INFRASOUND MONITORING OF LOCAL, REGIONAL AND GLOBAL EVENTS

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ABSTRACT

Methodologies for the detection, association, location and identification of infrasound sources at local, regional and global distances are discussed. In the first part of this paper we apply a new regional monitoring method to data from the Washington State seismo-acoustic network and identify 206 local and regional infrasonic events in a dataset comprising 28 days of data. We detect multiple signals from mining explosions at two sites in Washington State, including 5 events that were recorded in a regional seismic bulletin. We also automatically detect and associate signals from the March 9th 2005 eruption at Mount Saint Helens, and locate the event to be within 5 km of the caldera. The second part of this paper outlines a technique for identifying infrasound signals from large known events on a global scale. We apply the technique to data from International Monitoring System (IMS) infrasound arrays for three super-bolides occurring on September 3rd, 2004, over Antarctica; on October 7th, 2004, over the Indian Ocean; and on December 9th, 2006, over North Africa. For each bolide we observe signals at multiple infrasonic arrays, with observations at ranges from ~1,000 to ~13,000 km. We investigate the causes of the asymmetric distributions of observations and show that site-noise is a dominant effect up to a range of ~10,000 km. We discuss how the preliminary work outlined in this paper provides important constraints for the purpose of event identification at local, regional and global distances. For large events, we outline how the synthesis of local, regional and global infrasonic data would provide the optimum dataset for event location and identification.

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OBJECTIVES

This research encompasses four objectives, as follows.

1–Development of Automatic Local and Regional Infrasound Monitoring Tools

The objective of the first part of this study is to develop a suite of automatic local and regional infrasound monitoring tools. The separate algorithms, which broadly comprise detection, association, location, and identification algorithms, will be integrated into a fully-automatic infrasound monitoring package.

2-Assessment of Infrasound Events in Washington State

The second objective is to apply the infrasound monitoring algorithms to data from the Washington State seismo-acoustic network, which is jointly operated by the University of California at San Diego and the Geological Survey of Canada.

3-Development of a Global Event-Based Infrasonic Association Tool

The third objective is to develop an event-based algorithm for associating infrasound detections at IMS infrasound arrays with known events on a global scale.

4-Assessment of the Global Infrasonic Detection of Three Superbolides

The final objective is to test the event-based global association tool by applying it to three superbolide events.

RESEARCH ACCOMPLISHED

1-Development of Automatic Local and Regional Infrasound Monitoring Tools

In this section we provide a broad summary of the development of regional infrasonic detection, association, location, and identification algorithms to date. Further details on each methodology will be provided in future publications.

The development of an automatic infrasonic detection algorithm is at an early stage. We are currently working on comparing existing detection algorithms (e.g., f-statistic and correlation-based methods) using real signals, and on developing a novel multivariate infrasonic detection algorithm.

To date, the bulk of work under this objective has been on developing a regional infrasound association tool. The input data to this tool are a set of infrasonic detections of arrivals at multiple spatially-separated arrays. The association algorithm is comprised of two main parts: (1) the association of separate phases from the same event at an individual array, and (2) the association of events at multiple spatially-separated arrays. We term these two components "phase association" and "event association" respectively. Due to the complexity associated with the explicit identification of an infrasonic phase based on the propagation path (Brown et al., 2002), we have developed an algorithm to identify two types of phases: first arrivals and later arrivals. A given event can then produce a single first arrival and N later arrivals at a particular infrasound array. There are three criteria used to determine if a given arrival is associated with an earlier arrival: (1) Arrival time (i.e., the difference in arrival time should be less than some threshold), (2) Backazimuth (i.e., the difference in backazimuth should be less than some threshold), and (3) Event duration (i.e., each event, which comprises a first arrival and N later arrivals ($N \geq 0$), should not exceed a threshold duration at an individual array). If an individual arrival is not associated with any preceding arrivals, it is automatically flagged as a first arrival ("I"), otherwise it is flagged as a later arrival ("Ix"). An obvious limitation of this technique is for highly repetitive sources where separate events will be associated, leading to an underestimation of the total number of events. However, a side benefit is the identification of highly-repetitive sources, which are associated with large numbers of later arrivals.

