DISCRIMINATION OF EARTHQUAKES AND MINING BLASTS USING INFRASOUND

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ABSTRACT

Infrasonic signals from 31 large earthquakes have been observed by arrays of microphones operated by the Los Alamos National Laboratory (LANL) over the period of 1983 to 2003. Signal amplitudes, corrected for propagation and distance, have been used to determine a relationship with seismic magnitude. The variance in the relationship can be understood primarily in terms of the uncertainties in the ground motion, deduced from an independent data set, and the middle atmospheric winds, which strongly influence signal propagation. Signal durations can extend over many minutes, and a relationship was also found between signal duration and magnitude. To understand this relation, we have proposed a model in which regions distant from the epicenter are excited by seismic surface waves. The surface motion of these regions in turn, produce signals that precede or follow signals from the epicenter. Standard signal processing analysis failed to detect signals from 56 earthquakes during the observation period. The predicted signal-to-noise ratios (SNR) for these earthquakes generally indicated that signals would have been too weak to be detected.

During the past year we have also systematically and independently investigated infrasonic detection of small earthquakes and mining blasts in the Western USA, and have found that small mining blasts were routinely easier to detect. Part of the reason for this relative efficiency of mining-blast detection is that earthquakes must shake the earth's surface to create a significant amplitude infrasonic signal, and yet earthquakes can deposit most of their energy at great depths below the surface. In addition, there are at least three earthquake-faulting mechanisms and only for the up-down type is significant infrasonic emission expected. Lastly, not all earthquakes have infrasonic waves emanating from their epicenter. These facts not withstanding, we have still managed to detect 13 earthquakes from some 90 events that were examined, In the case of small mining blasts, we detected 13 of 40 events that were searched. All events generally had local seismic magnitudes between 3 and 4. In all detections, we have found a repetition of source locations either from the same sets of mines (for example, Morenci in Arizona and Wyoming's Powder River Basin) or the same sets of geologically active regions, i.e., the southern California/Baja region, etc.

The goal of this latter research is to be able to reliably distinguish between earthquakes and small mining blasts using discriminants established through either infrasound signals alone or in conjunction with seismic data. We have already suggested several possible discriminants, and are presently in the process of evaluating them along with continuing to search our database for additional infrasonic detections of earthquake and mining blasts. The earthquake and mining-blast discriminants currently being examined include: 1) the amplitude of infrasound as corrected for range and stratospheric wind effects, but not for winds in the case of thermospheric arrivals, 2) FFT (Fast Fourier Transform) power spectral analysis differences, 3) seismic R_g phases for separating earthquake signals from mining blasts, i.e., as a fundamental depth discriminant concept and finally, 4) the separation of signals by types of arriving infrasonic returns (phases) as a function of their source type.

OBJECTIVE

We will present the results of our analyses of earthquake generated infrasound and mining explosions. We start with a summary of results for the larger events in order to gain confidence in our analysis techniques and subsequently focus attention on only ***regional*** detections of small earthquakes and mining blasts (with local seismic magnitudes generally < 4 at ranges < 1500 km). The goal in this work is to establish reliable discriminants for distinguishing earthquakes from mining blasts over ***regional*** propagation distances.

RESEARCH ACCOMPLISHED

We analyzed large-event observations from 1983 through 2003, but emphasized the period through 1992. At LANL we have a very long history of processing and analysis of such earthquake infrasound records (Mutschlecner *et al*, 1985; Mutschlecner and Whitaker, 1994; Mutschlecner *et al*, 1999). A total of 31 earthquakes were detected through 2003 of which 13 were detected by two or more infrasound arrays, for a total of 47 recorded signals. All, but nine of the earthquakes were in California. Station to event distances ranged from 165 kilometers to 4100 kilometers. All magnitudes were obtained from the National Earthquake Information Center and placed on a common M_L scale by the use of transformations given by Utsu (2003) with additional information given in the review by Lay and Wallace (1995).

