INFRASOUND AS A DEPTH DISCRIMINANT: CONSTRUCTION OF A UNIQUE DATASET AND PRELIMINARY ANALYSES

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ABSTRACT

In ground-based nuclear explosion monitoring, the depth of an event is an important consideration for event identification. However, without a station near the epicenter, seismic depth determination of small, shallow events is difficult. A current capability for the identification of shallow sources is the presence of the seismic phase, Rg. However, Rg is often not observed seismically, as it is very sensitive to the details of the structure of the upper crust and is disrupted by horizontal changes in structure and topography. Infrasound signals can be generated by near-source pumping of the atmosphere from shallow sources. Therefore, an infrasound detection is generally an indicator of a shallow (or surface) source, and has the potential to be used as a surrogate for Rg. As a first step towards constructing an infrasonic depth discriminant, we are constructing a large dataset of shallow earthquakes and explosions with well-constrained depths and associated infrasound signals at multiple arrays. By correcting for the effects of stratospheric and thermospheric winds on infrasonic amplitudes, we are exploring a multiple linear regression approach for separating effects of depth, source mechanism, magnitude and distance (predictor variables) on observed infrasonic amplitudes (dependent variable). This empirical approach will be complemented by the development of physical models that tie with the observations. To highlight our approach, we focus on infrasonic and seismic observations from the Wells, Nevada earthquake sequence. We demonstrate the importance of separating epicentral and secondary infrasonic arrivals, and report on our preliminary findings.

OBJECTIVES

Our goal in this effort is to develop an infrasonic discriminant for event depth. The aim is to develop infrasonic amplitude corrections for various source, path, and receiver effects so that – if location, mechanism, and magnitude are known seismically – we can estimate the event depth for shallow events based on infrasonic constraints.

The two objectives for Year 1 of this project are as follows:

- **Compilation of a dataset of events.** As outlined below, we are compiling a unique dataset for tackling this problem.

- **Preliminary analysis of factors affecting infrasound detection.** We have begun assessing source effects (using earthquake sequences) and path effects (using ground-truth surface explosions). This component lays the foundation for our research objectives in Years 2 and 3.

RESEARCH ACCOMPLISHED

Compilation of a Dataset of Events

(a) Dataset Specifications

A major focus of the first year of this effort is the construction of an extensive dataset of infrasonic observations of surface explosions and earthquakes with well-constrained focal depths. In contrast with previous studies, we require a rigorous set of conditions to be met:

- **Each event must be recorded at >1 infrasound array.** The infrasound association problem is inherently non-unique for a single array due to the long window of possible arrival times and current limitations in predicting observed phases. In addition, as outlined below, a single array observation cannot reliably distinguish between *epicentral* and *secondary* infrasound. In order to robustly associate an infrasound signal with a particular physical mechanism, we require that the event be observed at multiple arrays.
- **Each event must have an accurate focal depth, magnitude, and mechanism.** It is important that we have accurate independently determined source parameters with associated uncertainties. Relying purely upon conventional seismic catalogs is insufficient due to the trade-off between origin-time and depth (unless a seismic station is located directly above the epicenter). Thus, we require either ground truth on surface explosions or detailed seismic modeling/relocation of event depths for earthquakes.
- **Each event must be associated with high-resolution atmospheric specifications.** As shown by Mutschlecner et al. (1999), winds can have a significant effect on infrasonic amplitudes. Thus, we require 3D atmospheric wind specifications for each event in order to correct for this effect. As part of this effort, we propose to extend the Mutschlecner et al. (1999) relationship, which utilized only winds between 45 and 55 km altitude.

Given these tight constraints, we are focusing on regional-scale infrasound networks in Korea and the Western U.S., where we are able to obtain high-quality ground truth and the array density is sufficient to obtain multiple observations of seismo-acoustic events (Figures 1 and 2). Figure 1 shows the locations of events in the Western U.S. from which we are currently searching for infrasound signals at >1 array. We are also measuring infrasonic amplitudes of ground-truth events in the Korean peninsula (Figure 2).

