SEISMO-ACOUSTIC GENERATION BY EARTHQUAKES AND EXPLOSIONS AND NEAR-REGIONAL PROPAGATION

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ABSTRACT

Seismo-acoustic measurements provide an opportunity to quantify natural and man-made sources that are at or near the Earth's surface. We have operated three acoustic arrays collocated with seismometers from the University of Utah Seismograph Stations (BGU, EPU, NOQ). We report on progress in three separate areas of research related to these seismo-acoustic databases. The first topic investigates seismo-acoustic signals from the Wells, Nevada earthquake that occurred on February 21, 2008 at 14:16:02 UTC (M_W 6.0). The detailed research and interpretation of this event has been conducted under a separate effort (Arrowsmith et al., 2009c, these Proceedings). The focus in this work is on the data acquisition and highlighting the sources of seismo-acoustic signals that can be observed on regional seismo-acoustic arrays. This event was well recorded by many seismic stations, including the EarthScope Transportable Array (TA) stations, and was also recorded by three infrasonic arrays in Utah (BGU, EPU, NOQ), one in Nevada (NVIAR), and one in Wyoming (PDIAR). The waveforms recorded from the Wells sequence (main event and aftershocks) at the five infrasonic arrays are characterized by complex signals that correspond to: (1) *P* and *S* arrivals, a result of the coupling-to-air of the seismic waves that traveled to the vicinity of the infrasonic stations (local infrasound); (2) a secondary source of infrasound between the source and receiver; and (3) epicentral infrasound (acoustic energy that was generated by the ground motion at the epicenter and traveled through the atmosphere to the arrays at air sound speed). The second area of work focuses on characterizing acoustic to seismic coupling. In August 2007, infrasound microphones were added at Earthscope stations P13A, M13A, M14A, and N12A as part of an experiment to record 40,000 lb explosions at the Utah Test and Training Range on Hill Air Force Base (AFB). These multiple observations provide insight into the infrasound-to-seismic transfer functions during this time. Thirteen seismic/infrasound stations in the University of Utah Regional Seismic Network provide additional observations on infrasound-to-seismic coupling. Strong infrasound-to-seismic coupling is observed at most stations and in most cases can be described with a few term pole-zero empirical transfer function. At some stations, additional infrasound-to-seismic converted signals were observed at significant distances from the site. These converted signals seem to be site dependent but may also be source dependent. Understanding of where the coupling occurs is useful for characterizing infrasound propagation and should provide information about the very shallow velocity structure in the region. Finally, additional work has been completed in assessing infrasound wave propagation inside of the "zone of silence" (McKenna, 2005). Data from the August 2007 experiment have been further analyzed including the use of atmospheric data from rawinsondes. Based on the data analysis, the infrasonic arrivals were classified into two groups: the arrivals at the distance less than 100 km (local arrivals) and those between 150 and 210 km (regional arrivals). Group velocities at local distances are near the speed of sound at the surface, indicative of guided phases along this boundary, while those at regional distances are greater, indicative of turning rays from the stratosphere or thermosphere. Parabolic equation (PE) modeling based on atmospheric models from the rawinsondes is used to explore the trapped infrasonic wave propagation. The spatial and temporal variability of these models is quantified. The seismic stations deployed in NE China as part of this contract were removed in 2008. Analysis of these seismic data continues. Shear wave velocities beneath the Yanqing-Huailai Basin were estimated from the joint inversion of surface wave phase velocities and teleseismic receiver functions. The resulting models suggest low-velocity basin sediments to 2 km followed by a positive velocity gradient to 15 km, with shear wave velocity increasing from 2.0 to 3.55 km/sec. The total crustal thickness is 38 to 42 km with a smooth Moho transition to an upper mantle shear velocity of 4.3 km/sec. We are continuing the joint inversion study for crustal shear velocity structure in the second focus area, Haicheng, NE China.

OBJECTIVES

The primary goal of the collaborative study between Southern Methodist University and the Institute of Geophysics, China Earthquake Administration (formerly the Institute of Geology, China Seismological Bureau) is to develop a database of seismic events in NE China; to refine crust and upper mantle structure in Yanqing-Huailai Basin and Haicheng area; to understand source characterization of natural and human-induced events; and to separate source and propagation path effects at regional distance.

