INFRASOUND CALIBRATION EXPLOSIONS FROM ROCKETS LAUNCHED AT WHITE SANDS MISSILE RANGE

Eugene Herrin[1], Paul Golden[1], Petru Negraru[1], William Andre[2], Henry Bass[3], Milton Garces[4], Michael Hedlin[5], Mihan McKenna[6], David Norris[7], Daniel Osborne[8], and Rodney Whitaker[9]

Southern Methodist University[1], US Army Space and Missile Defense Command[2], University of Mississippi[3], University of Hawaii, Manoa[4], University of California, San Diego[5], US Army Engineer Research and Development Center-GSL[6], BBN Technologies Inc.[7], University of Alaska, Fairbanks[8], and Los Alamos National Laboratory[9]

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ABSTRACT

A national infrasound research team has been established to conduct large-scale experiments utilizing atmospheric explosions to study infrasound propagation phenomenology and to calibrate a network of infrasound arrays. In the last two years, calibration experiments were carried out at the White Sands Missile Range (WSMR) in which explosions with yields of 70 lb TNT equivalent were conducted at altitudes greater than 30 km. The next calibration experiment is scheduled to take place in late July 2006. Infrasound data from the explosions were collected by the team members at more than 20 locations in the southwest US. The recorded waveforms represent a truly unique dataset due to the high source altitude, and yield information availability.

The primary goal of the project is to improve understanding of the fundamental physics of the atmospheric properties affecting propagation of infrasound signals. A secondary goal is to validate the yield/dominant frequency and yield/pressure amplitude scaling relationships. To a first order approximation, both goals have been achieved. The signal detection pattern of the experiments related to receiver location is in agreement with the predictions based on average atmospheric models. The validity of yield/frequency and yield/pressure relationships is currently being investigated.

OBJECTIVES

An infrasound research team has been established to conduct a large-scale experiment utilizing high altitude atmospheric explosions to study infrasound propagation phenomenology. Two infrasound calibration experiments involving explosions of 70 lb TNT at altitudes greater than 30 km over White Sands Missile Range, New Mexico, were successfully conducted in the fall of 2005 and spring of 2006. A third experiment is scheduled for late July 2006. Infrasound data from the explosions were collected by the team members at many locations in the southwest US. The resulting waveforms represent a truly unique dataset in terms of ground truth information including source location and yield. The efforts of the team to date included only acquisition and quick-look analysis of the data, but in-depth analysis will focus on atmospheric and propagation modeling, and validating those models. An additional goal of this project is to validate the yield/dominant frequency and yield/pressure scaling relationships.

RESEARCH ACCOMPLISHED

Atmospheric modeling has played a key role in determining the schedules and locations of portable deployments of infrasound arrays for the previous explosion experiments. Figure 1 illustrates atmospheric modeling showing seasonal trends in effective sound profiles at the WSMR source site. These profiles are based entirely on climatology and attempt to resolve mean seasonal and diurnal atmospheric trends. In the northern hemisphere, strong westward ducts form during the summer months, with a peak in July. To take advantage of the possibility of strong ducting, which could provide increased distance for recording signals to the west, a third test (WSMR3) was scheduled for July 2006.

