

INFRASOUND RESOURCES OF THE SMDC MONITORING RESEARCH PROGRAM

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Science Applications International Corporation

Sponsored by Army Space and Missile Defense Command

Contract No. DASG60-03-C-0009

ABSTRACT

The Research and Development Support Services (RDSS) project of the Space Mission Defense Command (SMDC) Monitoring Research Program provides a variety of resources for nuclear explosion monitoring R&D. A large archive of continuous hydroacoustic, infrasound and seismic data can be viewed and downloaded from the RDSS web page (www.rdss.info), and a number of research datasets have been developed and are also available from the RDSS. These resources are particularly well-developed for infrasound. The RDSS has an extensive archive of infrasound waveform data including continuous waveform data from International Monitoring System (IMS) and non-IMS stations over the period 1995–2006. At present, data from 36 infrasound stations located on seven continents are being received and made available in near-real time

As the availability of infrasound data from a global network grows, increasing numbers of source events are being discovered. Such events are identified from the scientific literature, press reports (accidental explosions) and by routinely searching the waveform archive for signals from recent events listed in bulletins of seismic, volcanic, mining, bolide and rocket launch activity. Source information for several hundred events with infrasound signals is given on the RDSS web page, together with the associated signal waveforms. Some events are recorded on several infrasound stations, and thus can be used to develop and test techniques for locating infrasound events, and there are a number of instances of repeated observations over the same source-receiver path. The latter are particularly useful for modeling the atmospheric propagation of infrasound in a wide variety of meteorological conditions, and examples include mining explosions in North America and Eurasia, volcanic eruptions in South America, the southwest Pacific and Alaska, and rocket launches from a variety of locations around the globe. The RDSS is also responsible for the collection and distribution of data and metadata for the rocket experiments at White Sands Missile Range during 2005–2006.

A systematic effort to characterize all these signals is now underway. A standardized procedure is being applied to measure signal onset time, azimuth, slowness, duration, frequency content, amplitude and dominant period, coherence, and other measures. These parameters will be stored in the infrasound database and a subset included in infrasound event bulletins that will be provided on the RDSS web page. Statistical analyses of azimuth and slowness residuals, and such relationships as frequency versus distance, should provide insights into the detection and identification of infrasound signals, and their use for event location.

OBJECTIVES

The objective of the RDSS is to support the nuclear explosion monitoring research and development community with a wide range of data, state-of-the-art data access tools, and value-added datasets.

RESEARCH ACCOMPLISHED

Archive of Continuous Infrasound Data

The RDSS has been acquiring infrasound data since 1996. Initial holdings are from research arrays in the United States, and the archive has been greatly enlarged by the growth of the IMS, with over 35 stations installed on all seven continents and many remote islands. Figure 1 summarizes the infrasound archive.

Figure 2 shows the location of the infrasound arrays for which data are available from the RDSS. The arrays range in aperture from 0.5 to 3 km, and consist of 4 to 9 elements. Detailed metadata, including array layout and instrumentation, are available from the RDSS web site for each array. The IMS infrasound network is now more than 50% complete (the full network will comprise 60 arrays) and, except for Eurasia, already provides very good coverage.

Infrasound Ground Truth Database (IDB)

The IDB draws on a unique collection of waveforms (many of which are not archived anywhere else) from infrasound arrays operated by the Department of Energy (DOE), IMS, and other organizations. In addition to events recorded on the arrays shown in Figure 2, it also includes historical recordings of Soviet and U.S. atmospheric nuclear explosions. These older recordings are digitized from the original analog records, and thus are of variable quality, but nevertheless are invaluable representations of their source type.

