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6.3 A New Source of Seismo-Acoustic Events for the Study of Infrasound Propagation over Regional Distances

Since June 8, 2007, a seismic event alert system has been operational at NORSAR to provide early notification of, and robust preliminary location estimates for, earthquakes and other seismic events in the European Arctic. It is based on the NORSAR Event Warning System (NEWS: Schweitzer, 2003) but with parameters tuned specifically for seismic phases likely to be generated by events in the region of interest. On October 2, 2009, the system provided a trigger for an event at approximately 08.54.42 GMT in Central Lapland, Finland, at a distance of approximately 180 km south of the ARCES seismic array. Attention was drawn to this event because the seismic phases at ARCES were followed after approximately 10 minutes by infrasonic phases from the same direction, and because the uncertainty ellipses associated with the event location estimate include a site of military explosions at Hukkakero (67.934 N, 25.832 E) which has raised significant interest in recent years due to the generation of infrasound (Gibbons et al., 2007).

Hukkakero is the site of between 20 and 50 near-surface explosions every year for the destruction of expired ammunition. The events occur on consecutive days in August and September and provide a useful data set for the study of infrasound propagation for a number of reasons:

1. The location of the events is known. All explosions are known to take place within approximately 300 meters of the coordinates stated.
2. The sources are almost identical both in terms of yield (approximately 20000 kg per explosion) and source-time function (there are no multiple or ripple-fired explosions as are common in open-cast mining: see, for example, Gibbons et al., 2005).
3. The similarity of the waveforms makes the events amenable to detection using waveform correlation detectors (Gibbons and Ringdal, 2006). This means that every event can be detected with an almost negligible false alarm rate and also that the origin times of explosions can be constrained very accurately.

The October 2 event occurred shortly after the end of the 2009 Hukkakero explosion sequence but, due to the event origin time and poor signal correlation with known events, was deemed unlikely to be from the same source location. Using seismic waveforms from stations of the Finnish national seismic network, in addition to ARCES, indicated an event location approximately 10 km to the west of the Hukkakero site. A consultation with colleagues at the Institute of Seismology at the University of Helsinki concluded that the source of the October 2 event was almost certainly the Kittilä Gold Mine, operated by Agnico-Eagle, at Suurikuusikko (67.90154 N, 25.39102 E). Figure 6.3.1 displays the location of the sources together with waveforms from one event from each of the two sites.

Agnico-Eagle Mines Limited provide information about the operations at the Suurikuusikko mine on their website[1] and Figure 6.3.2 displays a view of the site showing a large region already excavated and an even larger volume of rock to be mined in the future. We conclude that this mine has probably been the site of large number of explosions in recent years and that this is likely to continue for a long time into the future. The magnitude estimate for the seismic event on October 2, 2009, was just in excess of 1.0 and, while such events are routinely

1. http://www.agnico-eagle.com/English/OperatingMines/Kittila/OperationsUpdate/default.aspx

detected and included in the fully automatic seismic event bulletins at NORSAR, they are not large enough to be reviewed manually and included in the published analyst bulletin. We therefore use a correlation detector to try to catch as many occurrences as possible of seismic events at this mine.