A second objective of this project is the instrumental quantification of seismic and infrasound signals observed at regional distances. The focus in this case is on man-made and natural sources that generate both infrasound and seismic waves. Initially, plans called for infrasound gauges to be collocated with the seismometers deployed in NE China. After acquisition of the infrasound gauges, the deployment was made in the US, collocating infrasound gauges with seismometers operated by University of Utah Seismograph Stations (UUSS). These data are being used to assess atmospheric propagation path effects from known explosion sources.

RESEARCH ACCOMPLISHED

Infrasound Observations of the Wells Earthquake

Most studies documenting earthquake-generated infrasound are based on the analysis of very large earthquakes (Le Pichon et al., 2002; Kim et al., 2004; Le Pichon et al., 2006). The February 2008 Wells, Nevada earthquake is an interesting case because it is a moderate-strong earthquake (M_W 6.0) that was recorded regionally by multiple infrasound arrays, as well as seismic stations including the EarthScope TA. This well-recorded event provides a good opportunity to advance our understanding of the mechanism by which earthquakes generate infrasound. Three infrasonic arrays in Utah (BGU, EPU, and NOQ), one in Nevada (NVIAR), and one in Wyoming (PDIAR) recorded the main event and some of the aftershocks. The waveforms recorded from the Wells sequence at the five infrasonic arrays are characterized by complex signals that correspond to: (1) *P* and *S* arrivals that are the result of coupling-to-air of the seismic waves that traveled to the vicinity of the infrasonic stations (local infrasound); (2) epicentral infrasound (acoustic energy that was generated by the ground motion at the epicenter and traveled through the atmosphere to the arrays at air sound speed; and (3) a secondary source of infrasound between the source and receiver.

To understand the infrasound signal character, we used the software package InfraMonitor (Arrowsmith et al., 2008). InfraMonitor uses a coherent detector with an adaptive noise hypothesis to account for variations in ambient noise (Arrowsmith et al., 2009b). Using the bulletin data generated by the coherent detector, the InfraMonitor software package searches a geographic region (using a grid-search algorithm) to locate the source based on estimated backazimuths and inter-array delay times. Figures 1 and 2 present a summary of the infrasonic observations of the Wells mainshock and the location polygon generated by the InfraMonitor software.

An interesting observation is related to high-amplitude signals recorded at the array BGU, arriving between the seismic arrivals and epicentral infrasound labeled 'Ground-air coupled infrasound' (Figure 1), that are not associated with corresponding signals at the other arrays. An in-depth analysis of these signals is presented in Arrowsmith et al. (2009a) and is discussed in more detail in Arrowsmith et al. (2009c, these Proceedings).

