INFRASOUND FROM EARTHQUAKES: SIGNAL CHARACTERIZATION

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ABSTRACT

There is a need to improve the understanding of the scaling and physics involved in regional recordings of epicentral infrasound from small earthquakes. This need stems from a wish to use infrasound presence and characteristics to improve depth discriminants. Current regional depth discriminants rely on recording the *Rg* seismic phase or intermediate period surface waves. These phases are sensitive to upper crustal structural details, but are often disrupted by horizontal changes in structure and topography. A number of studies have used single infrasound array data to argue that small earthquakes (M<4) generate infrasound signals. Wide spatial separation of infrasound arrays coupled with the time variation of atmospheric models make the association of infrasound signals from small earthquakes with seismic observations non-unique. This is because event association is often dependent on a single backazimuth estimate within a relatively wide range of arrival times. We propose to address this non-uniqueness, as well as assess smaller magnitude events, by deploying a total of six infrasound arrays in and around the Intermountain seismic belt in Utah. The University of Utah (UU) is the regional seismic network operator responsible for the location and characterization of earthquakes in the region and will integrate the six proposed infrasound arrays into the daily network operations. These arrays will provide the data needed to independently locate the infrasound sources using crossing backazimuth estimates for unique association with the seismic sources. Models of infrasound generation by earthquakes will be developed using a collection of earthquake scaling relations dependent on depth, magnitude and mechanism that are currently used for strong-ground motion assessment for earthquake hazards. Special attention to earthquake depth estimation, including synthetic modeling of seismograms and analysis of the *Rg* phase, will provide an assessment of both the depth estimate and its variance. The infrasound and ground motion observations made during the course of this study will be used to refine the source excitation model for infrasound using two different approaches, including the application of the Rayleigh integral. The application of this physical based approach to infrasound generation is intended to lead to a possible infrasound based depth discriminant that could be integrated into the Event Classification Matrix (ECM) (Anderson, 2007). In a related effort, preliminary analysis of infrasound from the Wells earthquake sequence is reported in Stump et al. (2009, these Proceedings), which describes the first deployment of infrasound gauges in Utah.

OBJECTIVES

Objective 1: Improved understanding of earthquake generated infrasound.

An understanding of earthquake-generated infrasound is critical to the development of seismo-acoustic discriminants that distinguish between surface explosions and earthquakes. Numerous studies have identified infrasound from surface explosions (Arrowsmith et al., 2008; McKenna et al., 2007; Che et al., 2002), but have also recognized that varying atmospheric conditions and propagation characteristics may suppress recording at a particular station on a particular day. Previous studies of earthquake generated infrasound signals (epicentral infrasound) recorded at distances beyond 220 km have shown that medium to large earthquakes can generate infrasound (e.g., Mutshlecner and Whitaker, 2005; Le Pichon et al., 2006). The observations suggest a linear relationship between earthquake magnitude and infrasound duration and a linear relationship between earthquake magnitude and the log of infrasonic amplitude (Figure 1).

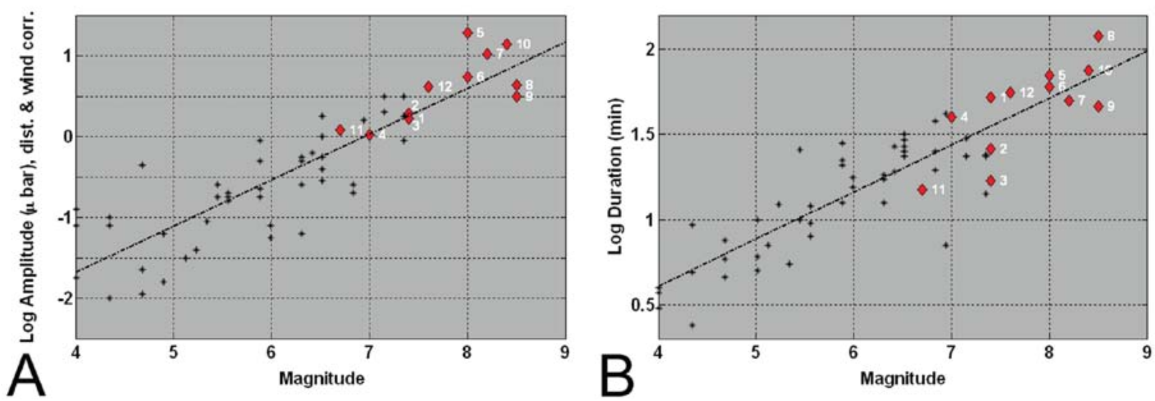

Figure 1. Previous observations of earthquake-generated infrasound showing the relationship between wind-corrected amplitudes (A) and signal durations (B) with earthquake magnitude. Black dots are from the analysis of infrasound signals for the set of earthquakes in Mutschlecner and Whitaker (2005). The red points are from an independent study by Le Pichon et al. (2006) for a different set of generally larger events. The combined datasets cover a magnitude range of four to nearly nine. Earthquakes less than magnitude four were not analyzed (from Le Pichon et al. [2006]).

