BASIC RESEARCH ON SEISMIC AND INFRASONIC MONITORING OF THE EUROPEAN ARCTIC

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ABSTRACT

This project is a research effort aimed at improving seismic and infrasonic monitoring tools at regional distances, with emphasis on the European Arctic region, which includes the former Novaya Zemlya test site. The project has three main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe, b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region and c) to carry out experimental operation, evaluation and tuning of the seismic threshold monitoring technique.

On 11 November 2009, signals from a magnitude 3.2 event in the eastern Barents Sea were recorded by seismic stations in the Nordic countries and in NW Russia. This part of the Barents Sea has no known history of significant earthquake activity. However, over the past decades, several seismic events at various locations in this region have been detected, and several of these have been confidently associated with anthropogenic activity, like the Kursk submarine accident. As to the source type of the 11 November 2009 event, we are not in a position to draw a firm conclusion. Observations at the ARCES array, at a distance of 800 km, show signal energy up to 40 Hz and show no indication of spectral banding or cepstral peaks. This is quite different from the characteristics of underwater explosions in this area, suggesting that the event is more likely to be an earthquake. This study further illustrates the very efficient high-frequency seismic energy propagation characteristics of the Barents Sea area.

Seismic and infrasound signals at ARCES have recently been associated with blasting at the Suurikuusikko gold mine in northern Finland, approximately 10 km to the west of Hukkakero. This mine started operations in the summer of 2006 and, in order to develop a database of explosions, multi-channel waveform correlation detectors were initiated using ARCES seismic signals as templates. Many hundreds of clear detections have been made indicating several events per week. The absence of detections prior to June 2006, and the absence of detections outside of characteristic times of days, indicate a low false alarm rate. A majority of the over 500 events detected since June 2006 have been associated with infrasound detections at ARCES and at stations of the infrasound networks of Sweden, Finland, and Russia, all at regional distances from the source and with a fortuitous coverage of directions from the mine. While the events appear to be less efficient generators of infrasound than the military munitions explosions at Hukkakero, the blasts occur throughout the year and so will sample a far greater spectrum of atmospheric profiles. Examining long time-series of observations from these well-constrained sources will hopefully improve our understanding of the conditions under which infrasound is observed within and on the edge of the so-called “Zone of Silence”.

International news media reported in July 2009 on an unsuccessful launch of the new Russian intercontinental Bulava missile. The missile was launched from a submarine in the White Sea on 15 July 2009, and was reported to self-destruct during the first stage of flight. The effect of another launch failure of the Bulava missile was visually observed in northern Scandinavia on 9 December 2009, in terms of strange light phenomena in the sky. This caused considerable public attention, and it was reported after some time that the phenomena were believed to originate from an engine failure and self-destruction in the third stage of a Bulava missile. Infrasound signals from both of these launches were well recorded at several infrasound arrays in the region. Array analysis followed by tracing of the estimated back-azimuths located both infrasound sources to the White Sea. During recent years, infrasound signals been observed in the Nordic region from several rocket launches and meteors entering the atmosphere. Establishing a database of such events is important for future studies of infrasound wave propagation.

OBJECTIVE

The objective of the project is to carry out research to improve the current capabilities for monitoring small seismic events in the European Arctic, which includes the former Russian test site at Novaya Zemlya. The project has three main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe, b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region and c) to carry out experimental operation, evaluation and tuning of the seismic threshold monitoring technique, with application to various regions of monitoring interest.

RESEARCH ACCOMPLISHED

On 11 November 2009, at 04:18 GMT, signals from a seismic event in the eastern Barents Sea were recorded by seismic stations in the Nordic countries as well as in NW Russia. This part of the Barents Sea has no known history of significant earthquake activity. However, over the past decades, NORSAR has recorded several seismic events at various locations in this region as listed in the NORSAR reviewed regional seismic bulletin. Since January 2006, five small seismic events near Novaya Zemlya have been detected (Table 1 and Figure 1).

Table 1. Seismic events near Novaya Zemlya detected during 01/2006-01/2010

Date	Origin time	Latitude (N)	Longitude (E)	Magnitude (mb)
05/03/2006	23:17:35.7	76.80	66.04	2.65
14/03/2006	20:57:02.4	75.07	53.05	2.23
30/03/2006	10:46:02.8	70.79	51.50	2.30
26/06/2007	03:19:05.0	73.45	53.43	2.75
11/11/2009	04:18:21.0	71.58	46.09	3.20