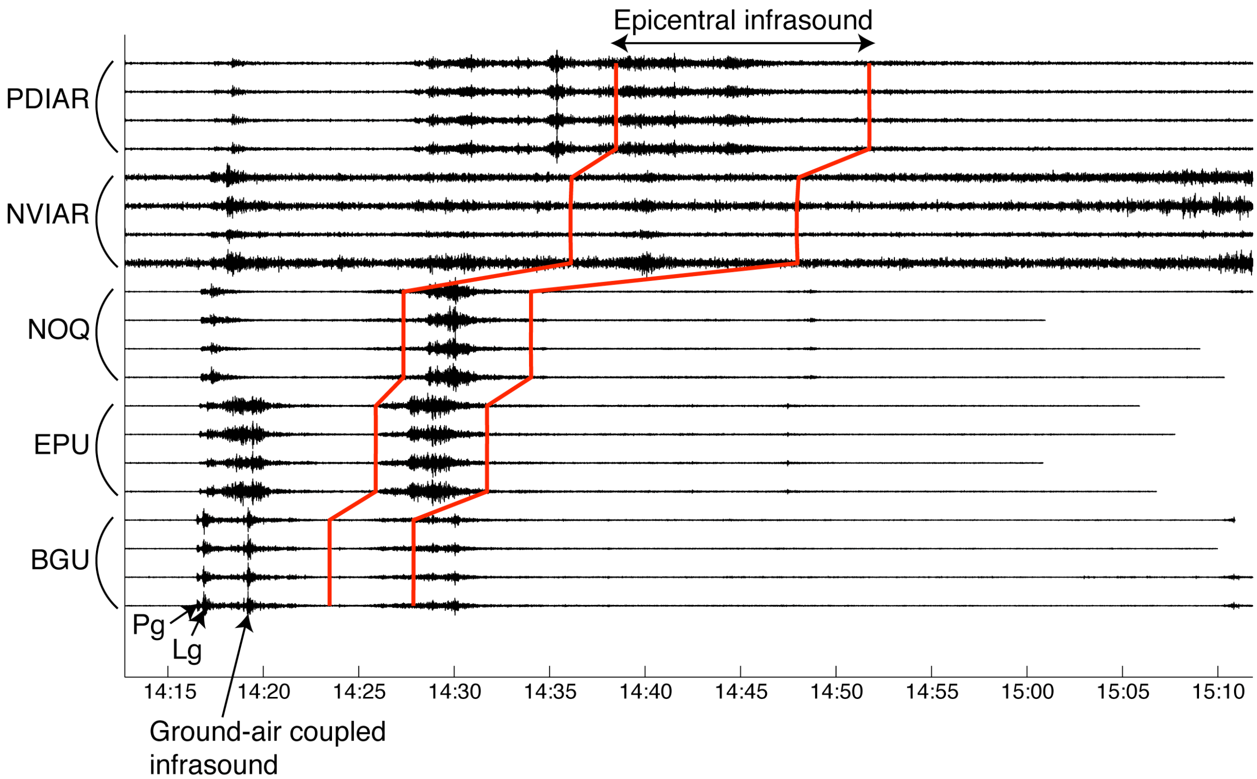

Figure 1. Summary of all infrasonic observations of the Wells, Nevada earthquake mainshock. Epicentral infrasound, observed at all five arrays (within the red lines), is located using the technique outlined in Arrowsmith et al., 2008.

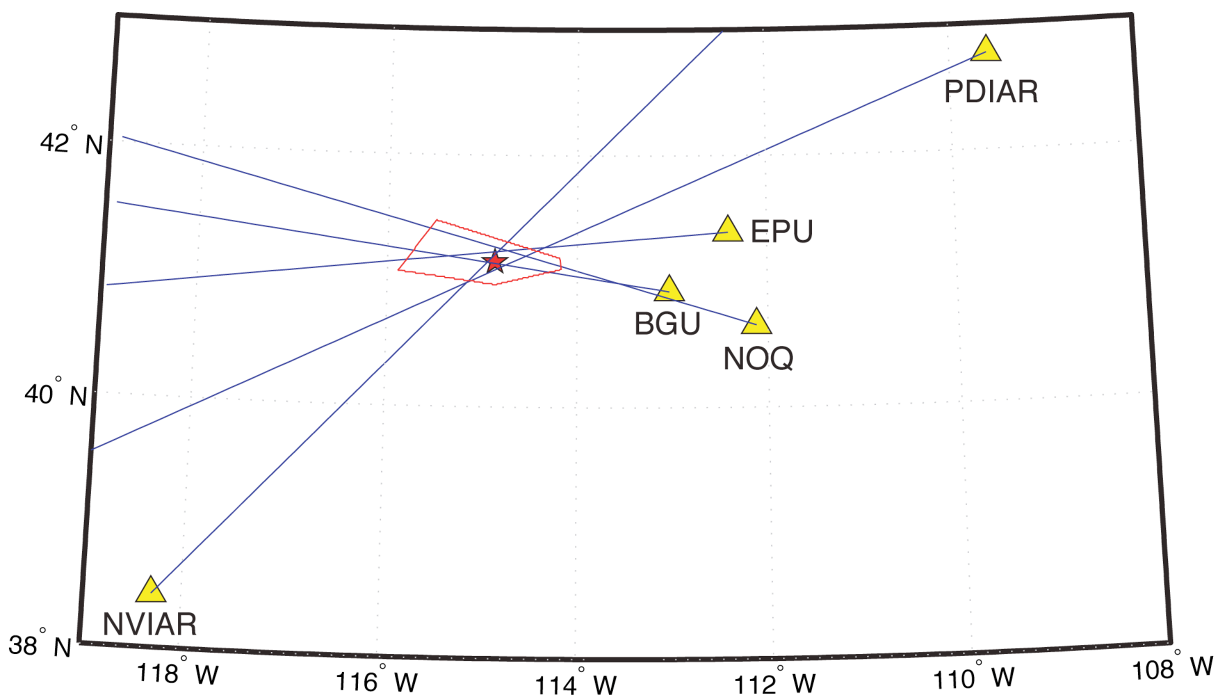

Figure 2. The location polygon obtained using InfraMonitor for the epicentral infrasound (red polygon), with the corresponding seismic location (red star) shown for reference.