For event association we use a grid-search algorithm to identify events (i.e., groups of "I" arrivals at the different arrays that are associated). To this end, an irregularly spaced geographic grid is constructed that covers the region of interest (e.g., Figure 1 shows the grid that was constructed for monitoring the Washington State region). The spacing between grid nodes is chosen based on the event localization resolution of the infrasound network. For each grid node location we compute a set of great-circle backazimuths (at each array) and maximum and minimum delay times (between each pair of arrays). We then apply a grid-search procedure, where we perform a for-loop over each grid node location and search for groups of "I" arrivals where the observed delay-times and backazimuths are consistent with the given grid node.

The event location method that we have developed to date assumes a uniform atmosphere. Further development will allow for the use of 3D atmospheric models. Event locations are obtained using a least squares strategy, where an initial guess of the event location (taken from the backazimuth intersection point for two arrays) is refined in an iterative fashion. We compute error ellipses following the procedure of Flinn (1965), where the partial derivative matrix relates an east-west or north-south deviation to a change in the backazimuth recorded at the array.

The development of a regional infrasonic discrimination/identification algorithm is in its early stages. At present, we are working on identifying common characteristics within clusters of events, and using this information as a preliminary constraint on event identification. However, we will focus more on this problem in the future, building on work by ReVelle (2006).

2-Assessment of Infrasound Events in Washington State

We have applied automatic infrasound detection, association, and location algorithms to data from the Washington State seismo-acoustic array (Figure 1). To date, we have utilized the PMCC infrasonic detector (Cansi, 1995) for automatic detection of events. The PMCC detector has been fully integrated into our automatic processing scheme. However, we plan to integrate the new multivariate detector into the processing scheme following further development and comparison with existing detectors.

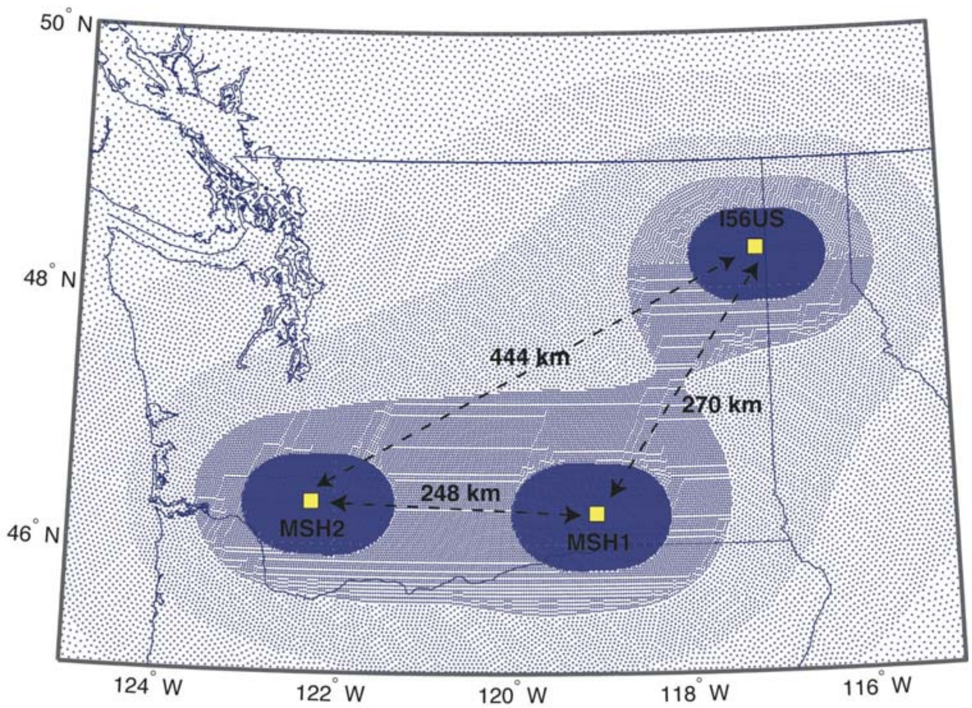

Figure 1. Map showing the locations of three seismo-acoustic arrays from the Washington State seismo-acoustic network. Great-circle distances between each array are displayed. Grid nodes used in the grid-search algorithm are denoted by pixels.