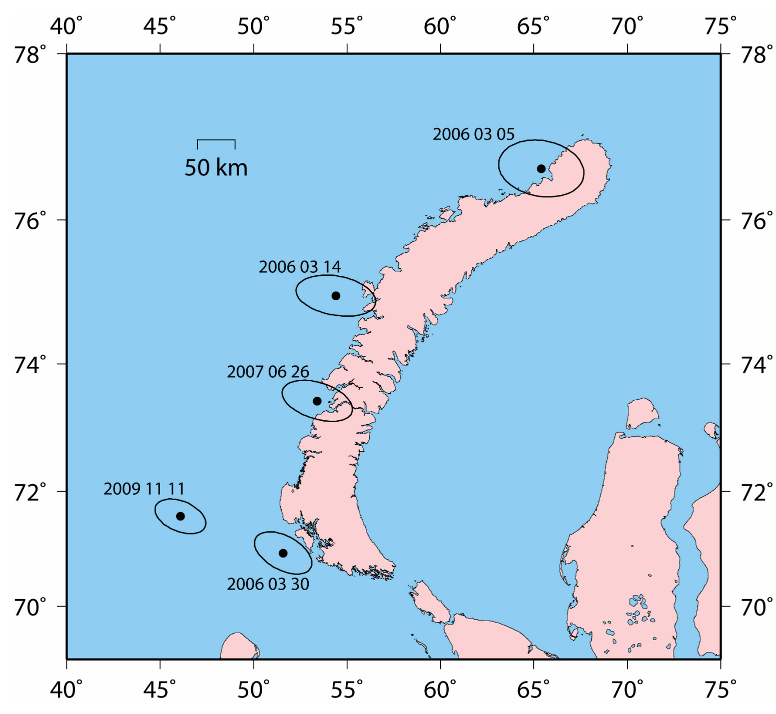

Figure 1. Location of seismic events near Novaya Zemlya between 2006 and 2010 as published in the regional NORSAR bulletin. The 95% location confidence ellipses are indicated for each event.

Observations at ARCES

We have analyzed data from the ARCES array in northern Norway recorded for the event on 11 November 2009. Figure 2 shows filtered recordings (2-16 Hz) of the three-component center seismometer of ARCES. The characteristics of the traces are similar to previous events from this region, with clear Pn and Sn phases, whereas the Pg and Lg phases are not discernible, at least not in this frequency band. We also note that the direction of the event is nearly due east of ARCES, and that consequently the radial component (se) of the Pn-phase is about as strong as the vertical component, while the Sn phase is by far the most prominent on the transverse (sn) component. This is an important confirmation of the advantages of using the transverse component of the seismogram to increase the probability of detecting S-type phases.

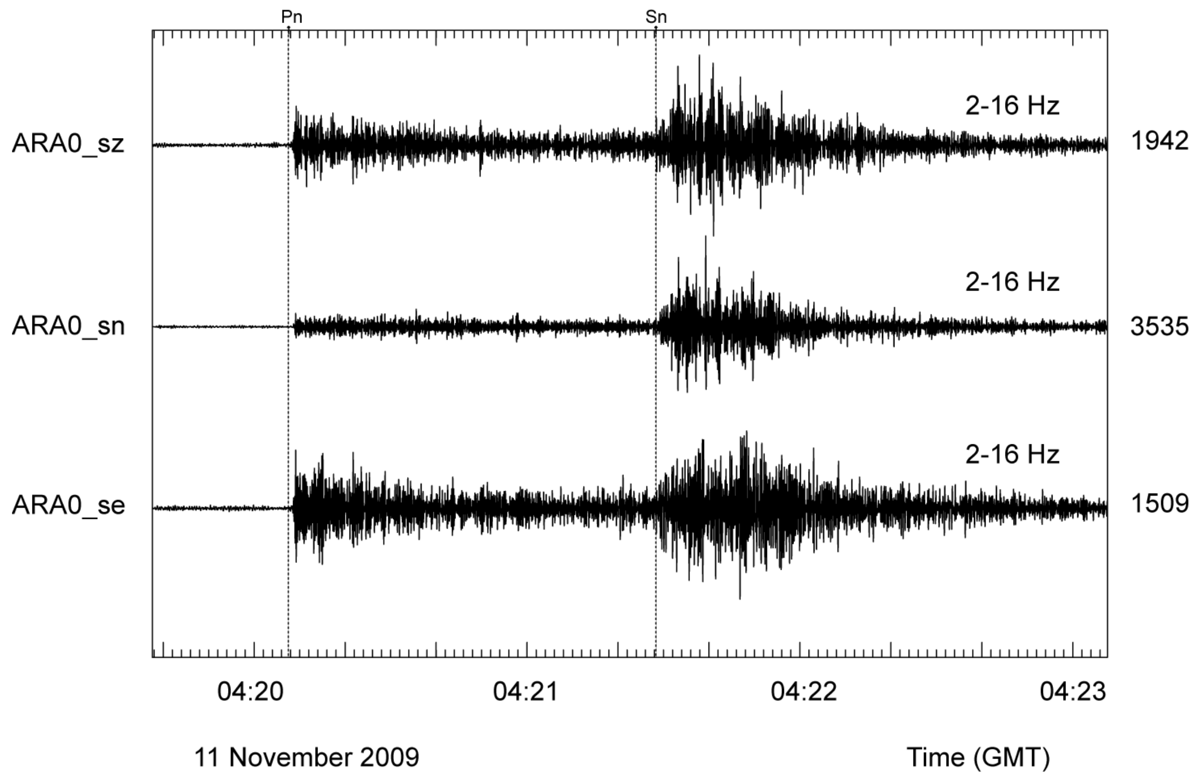

Figure 2. Recordings by the three-component center seismometer of the ARCES array of the seismic event in the Barents Sea on 11 November 2009. The traces have been filtered in the 2-16 Hz frequency band.