Observations of Acoustic to Seismic Coupling

The three permanent infrasound arrays deployed in Utah as a result of this effort motivated the installation of additional infrasound gauges at both UUSS and EarthScope stations for a short time period in August of 2007. As reported previously (Stump et al., 2007a, 2007b), these deployments were designed to characterize infrasound wave propagation in the 1 to 210 km distance range from large surface explosions. Figure 3 documents the effective seismic-to-acoustic coupling observed. In this case, twenty explosions from the Utah Test and Training Range (UTTR) are recorded at the EarthScope site N15A. The seismic waveforms are quite consistent from blast to blast, primarily reflecting the differences in explosive yield. The acoustic-to-seismic coupled energy is robust, documenting differences in propagation path in the atmosphere for the individual days of the explosions.

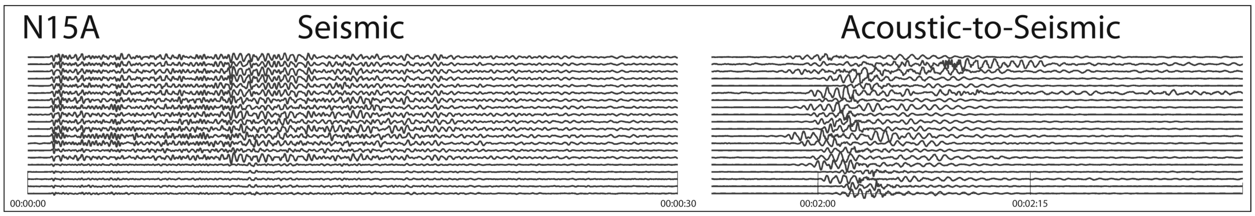

Figure 3. Seismic records from twenty explosions at UTTR as observed at the EarthScope site N15A. The left panel displays the seismic waves and the right panel the acoustic-to-seismic coupling at the site.

Observations like those displayed in Figure 3 illustrate the utility of using seismic stations to quantify infrasonic arrivals as result of acoustic to seismic coupling at seismic receivers. These observations have motivated two parallel lines of investigation. First, seismic stations can be used to produce robust record sections of infrasonic arrivals for purposes of characterizing wave propagation in the atmosphere and second, acoustic-to-seismic transfer functions can be calculated to understand the physical parameters that control coupling. Seismic and infrasound record sections for UTTR were constructed using seismometers and are displayed in Figure 4.