(b) Semi-automatic amplitude measurement

For each event, we compute the amplitudes of the associated infrasound arrivals using a semi-automated procedure. Infrasonic amplitudes have conventionally been measured as a simple peak-to-peak amplitude of the maximum phase in the signal (e.g., Mutschlecner and Whitaker, 2005). However, this measurement has two limitations: (1) it cannot be reliably measured automatically, and (2) it is less representative of the average strength of a signal than the root mean square (RMS) power (e.g., Brown et al., 2008). For the dataset we are acquiring in this project, it is impractical to pick amplitudes for every arrival, and it is therefore essential that we can reliably measure amplitudes in a semi-automated way. We utilize an algorithm (illustrated in Figure 3) that is similar to a multiple frequency band, automatic amplitude measurement algorithm developed for seismic data (Hartse et al., 1997), with two modifications:

- Since we cannot reliably predict the arrival time of the signal, we compute the time of the maximum waveform envelope within the possible arrival window (computed using a group velocity range from 0.34 km/s to 0.22

km/s), and apply an additional check that the backazimuth of the beam at that time must be consistent with the known great-circle backazimuth for the event.

- A subset of automated amplitude measurements are checked manually in order to validate that the algorithm is working effectively.

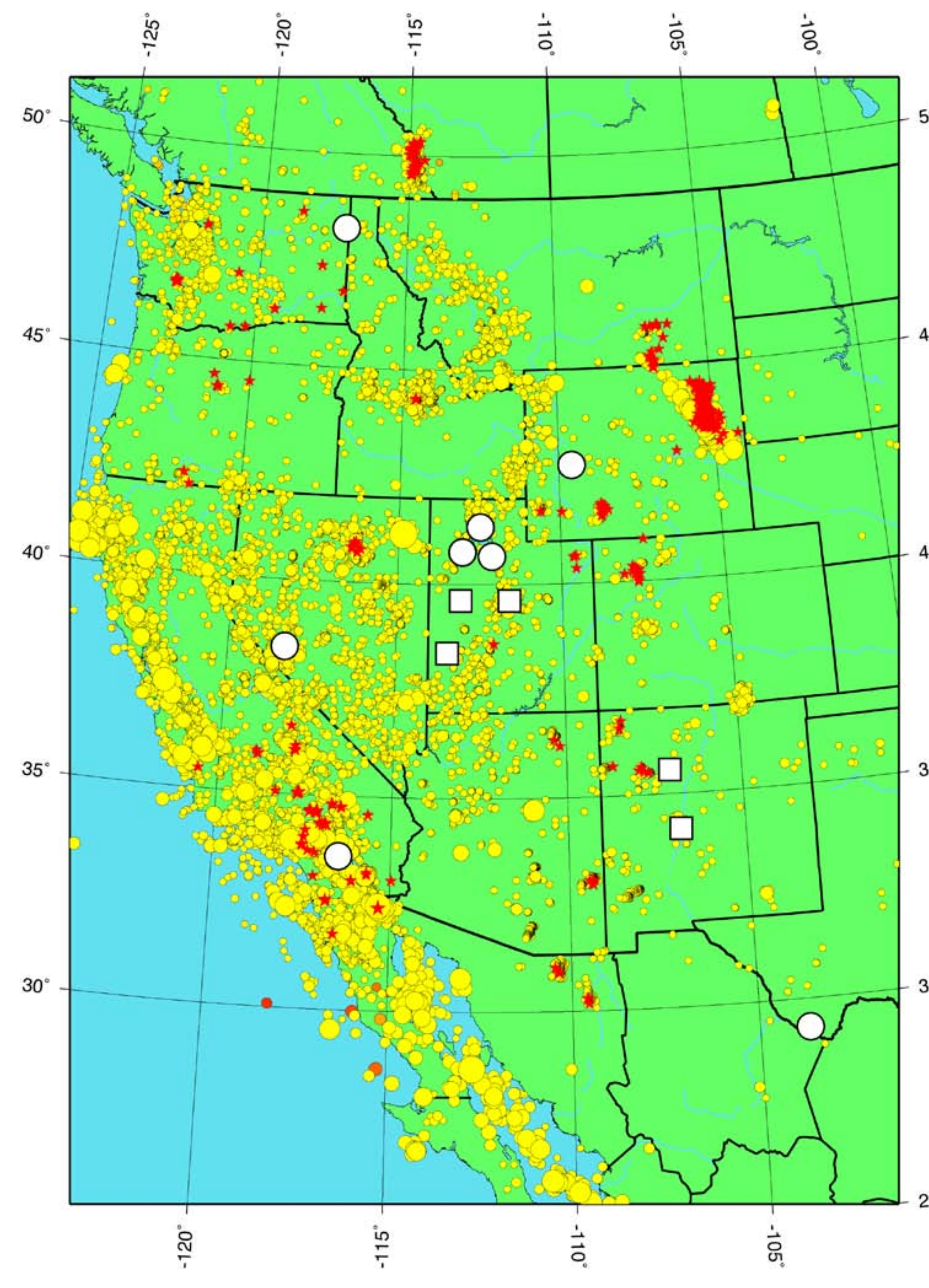

Figure 1. Summary of earthquakes (yellow circles) and mining explosions (red stars) in the Western U.S. between 2004 and 2009. Mining explosions are obtained from the USGS mining event list (however, some reported earthquakes may actually be mining explosions). Operational infrasound arrays are shown as white circles, while approximate locations of planned arrays are shown as white squares (we will leverage data from these arrays for Years 2 and 3 of this project).

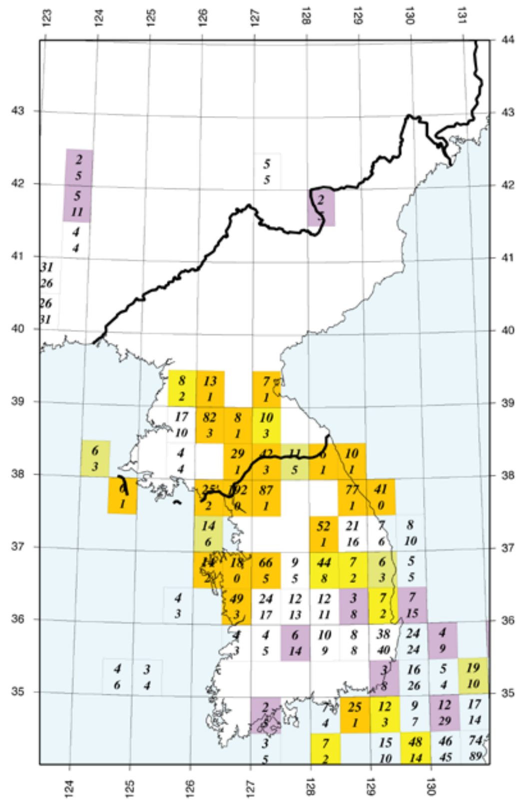

Figure 2. Summary of Korean dataset (largely consisting of ground-truth seismo-acoustic events from surface explosions, courtesy of Il-Young Che at KIGAM). Each 0.5°×0.5° bin lists the number of daytime events (top number) and nighttime events (bottom number) and is color-coded by the percentage of daytime versus nighttime events. Regions with large percentages of manmade events are shaded orange and yellow.