The data from the larger earthquakes were recorded at arrays operated by LANL. These data included infrasonic detections at Los Alamos, New Mexico at both the small baseline research arrays as well as at DLIAR (DOE LANL Prototype array), and at two other small baseline arrays, namely at St. George, Utah and Mercury, Nevada (NTS). We have searched for detections of small earthquakes and mining blasts only at the LANL, DLIAR array so far in this work that is a research in progress. The LANL research arrays have four very low frequency microphones spaced at distances of about 100 m from a central point and cover an overall distance of about 300 m. The microphones are Globe 100C or Chaparral Physics Model II. Wind noise reducers consisting of porous hoses are attached to each microphone in a radial pattern with a diameter of about 30 m. Two of the earthquakes were also observed at the DLIAR prototype array at Los Alamos with an overall diameter of 1.2 km. Data were sampled 20 times/sec except for the prototype array for which the rate was 10 times/sec. The Chaparral microphone frequency band pass is ~0.1-10 Hz, while the corresponding band pass for DLIAR is 0.1-4 Hz.

Data were processed by using a Fourier-domain correlation beam-former that employs frequency-slowness plane variables. For the smaller events, Matseis software was used for the routine data processing (available from Sandia National Laboratories [SNL], Albuquerque). For the larger events, the standard Matseis data-analysis software with enhancements from the work of Young and Hoyle (1975) were also included. Time windows were generally 20 sec with 50 % overlap. The most frequent noise sources were local winds or microbaroms (sea-storm generated infrasound), which typically have a peak power near 0.2 Hz. The frequency pass band used for most analysis was 0.5 to 3.0 Hz to reduce the effects of the microbaroms and local wind noise while still including most of the earthquake signal. In a few cases this band pass was altered to give a greater SNR. The larger events generally had semi-automatic detections within the Matseis software whereas the smaller events were almost always detected manually by varying either the data-window size or the degree of overlap or by varying the allowed band-passed frequency range, etc.

The results of the processing are: average pair-wise channel cross-correlations, azimuth of the correlated energy, trace velocity, frequency of the peak power determined from a power spectrum, and power. An example of the processing is given in Figure 1 for the earthquake of 2 February 2002 that occurred in the Southern California/Baja California region.

Peak-to-peak amplitudes were determined as averages over major correlated signal features and averaged over all microphone channels. Amplitudes were converted from microphone output voltage to pressure in microbars (1 μb = 0.1 Pascal) using calibrations determined for each microphone at reasonably frequent intervals and have an estimated accuracy of 15% (Mutschlecner and Whitaker, 1997).

The observed amplitudes, A_O, have been normalized for the effects of distance and stratospheric wind effects by the use of the relation:

$$A_n = A_o 10^{-kv_d} \left(\frac{R}{R_s}\right)^S \tag{1}$$

where A_n is the normalized amplitude, R is the great-circle distance to the epicenter, R_S is an arbitrary standard distance, and v_d is the stratospheric wind component directed from source to array. S and k are empirically curve-fitted parameters. Mutschlecner et al. (1999) discuss the background for this normalization process and determinations of S and k. Based upon analysis of signals from numerous atmospheric nuclear explosions and large high-explosive tests, we have adopted S = 1.45, k = 0.018 s/m and R_S = 1000 km which is approximately the average of the distances for the larger earthquakes.

Stratospheric wind data are needed to normalize the signals as indicated in (1). These data were taken from National Climate Data Center records of high altitude winds observed by rocketsonde flights. Rocketsonde stations included Point Mugu, California; White Sands, New Mexico; Wallops Island, Virginia; and Cape Canaveral, Florida. We employed data from all stations that were available and close to the required date, but we emphasized data from Point Mugu and White Sands for the California earthquakes. Zonal and meridional components of the wind were averaged from the records for altitudes between 45 and 55 km. This procedure is in agreement with the protocol used for the Stratospheric Circulation Index described by Webb (1969), and closely represents the region of the stratosphere involved in the return of signals to earth where the wind velocity is critical. Because wind data for a specific earthquake date were usually not available, data were interpolated for the zonal and meridional components from nearby dates. If no at all wind were available, values were taken from statistical models as given in Mutschlecner et al. (1999).

In addition to the infrasound detections described here, signals from 56 earthquakes were searched for but not found; 32 of these earthquakes were located in California. In 14 instances two or more arrays were employed for a total of 71 non-detections (NDs). For several of the NDs the causes are rather obvious: either all epicenters are at very large distances or there was very high wind noise or both possibilities occurred.