More recent events in the IDB were identified from scientific publications, bulletins of earthquake, mining and volcanic activity, and media reports, particularly of industrial accidents. Source types include

- Chemical explosions, both surface and in the upper atmosphere (White Sands rocket grenade experiments, described elsewhere in this volume). Some of these have ground truth location and origin time, but others are the results of industrial accidents and, while the location can be determined fairly accurately, there may be uncertainty in the origin time.
- Known and suspected mine blasts. Known mine blasts are identified from publications and bulletins such as the United States Geological Survey (USGS) list of U.S. mining events, while suspected ones are inferred (e.g., the vast majority of seismic events reported from northeast Wyoming and from mining areas of Russia, the Ukraine and Australia can reasonably be assumed to be related to mining, particularly if a corresponding infrasound signal is observed). Origin times and locations can be quite well constrained if provided by seismic locations.
- Volcanoes. Explosive eruptions on all continents have been well recorded; as for many of the other source types above, location is well-established but origin time often uncertain.
- Earthquakes. Both large (e.g., International Data Center [IDC] bulletins occasionally include infrasound observations) and small (e.g., Reville, 2005) earthquakes can generate infrasound.
- Bolidés. These can produce very large signals recorded around the globe.
- Avalanches. The Mt. Steller avalanche in Alaska (Arnoult et al., 2005) was well-recorded at three infrasound arrays.
- Rocket launches. Large launches such as those of the space shuttle are routinely recorded at considerable distances. The observed signals may however originate over several hundreds of km of the initial flight path, and often correspond to the ignition of secondary stages.

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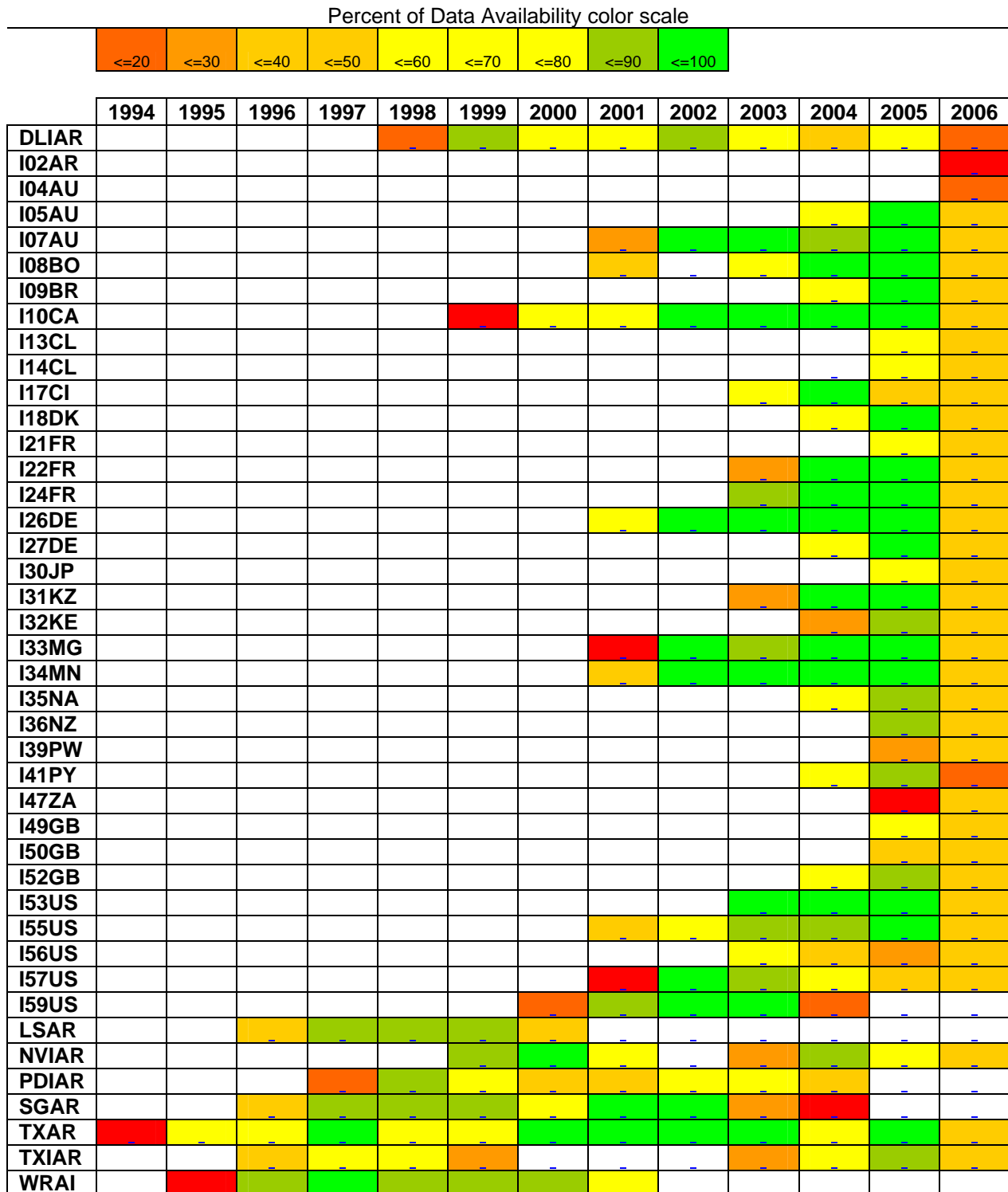