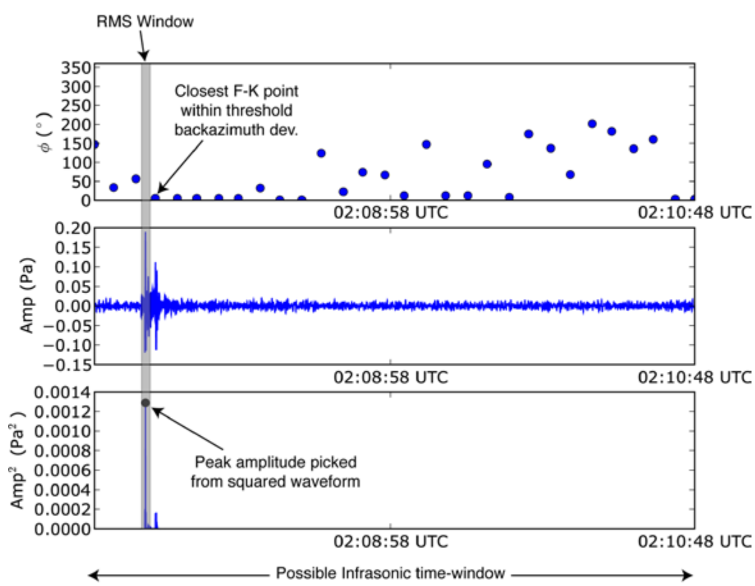

Figure 3. Illustration of the automatic amplitude measurement algorithm developed for this study. The time corresponding to the peak amplitude is measured from the squared waveform (bottom panel). The RMS amplitude is then measured within a time window of duration equal to 5 cycles (for the lowest frequency) (middle panel). Finally, an additional check is applied that the time corresponding to the amplitude must be within a threshold deviation from the ground-truth backazimuth (top panel).

Preliminary Analysis

(a) Separation of different physical mechanisms for infrasound generation

Since our ultimate goal is to relate infrasound amplitudes – corrected for magnitude, slip angle, distance, and atmospheric winds – to source depth, it is essential that we can separate infrasound signals that are generated by different physical mechanisms. Here, we define the following terms:

- **Epicentral infrasound.** This is infrasound that is generated at the epicenter by direct pumping of the atmosphere.
- **Secondary infrasound.** This is infrasound that is generated by the interaction of seismic surface waves and crustal structure (e.g., topography) away from the epicenter.

In a recent paper on this project work, published in *Geophysical Research Letters* (Arrowsmith et al., 2009), we show that secondary infrasound from the Wells, Nevada earthquake sequence is generated by the mainshock and numerous aftershocks, and that it manifests as high amplitude signals (greater in amplitude than epicentral infrasound). For this event sequence, secondary infrasound appears to be unique at each array, whereas epicentral infrasound can be distinguished as being common to multiple arrays. At station BGU, secondary infrasound can be uniquely identified as being generated by the interaction of surface waves with an isolated peak called Floating Island (Figures 4 and 5).

