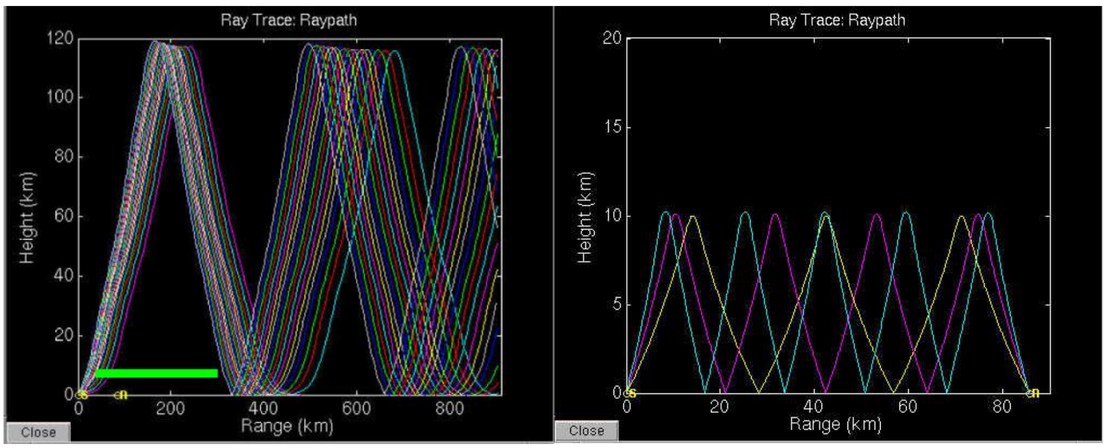

Figure 10: Ray tracing results using the MSIS/HWM (left) and local model based on low altitude sounding data (right) at the time of one of the UTTR rocket motor explosions.

June 4, 2007, UTTR Rocket Motor Detonation

As part of the planning exercise for the summer of 2007 experiment a visit was made to UTTR and one of the rocket motor detonations was observed. The visit included discussions with UTTR personnel concerning atmospheric monitoring during the detonations. At the time of the detonation two of the infrasound arrays, BGU (Figure 11) and NOQ (Figure 12), were operating. Data from these two arrays as well as seismic observations across the UUSS seismic network (Figure 13) provided the basis for the experiment plan as illustrated in Figure 1. The June 4, 2007, detonation was recorded both by the UUSS seismic network and by the 2 infrasound arrays (NOQ and BGU).

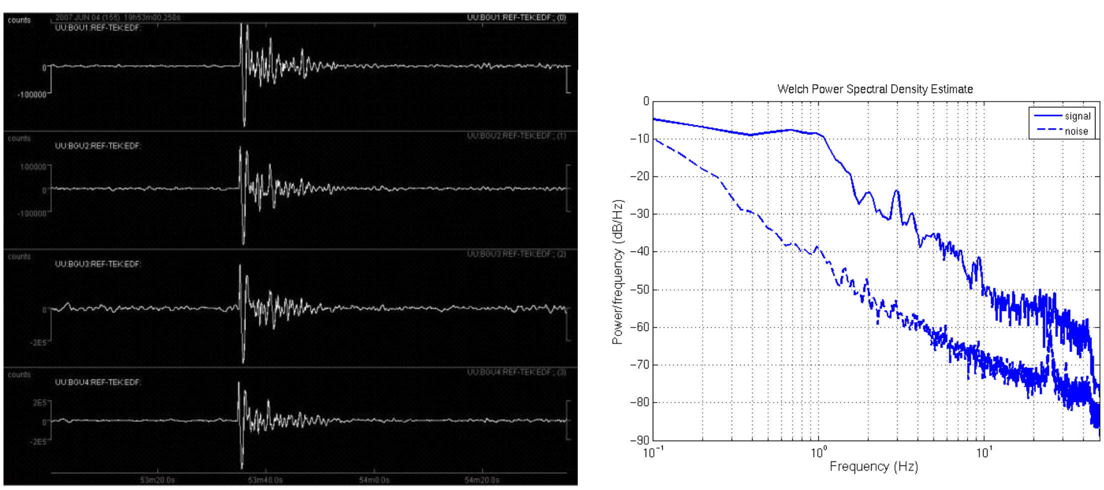

Figure 11. Observation of the June 4, 2007, UTTR explosion at the array BGU (Figure 1), Noise and signal spectra for the BGU1 element of the BGU infra array are displayed to the right.