Figure 1. Summary of infrasound data available from the RDSS. The color coding (legend at top) indicates the overall availability of data for each station and year. Availability for 2006 appears low only because the year is not yet complete.



Figure 2. Location of arrays for which infrasound data are available from the RDSS archive (see Figure 1).

Figure 3 shows events in the IDB, together with the great-circle paths of the associated signals. While many of the events, such as bolides and accidental explosions are “one-off,” a surprising number are repeated occurrences at the same location. Repeated observations over the same path provide an opportunity to model the variability of atmospheric propagation (for an example, see the last section of this paper). Multiple observations over the same path have been made for the following:

- Volcanic eruptions—For example, the many episodes of the early-2006 eruption of St. Augustine (Alaska) and several eruptions of Lascar (Chile).
- Mine blasts—Many tens of observations of mine blasts in Wyoming have been made at I10CA, and a similar number of observations of events at a large Russian mine are described later in this paper.
- Repeated experiments—Some (such as those at White Sands during 2005–2006) are expressly designed to facilitate propagation studies.

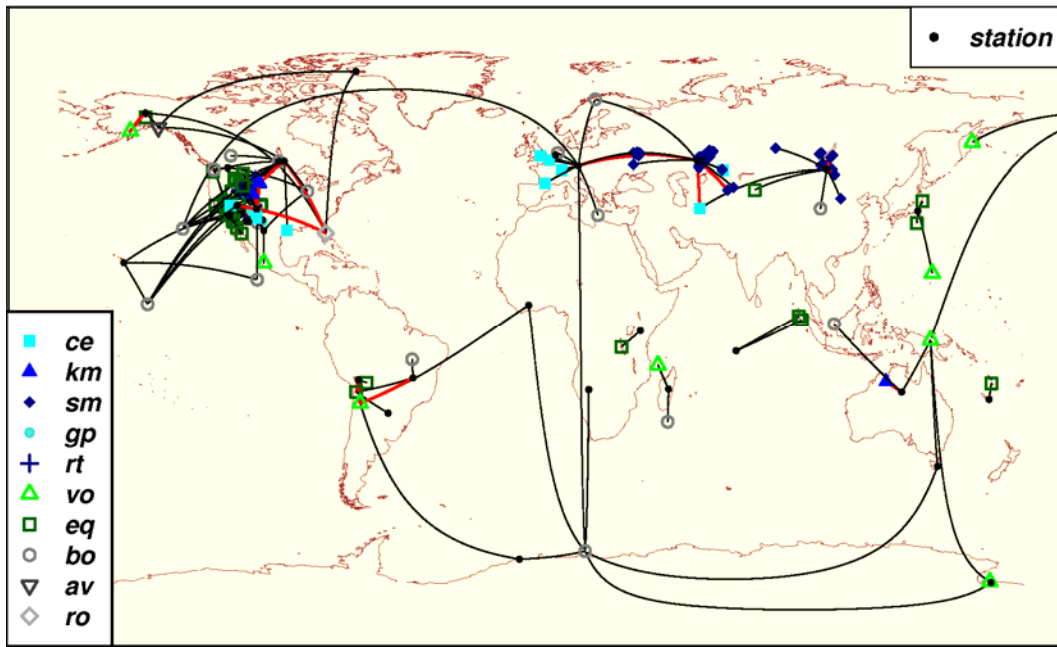