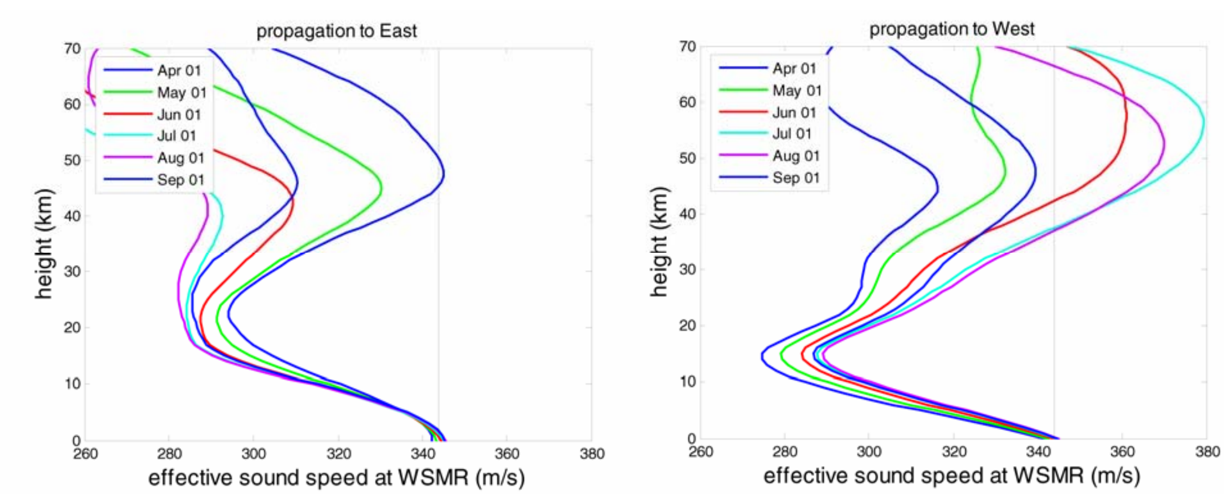

Figure 1. Effective sound speed profiles used in selecting optimal test dates.

As a second example of planning research, Figure 2 shows parabolic equation (PE) predictions from the WSMR source to the Los Alamos station, DLIAR 260 km to the north. This prediction was part of a pre-test study in support of the September 2006 WSMR1 explosive experiment. The source level was predicted using the ANSI S2.20-1083 standard and then combined with PE model predictions of signal attenuation at each station to compute theoretical station signal-to-noise levels.

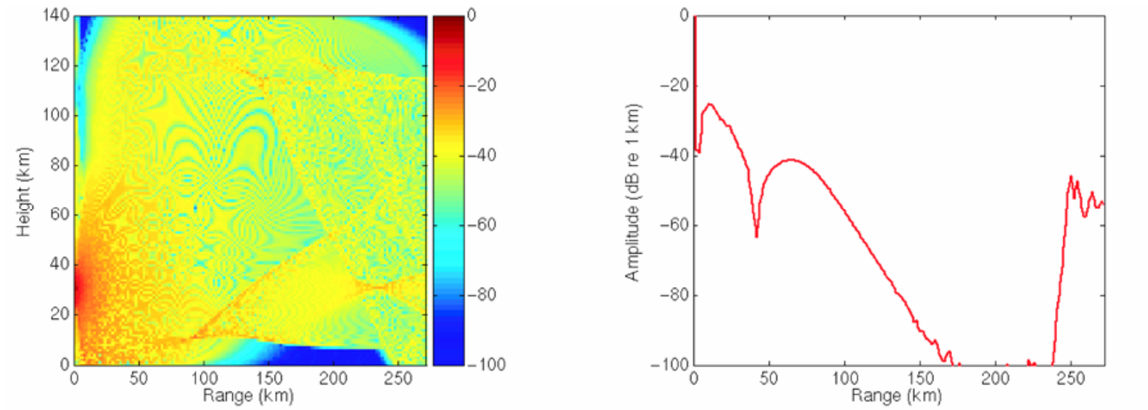

Figure 2. Pre-test Parabolic Equation (PE) predictions from source to station at Los Alamos, New Mexico (DLIAR).

The resulting signal-to-noise ratio (SNR) predictions for all preliminary station locations are given in Figure 3. The uncertainty bars were based upon the difference between predictions using climatology and those using NRL-G2S characterizations. Also shown are expected signal-to-noise levels for low, moderate and high wind noise. This modeling study was instrumental in selection of the temporary station locations and in providing an analytical basis for expected detection ranges.

