BASIC RESEARCH ON SEISMIC AND INFRASONIC MONITORING OF THE EUROPEAN ARCTIC

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ABSTRACT

This project represents a three-year 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, with application to various regions of monitoring interest.

We have begun exploiting the data from the Swedish infrasound array network, which provides a useful supplement to the seismic and infrasonic arrays in Norway and NW Russia. We continue our work towards developing and evaluating a joint seismic/infrasonic bulletin for northern Fennoscandia and adjacent regions. This bulletin would be similar to the automatic seismic bulletin that we are currently providing on the NORSAR Web pages, but it would also contain infrasonic phase associations. Furthermore, we plan to generate an infrasonic event bulletin using only the estimated azimuths and detection times of infrasound phases recorded by stations in the Nordic network.

We have continued our studies of seismic and infrasonic recordings of a set of more than 100 surface explosions in northern Finland, carried out for the purpose of destroying old ammunition. Waveform correlation analysis indicates that these explosions were very closely spaced, and occurred at most within a few hundred meters of each other. This is a unique set of events given the repeatable nature of the source. Very similar waveforms and amplitudes are observed for the seismic phase arrivals, indicating a similar explosion yield and source function for each event. In contrast, the infrasonic recordings show great variation between events, both with regard to the number and amplitudes of detected infrasonic phases, as well as their travel times. A variation of several tens of seconds in travel times for corresponding phases for different events is observed at a distance of about 175 km.

The recent upgrade of the Spitsbergen seismic array, which has included installation of five new three-component seismometers, as well as an increase in the sampling rate from 40 to 80 Hz, has resulted in significant improvements in high frequency signal characterization as well as S-phase detection. We demonstrate some results from analysis of recent small seismic events near Novaya Zemlya and in the Barents Sea.

We have analyzed the recorded waveforms from the 9 October 2006 North Korean nuclear explosion in order to investigate the capability of the Seismic International Monitoring System (IMS) network to monitor the North Korean test site for possible future explosions. Our analysis is based upon the so-called Site-Specific Threshold Monitoring (SSTM) approach. Using actual seismic data recorded by a given network, SSTM calculates a continuous “threshold trace,” which provides, at any instant in time, a probabilistic upper magnitude bound on any seismic event that could have occurred at the target site at that time. We find that the current IMS primary network has a typical “threshold monitoring capability” of between mb 2.3 and 2.5 for the North Korean test site. Not unexpectedly, it turns out that the Korean array (KSRS) is of essential importance in obtaining such low thresholds. Non-IMS stations could also make important contributions, and we find that by adding the nearby Incorporated Institutions for Seismology (IRIS) station MDJ in China, the threshold monitoring capability is improved to between magnitude 2.1 and 2.3. For comparison, the three-station network detection threshold is found to be typically one magnitude higher than these numbers. We note, however, that the SSTM approach is not aimed at detecting events, but rather to supplement traditional detection processing by enabling the analyst to focus on and analyze extensively instances where a possibly undetected event of monitoring interest could have occurred.

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

Establishing a Nordic Network of Infrasound Arrays

An important aspect of the infrasonic studies is the availability of data from a distributed network of arrays. The Swedish infrasound array network provides a useful supplement to the seismic and infrasonic arrays in Norway and NW Russia. We have begun exploiting the data from this combined network, which will allow a much improved joint seismic/infrasonic regional processing at NORSAR. The Apatity infrasound array is a three-element array co-located with the nine-element Apatity short-period regional seismic array, which was installed in 1992 on the Kola Peninsula, Russia by the Kola Regional Seismological Centre (KRSC). The 25 element ARCES array is a short-period regional seismic array, located in northern Norway. ARCES has no infrasound sensors, but because of the near surface installation conditions, many of its seismic sensors are also sensitive to infrasound signals (e.g., Ringdal and Gibbons, 2006). Current plans are to install an infrasound array near the ARCES site in 2007/2008. The Swedish Infrasound Network (Liszka, 2007) has been in operation since the beginning of the 1970s. Operated by the Swedish Institute of Space Physics, the network has until recently comprised four infrasound stations: Kiruna, Jämtön, Lycksele and Uppsala. The station in Uppsala was moved to Sodankylä, Finland, during the summer of 2006. The currently available network of arrays for infrasound processing in the Nordic region is shown in Figure 1.