Figure 3. Great-circle paths for signals included in the IDB. Paths over which multiple observations have been made (repeated sources at the same location) are shown in red. Source types are chemical explosions (ce), known mine blasts (km) and suspected mine blasts (sm), gas pipeline accidents (gp), static rocket tests (rt), volcanic eruptions (vo), earthquakes (eq), bolides (bo), avalanches (av) and rocket launches (ro). Details of paths in North America are shown in Figure 4.

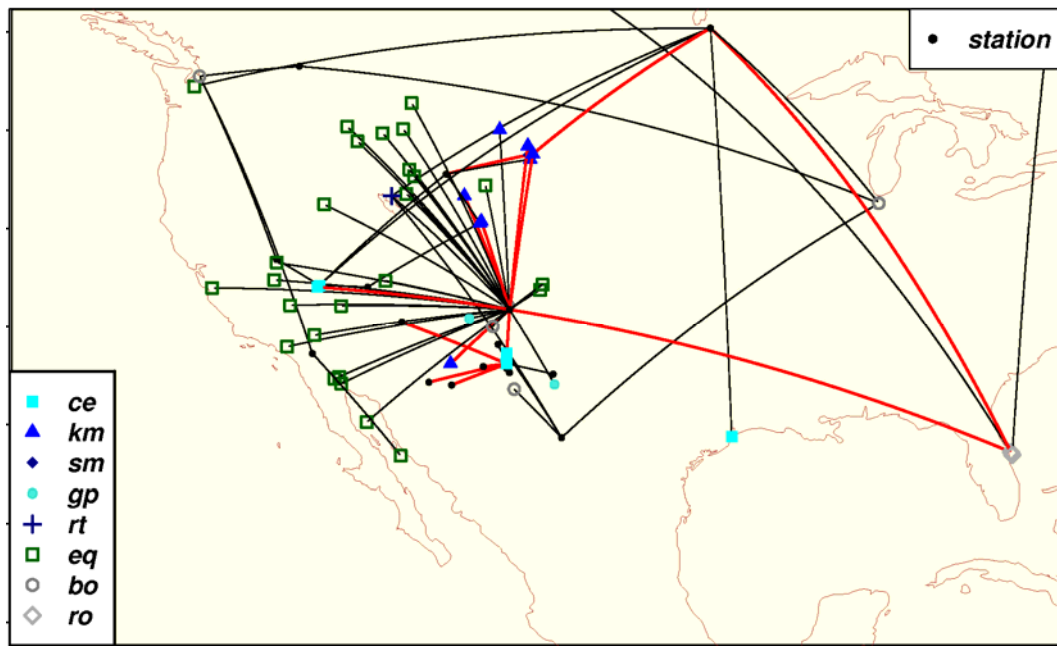


Figure 4. As Figure 3, but scaled to show details of paths in North America.

Infrasound Signal Characterization

Standardized measurements have been defined for seismic observations for more than half a century, but no such standards exist for infrasound signal measurements. As a result, it is hard to interpret, and almost impossible to reproduce, measurements of infrasound signals that are reported in the literature. We have embarked upon a process of systematically measuring signals in the IDB (previous section) and storing the results, some of which are also reported as the characteristics of “phase arrivals” given for each event on the IDB section of the RDSS web page. These arrivals are reported in a format that was developed for seismic bulletins, and is not really appropriate for infrasound; a new infrasound “bulletin” format is being developed and will be used in the future.