Previous studies of earthquake generated infrasound suffer from the following four primary limitations: (1) most observations for smaller magnitude events are single-array only; (2) effects of earthquake depth, focal mechanism, and local geology were not studied nor modeled in detail; (3) there have been no detailed studies of infrasound from small earthquakes, M < 4; and (4) observational studies have focused on long-range infrasound (i.e., stratospheric and thermospheric returns) and not on local or near-regional infrasound (i.e., distances < 220 km).

This work will address the limitations as follows:

- **Previous studies only consider single-array observations.** When observations are limited to a single-array, signal association of a particular earthquake with an infrasound arrival is based on a single backazimuth estimate within a relatively wide range of arrival times. The complex temporal atmospheric variability, the large number of extraneous coherent infrasound signals, and highly variable site noise conditions make conclusive seismic-to-infrasound association or non-association difficult. At the International Data Centre (IDC), 90% of infrasound detections are from coherent noise sources (Brachet and Coyne, 2006). To robustly associate infrasound signals with seismic events requires multiple observations on a network of infrasound arrays (Arrowsmith et al., 2008). This research will include extending the operation of three existing Utah seismo-acoustic stations (Stump et al., 2007) and collocating three additional infrasound arrays at existing UU seismic stations. Robust detection and association algorithms, recently developed in collaboration between Los Alamos National Laboratory (LANL), Southern Methodist University (SMU), UU and Rocky Mountain Geophysics (RMG) (Arrowsmith et al., 2008), will be employed to address the non-uniqueness limitation of previous studies.
- **Previous studies only consider earthquake magnitude scaling relations.** Other than magnitude, there has been no detailed study of the relationship between earthquake source characteristics and infrasound generation. This study will address the problem in two steps. First, observational earthquake infrasound scaling relations

will be developed using seismically constrained depth and peak ground motion estimates. Second, epicentral infrasound will be modeled based upon predicted or observed ground accelerations and used to calculate the resultant recorded infrasound signal (Whitaker, 2007). Modeled results will be compared with observational records to refine the infrasound source excitation model.

- **Previous studies only consider infrasound from large earthquakes.** There has been no study of infrasound generation or its absence from small earthquakes (M < 4). This study includes a large dataset of small magnitude earthquakes (Figure 2).
- **Previous studies only investigate infrasound at long ranges.** Previous studies have focused only on long-range observations. This study will utilize six acoustic arrays in an active seismic region (Figure 2). At distances less than 220 km, waveform characteristics, especially amplitude, vary significantly with source-to-receiver range. This is an effect of the highly variable lower atmosphere that dominates the propagation characteristics. The dataset acquired as part of this proposal will provide the basis for a detailed exploration of such waveform characteristics.

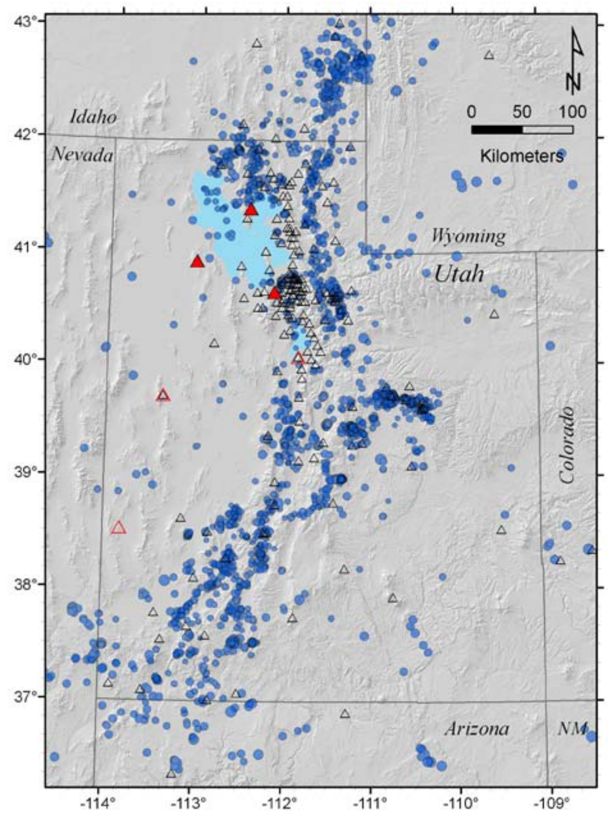

Figure 2. Map of existing Utah seismo-acoustic stations (red filled triangles), proposed seismo-acoustic stations (red open triangles), seismic stations (black open triangles) and three years of crustal earthquakes from the UUSS catalog, approximately the same duration as the proposed project (light blue circles).