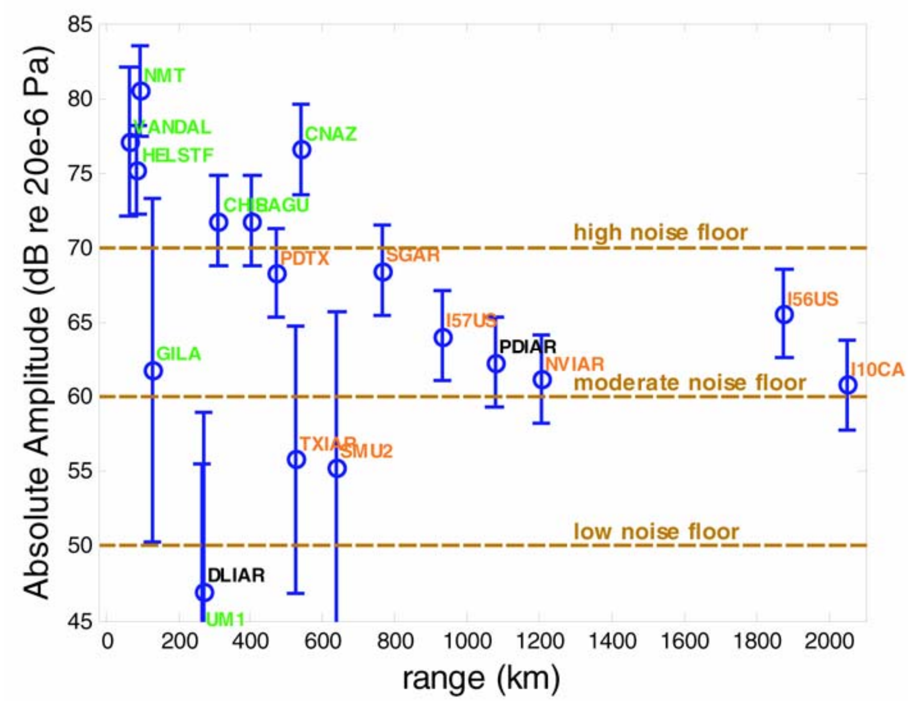

Figure 3. SNR predictions of pre-test station configuration for the September 2006 WSMR rocket test. Permanent stations are in orange and temporary station in green.

Based on the expected climatic conditions, two infrasound calibration experiments were conducted at White Sands Missile Range, New Mexico, on September 9, 2005, and March 25, 2006. During each experiment two missiles were launched at approximately 4-hour intervals. Although plans were for detonations at 40 km altitude WSMR1, detonations were limited to approximately 30 km due to range safety concerns. WSMR2 detonations were allowed at an altitude of approximately 35 km after additional debris modeling was completed. We anticipate detonation at 35 km for the experiment planned for July 2006. The main goal of the experiments is to provide further understanding of the atmosphere propagation of infrasound signals during different atmospheric conditions. A second goal was validating the yield/dominant frequency and yield/pressure scaling relationships. Preliminary analyses suggest that to a first order approximation both goals were achieved.

Figure 4 shows the location of the permanent and temporary infrasound arrays deployed for the first experiment, in September 2005. In total there were 20 arrays or stations at ranges from 63 to 2049 km. For the second experiment, the number of arrays increased to 23, covering the same distance ranges. The temporary infrasound arrays were placed mostly west of the source for the September 2005 experiment, and east of the source for the March 2006 experiment. This pattern was chosen in agreement with the direction of the zonal stratospheric winds. Past observations of the zonal stratospheric winds are predominantly westward (at around 10 m/s) for the beginning of September, while at the end of March the winds are predominantly eastward, with variable strength. However, observations suggest the second experiment was carried out close to the time when the zonal winds were turning to the west.