Procedures have been defined and are being employed to measure the following parameters for each distinct infrasound signal (several signals may be identified at one array from a given source event):

- Onset time*
- Signal duration
- Slowness* (and slowness “slope”, where values change over the signal duration)
- Azimuth* and azimuth slope
- High- and low-frequency limits of the signal
- Dominant period*
- Peak amplitude* and corresponding time
- Signal-to-noise ratio (SNR)*
- Coherence and corresponding coherence SNR
- Fstat

Parameters above that are followed by an asterisk are included in the “bulletin” listing for each event on the IDB portion of the RDSS web page. Most parameters are also accompanied by an error estimate.

At the time of writing, parameters had been measured for approximately one third of the events in the IDB.

Infrasound from Mining Explosions in Eurasia

It is well known that many of the signals recorded on infrasound stations are from chemical explosions detonated in mines and quarries in the region (typically within a few hundred, occasionally a few thousand kilometers of the stations). The IMS infrasound stations I31KZ at Aktyubinsk, Kazakhstan, I34MN at Songino, Mongolia and I26DE at Freyung, Germany, have been operating and recording such signals from events in Eurasia since September 2003, July 2001, and April 2001, respectively. Here we report on the development of a database of several hundred infrasound signals from presumed mine explosions with source-receiver propagation paths ranging from 50 to 1,500 km. These events and associated signals will be incorporated into the IDB (see above).

First we looked for evidence of mining operations at locations known from published sources to be mines or quarries generating infrasound or seismic signals. For example Bayarsaikhan et al. (2002) yielded approximate location information on seven mines in Mongolia, and Richards et al. (2004) provided information on mines in Kazakhstan. (For a comprehensive list of over a dozen references, see Kohl, 2006). We examined medium resolution LandSAT imagery (14.25 m/pixel) to confirm above ground mining activity at these sites and obtained accurate absolute locations. Much of the imagery analysis was done using false-color LandSAT imagery. In our preferred spectral combination, freshly exposed rock appears blue or magenta in the images allowing for ready identification of recent mining activity. We exploited the knowledge gained by examining known sites to scan the imagery for new sites with the same type of features, e.g., large pits, extensive tailing piles, roads. In total we

identified 104 distinct mining operations, 37 of which were not previously identified in published sources. Figure 5 shows the locations of these features with respect to the infrasound stations.