Objective 2: Development of an infrasonic depth discriminant.

The dataset created in Objective 1 will be used for research and development of an infrasound depth discriminant to be incorporated into the ECM framework currently being developed at the National Laboratories. This implementation will address a significant limitation with existing depth discrimination capabilities, which rely on the presence of the seismic phase *Rg*, commonly not observed. A key prerequisite for developing and testing an infrasound depth discriminant is an independent robust depth determination. As part of this proposal, we will have access to a large number of well-constrained earthquake depths (see the section entitled *Seismic network description and known sources*). In addition, we will utilize *Rg* and intermediate period surface wave seismic arrivals with a forward modeling approach to better constrain earthquake depths for additional events.

RESEARCH PLANNED

Seismic network description and known sources

The University of Utah Seismograph Stations (UUSS) operates a regional and urban seismic network of more than 200 seismic stations. Data and metadata from UUSS seismic stations are archived at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC). An overview of data processing and analysis procedures can be found on the UUSS website at http://www.quake.utah.edu/EQCENTER/LISTINGS/overview.htm. In addition, beginning May 2007, UUSS began integrating EarthScope Transportable Array (TA) stations into routine analysis, processing, and data product generation. Many of the TA stations have been moved, but while deployed, the TA stations in Utah contributed to improved event azimuthal coverage, and provided important additions to observations of the Crandall Canyon mine event (August 2007) and the Wells, Nevada earthquake sequence (February 2008).

To characterize the instrumental seismicity of the Utah region, we categorized events from the UUSS earthquake catalog with minimum magnitude M 0.0 for the period January 1, 1981 to December 31, 2007. For this period, more than 36,000 events were identified; 49% of these events occurred in the mining area of Wasatch Plateau and Book Cliffs (Arabasz et al., 2007) and 15% have well-constrained focal depths (for the definition of well-constrained focal depth, we use the criteria from Arabasz et al. [1992], where the distance to the nearest station is less than the focal depth or 5.0 km, and the depth error is less than or equal to 2.0 km). The depth for the subset of events with well-constrained focal depths varies from 0 to 29 km (one event recorded in 1992 has a depth of 55 km) and the magnitudes (duration or local) vary between 0.0 and 4.6. Figure 2 shows the location of seismic stations, existing and proposed acoustic arrays, and epicenters for 2005–2007.

In addition to the cataloged seismicity, UUSS also records energy generated by man-made sources such as mining blasts, highway construction, and rocket motor detonations. Each quarter, blasts are identified and eliminated from the UUSS earthquake catalog using information from the mine operators or waveform cross-correlation with known blasting areas.

Routine UUSS data processing includes generation of peak ground-motion amplitudes (acceleration and velocity) and 5% damped spectral response values for three different periods (0.3, 1 and 3 seconds) from all strong-motion and broadband stations in the network (including TA stations). For Utah earthquakes greater than magnitude 3.0, UUSS uses the computed amplitudes and spectral response values to produce a regional ShakeMap, a graphical representation of ground shaking from earthquakes (Wald et al., 1999). UUSS also generates scenario ShakeMaps, using regionally appropriate predictive ground motion relations. ShakeMaps for observed events and scenarios describe spatial variance of ground-motion amplitudes as a function of source distance, local geology, depth, and earthquake mechanism. These ground motion estimates can be used to drive models of earthquake-generated infrasound.

Existing and planned acoustic arrays

Six seismo-acoustic arrays are planned for this project. Three arrays are already installed and are integrated into the UUSS network (the acoustic arrays are collocated with existing seismic stations at BGU, EPU, and NOQ; Figure 2). Table 1 describes the characteristics of the three existing seismo-acoustic arrays operated by UUSS.

Table 1. Existing seismo-acoustic arrays operated by UUSS.