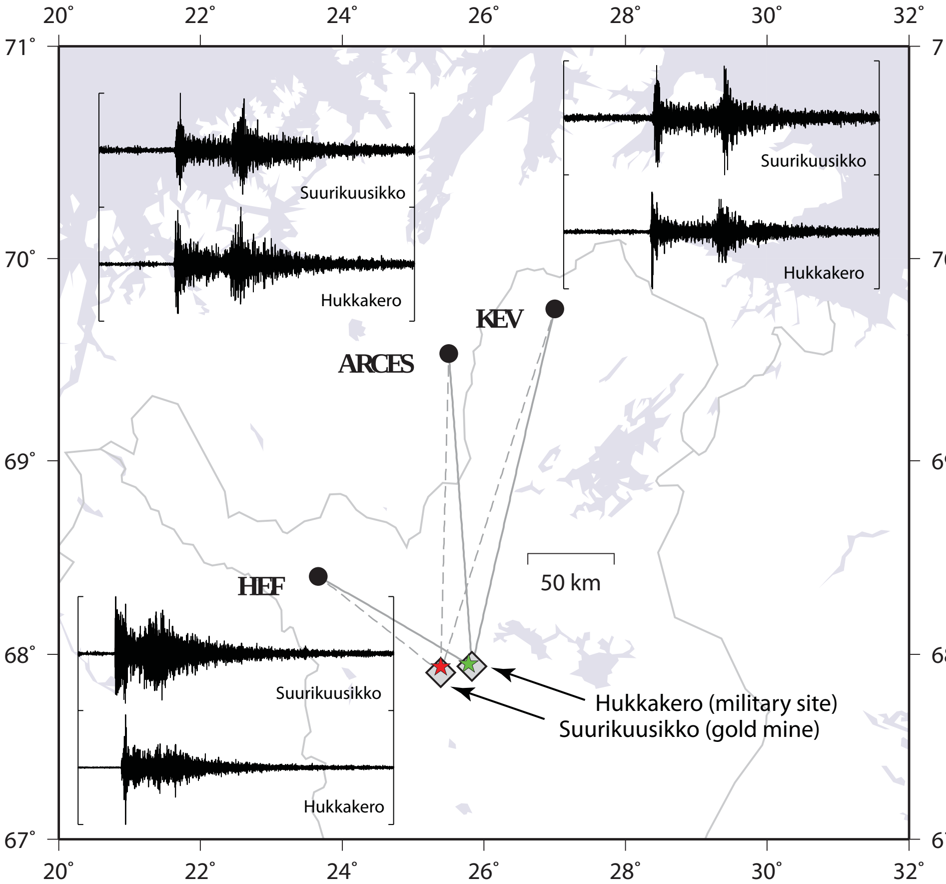

Fig. 6.3.1. Locations of the Hukkakero military explosion site (67.934 N, 25.832 E) and the Suurikuusikko gold mine (67.902 N, 25.391 E) in relation to the ARCES seismic array and the HEF and KEV 3-component stations of the Finnish seismic network. Two minutes of data are displayed for each trace beginning at the estimated event origin time and all waveforms are bandpass filte ed 3-16 Hz. The green and red stars denote event location estimates for a Hukkakero and a Suurikuusikko event respectively using the network displayed.

Gibbons and Ringdal (2006) demonstrated that seismic arrays have a tremendous advantage over single stations for correlation detectors. Firstly, there is a great suppression of the background noise made possible by a stacking of the correlation coefficient traces. Secondly, we can perform a post-processing of detections by examining the alignment of the cross-correlation coefficients from the different channels and large numbers of false alarms can be eliminated in this way.

Fig. 6.3.2. Aerial view of the Suurikuusikko mine in September 2007. The circular road indicates the final xtent of the open pit. View to the North. Photo courtesy of Agnico-Eagles Mines Limited.

Figure 6.3.3 displays all of the detections attained using a correlation detector with signal at ARCES from the October 2, 2009, event as a template since 2006. A total of 493 detections have been made in the period shown. No convincing detections have been made prior to July 2006, and a consultation with the information provided by Agnico-Eagle confirms that this is consistent with operational history of the mine. The detections displayed in Figure 6.3.3 have yet to be screened manually for false alarms, but have been filtered using the criteria described by Gibbons and Ringdal (2006). Figure 6.3.4 shows the same detections displayed as a function of the local time at the ARCES array, and the concentration of detections at particular times of day and the absence of detections at night time suggests that false alarm rate is very small.