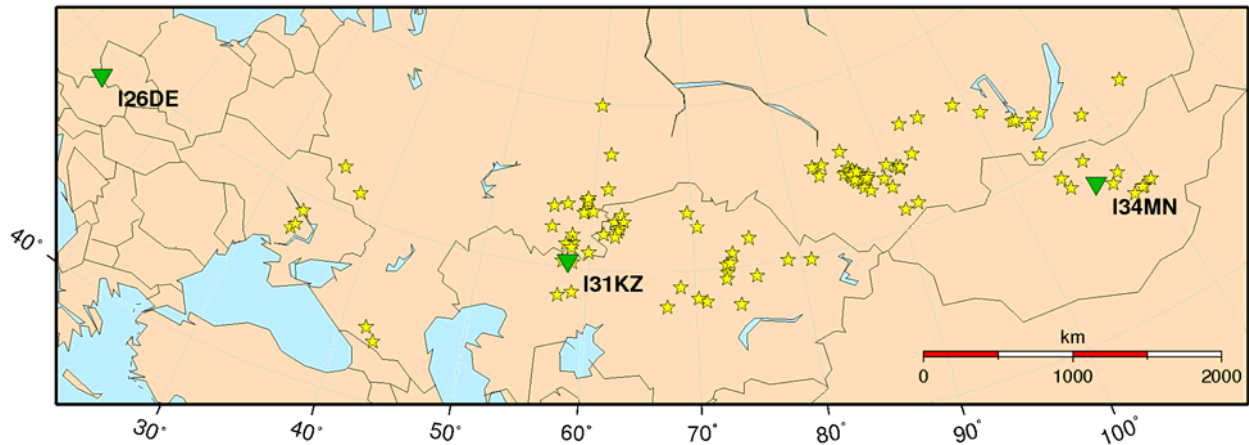


Figure 5. Map of 104 mines (yellow stars) in Eurasia observed in LandsAT imagery. All these sites are candidate sources of infrasound signals recorded at IMS infrasound stations (green inverted triangles).

In the second phase of our effort we exploited the fact that mine explosions large enough to generate infrasound that propagates over large distances are often detected and located seismically. We associated infrasound with events in seismic bulletins by looking for signals in a predicted time window with appropriate signal features (e.g., azimuth). The REB and the SEL1 and SEL3 automated events lists of the IDC and the bulletin of the Kazakhstan National Data Center (KNDC) were used as driver seismic bulletins. Further we exploited the automated detection list of the IDC for both infrasound and seismic signals and performed automated joint seismic/infrasound association based on the principles of the IDC's Global Association (GA) algorithm with the variation of using the infrasound signals as the driver arrivals and looking for corroborating seismic detections. In total this yielded several thousand candidate seismic/infrasound events. Given that many of these were based on automated processing, this included many false associations. To identify the seismic/infrasound events associated with mining activity we performed a nearest neighbor cluster analysis using epicentral distance and time-of-day in the distance metric. Further analysis of both the seismic and infrasound recordings of these events is underway to ensure that false associations are not included in the final database. Figure 6 shows a map of all the currently identified seismic/infrasound events plotted using these seismically determined location. Note that all these events are in the vicinity of a known feature.

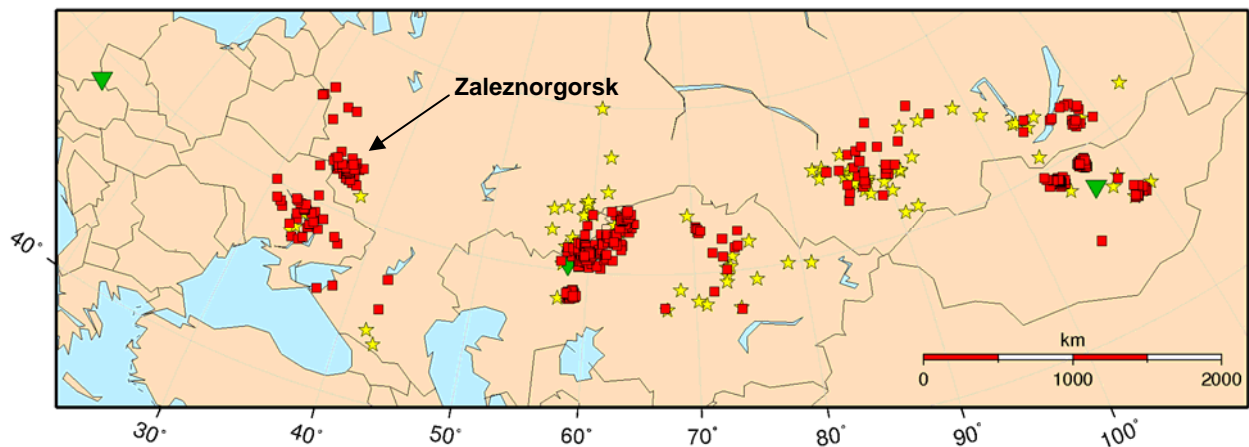


Figure 6. Map of infrasound generating events (red squares) in Eurasia.