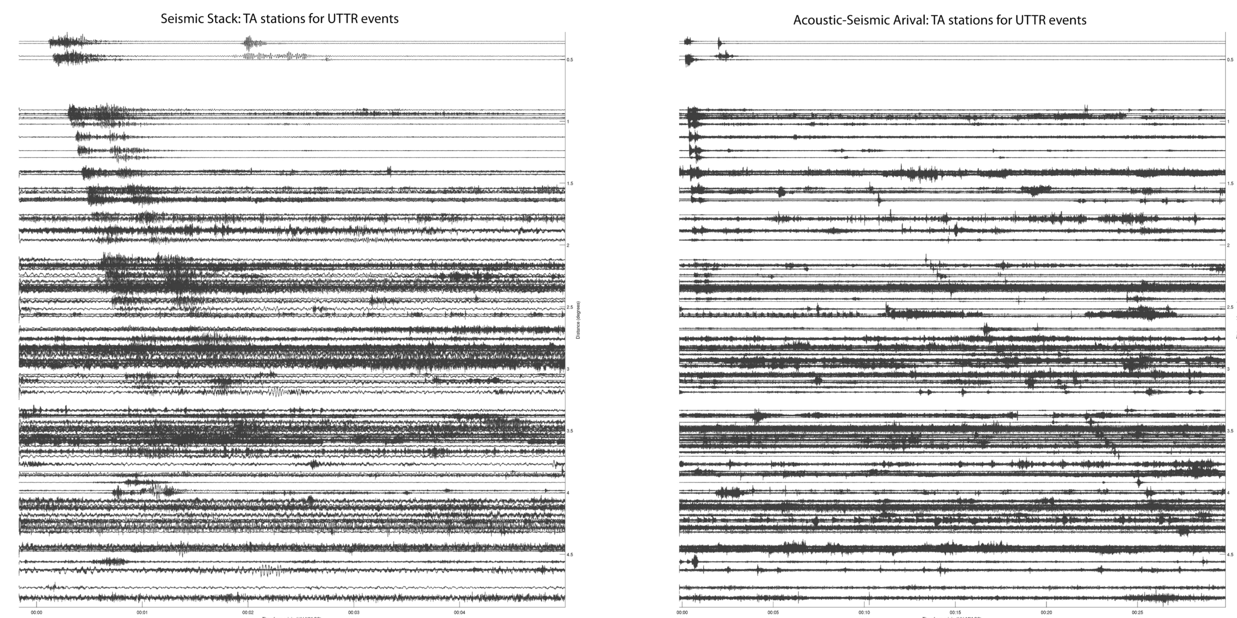

Figure 4. Record sections from the vertical (BHZ) component EarthScope stations. The left panel was produced by stacking four of the UTTR explosions while the right panel is the recording of a single UTTR blast windowed to emphasize the infrasound arrivals.

The data displayed in Figure 4 demonstrate the capability of seismic stations and EarthScope sites in general to document infrasound wave propagation at regional distances. The data demonstrate that for these near-surface explosions the infrasound signals are observed at greater distances than the accompanying seismic signals from the same event. Preliminary results from the transfer function analysis suggest that the transfer functions are highly variable from site to site and that further empirical studies are needed the quantify the variability.

Spatial and Temporal Variation in the Atmosphere and Impact on Infrasound Propagation

Interpretation of the near-regional infrasonic data has continued. We continue the analysis of observations in the 1 to 210 km distance range recorded from the UTTR explosions. Previous results identified the possible importance of shallow waveguides to the observations in this distance range. The new work has focused on the spatial and temporal variability of these waveguides. Two approaches were undertaken to explore this variability. The first is a quantification of the spatial and temporal variation in shallow atmospheric sampling based upon data from rawinsondes. The second approach involves the utilization of atmospheric models based upon the empirical data in developing PE models for the distances and azimuths for which there are infrasonic observations.

Balloon launches were made before and at the time of each of the detonations. Launches were made at the explosion site as well as at a distance of 50 km from the source. Acquisition of meteorological data contributes to the modeling of propagation path effects for the infrasound data. Spatial and temporal variations of atmospheric temperature and wind conditions are assessed from atmospheric sampling at the time of the four detonations at the UTTR source site and at a range of 50 km as depicted in Figure 5. Variation of temperature is relatively small compared to large variations in the near-surface winds. This result illustrates the importance of three-dimensional effects at these distance ranges.