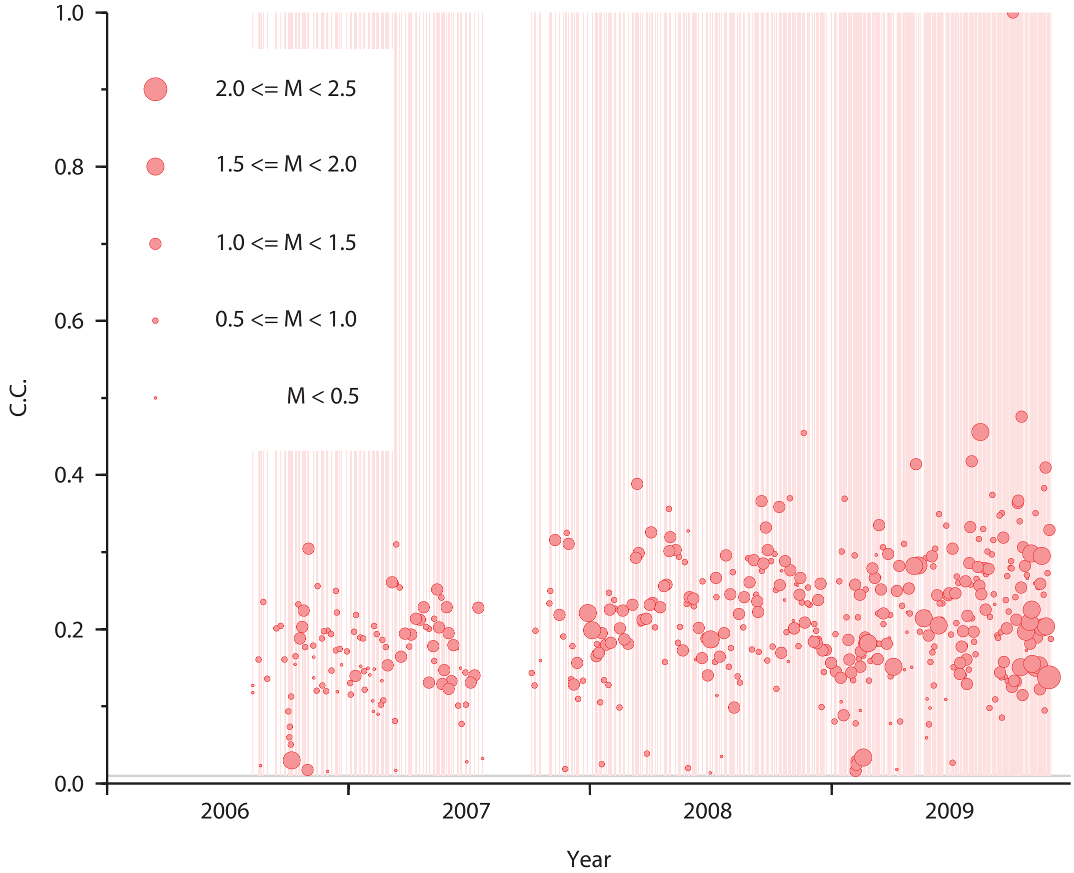

Fig. 6.3.3. Correlation detections on the ARCES array using a template of the signal from the October 2, 2009, event. In addition to a detection threshold based on the cross-correlation coefficient the detection list is screened using additional criteria of alignment of correlation traces as described in detail by Gibbons and Ringdal (2006). The correlation detector was run on archived data from years prior to 2006 and only very few detections were made with marginal values of the detection statistic. All detections prior to July 2006 were demonstrated to be false alarms. The magnitude estimates are made by comparing the amplitudes of the filte ed waveforms at ARCES with those generated from the largest of these events on November 25, 2009, which was assigned a network magnitude of 2.4.