The event on 11 November 2009 is of special importance since it is the first event near Novaya Zemlya since the high frequency element was installed at ARCES in early 2008. As noted by Ringdal et al. (2008) in their initial study of high frequency ARCES recordings, the available high-frequency data at that time did not include recordings of distant events to the east and north-east of the ARCES array, and the high-frequency propagation from the Novaya Zemlya region to ARCES could therefore not be assessed.

We have therefore made a special analysis of the associated ARCES high frequency recordings for the event on 11 November 2009, as described in Kværna and Ringdal (2010). Figure 3 shows spectra of the Pn and Sn phases as well as the spectrum of noise preceding the event. We note the significant high-frequency energy of the Pn and Sn phases, with the signal exceeding the noise for frequencies all the way up to 40 Hz for the Pn phase, and even above 40 Hz for the Sn phase.

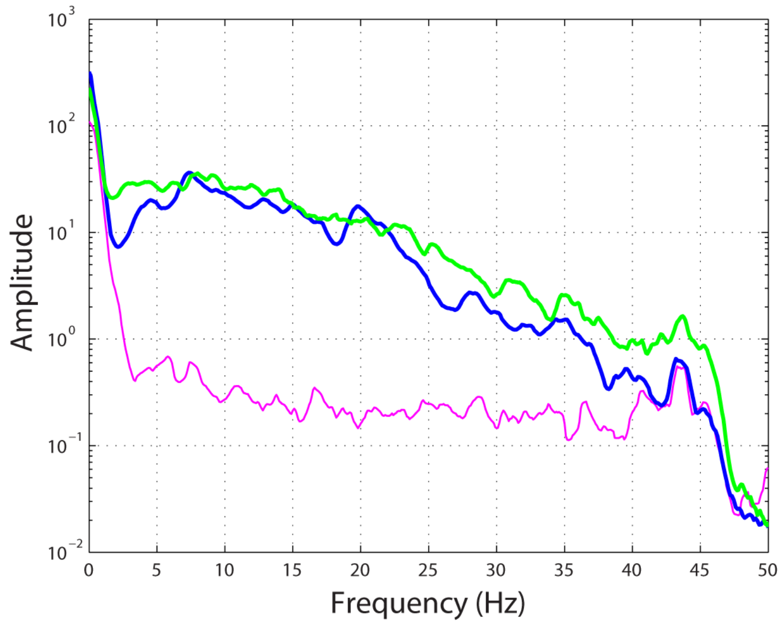

Figure 3. Spectra from the ARCES vertical high-frequency element of the Pn (blue) and Sn (green) phases of the 2009 event. The noise spectrum (magenta) preceding the event is also shown.