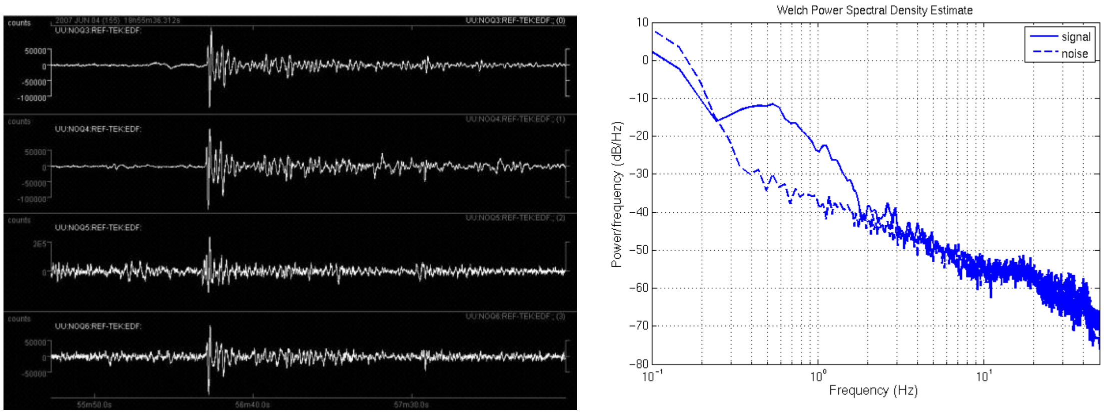

Figure 12. Observation of the June 4, 2007, UTTR explosion at the array NOQ (Figure 1). Noise and signal spectra for the NOQ3 element of the NOQ infra array are displayed to the right.

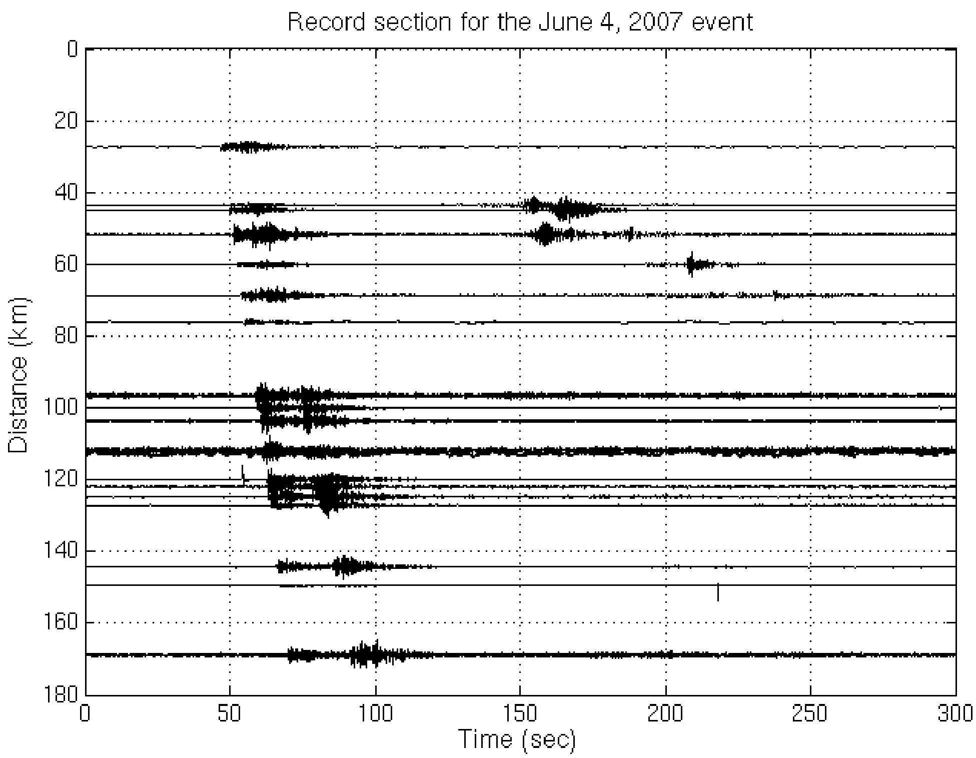

Figure 13. Record section of seismic stations from the UUSS regional network illustrating the seismo-acoustic signals from the June 4, 2007, UTTR detonation.

CONCLUSIONS AND RECOMMENDATIONS

A new type of infrasound gauge manufactured by Inter Mountain Laboratory has been acquired for the experiment. These gauges designed for avalanche monitoring are modest in cost and so provide the opportunity to use a larger number of sensors when compared to the cost of conventional gauges. Twenty-five of these gauges were acquired and tested and compared to a conventional infrasound gauge in our laboratory. This comparison indicates that these gauges will be useful in recording signals in the

1–10 Hz band and can be pushed to lower frequencies based on good coherence with signals from conventional gauges to periods as long as 50 seconds.

Two infrasound arrays have been installed at UUSS seismic sites in Utah. The infrasound array at NOQ, installed in May 2006, is regularly recording infrasound signals including repeated sources from mining explosions at Bingham Canyon Mine and Trident rocket motor detonation at UTTR. The variability of these signals and the ability to make infrasound observations on some of the seismic stations as part of the UUSS regional network has motivated a preliminary modeling study. This study suggests that short-term variations in the troposphere may greatly affect not only the amplitude but also the wave characteristics in the so-called zone of silence.

An experimental plan has been developed for deploying seismic and infrasound gauges to record UTTR near-surface explosions over a month time period. A total of six infrasound arrays, three close-in infrasound and seismic stations and 11 single infrasound gauges co-located with existing seismometers will be deployed. An approximate one-month deployment spanning August 2007 is planned during which several UTTR detonations are anticipated.

ACKNOWLEDGEMENTS

Instruments for the planned portable deployment described in Figure 1 are being provided by PASSCAL. Contract FA8718-05-C-0020, Air Force Research Laboratory, has supported the array deployments at NOQ and BGU separately.

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