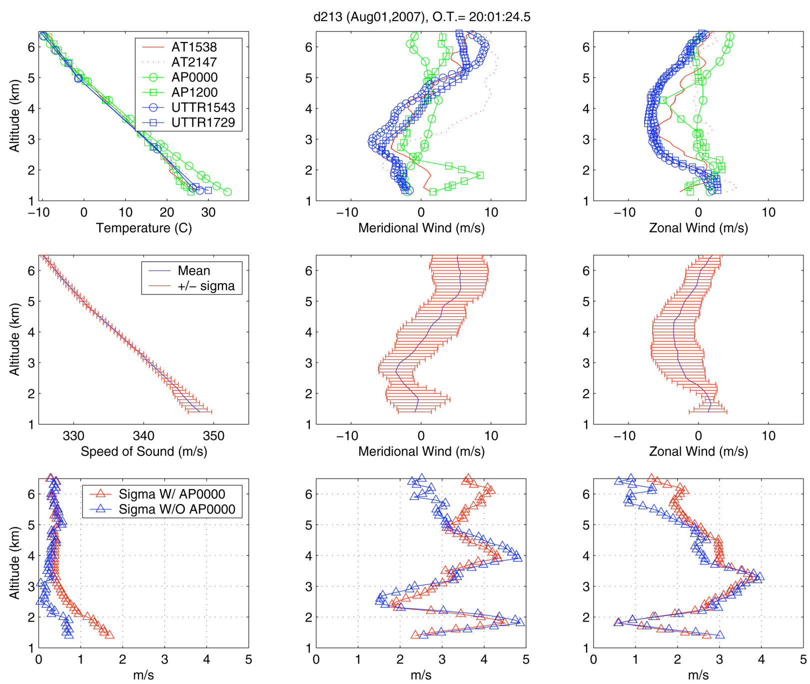

Figure 5. Atmospheric profiling was taken at three sites in the region where the UTTR explosions were undertaken 1 August 2007. The first location is at the detonation site (UTTR), the second site is 50 km to the SE of the shot at Antelope Island (AP) and the final location at the Salt Lake City airport (AP). The four digit numbers that accompany each site document the time of the atmospheric monitoring. The first row of figures represents the actual temperature, meridional and zonal winds at the three sites. The second row uses these data to create mean and variance estimates of atmospheric velocity.

The temporal variation of these wind patterns is documented by comparing the results from 1 August 2007 (Figure 5) with similar data from 6 August 2007 (Figure 6). These data also support the consistency of temperature data across the three sampling sites and the large variation in winds over the first 6 km. The absolute wind values and their directions are quite different between the two days illustrating the importance of such sampling in order to quantify the wave propagation path effects.

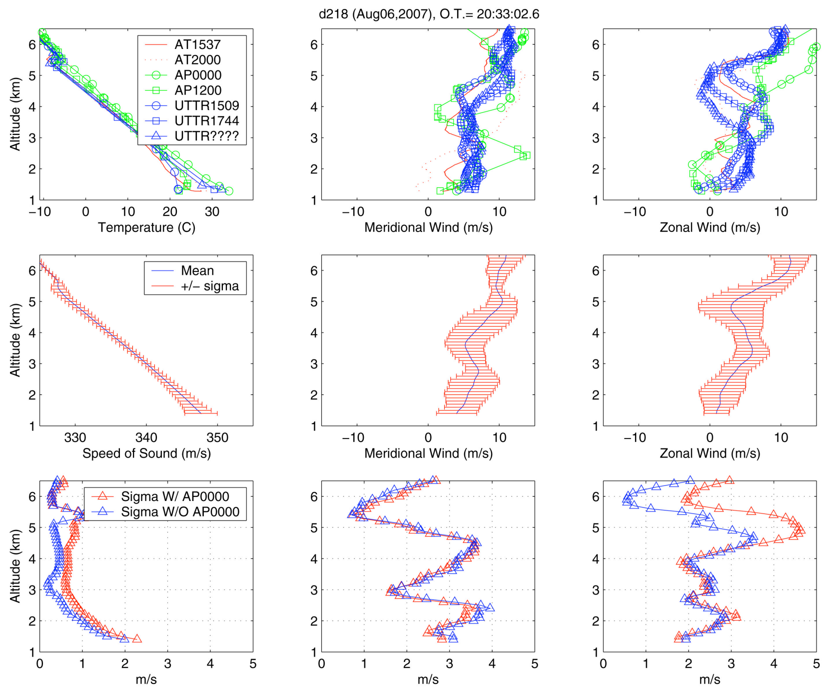

Figure 6. Atmospheric profiling was taken at three sites in the region where the UTTR explosions were undertaken 6 August 2007. Figure format is the same as in Figure 5.

PE modeling was conducted using these observations in order to quantify the effects of time and space on the predicted travel times and amplitudes. The effects are large in terms of predicted amplitudes from 1 to 210 km and suggest that temporal and spatial effects in the shallow atmosphere will be critical to the interpretation of the data.

Seismic Studies in NE China

The seismic stations deployed in NE China as part of this contract were removed in 2008. Analysis of these seismic data continues. Shear wave velocities beneath the Yanqing-Huailai Basin were estimated from the joint inversion of surface wave phase velocities and teleseismic receiver functions.