The detection and association algorithms were applied to 28 full days of data at MSH1, MSH2 and I56US. We selected days to study between November 1st 2004 and March 17th 2005, during which known events with the potential for generating infrasound occurred. The known events comprised 27 mining explosions (which were listed in the Pacific Northwest Seismic Network (PNSN) bulletin, with magnitudes from 2.0 to 3.1) and a large eruption of Mount Saint Helens on March 9th 2005, which is documented by Matoza et al. (2007). Figure 2 shows locations of the 206 infrasound sources that were obtained after applying the detector and association algorithms to the data at two stations only: MSH1 and MSH2. Each grid node used in the association algorithm is color-coded by the number of events that it is associated with (with hot colors indicating larger numbers of events). This figure provides a useful indication of the locations of sources of infrasound in Washington State and the surrounding region. Since these data were obtained during winter months, most sources are located to the west of the network (downwind of the dominant stratospheric wind direction). The details of the figure are sensitive to two free parameters for matching predictions at each grid-node with observed detections: the allowed deviation in backazimuth, and the allowed range of group-velocities (or "celerities"). The choice of these parameters is made by tuning the algorithm using known events, but this is beyond the scope of this summary paper.

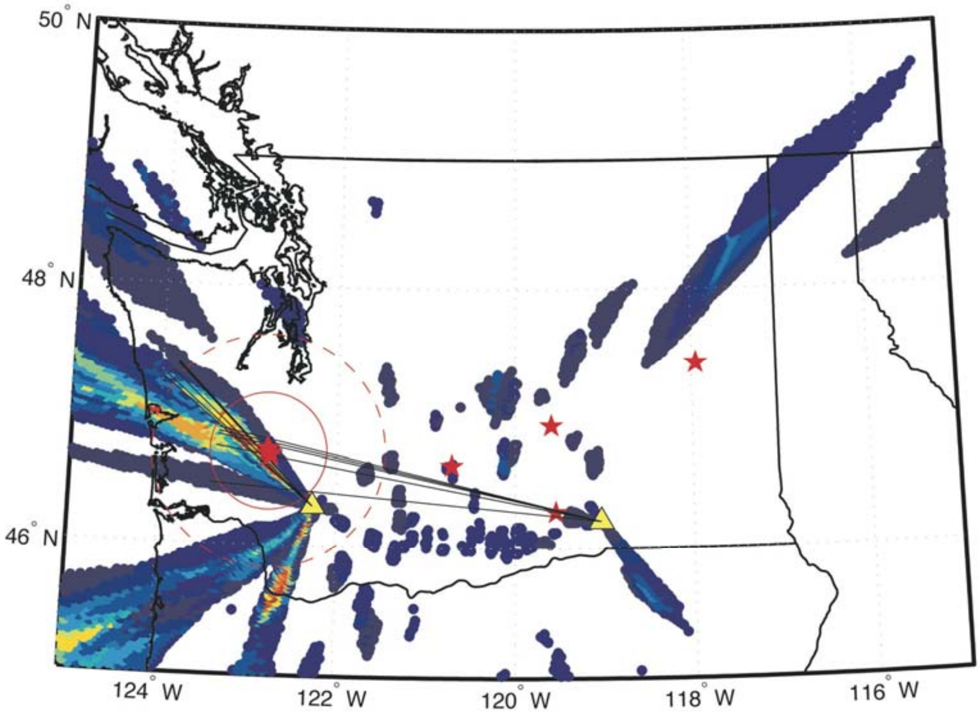

Figure 2. Map that shows the grid nodes that are associated with events recorded at two of the three infrasonic arrays (MSH1 and MSH2) shown in Figure 1. Each grid node is color coded by the number of events associated with that given location. Red stars denote the locations of mining explosions in the PNSN seismic catalog. The solid red circle denotes a range of 50 km from the most active mine (comprising > 20 events), while the dashed red circle denotes a range of 100 km. Solid black lines denote the backazimuths of signals at MSH1 and MSH2 that are associated with known mining explosions.

Figure 2 demonstrates that the automatic algorithm has successfully detected a number of signals from the active mine at ~ 46.7°N, 122.8°W. In total there are 13 events located within 50 km of the active mine (i.e., within the solid red circle), 5 of which can be directly tied to specific mining explosions in the seismic event bulletin. There are also some additional repeating sources that are picked up, for example there are several events that appear to come from the Portland area (located to the SSW of MSH2 near the state boundary). However, it is beyond the scope of this preliminary survey to discuss these signals in detail.

Figure 3 shows the infrasonic waveforms corresponding to the 5 mining explosions listed in the seismic bulletin that were detected at MSH1 and MSH2. Each signal is impulsive, clearly visible above the noise, and can be easily separated from the background "clutter" at each site.