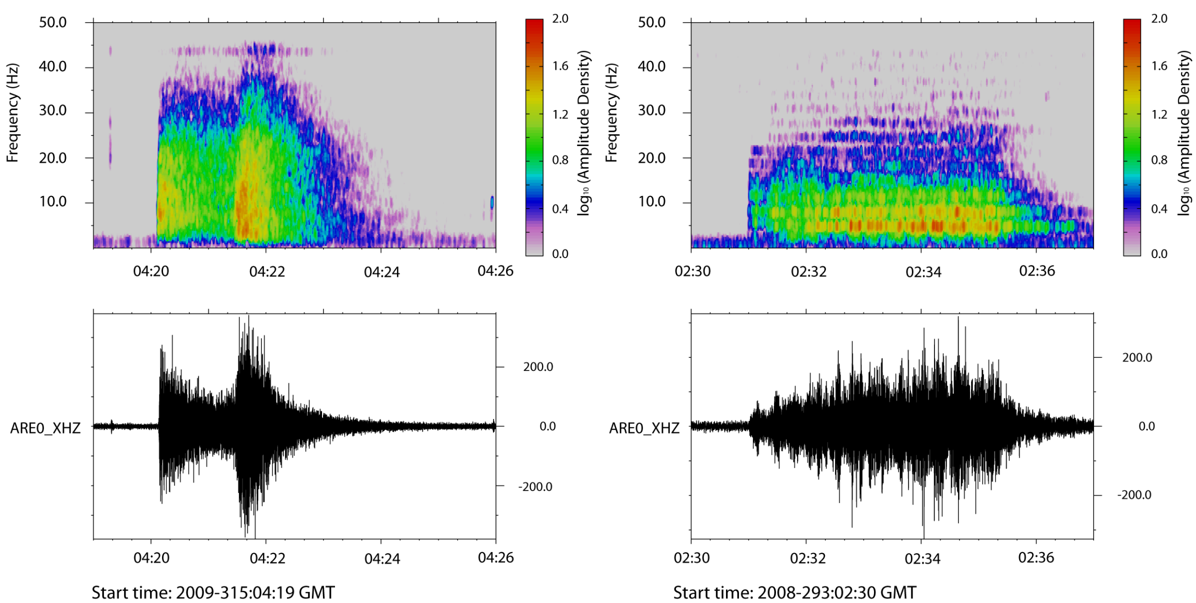

Figure 4. Spectrograms from the ARCES vertical high-frequency element of seismic events in the Barents Sea. The left plot shows the seismic event on 11 November 2009. The plot to the right shows a sequence of presumed underwater explosions near the northern coast of the Kola Peninsula on 19 October 2008. The traces have been high-pass filtered at 2.2 Hz. Note the significant differences between the two plots.

After the ARCES high-frequency element was installed, there have been a number of seismic events in or near the mining regions of NW Russia. However, the distance from ARCES to these events are 300 km or less, whereas the epicentral distance of the 11 November 2009 event was as large as 800 km. Nevertheless, it is of interest to compare the latter event to some of the presumed underwater explosions at about 300 km distance. One way to make such a comparison is illustrated in Figure 4. This figure shows spectrograms from the ARCES vertical high-frequency element of the 11 November 2009 event as well as a sequence of presumed underwater explosions near the northern coast of the Kola Peninsula on 19 October 2008. We note that the presumed explosions in 2008 have their dominant energy at much lower frequencies than the event in 2009, even though the latter event is at a much larger distance from ARCES. The spectral scalloping evident in the 2008 plot is typical of many underwater explosions, and is associated with multiple reflections from the bottom and surface of the water (e.g., Baumgardt and Der, 1998).

Kværna and Ringdal (2010) applied the software described by Oberg et al. (2004) to compare the cepstral peaks associated with various categories of events in the Barents Sea region. They concluded that the recordings from the 11 November 2009 event were more consistent with previous earthquake recordings than with recordings of known underwater explosions, although they noted that it is difficult to discriminate reliably using this criterion only.

Infrasound studies

The site of military explosions at Hukkakero, northern Finland (67.934 N, 25.832 E) 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:

- The location of the events is known. All explosions are known to take place within approximately 300 meters of the coordinates stated.
- 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).
- 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.

On October 2, 2009 we noted an event which occurred shortly after the end of the 2009 Hukkakero explosion sequence and was reported by the NORSAR Event Warning System (Schweitzer, 2003). Due to the event origin time and poor signal correlation with known events, this event 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 (67.90 N, 25.39 E). Figure 5 displays the location of the sources together with waveforms from one event from each of the two explosion sites.

The magnitude estimate for the seismic event on October 2, 2009, was just in excess of 1.0 and, while such events are routinely 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.

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.