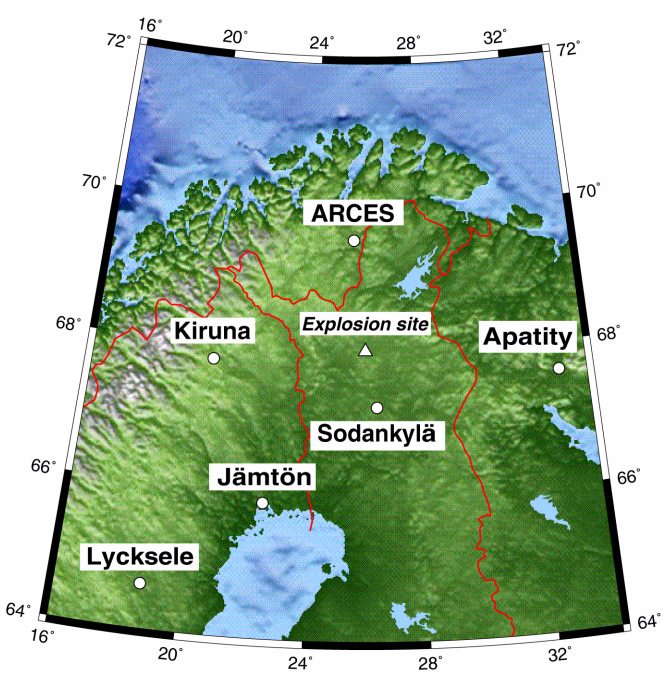

Figure 1. Locations of the arrays used for infrasonic processing in the Nordic countries. The site of the explosions in northern Finland discussed in this paper is marked on the map.

Case study of explosions in northern Finland

Each year between mid-August and mid-September, a series of explosions in the north of Finland has been recorded by the stations of the Finnish national seismograph network and also by the seismic arrays in northern Fennoscandia and NW Russia. Based upon event locations given in the seismic bulletin of the University of Helsinki, the geographical coordinates of the explosion site are assumed to be approximately 68.00^{o}N and 25.96^{o}E. The explosions are carried out by the Finnish military in order to destroy outdated ammunition and are easily identified from the automatic seismic bulletins at NORSAR for several reasons. Firstly, they are always detected with a high signal-to-noise ratio (SNR) on the ARCES array; secondly they register very stable azimuth estimates on the detection lists; and thirdly they take place at very characteristic times of day (the origin time indicated by the seismic observations almost invariably falls within a few seconds of, typically, a full hour or half-hour in the middle of the day).

Between 2001 and 2006, a total of 141 events were found that appeared to fit the general attributes of explosions from this site. The fully automatic location estimates displayed a rather large geographical spread and, assuming that these events are in fact essentially co-located, the origin times would be correspondingly spurious. However, by applying a waveform correlation procedure we could confirm that the explosions were indeed closely spaced, probably within an area of some hundred meters in diameter (Ringdal and Gibbons, 2006).

The signals recorded by the ARCES seismic array provide an excellent perspective of the differences in seismic and infrasonic recordings of the explosions, as illustrated in Figure 2 for the year 2005. A large amplitude infrasonic signal approximately 600 seconds after the origin time is observed for almost all of these events but, unlike the seismic signals which are almost identical for each explosion, the temporal characteristics and the amplitudes of the infrasonic arrivals differ greatly among events. There is also significant variability in the travel time of the infrasonic phases from event to event, and there is evidence of multiple infrasonic arrivals as well. The similarity of the seismic waveforms for these explosions not only constrains the events to be almost co-located but rule out the possibility of multiple explosions as is common for ripple-fired mining blasts (Gibbons et al., 2005). We conclude that differences in the occurrence and appearance of infrasonic arrivals from event to event are the result of atmospheric conditions alone. The seismic data also indicate very similar waveform amplitudes for the events from which we conclude very similar explosion yields. This will provide a useful measure of the variability in yield estimation from the sound waves.

To obtain a better overview of the occurrence of signals with typical sound velocities, we calculated a detection statistic, C(t), which is essentially identical to that defined in Equation (15) of Brown et al. (2002). Figure 3 displays a color-scaled indication of C(t) for the ARCES array for a five-minute long time-window following each of the events subject to C(t) exceeding a threshold of 0.01 and the estimated slowness and azimuth falling in the indicated ranges. The vast majority of the events register a candidate acoustic phase between approximately 620 and 660 seconds after the event. A smaller number of events also indicate an earlier arrival from approximately 500 seconds. This figure confirms that evidence of one or more atmospheric sound arrivals was observed for almost every explosion, even in cases where the signal amplitude was smaller than the ambient noise level. The most common arrivals occur approximately 600 seconds after the event with a superimposed variation which appears to vary quite smoothly over a several day time-scale.