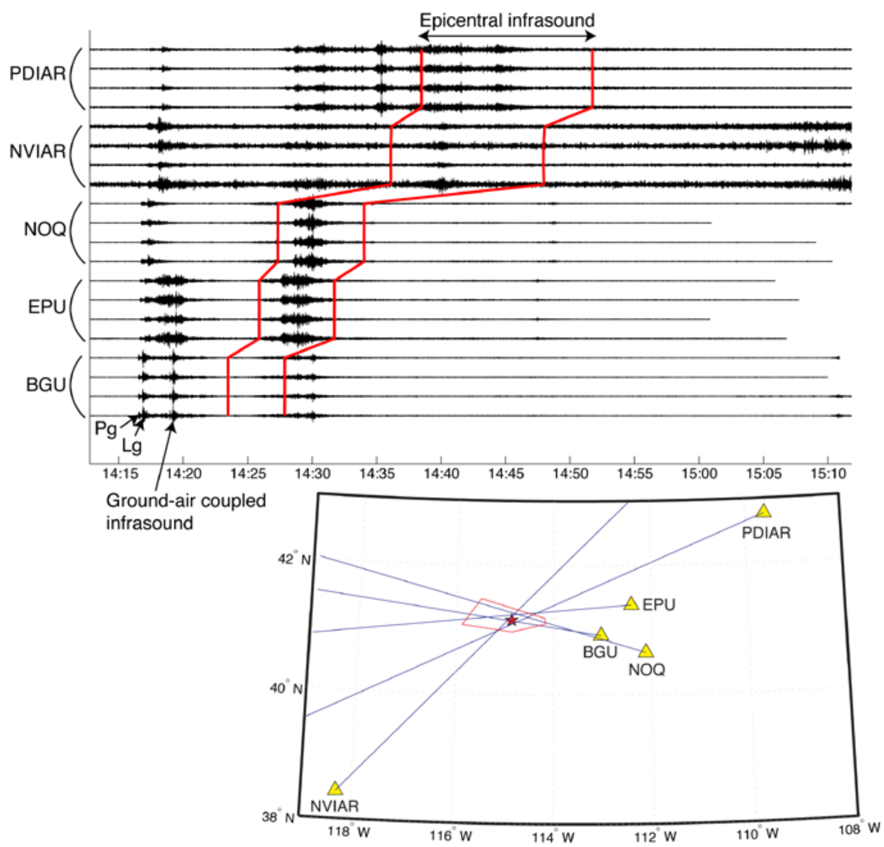

Figure 4. Infrasonic observations of the Wells, Nevada mainshock at five infrasound arrays in the Western U.S. Epicentral infrasound is common to all arrays, whereas secondary infrasound is unique to each array.

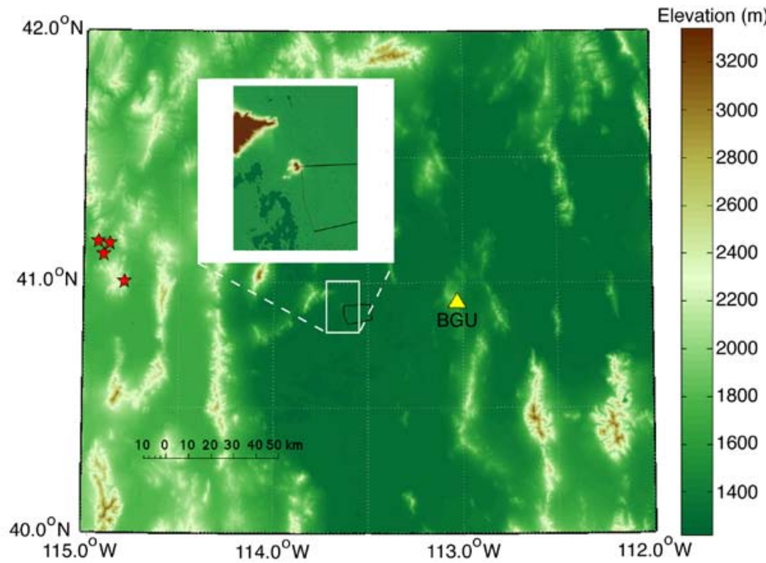

Figure 5. Map showing the locations of the Wells, Nevada mainshock and three major aftershocks (red stars), each of which generated signals from a point source associated with an isolated peak called Floating Island (inset map).

(b) The Wells earthquake sequence

Earthquake sequences provide a unique opportunity to study the effects of source parameters on relative differences in infrasonic amplitudes, because path effects can be assumed to be essentially fixed. Also, relative earthquake location algorithms can be used to determine accurate relative depths from seismic data. The Wells, Nevada earthquake sequence is highlighted in this paper as an invaluable research opportunity because a number of aftershocks were detected infrasonically at multiple arrays (Table 1).

Table 1. Infrasonic observations of the Wells, Nevada earthquake sequence.

Origin Time	Magnitude (ms)	Abs(Slip Angle)	Depth (relocated)	Amplitude at NOQ (Pa)
02/21/2008 14:16:02	5.8	90	9.824	1.9318
02/21/2008 14:20:51	4.4	-	8.923	0.2513
02/21/2008 14:34:43	3.67	-	10.728	0.3189
02/21/2008 22:47:28	2.86	-	3.885	0.4549
02/21/2008 23:57:51	4.35	51	-	0.1000
02/22/2008 23:27:45	3.78	85	14.507	0.1935
03/15/2008 16:22:33	3.33	85	8.974	0.4605

From a total of 37 events with Ml>3.5 (Smith et al., 2009), 7 were detected infrasonically. Figure 6 represents a summary of the observations. The source parameters (magnitude, depth, and slip angle) are represented on this plot as well as a simple summary of which events were detected. Larger magnitude events (Ms>3.5) that were not detected were all oblique-slip events. To our knowledge, these findings are the first documented evidence for infrasound signals from earthquakes with Ms<4.0 (Le Pichon et al., 2006). Although this dataset is relatively sparse, it highlights the interplay between magnitude, depth, and slip angle on infrasonic amplitudes. For example, events "a" and "b" in Figure 5 are essentially the same in all respects apart from magnitude (which is reflected by much larger amplitudes from the larger event, "b"). Events a and c are similar except for depth (which is reflected by lower amplitudes at the deeper event, "c"). Our goal in Years 2 and 3 of this project is to quantify these effects by incorporating 100's to 1000's of observations from the dataset described above.