Additional earthquake studies performed during the past year include the following:

- i) The normalized relationship between infrasonic amplitude and seismic magnitude was developed.
- ii) The relationship between the peak vertical ground motion near the source and the seismic magnitude was developed.
- iii) The most important parameters producing the large variance found for the relationship between the normalized infrasonic amplitude and the seismic magnitude were identified using Monte Carlo statistical simulations.
- iv) The relationship between the total infrasonic signal duration and the seismic magnitude was developed.
- v) The relationship between the limiting infrasonic observation distance from the earthquake epicenter and the seismic magnitude was developed.
- vi) The minimum, near-field, peak ground acceleration necessary for infrasound detection from earthquakes was developed.
- vii) Reasons for the non-detections of an additional 56 earthquakes within the database were examined.
- viii) Two new infrasonic signal-processing detectors to be used in Matseis/Infra_tool were developed with SNL.

In addition to the study described above that has only been partially presented here, an additional independent study of small earthquakes and small mining blasts was also undertaken. The latter study is still a work in progress, but will be described briefly. Data for the location and times of small earthquakes and mining blasts in the western United States from 2000-2002 were assembled with the help of Dr. B. Stump (Southern Methodist University, Dallas, Texas) and from a United States Geological Survey (USGS) website. Over 300 earthquakes and over 425 mining blasts were assembled as a list for a subsequent infrasonic search for coherent signals with the requisite great circle back azimuth, signal velocity and amplitude to be designated as a single station detection. For mining blasts we demanded a much closer back azimuth between observations and processed data than we did for the small earthquakes. Because other researchers have shown that the epicenter need not be the source of the strongest infrasonic waves, we chose to use a weaker azimuth constraint on the deduced infrasound back azimuth from earthquakes (Le Pichon et al, 2003).

The new study emphasized ***regional*** scale detection of small earthquakes and mining blasts whereas the earlier study emphasized regional and teleseismic detection of much larger earthquakes. In order to proceed with the domain of very small sources we wanted to establish a set of reasonable search criteria. Thus our new emphasis was to use the larger earthquakes as a guide for the successful detection of smaller events. The approach used in our semi-automatic "nominal" data processing analysis for small vents was as follows:

- i) A minimum cross-correlation threshold for three or more consecutive data windows was set
- ii) A specific limit of allowable array trace speed was established
- iii) A specific limit of allowable observed signal velocities was established
- iv) A maximum allowable deviation from the great circle back azimuth was set. This value was much smaller for mining blasts than for earthquakes
- v) Observed microbarom back azimuths in the time region of interest were determined in order to be confident that the observed signals were not microbarom related "bursts" (Less than 10 % of the final detections were deleted because of this constraint).
- vi) Comparisons between the Matseis/Infra_tool back azimuth and the f-k (frequency-wavenumber) slowness plane approach were made in order to confirm the detections made in Infra_tool. In addition, examination of Matseis spectrograms often allowed confirmation of the infrasonic detections at least as long as the time period of the signal was no too "noisy".

After a semi-automatic detection was established for the searched events, either the data window size or the upper and lower band-pass frequency limits were systematically varied in order to refine the search. This approach however took substantial amounts of time and needs to be further automated.

So far in our data processing search we have examined ~ 100 earthquakes and ~50 mining blasts using only a single array (DLIAR). The full details of this continuing search will be reported on at a later date. The distributions of the number of events versus local seismic magnitude and the number of events versus source-observer range for both earthquakes and mining blasts (from an earlier search encompassing only ~90 earthquakes with local seismic magnitudes between 3 and 5.8, and ~40 mining blasts with local seismic magnitudes between 3 and 3.6) is shown in Figure 2a and 2b. Of these 90 earthquakes, only 13 infrasonic detections were made with a high degree of certainty, whereas for the mining blasts a total of 13 high quality detections were made from a search of only 40 events in a similar local seismic magnitude range. A geographic summary of these infrasonic detections is given in Figure 3 where it is noted that for both source types, a repetition of source locations is clearly evident. In Figure 3, we have plotted the locations of both types of sources in the Western USA (for events during 2000 to 2002) including the locations of both detections and non-detections at DLIAR. A detailed, albeit brief summary of detections of small earthquakes and small mining lasts is also listed in the Tables 1 and 2.