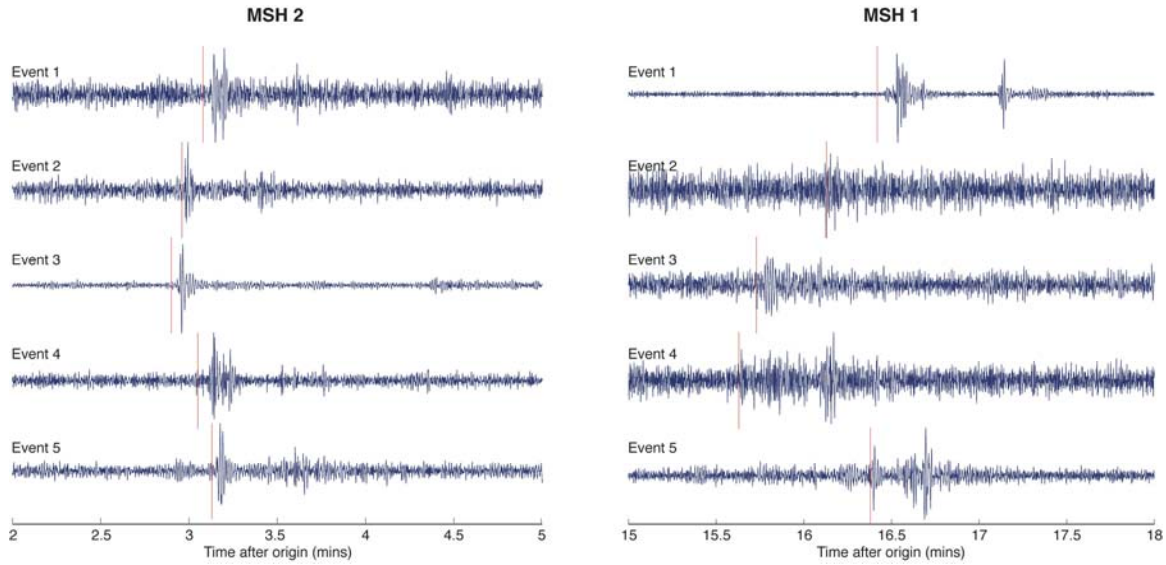

Figure 3. Infrasonic waveforms (band-pass filtered from 1 – 5 Hz) for each of the 5 ground-truth mining events that were automatically detected and associated at arrays MSH1 and MSH2. Red lines denote automatically picked arrival times.

None of the mining explosions that were detected at MSH1 and MSH2 (Figures 2 and 3) were also detected at I56US. Furthermore, despite a total of 206 events being detected at MSH1 and MSH2 ("two-station events"), there was only 1 three-station event that was detected at all three sites. However, the single event that was detected and associated automatically at all three sites was a known eruption of Mount Saint Helens. The infrasound signals from this event at MSH1 and MSH2 have been previously documented by Matoza et al. (2007), but the event was also recorded clearly at I56US. Figure 4 shows the locations of specific grid nodes that were associated with this event (un-associated nodes are not plotted). It is clear that the automatic procedure has been very successful in locating this event, as all three grid nodes are located within 5 km of the center of the caldera at Mount Saint Helens.

Figure 4. Locations of grid nodes that were automatically associated with detections at MSH1, MSH2 and I56US for the eruption of Mount Saint Helens on March 9th, 2005. The locations are superimposed on a satellite photograph, and are located within 5 km of the center of the caldera.

3-Development of a Global Event-Based Infrasonic Association Tool

Given the origin time and location for a large event, we have developed an automatic procedure for identifying associated infrasound signals at IMS stations on a global scale. The focus here is on “telesonic” events, rather than regional infrasonic events. The motivation for this portion of the study was provided by Wexler and Hass (1962) who documented the global detection of infrasonic signals from a nuclear explosion on October 30th 1961 as well as the detection of the Great Siberian bolide (Tunguska) that occurred on June 30, 1908. The first stage in the algorithm we have developed identifies signals at IMS stations that occur within a specified time of the event, and within a specified azimuthal-deviation from the great-circle path. The allowed times are calculated based on typical infrasonic group velocities (Ceplecha et al., 1998), and the allowed azimuthal-deviations are based on an empirical relation calculated for known explosions. Infrasound signals at each station are detected using the PMCC method (Cansi, 1995). The second stage removes signals at each station that are: (a) short-duration and narrow-band, and (b) occur at similar backazimuths to highly repetitive sources that also generate signals outside the range of possible arrival times for the given event. Test (b) utilizes backazimuth, frequency, trace velocity, arrival time, and the number of similar detections as criteria for rejecting detections. Such detections are typically either associated with small (local) events or repetitive sources near a given station.