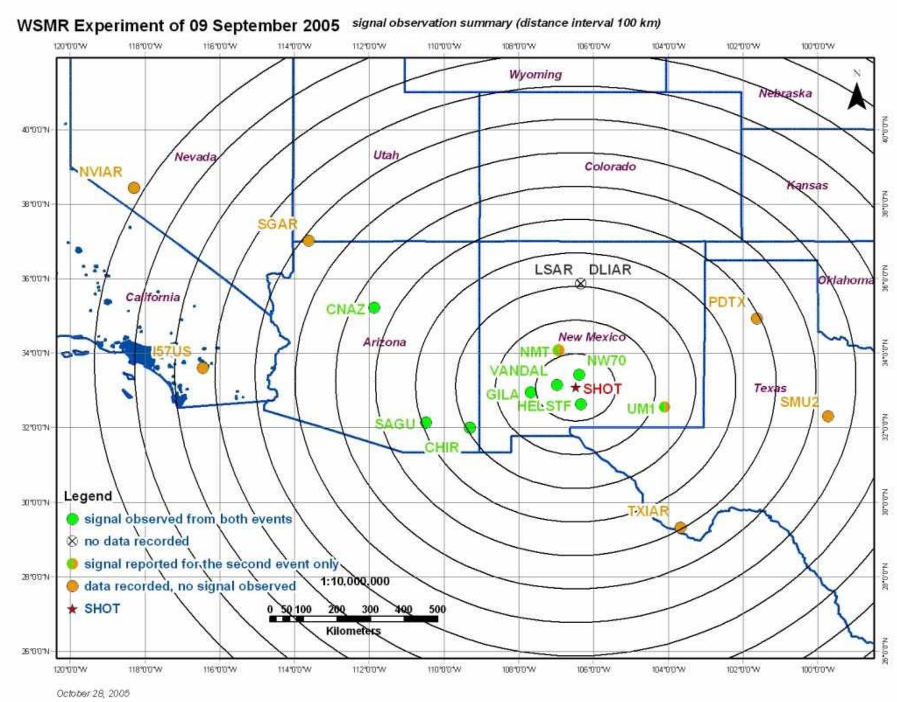

Figure 4. Map showing locations and distances from the source for infrasound arrays and stations deployed during the WSMR1 explosion experiment.

The detection pattern of the first calibration event was strongly dependent on the zonal winds, as the preliminary modeling suggested (see Figure 1). In September, when the winds were predominantly westward, detections to the west were recorded as far as Camp Navajo in Arizona (at a distance of 563 km), while to the east, except for the very close arrays, only UM1 (265 km) has a possible detection of a signal. Because the second calibration experiment was carried out recently, quick-look data analysis has not been finalized.

Quick-look analysis of data collected at Ft. Davis, Texas, during the WSMR2 experiment yielded interesting results. An event from an unknown source was recorded only minutes after the signal from the explosion. At first, this was thought to be a late thermospheric arrival, but this was ruled out after initial analysis. Figure 5 shows the signal recorded at Ft. Davis from the second explosion of WSMR2.

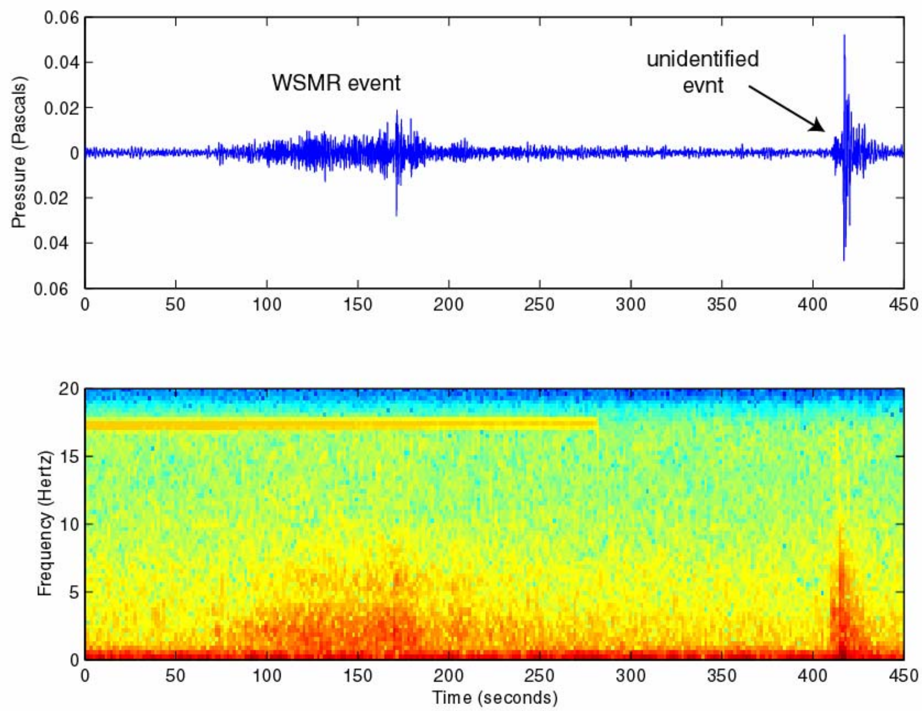

Figure 5. WSMR2 second explosion data (upper plot) recorded at Fort Davis and corresponding spectrogram (lower plot).