We are attempting to make direct measurements of Rg (short-period Rayleigh waves) from Wells aftershocks using nearby stations. The idea is to examine the minimum observed period of Rayleigh waves as a crude estimate of event depth. This technique was used in the Bayesian Single Event Technique (BSEL; Fagan et al., 2009) to set Bayesian priors on event depth. Figure 7 shows examples of four Wells, NV aftershocks that illustrate our strategy. Figures 7a and 7c show dispersion and group velocity grams for events detected by infrasound and Figures 7b and 7d for events not detected. The station from the USArray site N12A, that is located approximately 34 km to the southwest of the Wells, NV sequence along a predominantly basin path. The top two events were of similar size and occurred within approximately 1 hour of one another and reported to be of similar depth (~4 km). However, event 7a was recorded by infrasound and 7b was not. The main difference in the dispersion between the two events is that clear dispersion is observed for 7a for a period between approximately 1 and 3.5 seconds while the minimum observed period for event 7b is approximately 2.5 to 3 seconds. This could indicate that Event 7a occurred at a shallower depth than 7b and therefore generated infrasound signals. Event 7c was magnitude 4.8, had a reported depth of 10.5 km, and was clearly detected by infrasound. However, there is a suggestion of Rg dispersion between about 2 and 4.5 seconds that could indicate a shallower depth than that reported. Event 7d was of magnitude 3.2 and a reported depth of 14.5 km and was not recorded infrasonically. As expected for a deeper event, there is no evidence of short-period Rayleigh wave dispersion. We will be attempting to develop phase-matched filters and polarization filters to better enhance the Rg waves from the Wells, NV aftershocks in order to better constrain event depth.

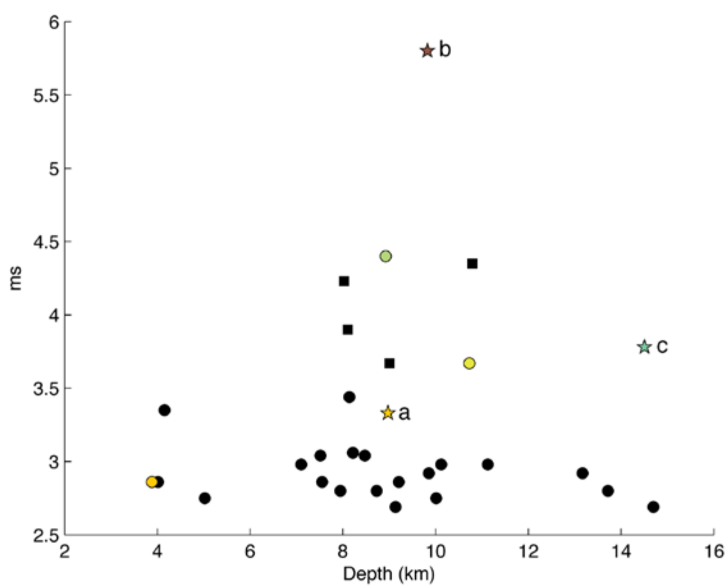

Figure 6. Graph summarizing detected (colored) and undetected (black) events in the Wells earthquake sequence. Colors represent the amplitudes recorded at NOQ (hot colors representing high amplitudes fade to cool colors for lower amplitudes). Symbols are representative of the slip angle as follows: pentagrams represent dip-slip events (80<s<=90), squares represent oblique-slip events (s<65) and circles represent events with unknown slips. Depths were computed using the HypoDD method by Ken Smith at UNR. Slip angles were obtained from moment tensor inversions by Bob Hermann at Saint Louis University.