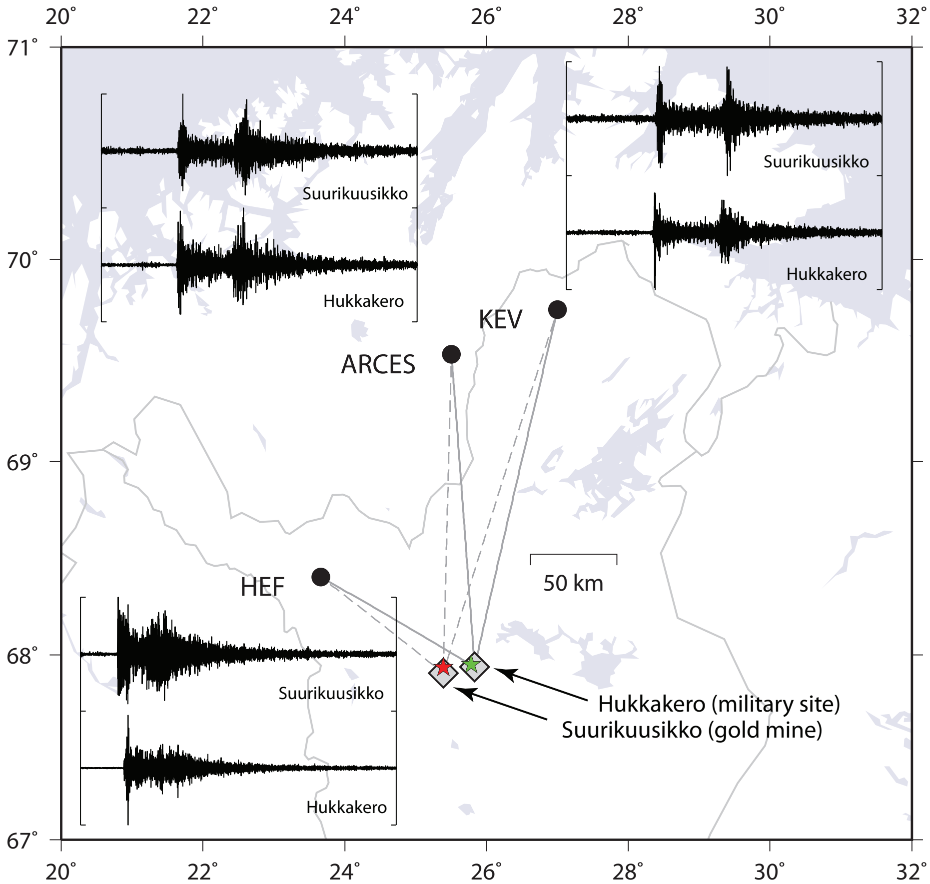

Figure 5. Locations of the Hukkakero military explosion site (67.934 N, 25.832 E) and the Suurikuusikko gold mine (67.902 N, 25.391 E) in relation to the ARCES seismic array and the HEF and KEV 3-component stations of the Finnish seismic network. Two minutes of data are displayed for each trace beginning at the estimated event origin time and all waveforms are bandpass filtered 3-16 Hz. The green and red stars denote event location estimates for a Hukkakero and a Suurikuusikko event respectively using the network displayed.

Figure 6 displays all of the detections attained since 2006 using a correlation detector with signal at ARCES from the October 2, 2009, event as a template. A total of 493 detections have been made in the period shown. No convincing detections were made prior to July 2006, and a consultation with the information provided by Agnico-Eagle confirms that this is consistent with the operational history of the mine. The detections displayed in Figure 6 have yet to be screened manually for false alarms, but have been filtered using the criteria described by Gibbons and Ringdal (2006). The concentration of detections at particular times of day and the absence of detections at night time suggest that the false alarm rate is 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 7) 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.

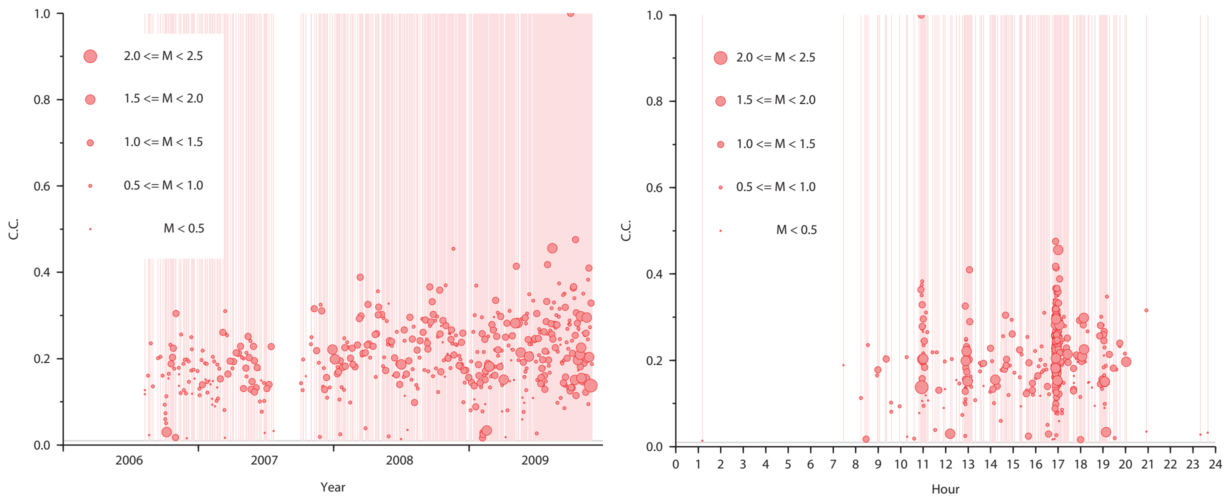

Figure 6. Correlation detections on the ARCES array using a template of the signal from the October 2, 2009, event. The left plot shows detections chronologically, the right plot shows detections by local time of day at ARCES. The detector was run on archived data from years prior to 2006 and the very few detections prior to July 2006 were all demonstrated to be false alarms. The time-of-day plot shows 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.