4-Assessment of the Global Infrasonic Detection of Three Superbolides

We have applied the global infrasonic detection algorithm to three superbolide events, which occurred on September 3rd, 2004 over Antarctica, on October 7th, 2004 over the Indian Ocean, and on December 9th, 2006 over North Africa. Figure 5 shows the locations of stations that detected the Antarctic event (after applying the global event association method described above). Similar plots were obtained for the two other events but are not presented here. The most significant results are the large numbers of stations that detect each event (6 stations for Event 09/03/04, 6 stations for Event 10/07/04, and 6 stations for Event 12/09/06), and the strongly asymmetrical distributions of observations. To provide further confidence that the detections are correctly associated, we have reapplied the global event association method to the same three events, but using arbitrary origin times (i.e., simply changing the origin time by 24 hours). We find that in each case we observe *at least* 66% more associated detections for the real event origin time. This provides confidence that the majority of the detections are correctly associated. Table 1 provides a summary of the associated infrasonic detections for each of the three superbolides.

Whether or not a given station detects an event appears to be strongly governed by factors other than range. In particular, two factors that influence the detectability of infrasound from an event are: (1) ambient noise levels at a given station, and (2) propagation effects. In order to assess the importance of ambient noise levels on the signal detection, we have computed pre-event noise spectra for each station. Each power spectrum was computed for a beamformed waveform at each array using a time window of ~ 1 hour (i.e., 2^{16} data points), and smoothed by averaging the power spectrum over 1/8 octave intervals. The resultant power spectra for stations at ranges less than 10,000 km are plotted in Figure 6. The plot demonstrates that for two events (Events 09/03/04 and 10/07/04), there is a clear separation between noise-levels at stations that detected the event and stations that did not detect the events. In fact, for these two events the difference in noise levels between stations that detected the events, and stations that did not, is approximately 20 dB on average. This suggests that site-noise effects play a dominant role on the detectability of infrasound from such large events. We note that such a separation is not observed for more distant stations (>10,000 km), suggesting that propagation effects may dominate noise effects at larger ranges. This observation is somewhat surprising as we generally expect smaller amplitudes at greater ranges, which would be more sensitive to corruption by noise.