Part of the reason for our success in detecting small mining blasts relative to earthquakes is a result of the source ground-coupling factor, and also the fact that the mining-blast source is very near ground level. Only earthquakes that have vertical ground motion are expected to generate significant infrasonic signals. In addition however, earthquake sources can also be at great depths. Since the generation of infrasound is fundamentally related to the up-down ground motion sustained near the source, deeper earthquakes are generally not expected to generate significant infrasound. For our study all earthquakes were shallow sources in a geophysical sense because all earthquakes events that we studied were within 25 km of the surface. The deepest source that was detected using infrasound so far was 13.8 km; the shallowest source was right at the earth's surface.

We also examined our detections in terms of establishing possible discriminants between small mining blast and earthquakes. We are currently examining earlier predictions of normalized infrasonic amplitude versus local seismic magnitudes that were developed for larger sources at generally longer ranges to determine if we can establish a similar regression curve for use in the small source-size range. Additional discriminants currently being investigated include the following:

i) Amplitude of infrasound as corrected for range and stratospheric wind effects, but not for winds in the case of thermospheric arrivals.
ii) FFT (Fast Fourier Transform) power spectral analysis differences between the two source types.
iii) Seismic R_g phases for separating earthquake signals from mining blasts over short-range shallow propagation paths, i.e., as a fundamental depth discriminant concept.
iv) The separation of signals by the types of arriving infrasonic returns (phases) as a function of their source type.

Finally, we have also examined sources of error and additional uncertainties in our observed and analyzed source and infrasonic detection and propagation parameters. These results will also be presented at a later date.

CONCLUSIONS AND RECOMMENDATIONS

We have examined a fairly wide range of earthquake and mining-blast magnitudes and distances. For large earthquakes, we determined that a relationship exits between the normalized infrasonic amplitude and local seismic magnitude. Within our new search for the infrasonic detection of much smaller sources that is currently under examination, we wish to determine if this relationship is still applicable. In any event, if a similar regression line can be established for such small sources over regional detection distances, a possible discriminant can be developed for separating mining-blast shots from earthquakes. This discrimination tool will be a very important development since a very large number of both types of sources occur annually worldwide.

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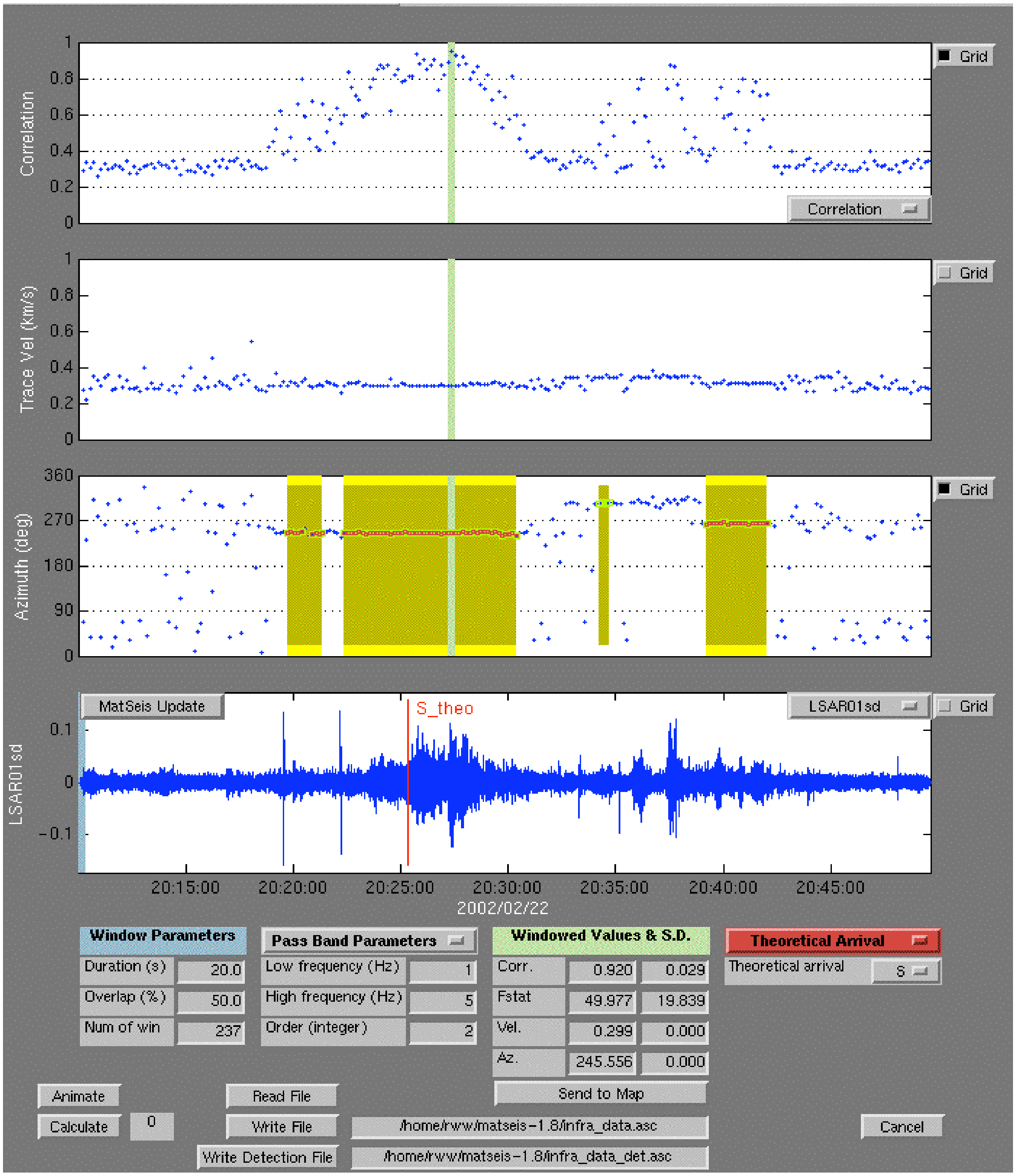