	NOQ array	BGU array	EPU array
Number of elements	4	4	4
Sensor type	Chaparral 2	Chaparral 2	Chaparral 2.5
Digitizer	REF TEK 130	REF TEK 130	REF TEK 130
Real-time telemetry	Yes	Yes	Yes
Aperture (m)	161 x 122	136 x 139	159 x 121
Average distance between sensors (m)	118	115	119
Installation date	May 4, 2006	April 17, 2007	July 13, 2007
Collocated seismic station	BB	BB	SP
Archived data start at IRIS DMC	May 4, 2006	N/A	N/A

Figure 2 also shows the provisional locations for the three additional acoustic arrays collocated with existing UUSS seismic stations FSU, WMUT, and a broadband seismic station to be installed in southwestern Utah as part of a state funded project. SMU will supply Chaparral microphones for the acoustic arrays at no cost to the project. An equipment request has been submitted to the Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) for the data recorders, solar panels, and telemetry systems needed to support the six acoustic arrays. Data will be telemetered to UUSS, saved in Seismic Analysis Code (SAC) format on DVDs and in SEED format at the IRIS DMC.

Data analysis

Data analysis will utilize the LANL developed InfraMonitor software package to detect, associate and locate events (Arrowsmith et al., 2008). This algorithm has been implemented for automatic pipeline processing of large quantities of data at LANL and UU. Events detected and associated at >1 seismo-acoustic array will be reviewed by an analyst.

The first component of InfraMonitor, the robust detection algorithm (Arrowsmith et al., 2008b), uses an adaptive noise hypothesis to account for variations in ambient noise, rather than using an idealized model. InfraMonitor includes a coherent detector for processing array data and an incoherent detector for processing single element data (Arrowsmith et al., 2008b). For this study, infrasound array data will be processed with a coherent detector and seismic data will be processed with an incoherent detector.

The incoherent detector developed and implemented in InfraMonitor first transforms the background noise into a near-normal distribution and then applies a robust outlier detection algorithm to identify signals (Arrowsmith et al., 2008b). In tests with seismic data, we have shown that the incoherent detector performs similarly well.

The second component of InfraMonitor searches for groups of signals at separate arrays that have a common source (associations) by scanning detection bulletins at each seismo-acoustic array and hypothesizing an approximate location. This process uses a grid-search algorithm where arrivals are associated based on backazimuth consistency and inter-array delay times. A region of interest is parameterized with a grid mesh and associated arrivals are searched for at each grid node.

The automatic detection and association algorithms described above will be used to search for infrasound signals from regional earthquakes. We will populate a database with infrasound observations (and non-observations), in order to develop relationships between infrasound waveform characteristics and earthquake magnitude, depth, source mechanism and local geology.

ANTICIPATED RESULTS AND IMPLICATIONS

Earthquake source development and validation

We plan to extend the relationships shown in Figure 1 (Mutshlecner and Whitaker, 2005; Le Pichon et al., 2006) to include other scaling relations between the earthquake source (such as depth and peak ground motion) and infrasound generation. Then ground motion estimates from the earthquake sources and propagation characteristics will be used to model coupling to the infrasound wavefield.

Earthquake scaling relations

Two parameters of particular interest in developing scaling relations are the source depth and peak ground-motion. Well-constrained depth estimates for earthquakes for correlation with infrasound detections will be obtained from results of temporary source region aftershock deployments and waveform modeling for events with moment tensor estimates. Since most of the Wells aftershock sequences and ~15% of the Utah seismic catalog events have good depth estimates, this study includes a substantial test dataset in contrast to less well instrumented regions of the world. Additionally, for events with moment tensor estimates, we have had success modeling event depth with long to intermediate period surface and body waves using simple earth models. A simple example is shown in Figure 3 using the vertical displacement data at Dugway, UT (DUG) for the Wells, NV event, the Harvard centroid moment tensor (CMT) mechanism, and reflectivity synthetics for a range of depths.

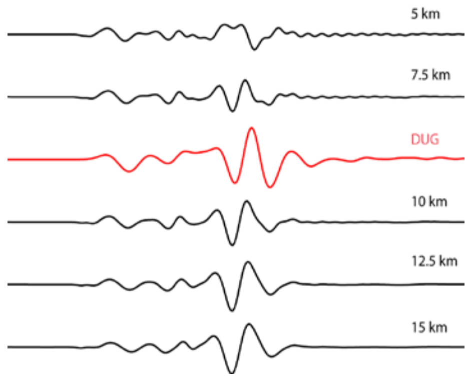

Figure 3. Comparison of synthetic seismograms for depths of 5, 7.5, 10, 12.5 and 15 km in black with the DUG displacement in red. Although the waveform fit is preliminary, the general arrival time of body and surface wave energy is good and the relative surface wave to body wave amplitudes indicate the depth is likely deeper than 7.5 km. All waveforms are on the same scale.