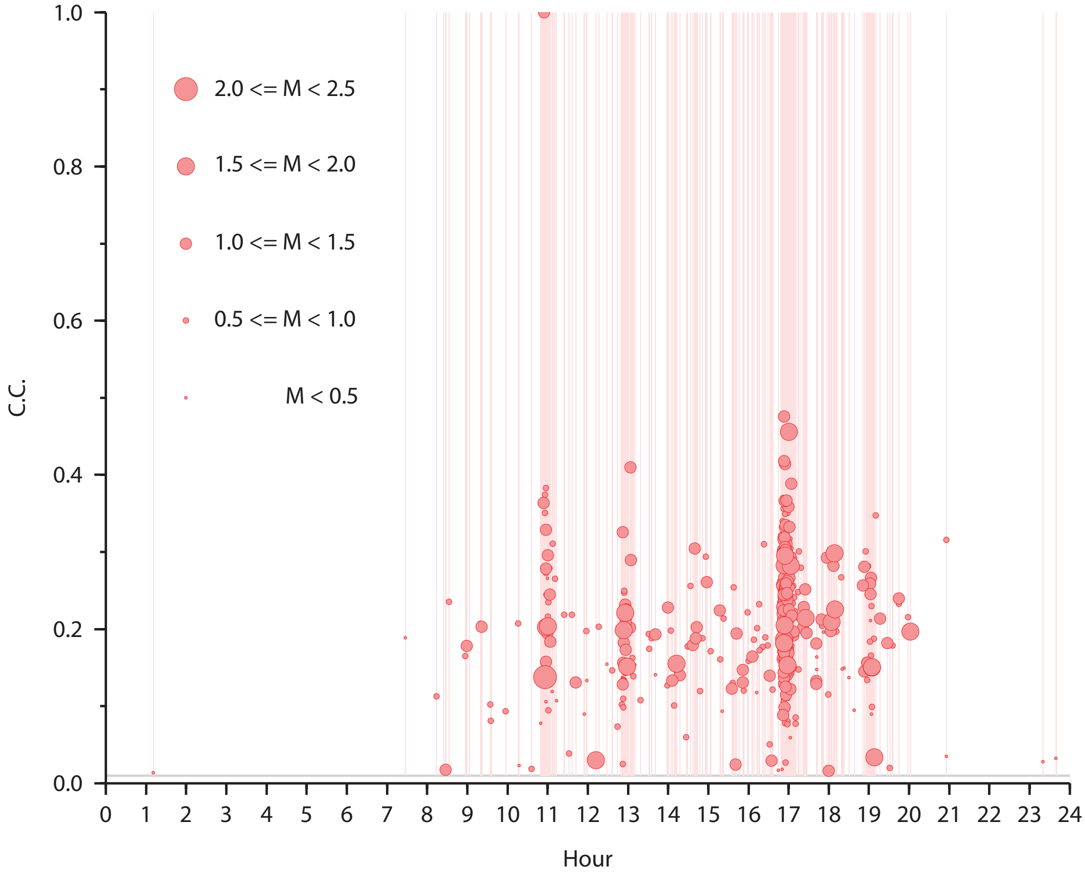

Fig. 6.3.4. Correlation detections on the ARCES array using a template of the signal from the October 2, 2009, event as a function of local time at the receiver. There are very clear clusters of events close to 1100, 1300, 1700 and 1900 hours. There are almost no detections between 2000 and 0800 hours which also suggests that the false alarm rate among these detections is probably very low.

The detection of infrasound signals at ARCES following many events in this sequence indicates that this source may be of great interest for the study of sound propagation of regional distances. The mine location is fortuitous in relation to the network of infrasound sensors in Norway, Sweden, Finland and Russia (Figure 6.3.5) which provide an almost optimal coverage of the different directions from the source. Some of the stations are located either at the edge of or well within the so-called "Zone of Silence" within which the propagation of infrasound is currently very poorly understood. While initial indications are that the Suurikuusikko mine is a less efficient generator of infrasound than the military explosions at Hukkakero, the new data set has a great advantage in that the events occur throughout the year, and so will sample many different atmospheric profiles, and may contribute more to understanding the conditions under which infrasound is observed from explosions at a known location.