Figure 1: Matseis signal processing and analysis: Infrasonic earthquake detection of 2/22/2002- Averaged pair-wise cross-correlation, trace velocity, back azimuth and a single channel time series.

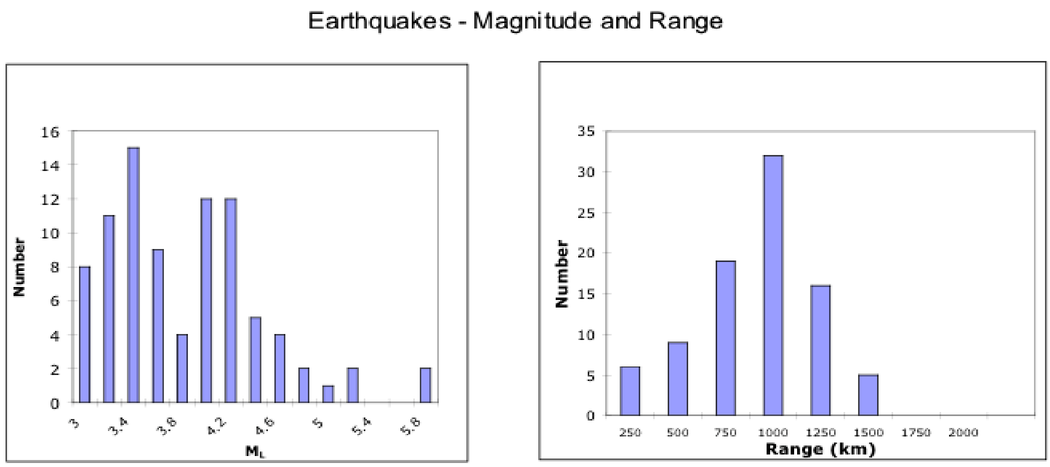
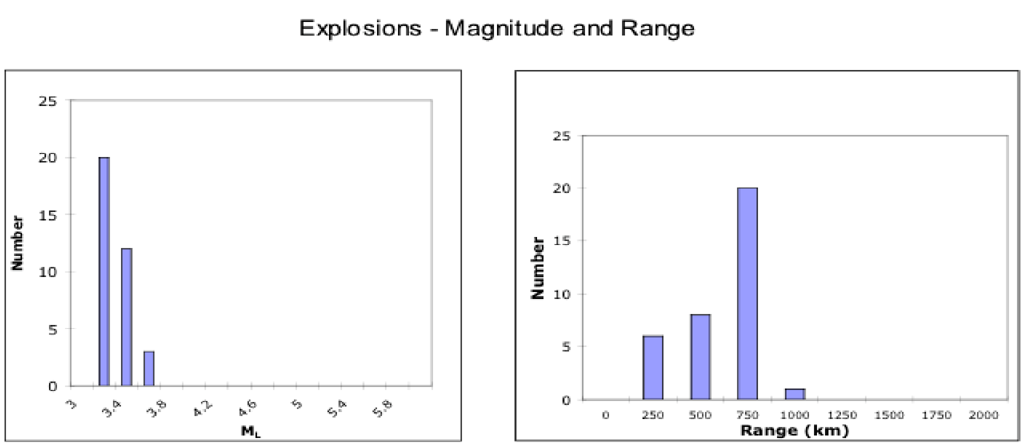