The second parameter of interest, the peak ground motion, is related to magnitude for which there is a scaling relation developed for stratospheric-ducted infrasound of medium to large earthquakes (Figure 1). However, peak ground motion is also a function of local geology – softer soils typically have higher ground motions than rock. In this analysis, we are interested in both near-source peak motions for the generation of 'epicentral infrasound' and in the spatial distribution of peak ground motions for the generation of secondary infrasound sources. ShakeMaps combining the measured ground-motion with predictive relations, such as Pankow and Pechmann (2004) or Boore et al. (1997), produce spatially coherent maps of ground-motion and intensity (for example see http://www.seis.utah.edu/ shake/1000012101 /pga.html). The ShakeMap methodology (Wald et al., 2003) produces: (1) estimates of the peak ground-motion in the near source region and (2) spatial maps of peak ground motions. For the above ShakeMap example (event ID 1000012101, an M 3.5 earthquake in northern Utah), the near-source had peak ground accelerations greater than 1.2% g. ShakeMaps can easily be generated for all earthquakes of interest and scenario events.

For the purposes of developing scaling relations, we will build a database of earthquake parameters including: location, magnitude, depth, depth quality factor, predicted peak ground acceleration and peak ground velocity in the source region, distance to the closest seismic station and type of station, average shear velocity in the upper 30 m (Vs30) in the source region, and faulting mechanism (when available). The estimated Vs30 in the source region will be obtained from locally produced Vs30 maps for the Utah region (Christenson et al., 2004) and topographically derived Vs30 maps (Wald and Allen, 2007) outside of the Utah region. The earthquake database will be combined with the infrasound data processing to generate scaling relations. In addition to the database, we will also construct a catalog of ground motion grid files. Combining the grid files with the scaling relations for peak ground motion will show potential sources of non-epicentral infrasound generation.

Infrasound modeling

Given an acceleration time and spatial history at the ground surface, the near source infrasound signal may be computed at an observation point above by application of the Rayleigh integral. The Rayleigh integral can be expressed (Pierce, 1989) as:

$$p(R_0,t) = \frac{\rho}{2\pi}\int \frac{a(r,(t-R/c))}{R} dA_s$$

where a is the acceleration of the ground, r is a location on the ground (referenced to a center position), dA_S is an element of area on the ground, R is the distance from the ground element to the observing point, t is time, ρ is the air density, c is the speed of sound in air, p is the air pressure, and R_0 is the observation location. The acceleration values may be derived from actual surface measurements and mapped to the desired radial/angular grid for the numerical integration. Alternatively measured surface ground motions could be the basis of parametric acceleration models that could be used in the integration. Then near-field infrasound signals may be computed and relations explored as a function of earthquake characteristics such as magnitude and depth.

Alternatively, a time-domain finite-difference numerical hydrodynamics program may be used to calculate the pressure field in a two-dimensional, cylindrically symmetric domain, (r,z) geometry where r is the radius and z is the height. LANL has used a version of the program Caveat (Addessio et al., 1992) for nearly 20 years. In this application, the ground motion provides a time dependent velocity boundary condition at the bottom (z=0) of the Caveat grid. The evolution of the resulting pressure wave field is easily followed.

Two sources of ground motion will be used as input for infrasound modeling. First, when actual recorded waveforms in the near-source region are available, such as the Wells aftershock sequence, the data will be interpolated and scaled to build the input grid for modeling. Second, for events where no near-source recordings exist, we will use data archived at the National Strong Motion Data Center. Waveforms will be selected to represent the appropriate tectonic regime, depth and magnitude. We can also select different waveforms based on frequency content and waveform characteristics to assess the variation in infrasound generation to the specifics of the waveform. The amplitudes of the selected waveforms will be scaled to match the peak ground acceleration grid generated in developing the scaling relations.

Implementation of results into ECM depth discrimination

The focus of this part of the proposal is to develop a method to identify a shallow seismic source based on a seismo-acoustic detection. We emphasize seismo-acoustic detection in this work because we are attempting to utilize infrasound signals to place constraints on the source type and depth of accompanying seismic signals. The method will be formulated so that it can be incorporated into the ECM of Anderson et al. (2007). It must therefore have a sound physical basis as well as a foundation in mathematical statistics. A common seismic indicator for the identification of a shallow source is the presence of the short-period surface wave, *Rg*. However, *Rg* is often not observed, because it is sensitive to the details of upper crustal structure. In contrast, infrasound signals can be generated by near-source pumping of the atmosphere from shallow sources or strong ground motion from large earthquakes. In other words, an infrasound signal associated with a corresponding seismic signal for a small event may act as a surrogate for an *Rg* detection. In this proposal, we will statistically quantify a seismo-acoustic detection as an indicator of a depth event in a form that can be included in the ECM.

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