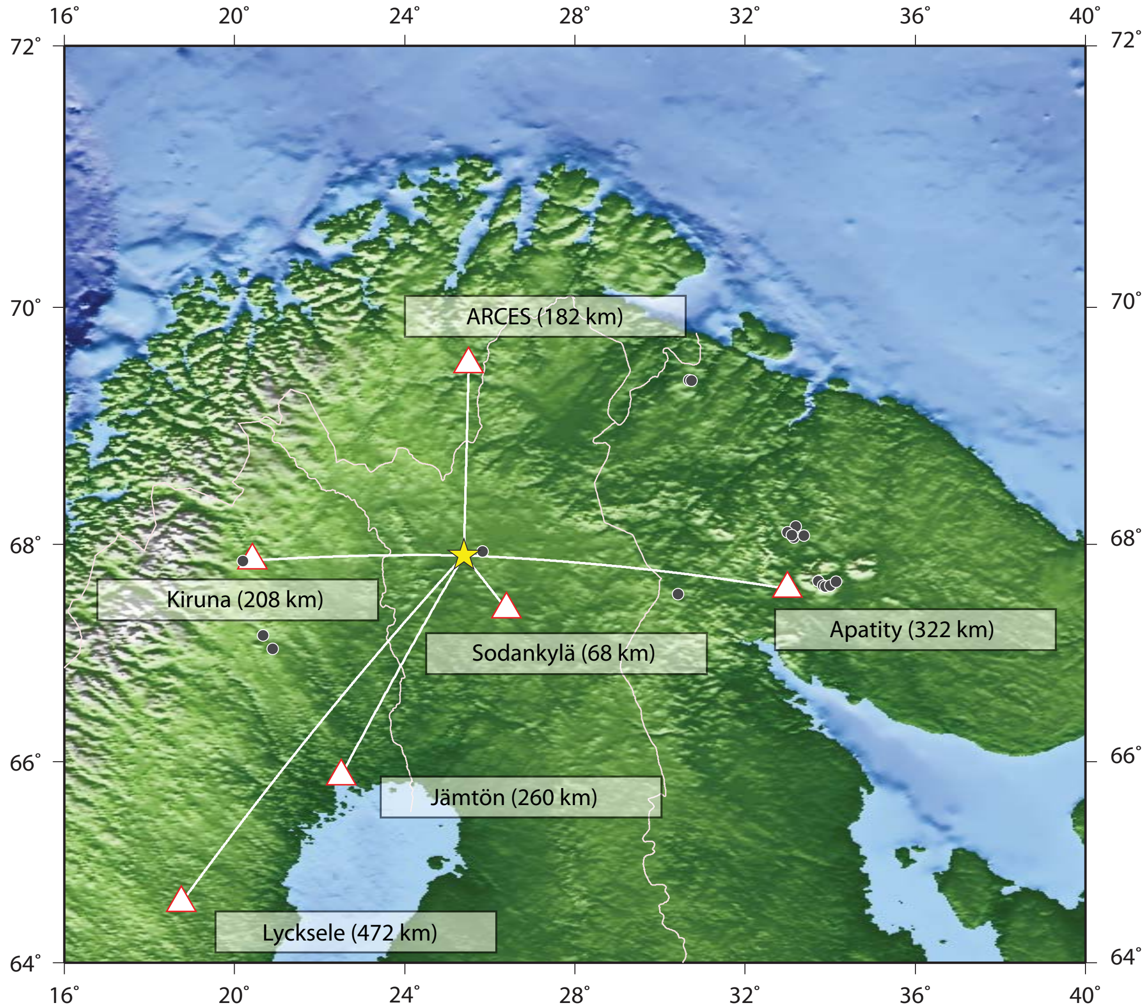

Fig. 6.3.5. Location of the Suurikuusikko gold mine in Central Lapland in relation to the ARCES and Apatity seismic/infrasonic arrays and the microphone arrays at Kiruna, Lycksele, Jämtön and Sodankylä. The coordinates 67.90154 N, 25.39102 E for the mine are taken from the website of the Geological Survey of Finland, GTK[2]*.*

The Sodankylä microphone array is located at only 68 km from the source (to the south). This station is located within the so-called Zone-of-Silence although it is accepted that infrasound can propagate to these distances in the lower atmosphere (the troposphere) given favourable wind and temperature profiles. Very clear infrasound signals have been observed for very many of these events at Sodankylä (see Figure 6.3.6) and it will be the subject of future research to understand the conditions under which infrasound is and is not detected at this and the other stations shown.