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Over 50 seismic/infrasound events were associated with the large iron mine (Figure 7) near Zaleznogorsk in western Russia. Propagation modeling using InfraMap (Norris and Gibson, 2004) is reasonably successful at predicting detection/non-detection of infrasound signals from these events. Figure 8 compares arrival times of eigenrays computed with InfraMap with observed arrivals at I31KZ and I26DE from Zalesznogorsk events reported in the IDC Reviewed Event Bulletin (REB) between 2004 and the first half of 2006. The patterns of detections and non-detections at the two stations vary with season and are almost opposite - events occurring during summer and winter are observed only at I26DE and I31KZ, respectively. This effect is in good agreement with the modeled results for eigenrays and is due to the seasonal variation of the horizontal wind velocity along the paths to the two stations.

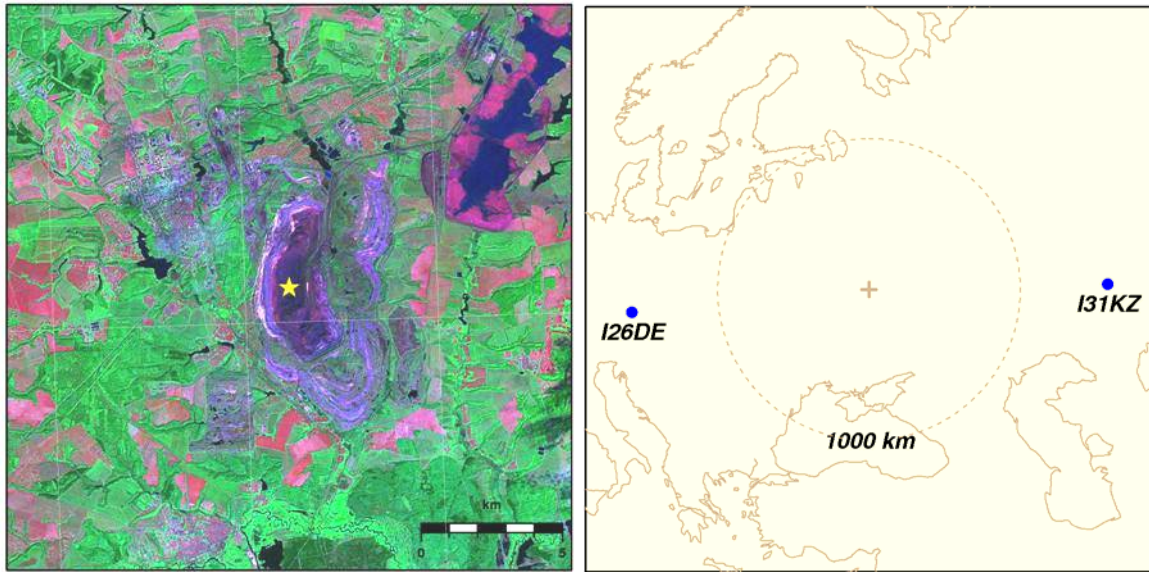


Figure 7. LandSAT image of the Zaleznogorsk iron mine (left panel) and map of mine location (right panel) with respect to the recording stations.