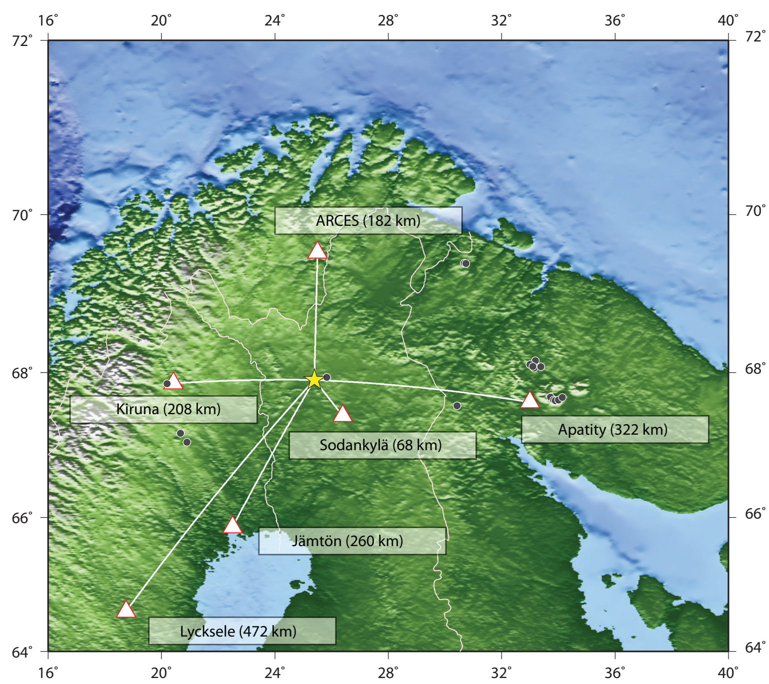

Figure 7. Location of the Suurikuusikko gold mine in Central Lapland in relation to the ARCES and Apatity seismic/infrasonic arrays and the microphone arrays at Kiruna, Lycksele, Jämtön and Sodankylä.

The 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 favorable wind and temperature profiles. Very clear infrasound signals have been observed for many of these events at Sodankylä (see Figure 8) 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.

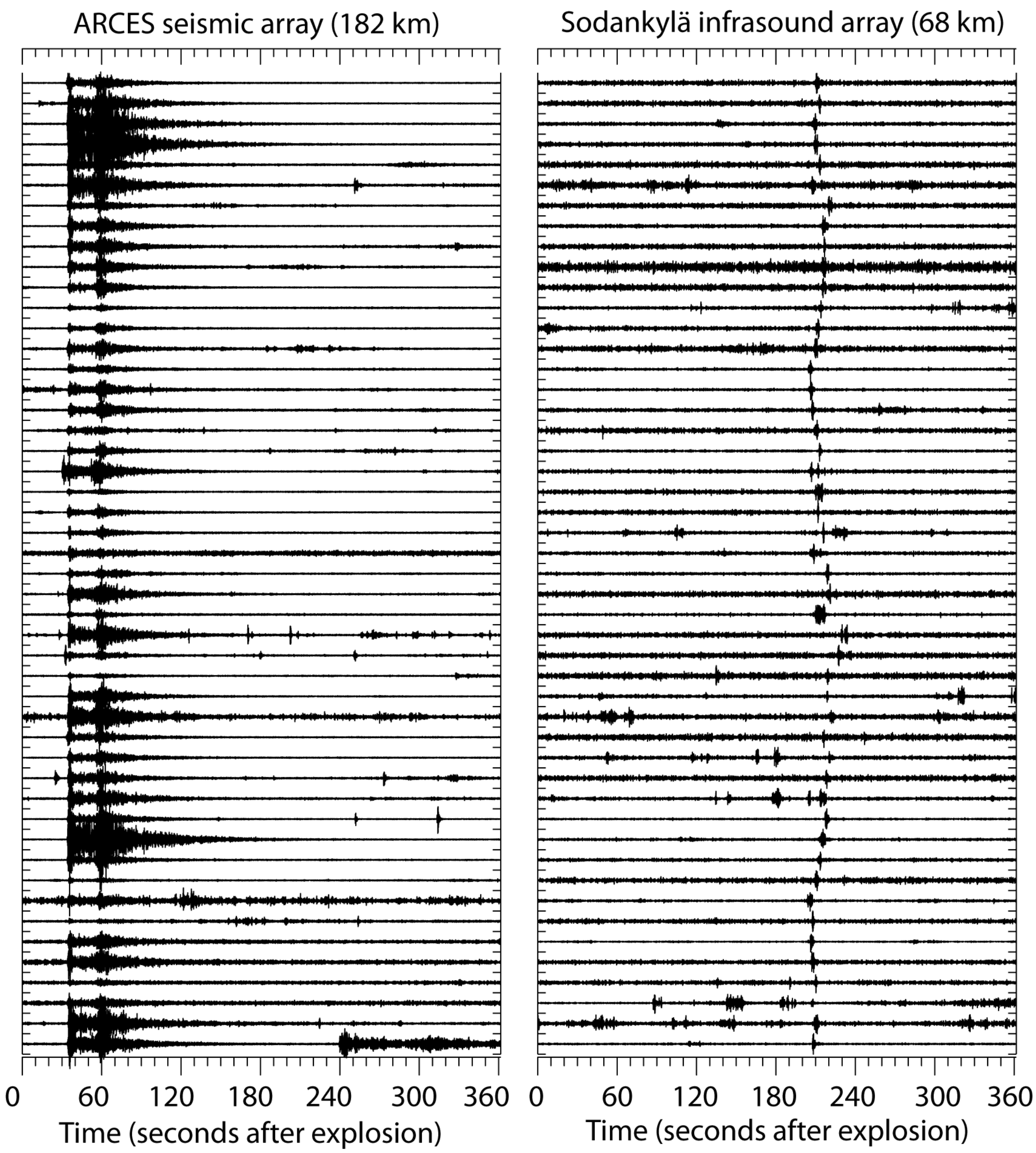

Figure 8. Waveforms at the ARCES seismic array (ARA0_sz channel, bandpass filtered 4-16 Hz) and the Sodankylä microphone array (SDA1_MI channel, bandpass filtered 2-5 Hz) for the 50 events with the greatest coherence of the associated infrasound signals. The ARCES waveforms are drawn to a common scale, demonstrating the variation in the event magnitudes. Each channel of the Sodankylä data is scaled individually. (Note that infrasound signals at ARCES arrive later than displayed here.)