An average velocity model for the region was determined by inverting all receiver functions from the seven stations with the phase velocities from the teleseismic events (Zhou et al., 2009). Figure 7 plots the station specific velocity models (red) against the averaged model for the region (blue). The individual velocity models at depth exhibit little or no difference across the network as expected based on the common surface wave dispersion data. The models have a positive velocity gradient from the surface to approximately 15 km with shear wave velocity increasing from 2.0 km/sec to 3.55 km/sec. A slight negative gradient in velocity starts at about 15 km resulting in an extended low velocity layer to approximately 25 km with velocity near 3.3 km/sec. There is evidence of a low velocity layer in the mid-crust at all stations. There is no sharp Moho interface with the Moho represented as a transition in velocity from 38 to 42 km, consistent with other studies in the region (Zhang et al., 1996; Zhao et al., 2005).

Predicted first arrival times (red) from the inverted model are compared with results from a nearby refraction/wide angle reflection profiles (blue) as well as the AK135F model (green) in Figure 8, the difference reflects the slower velocities in the very shallow crust in our models.

We are continuing the joint inversion study for crustal shear velocity structure in the second focus area, Haicheng, NE China. The radial component receiver functions for 81 and 64 events that occurred from September 2004 to May 2008 at FFANG and LJIA are plotted as a function of source azimuth in Figure 9.

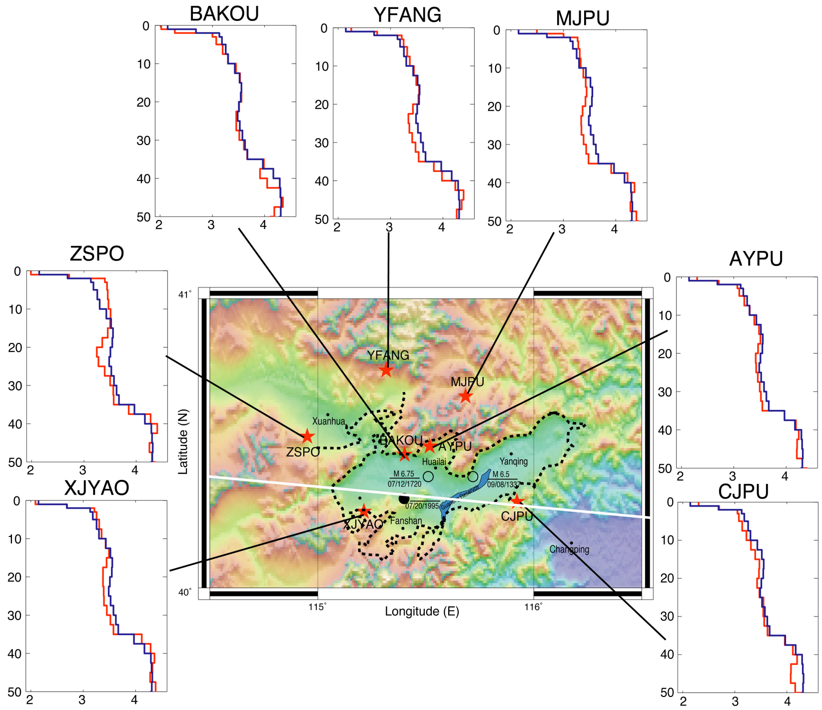

Figure 7. Map of stations and shear-wave velocity models from joint inversions at each of the seven stations (red) compared to the averaged model inverted using all seven stations (blue) simultaneously.