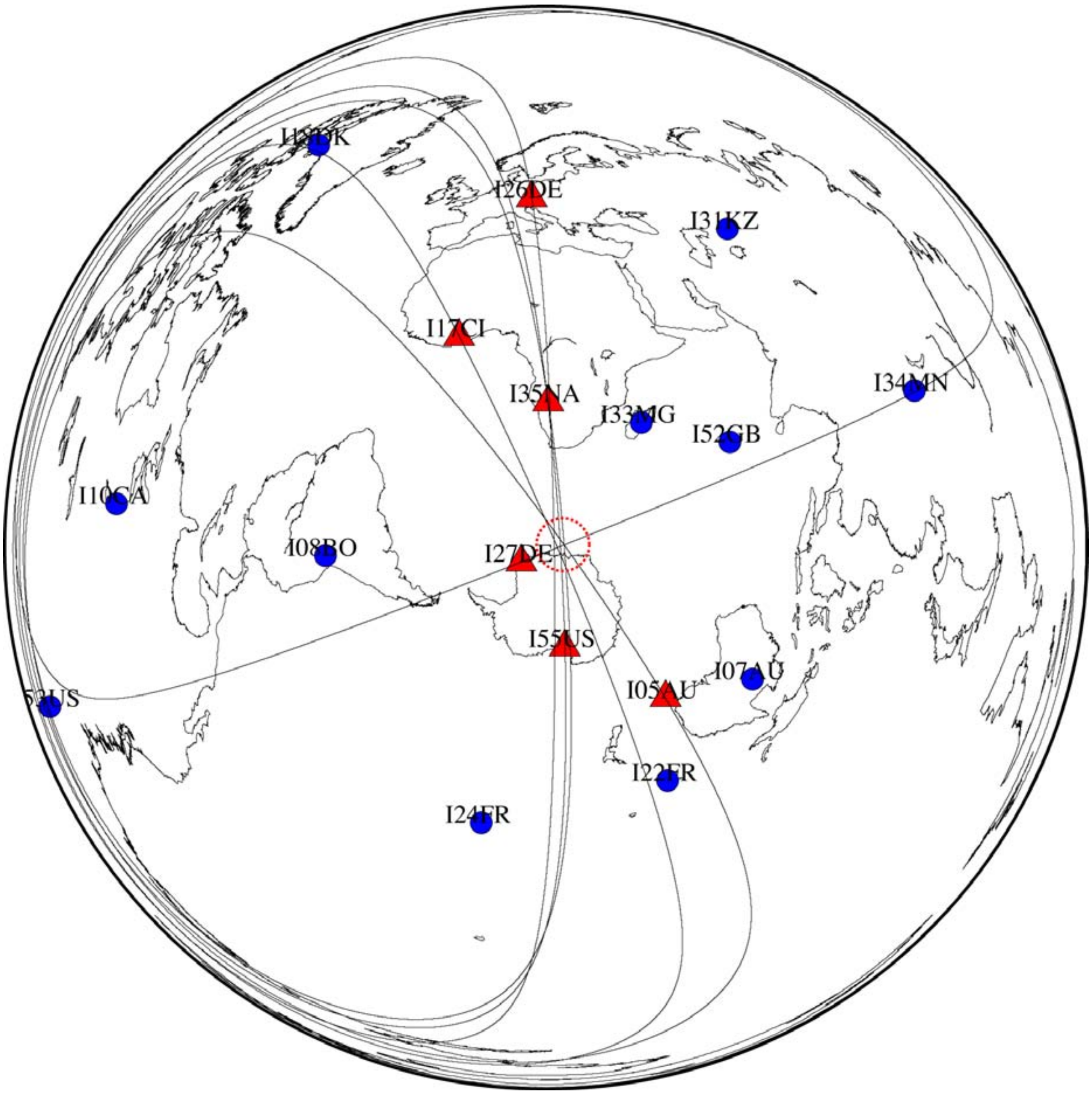

Figure 5. Azimuthal equidistant projection showing stations that detected the 09/03/04 Antarctic event (red triangles) and stations that did not (blue circles). The event was determined to be located in the center of the dashed red circle based on satellite observations. The plotted great-circle paths show the backazimuths of observed signals at each array projected back towards the source location.