<u>Infrasound Recordings of the Bulava Missile</u>

International news media reported in July 2009 on an unsuccessful launch of the new Russian intercontinental Bulava missile. The missile was launched from a submarine in the White Sea on 15 July. Infrasound signals associated with this launch were recorded at NORSAR's experimental infrasound station at ARCES (Roth et al., 2008) and the four stations in Sweden and Finland operated by the Swedish Institute of Space Physics (IRF). Another Bulava launch took place on 9 December 2009. Around 6:50 UTC on that day, strange light phenomena were observed in northern Norway. These observations caused a lot of attention in the news media, and after a while it became evident that the phenomena were associated with this launch. According to the Russian Defence Ministry there was an engine failure in the third stage of the flight that caused the problem. According to recent information provided by the Norwegian Ministry of Defence, they believe that the missile exploded at an altitude between 100 and 300 km above the Novaya Zemlya region, and that the missile was launched from a submarine in the north-eastern part of the White Sea. Infrasound signals believed to originate from this missile launch were observed at ARCES as well as at the infrasound station in Apatity on the Kola peninsula. No infrasound signals were found at the stations of the IRF network for the 9 December event.

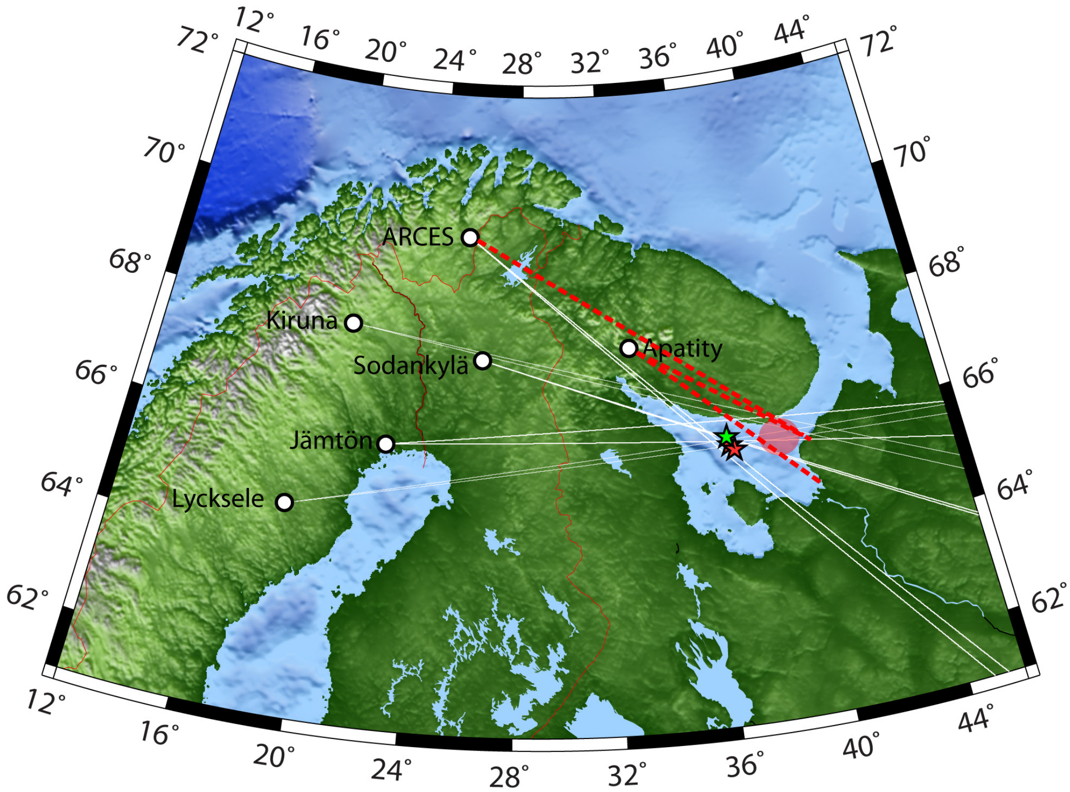

Figure 9. The dashed red lines show estimated back-azimuths from the ARCES and Apatity infrasound arrays for the 9 December 2009 event. See text for details.