Figure 2a: Number of earthquakes versus local seismic magnitude and versus source-observer range.



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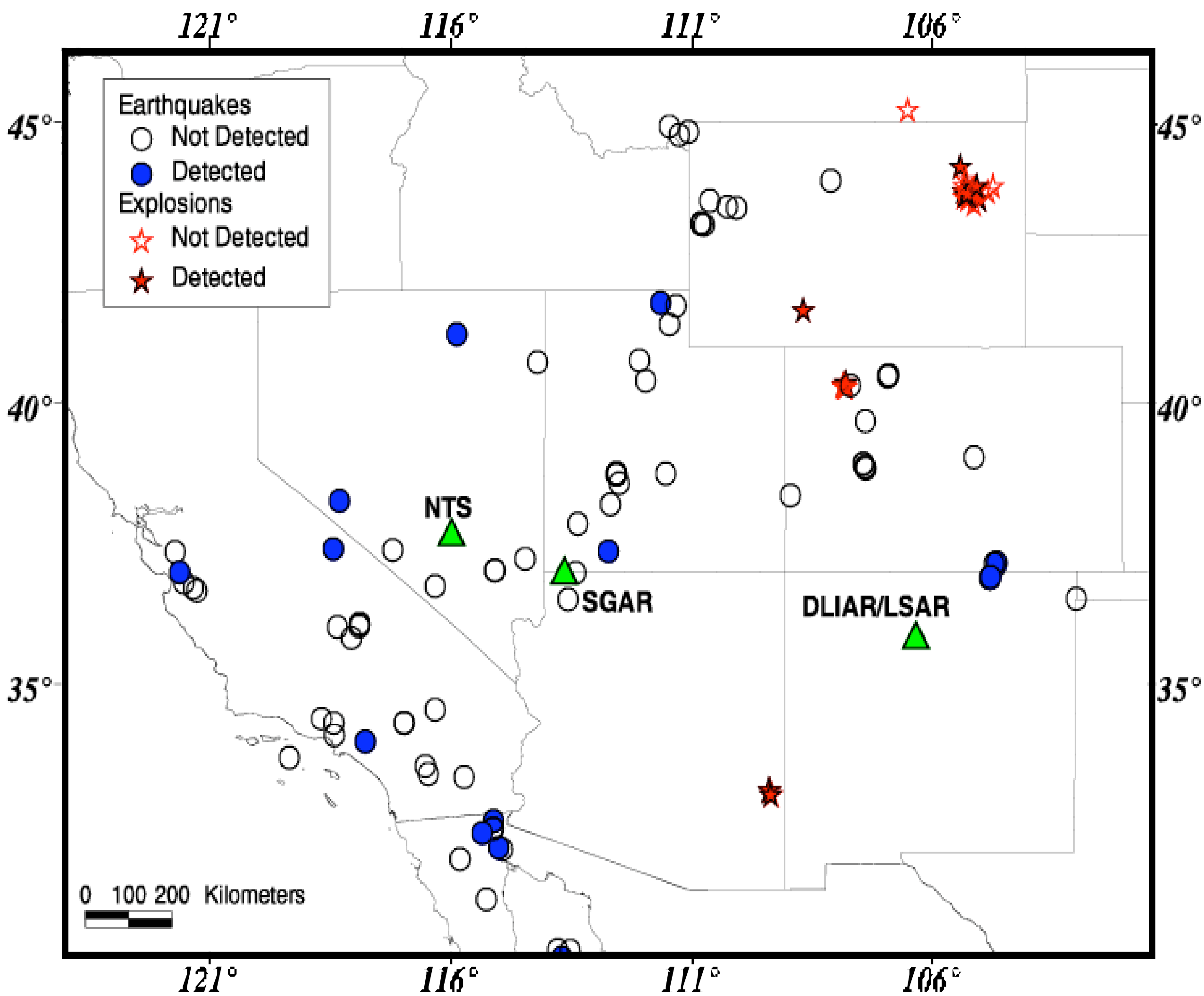