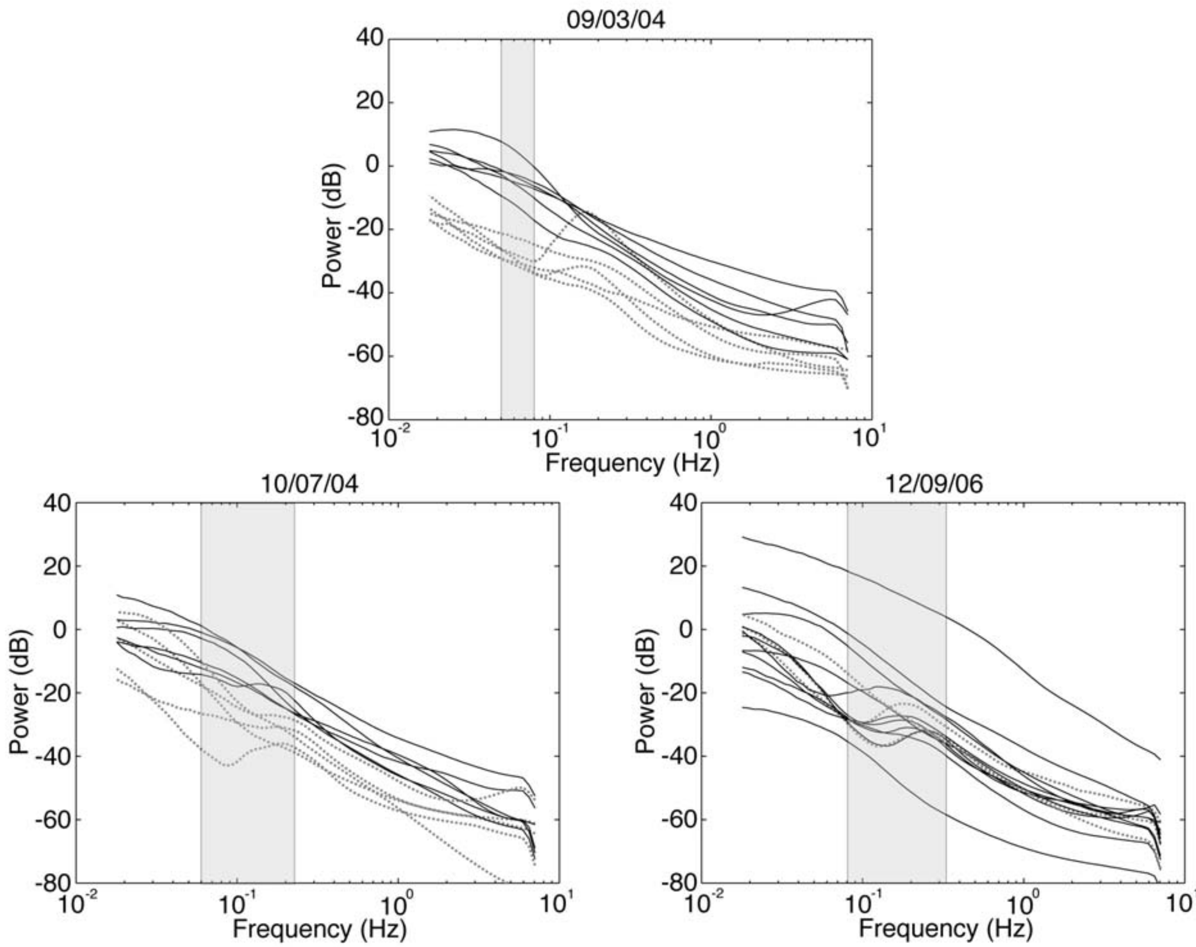

Figure 6. Noise spectra for each of the three bolides. Solid black lines denote spectra for stations that did not detect the events and gray dashed lines denote spectra for stations that did (for stations at ranges less than ~10,000 km). Regions shaded gray denote the frequency band over which detections were observed from each bolide.

CONCLUSIONS AND RECOMMENDATIONS

This paper comprises two main parts: The first part addresses local/regional infrasonic monitoring, and the second part addresses global infrasonic monitoring. In each case we outline new algorithms for detecting and associating infrasound signals from events of interest. We then apply the techniques to a regional dataset in Washington State and to global data from the IMS infrasound array. In the first case we detect, associate and locate 206 events in the Washington State region for a dataset comprising 28 days, and in the second case we identify multiple signals from large events at ranges of up to ~13,000 km, and comment on the factors that influence the detectability of these events. The two cases have slightly different applications: the local/regional monitoring algorithms are fully automatic and will be applicable to processing real-time data, while the global algorithms are event-based and focused on known events of interest. However, both cases will be complementary for the case of large events that are detected at a regional scale, which can provide a seed origin time and location for searching for global "telesonic" infrasound. In a nuclear monitoring regime, the use of both local/regional and global data will provide an optimum dataset for event location and identification, particularly where regional data is sparse.

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Table 1. Summary of associated detections at IMS infrasound arrays for the three superbolide events.

Event	Array	Range (km)	Arrival time (UT)	Duration (s)
09/03/04	I27DE	1044	13:15:25	1300
09/03/04	I55US	3743	15:50:03	1565
09/03/04	I35NA	5390	17:20:45	1650
09/03/04	I05AU	7114	18:47:55	1900
09/03/04	I17CI	8423	20:26:15	2550
09/03/04	I26DE	12918	00:27:45 (on 09/04)	2000
10/07/04	I52GB	2201	15:50:50	540
10/07/04	I32KE	4679	17:38:50	80
10/07/04	I55US	7204	20:01:15	1250
10/07/04	I17CI	9001	21:45:50	100
10/07/04	I26DE	10182	23:02:55	6150
10/07/04	I10CA	17241	06:17:55 (on 10/08)	1700
12/09/06	I26DE	2727	06:08:43	750
12/09/06	I35NA	5094	11:40:30	1360
12/09/06	I30JP	10320	15:13:30	70
12/09/06	I41PY	10632	16:05:20	110
12/09/06	I56US	10979	20:11:20	70
12/09/06	I04AU	11629	16:57:50	150

Footnote: The signal durations observed for these three superbolides do not increase as a function of range, as would be predicted theoretically. We speculate that the reason for this discrepancy is due to site noise, which degrades the signal detectability at each site.