Figure 9 shows the results of our analysis of these two events. The approximate source region of the 9 December event is indicated by the red ellipse. For comparison, the red and green stars show the estimated locations of the 15 July 2009 event. The red stars show locations provided by Prof. L. Liszka of the Swedish Institute of Space Physics, and the green star is from the study by Kværna (2010).

CONCLUSIONS AND RECOMMENDATIONS

Seismic events in the eastern Barents Sea are rare, and the event on 11 November 2009 is therefore of considerable interest. It is the first recorded seismic event in this region since the new high-frequency system was installed at the ARCES array on 23 March 2008. Our analysis of this event confirms the preliminary results of Ringdal et al. (2008) that there is a remarkably efficient propagation from regional events recorded at ARCES at frequencies up to 30 Hz and above.

This result is similar to what has been previously observed at the Spitsbergen array for paths from Novaya Zemlya crossing the Barents Sea. The Spitsbergen studies showed that energy up to 30 Hz and above can be recorded with good signal-to-noise ratio even for small events at epicentral distances as large as 1000 km and we see a similar result in this study, although the event is at a slightly shorter distance (800 km). We consider that there is still much to be gained by making improved use of the high-frequency recordings in the European Arctic, and we recommend that a systematic mapping of the high-frequency propagation characteristics of this region be undertaken.

As discussed by Ringdal et al. (2008), there are several advantages of high-frequency recordings in a nuclear monitoring context. Although the best filter band for event detection over paths across the Barents region generally appears to be either 4-8 Hz or 8-16 Hz, the most remarkable result shown in our previous papers as well as the current study is the strong SNR even at the highest frequencies (up to 40 Hz). While such frequencies would not be used for detection purposes, the high frequency data could be very important for signal characterization, as also pointed out by Bowers et. al. (2001) in their paper discussing the level of deterrence to possible CTBT violations in the Novaya Zemlya region provided by data from the Spitsbergen array. In fact, it appears from the present study that similar advantages are provided by the ARCES array.

The infrasound databases that have been developed based on the explosions in northern Finland provides a unique resource for studies of infrasonic propagation from well-constrained sources. One of the main topics to be studied is the surprising observations of various infrasound phases in what is often denoted a "zone of silence" (less than 200 km distance). We plan to carry out various modelling exercises in order to further investigate the propagation of infrasound phases at local distances. At the same time we recommend that the ongoing accumulation of ground truth data of a variety of infrasound sources should be continued.

During recent years, infrasound signals been observed in the Nordic region from several rocket launches and meteors entering the atmosphere. Establishing a database of such events is important for future studies of infrasound wave propagation.

REFERENCES

Baumgardt, D.R. and Der, Z. (1998). Identification of presumed shallow under-water chemical explosions using land-based regional arrays. *Bull. Seismol. Soc. Am*. 88:581–595.

Bowers, D., P. D. Marshall, and A. Douglas (2001). The level of deterrence provided by data from the SPITS seismometer array to possible violations of the Comprehensive Test Ban in the Novaya Zemlya region, *Geophys. J. Int.* 146: 425–438.

Gibbons, S. J. and Ringdal, F. (2006). The detection of low magnitude seismic events using array-based waveform correlation, *Geophys. J. Int.* 165: 149–166.

Gibbons, S. J., Ringdal, F., and Kværna, T. (2007). Joint seismic-infrasonic processing of recordings from a repeating source of atmospheric explosions. *J. Acoust. Soc. Am.* 122: EL158-EL164.

Kværna, T. (2010). Infrasound signals from recent rocket launches in the White Sea. *In NORSAR Scientific Report No. 1-2010: Semiannual Technical Summary, NORSAR, Kjeller, Norway.* pp. 35–43.

Kværna, T. and Ringdal, F. (2010). Seismic event in the eastern Barents Sea, 11 November 2009. *In NORSAR Scientific Report No. 1-2010: Semiannual Technical Summary, NORSAR, Kjeller, Norway*. pp. 26–34.

Oberg, D., Kværna, T. and Ringdal, F. (2004). Discriminants for seismic monitoring. *In NORSAR Scientific Report No. 2-2004: Semiannual Technical Summary, NORSAR, Kjeller, Norway*. pp. 57–69.

Ringdal, F., Kværna, T., and Gibbons, S. J. (2008). Initial studies of high-frequency signals recorded at ARCES. *In NORSAR Scientific Report No. 2-2008: Semiannual Technical Summary, NORSAR, Kjeller, Norway*. pp. 27–51.

Roth, M., Fyen, J., and Larsen, P. W. (2008). Setup of an experimental infrasound deployment within the ARCES array. *In NORSAR Scientific Report No. 2-2008: Semiannual Technical Summary, NORSAR, Kjeller, Norway*. pp. 52–59.

Schweitzer, J. (2003). NORSAR's Event Warning System (NEWS), *In NORSAR Scientific Report No. 1-2003: Semiannual Technical Summary, NORSAR, Kjeller, Norway*. pp. 27-32.