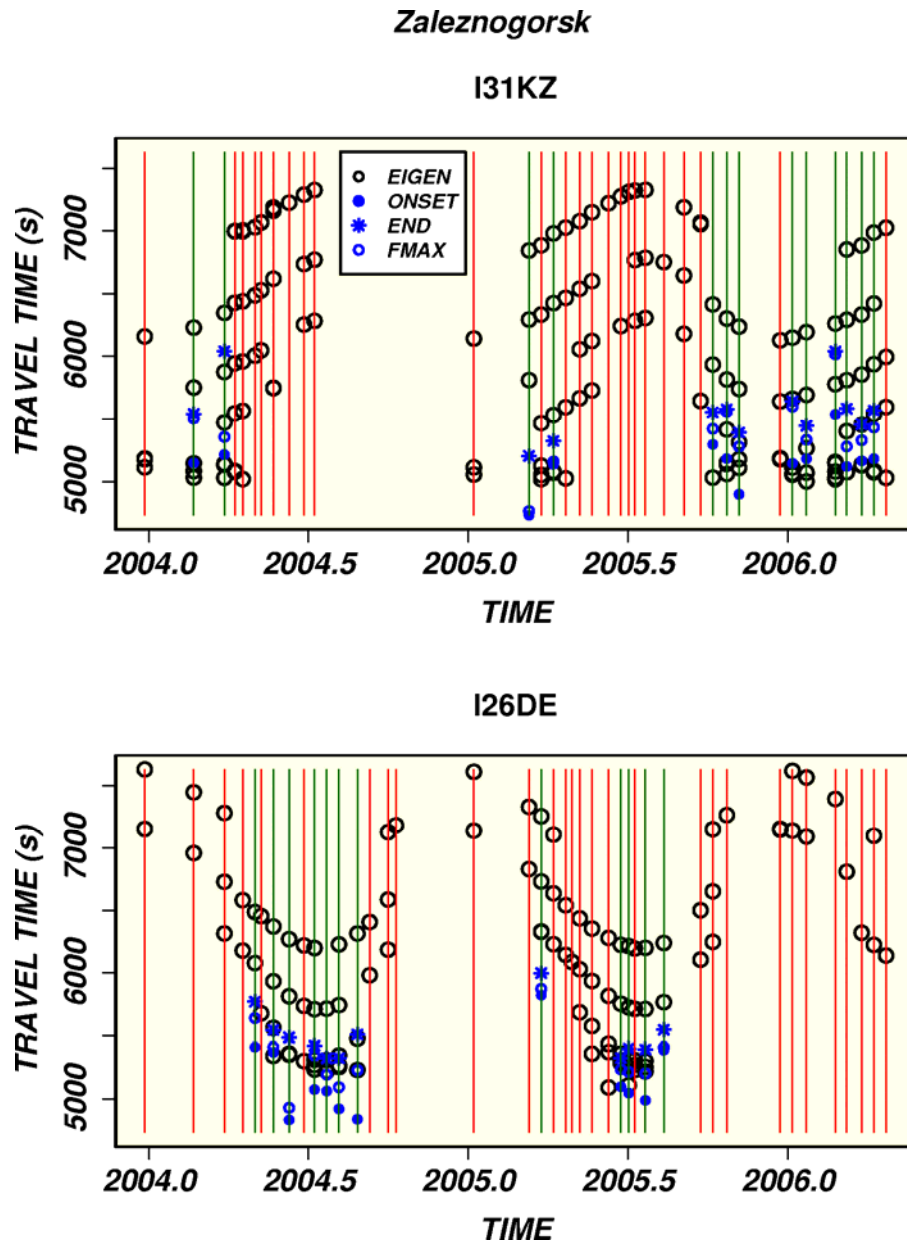


Figure 8. The diagrams show detection and non-detection at I31KZ (top) and I26DE (bottom) of Zalesnogorsk events as a function of season between 2004 and the first half of 2006. Green and red vertical bars indicate detection and non-detection respectively. Observed arrival times of detected signals are marked with blue symbols—filled circles for onset, stars for end of signals and open circles mark the time of maximum of the F trace. The black open circles indicate the arrival times of eigenrays calculated with InfraMap using the standard HWM-93 and MSIS models (Norris and Gibson, 2004). Note that signals are usually observed when eigenrays with early arrivals (~5,000 s) or stratospheric phases are predicted.

CONCLUSIONS AND RECOMMENDATIONS

An extensive archive of infrasound data has been assembled by the RDSS and continues to grow. An increased number of stations provides an opportunity to search for signals from many types of events and to characterize them so that the results may be used to improve both automatic processing and analysis of infrasound. As an example, semi-automated processing of infrasound and seismic data has identified many hundreds of events with infrasound signals in Eurasia.

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