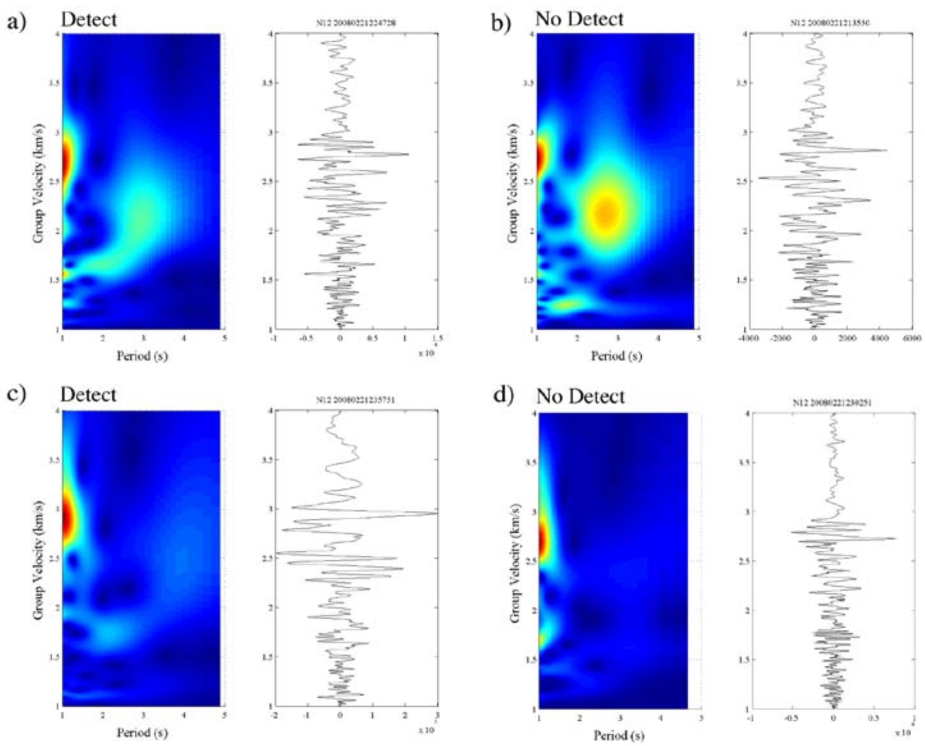

Figure 7. Dispersion plots and group-velocity grams for four Wells, NV aftershocks recorded at USArray station N12A (see text for details).

(c) Earthquakes and Explosions: Source vs. path effects

The dataset we are acquiring comprises both earthquakes and surface explosions in order to exploit the advantages of each. While surface explosions do not have a depth component, or a slip component, we are able to obtain many more robust observations of surface explosions than earthquakes (in part, due to the fact that they are more efficient generators of infrasound). A preliminary analysis of amplitudes from this extensive dataset of surface explosions is underway. We propose to exploit this dataset to develop reliable infrasonic path corrections that extend the earlier relationship of Mutschlecner et al. (1999). The relationship of Mutschlecner et al. (1999) reduces the effect of stratospheric winds on infrasonic amplitudes, and has proven effective in allowing for the regression of corrected amplitudes with source magnitude (Mutschlecner and Whitaker, 2005; Le Pichon et al., 2006). However, there is still scatter in corrected amplitudes that may be due to either source or path effects. With the recent availability of state-of-the-art 4D atmospheric models (3D+time), we have an opportunity to extend this relationship, which previously relied upon the only wind specifications readily available at the time (winds between 45 and 55 km).

CONCLUSIONS AND RECOMMENDATIONS

An unprecedented dataset is needed to address the fundamental research question of this effort: How can we estimate event depth using infrasound? The major focus of Year 1 of this effort has been on acquiring a dataset that is sufficiently robust to address this issue. A parallel focus has been to begin to explore the factors influencing the amplitudes of infrasound signals that we observe at regional scales. The goal for Years 2 and 3 of this effort is to develop these preliminary qualitative observations into quantitative relationships that can provide the framework for an infrasound depth discriminant.

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