The unidentified event begins approximately 5 minutes after the signal associated with the calibration experiments. Both the frequency content and estimated azimuth suggest the second event has a different origin, which has not yet been identified. The WSMR calibration experiments have little or no energy above 5 Hz, while the unidentified event shows a broader spectrum, with energy above 8 Hz. In addition, the difference in the estimated azimuths for the two signals is more than 10°, which suggests that they have different source locations.

A few interesting observations have been made for both sets of experiments. First, although the explosions of the individual experiments were carried out approximately four hours apart, signals show significant waveform variations. This suggests that dynamics of the atmosphere can change quickly and do strongly affect the amplitudes and arrivals of signals. Figure 6 is an example of waveforms from the first and second explosions recorded from WSMR1 recorded at Camp Navajo, Arizona. The first shot is clearly more impulsive than the second one, while on the second shot more arrivals could be identified. It is important to note that the peak frequency of the signals is almost the same. Therefore only the phase of the signals appears to be strongly distorted by the short-term dynamics of the atmosphere.

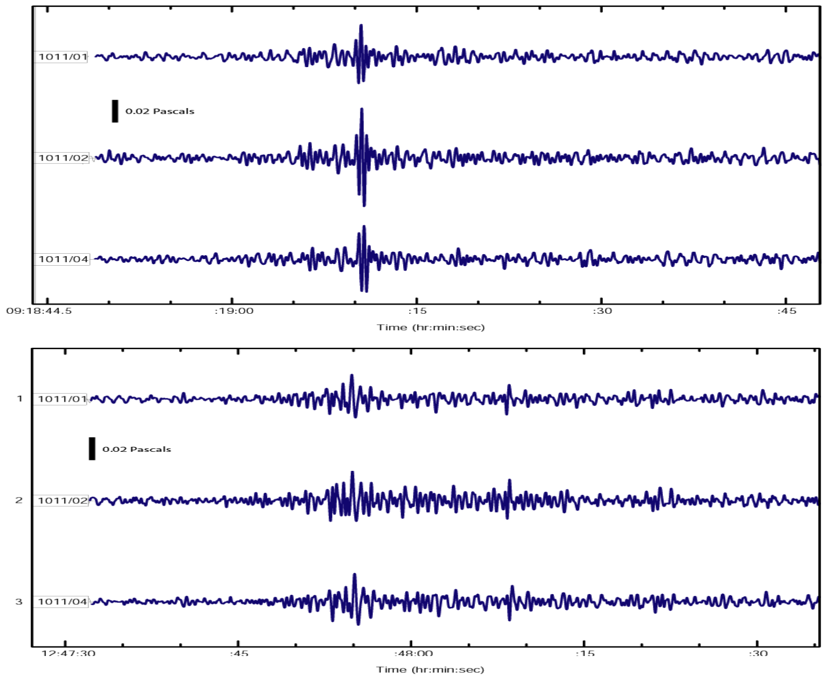

Figure 6. Recordings of the WSMR 1 experiment at Camp Navajo, Arizona. Although the shots were only 4 hours apart and the source is not believed to vary significantly, the differences in the phase of the signal is significant.

In addition, the dominant period/yield scaling relationship for the explosions shows consistent results. Figure 7 shows the frequency estimates for signals recorded by SMU for the first two WSMR experiments. For comparison purposes the unidentified event recorded at Fort Davis is also shown.