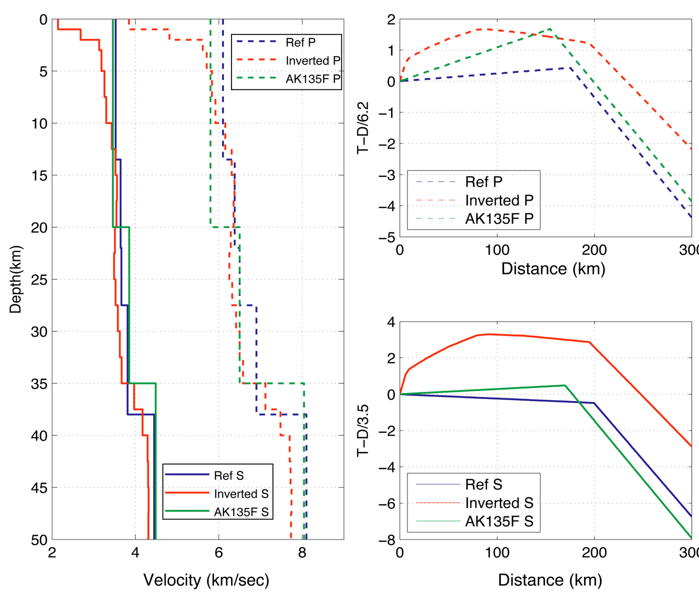

Figure 8. Comparison between the model resulting from the joint inversion (receiver functions and phase velocities) using all station data (red) and the model from a refraction/wide-angle reflection survey (blue), and AK135F model (green). Right: Predicted first arrival times of *P* (upper) and *S* (lower) from the three different models.

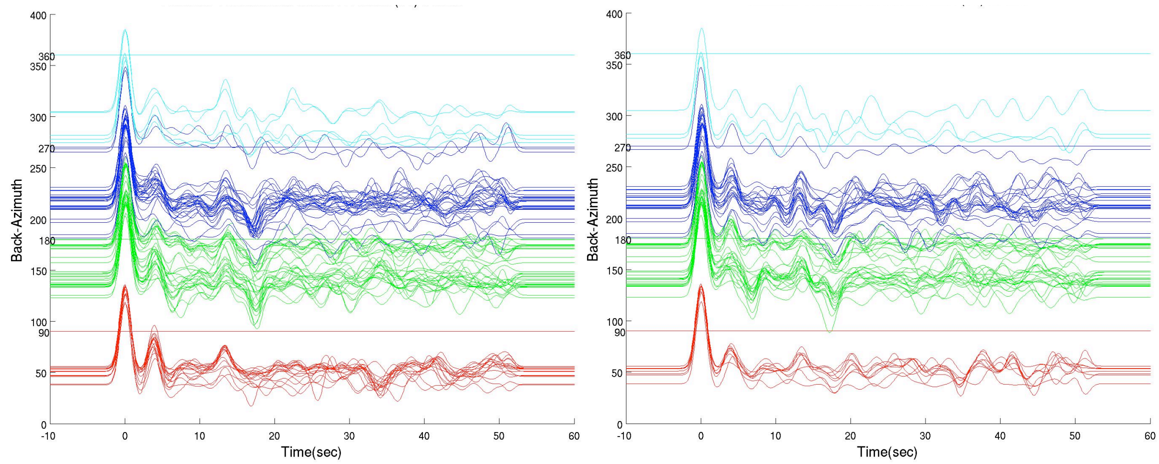

Figure 9. Plot of receiver functions (Gaussian window parameter α = 1.0) versus back-azimuth for events recorded at station FFANG (left, 81 events) and LJIA (right, 64 events).

CONCLUSIONS AND RECOMMENDATIONS

Infrasound Observations of the Wells Earthquake – A number of infrasound observations obtained from the Wells earthquake were recovered from stations deployed as part of this contract. These observations have been used to locate the event using infrasound arrivals, as well as identify infrasound generated not only in the epicentral region but also along the path from the event to receiver. A more detailed account of this analysis can be found in the companion paper in Arrowsmith et al. (2009c, these Proceedings).

Observations of Acoustic to Seismic Coupling – Strong acoustic-to-seismic coupling is observed at EarthScope stations out to nearly five degrees from the UTTR explosions. These observations illustrate that seismic observations can be used to interpret infrasonic wave propagation in the absence of acoustic gauges. The details of the acoustic to seismic coupling are station dependent and need further study. Infrasonic observations of UTTR explosions extend to a greater range than the seismic observations.

Spatial and Temporal Variation in the Atmosphere and Impact on Infrasound Propagation – Atmospheric temperature and wind profiles based on rawinsondes illustrate significant temporal and regional spatial scale variation. Utilization of these models illustrates that they can have a significant effect on infrasonic wave propagation in the 1 to 210 km distance range. Preliminary results suggest that 3D effects may play an important role in the explaining observations.

Seismic Studies in NE China – The seismic deployments in NE China are complete. A velocity model for the Yanqing-Huailai Basin region near Beijing has now been developed and published using receiver functions and surface wave analysis. These methods are being extended to Haicheng area where the stations were deployed at the end of the experiment.

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