Figure 3: Geographic summary of infrasonic detections of small earthquakes and mining blasts.

Table 1: Infrasonic earthquake detections at DLIAR

Earth-quake	Date	Location	Time: UT	Magnitude and Depth	Range km	Azimuth •	Raw ampl. Pa	Signal velocity: km/s
# 133	2/17/01	CA-NV	22:54	4.1,12.4km	1092.6	280.4	0.037	0.17
# 177	9/04/01	CO	12:45	4.0, 5 km	206.9	47.2	0.030	0.29
# 192	10/08/01	NV	05:37	4.6, 0 km	1018.4	302.7	0.010	0.22
# 206	12/09/01	W. AZ - Sonora	01:42	4.5, 10 km	901.8	239.7	0.031	0.26
# 209	12/14/01	S. CA	12:01	4, 13.8 km	1061.4	255.2	0.012	0.25
# 217	1/04/02	CA-Baja	19:38	3.1, 7 km	885.4	242.9	0.100	0.26
# 225	1/08/02	UT	17:26	3.2,8.2 km	592.1	281.1	0.050	0.22
# 239	2/22/02	CA-Baja	19:32	5.5, 7 km	916.3	242.0	0.087	0.29
# 242	3/19/02	Gulf CA	22:14	4.1, 10 km	935.3	225.0	0.113	0.28
# 264	5/11/02	UT	06:30	3.0, 9.2 km	800.5	323.4	0.128	0.24
# 265	5/14/02	Cntl CA	05:00	4.9, 7.7 km	1370.0	270.5	0.052	0.14
# 273	6/18/02	NM	09:12	3.5, 5.0 km	179.2	51.5	0.032	0.07 (•)
# 278	7/15/02	CA-NV	20:18	4.1, 13 km	1089.7	275.3	0.050 0.075	0.16, 0.34

(*): This event is still under study because the earthquake fault type is strike-slip and since the resulting signal velocity arrival is so low. This type of earthquake faulting mechanism is not expected to produce significant infrasonic amplitude at either local or great ranges (personal communication, T. Wallace, 2004).

Table 2: Infrasonic Mining Blasts at DLIAR

Mining blast	Date	Time: UT	Magnitude	Range: km	Azimuth: °	Amplitude: Pa	Signal velocity: km/s
Gillette, WY	21901	18:59	3.3	880.5	6.5	0.037	0.16
Newcastle, WY	22601	21:09	3.5	871.0	7.9	0.035	0.28
Craig, CO	22801	23:06	3.3	510.7	344.8	0.032	0.27
Safford, AZ	32201	19:19	3.2	417.2	221.2	0.05 0.05	0.30 0.15
Gillette, WY	32701	21:17	3.1	880.5	6.5	0.13	0.35
Gillette, WY	40101	20:10	3.1	880.5	6.5	0.13	0.32
Craig, CO	40401	22:02	3.1	510.7	344.8	0.025	0.27
Gillette, WY	42001a	19:02	3.4	880.5	6.5	0.25 1.875	0.28 0.13
Rock Springs, WY	42001b	20:58	3.1	674.9	341.9	1.50	0.19
Gillette, WY	42501a	20:04	3.2	880.5	6.5	0.25	0.31
Safford, AZ	42501b	22:13	3.4	417.2	221.5	0.017	0.28
Safford, AZ	43001	18:50	3.1	417.2	221.5	0.35 0.045	0.25 0.17
Gillette, WY	51201	20:02	3.3	880.5	6.5	0.25	0.14