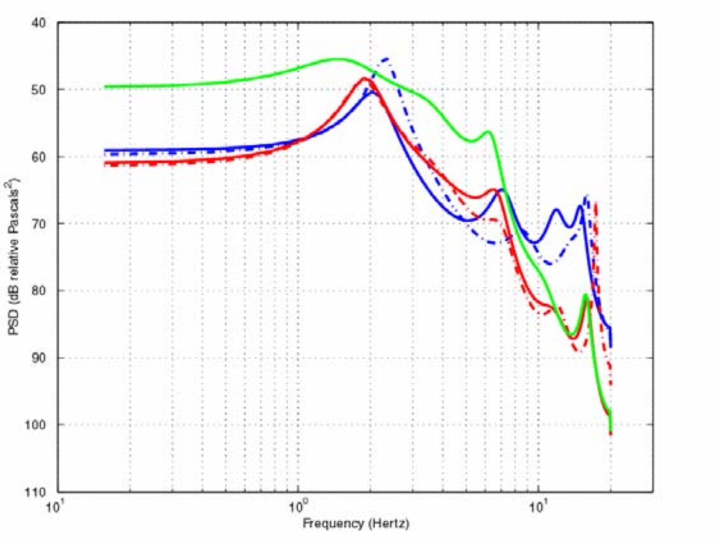

Figure 7. Power Spectra of the WSMR experiments and the unidentified event. The WSMR1 experiments are shown as blue and dash-dot blue lines, WSMR2 are shown as red and dash-dot red lines and the unidentified event is the green line.

The power spectral estimates were obtained using an autoregressive process of order 10 via Burg's method. Pre-filtering of the data with a high pass (1 Hz) zero-phase Butterworth filter was required due to the fact that the roots of the polynomial are dominated by the long period background pressure variations. Shown on the graph are the power spectra of the WSMR1 experiments (blue and dash-dot blue lines) recorded at Camp Navajo, Arizona, WSMR2 experiments (red and dash-dot red lines) recorded at Fort Davis, Texas (site SMU4), and the unidentified event (green line) clearly showing the difference in dominant period. Table 1 gives the dominant frequencies for the different arrivals. The dominant frequency is dependent on the altitude and yield of the event as predicted by the scaling relationship. A secondary conclusion is the difference in the dominant frequency of the peak between the WSMR experiments and the unidentified event. The WSMR signals have predominant frequencies around 2 Hz, while the unidentified event has strong frequencies between 1 and 8 Hz.

Table 1. Altitudes and dominant frequencies of arrivals recorded by SMU for both WSMR experiments

Signals	Dominant Frequency (Hz)	Altitude (km)
WSMR1, shot 1	2.3	31.1
WSMR1, shot 2	2.1	31.6
WSMR2, shot 1	1.9	35
WSMR2, shot 2	1.9	35.18
Unidentified event	1.4	?

An additional goal of this proposal is to validate empirical formulas for the frequency/yield and pressure amplitudes/yield developed by Air Force Technical Applications Center (AFTAC) and Los Alamos respectively. The AFTAC yield/dominant frequency scaling relationship is based on surface or low altitude nuclear explosions. The formula is written as

$$Y \approx (2) \times 2.63 \times T^{3.34} \ ,$$

where Y is the yield in metric tons and T is the dominant period of the signal (seconds). An altitude correction was provided by Armstrong, (1998). For a constant period the yield estimate (Y) is proportional to ambient pressure $P(z) = P_o e^{-Z/H}$, where H is the pressure scale height of atmosphere. However, the correction was based on surface or low altitude nuclear explosions, and scaling to higher altitudes was not verified by ground truth data. The only recorded event at a known location at such high altitude was the Columbia shuttle disaster, but this event provided ground truth only in terms of location (x, y, z position), not in terms of yield. The height was just over 63 km, and using the altitude correction of Armstrong, the estimated yield of the explosion was between 2 and 3 lb of TNT equivalent (McKenna and Herrin, 2006).

A second approach was developed at LANL using data based on high-explosive (HE) shots covering charge weights of ~20 to 4,880 tons, (Mutschlecner and Whitaker, 2005). The formula uses wind corrected pressure amplitudes and scaled ranges. The data are shown in Figure 8.