2. http://en.gtk.fi/ExplorationFinland/Commodities/Gold/suurikuusikko.html

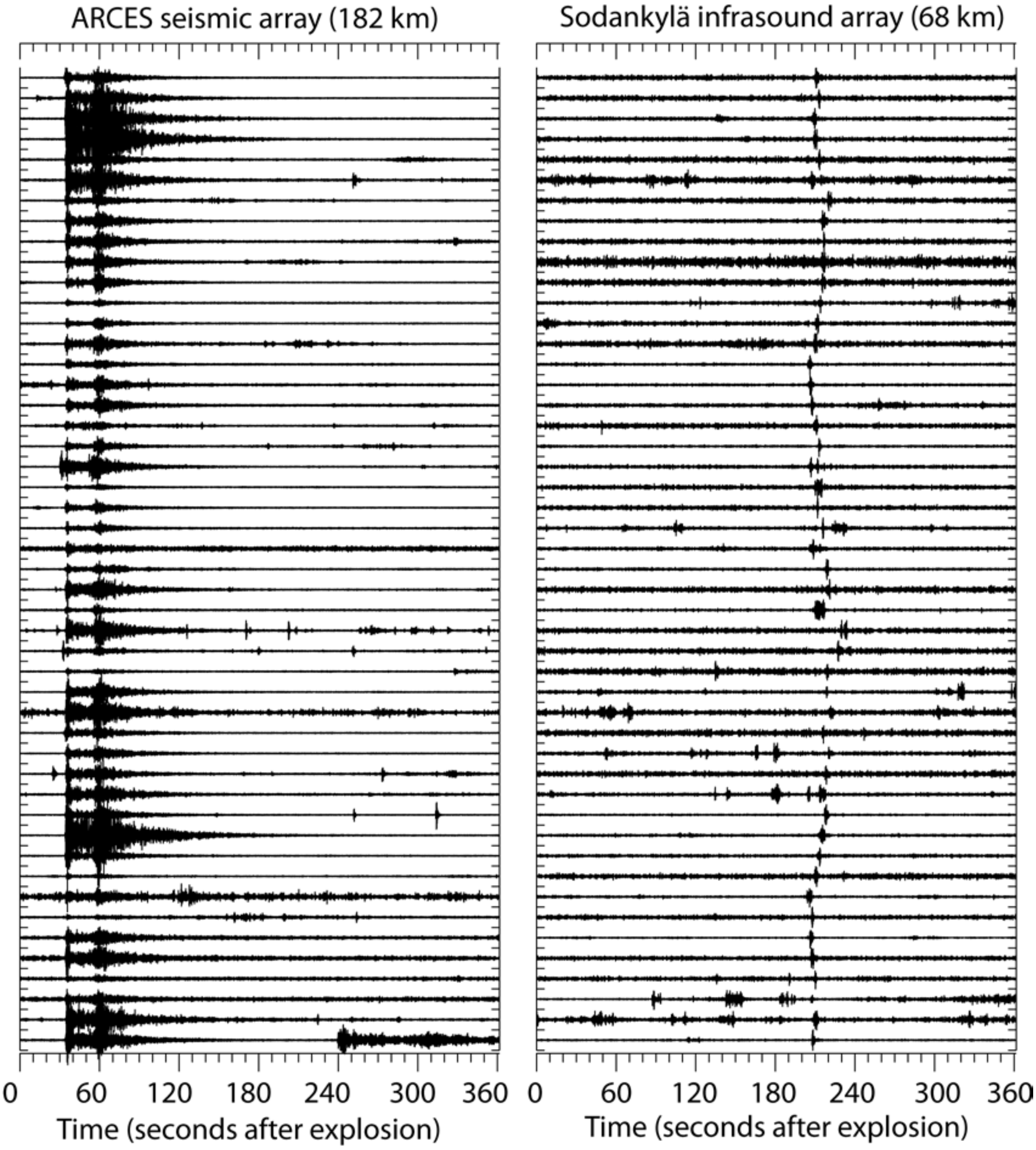

Fig. 6.3.6. Waveforms at the ARCES seismic array (ARA0_sz channel, bandpass filte ed 4-16 Hz) and the Sodankylä microphone array (SDA1_MI channel, bandpass filte ed 2-5 Hz) for the 50 events with the greatest coherence of the associated infrasound signals. The ARCES waveforms are drawn to a common scale, demonstrating the variation in the event magnitudes. Each channel of the Sodankylä data is scaled individually.

Acknowledgements

Maps were created using GMT software (Wessel and Smith, 1995). We are grateful to Agnico-Eagle Mines Limited for permission to use the photograph of the Suurikuusikko mine and to Ludwik Liszka of the Swedish Institute of Space Physics for providing data from the Sodankylä array.

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