The range, R, in km, is scaled as: $(R/(2*\text{charge weight})^{0.5}$, charge weight in kilotons of HE. Pressures are in microbars. The observing stations had distances of 250 km to 5330 km, but the 5330 km station was only on for one event. The regression fit for these data is

$$P_{wca} = 5.95E04*(SR)^{-1.4072} \text{ with an } R^2 \text{ of } 0.93 \ .$$

The raw amplitudes are normalized for the effects of the seasonal stratospheric winds, using the wind speed at 50 km altitude, in the direction of propagation.

$$\begin{aligned} \log\left(P_{wca}\right) &= \log\left(P_{raw}\right) - kV_d \\ V_d &= -\left(V_Z \sin\left(\Theta\right) + V_m \cos\left(\Theta\right)\right) \end{aligned} ,$$

where the empirically derived wind parameters (in meters/second) are as follows: V_d - wind component directed, source to array; V_z - zonal component of stratospheric wind; V_m - meridional component of stratospheric wind, θ is azimuth to source, and k = 0.018. Pressure amplitudes are measured peak to peak, at the dominant period.

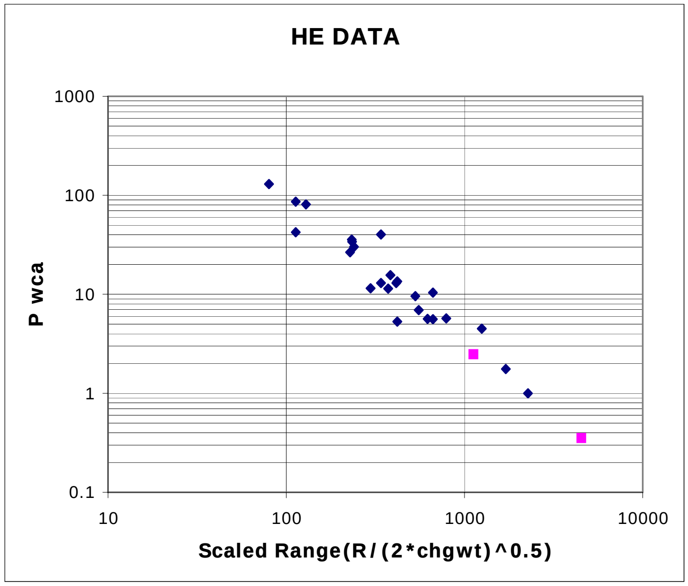

Figure 8. Wind corrected pressure amplitudes vs range for observed data for HE tests provided by Los Alamos National Laboratory. The blue diamonds are DNA explosions at WSMR from 1981–1992; the red squares are for Watusi experiments at the Nevada Test Site.

The purpose of wind normalization is to estimate signal amplitudes as if there were a zero wind condition. Thus, if one is in favorable wind propagation, the normalized amplitude would be less than observed. If in an unfavorable wind propagation, the normalized amplitude is greater than the observed. In the northern hemisphere, favorable conditions would be a source west of the receiver in the winter, because winds would be west to east, and in this case the receiver is downwind of the source. Unfavorable conditions would be a source west of the receiver in summer months.

The energy of the source is folded into the scaled range term. So here one would take the observed raw peak-to-peak amplitude, do the wind normalization to get P_{wca}, and then with the range to the source, use the regression relation to calculate the yield of the explosion.

CONCLUSIONS AND RECOMMENDATIONS

Successful calibration experiments were carried out at WSMR in fall 2005 and spring 2006 with the main purpose of understanding the temporal dynamics of the atmosphere. The calibration experiments involved high altitude atmospheric sources for which the locations and yields were known with a high degree of accuracy. The initial goal of the calibration experiments was achieved, and detection patterns of the signals relative to the source locations were in agreement with predicted atmospheric conditions. Post-event modeling will use atmospheric observations at the time of the shot, and will try to relate the observed signal to the atmosphere variations. As a byproduct of the modeling technique, the current infrasound modeling codes developed by BBN Technologies will be tested and validated.

There are established procedures for estimating the yield of an atmospheric explosion from the recorded infrasound signal. However, a problem could arise from the fact that the scaling relationships were developed using surface or low altitude explosions. Using the new ground truth data acquired during the WSMR experiments the formulas can be validated for higher altitudes.

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