There are many interesting questions which need further investigation. For the recordings at ARCES, the infrasonic arrivals after approximately 650 seconds are quite consistent despite showing far greater variation than the corresponding seismic signals. On the other hand, the arrivals at approximately 550 seconds occur relatively seldom and, when they occur, they appear to produce a larger amplitude seismic response than the later signals (see, for example, the waveforms from Aug. 27, Sep. 3, and Sep. 14 on Figure 2). More detailed information about the atmospheric conditions along the path from the explosion site to the ARCES array would be useful in order to address these questions.

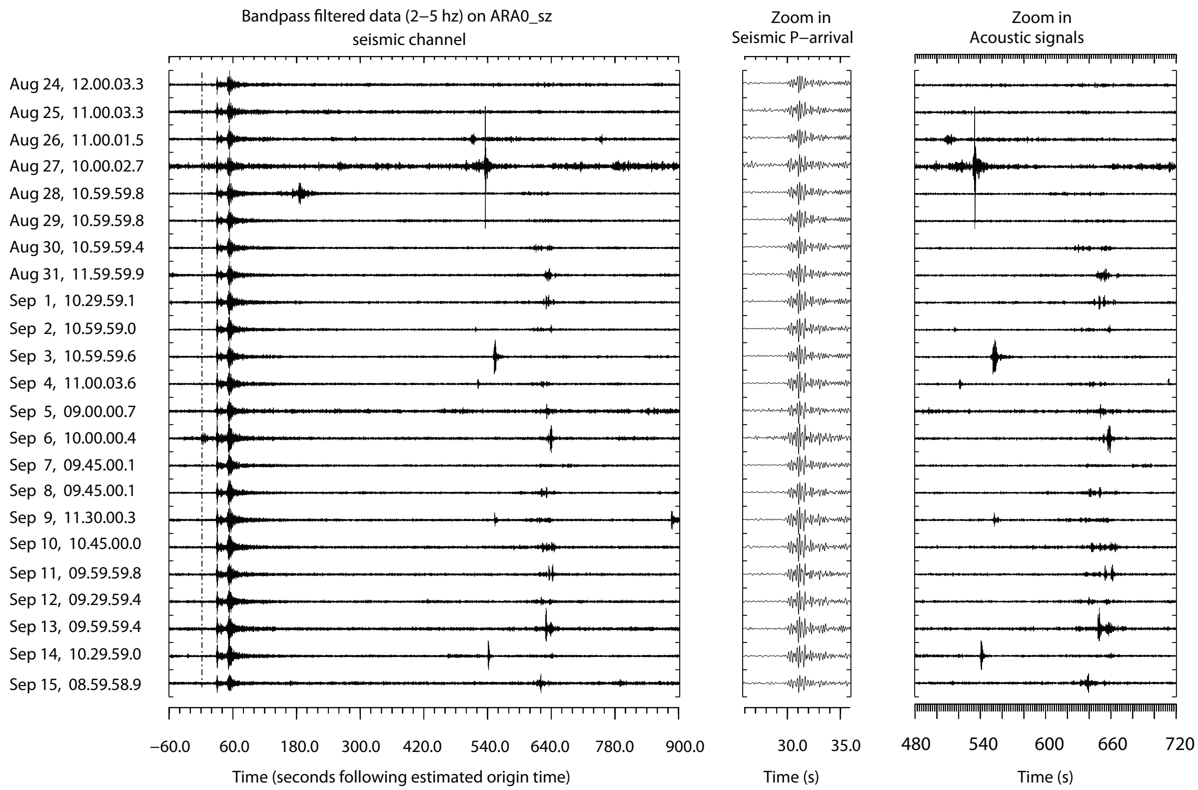

Figure 2. Recordings on the ARCES seismic array (channel ARA0_sz) of 23 events at the Finnish explosion site in August and September 2005. The time provided to the left is the estimated event UTC origin time. All waveforms are aligned to the maximum correlation coefficient and have identical vertical scaling. Signals arriving between 450 and 700 seconds after origin time are demonstrated by array analysis to propagate with sound velocity from an approximate 173 degrees backazimuth. All arrivals between 200 and 450 seconds correspond to unrelated seismic events.

Detection of Small Seismic Events near Novaya Zemlya

The recent upgrade of the Spitsbergen seismic array, which has included installation of five new three-component seismometers as well as an upgrading of the sampling rate from 40 to 80 Hz, has resulted in large improvements in the processing of seismic events at regional distances. As shown by Ringdal et al. (2006), S-phase detection at the array has been significantly improved. Furthermore, the increased sample rate has made possible more detailed studies of high-frequency propagation in the vicinity of the array. Since January 2006 four small seismic events near Novaya Zemlya have been detected (Table 1).

Table 1. Seismic events near Novaya Zemlya detected during 01/2006-06/2007.

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

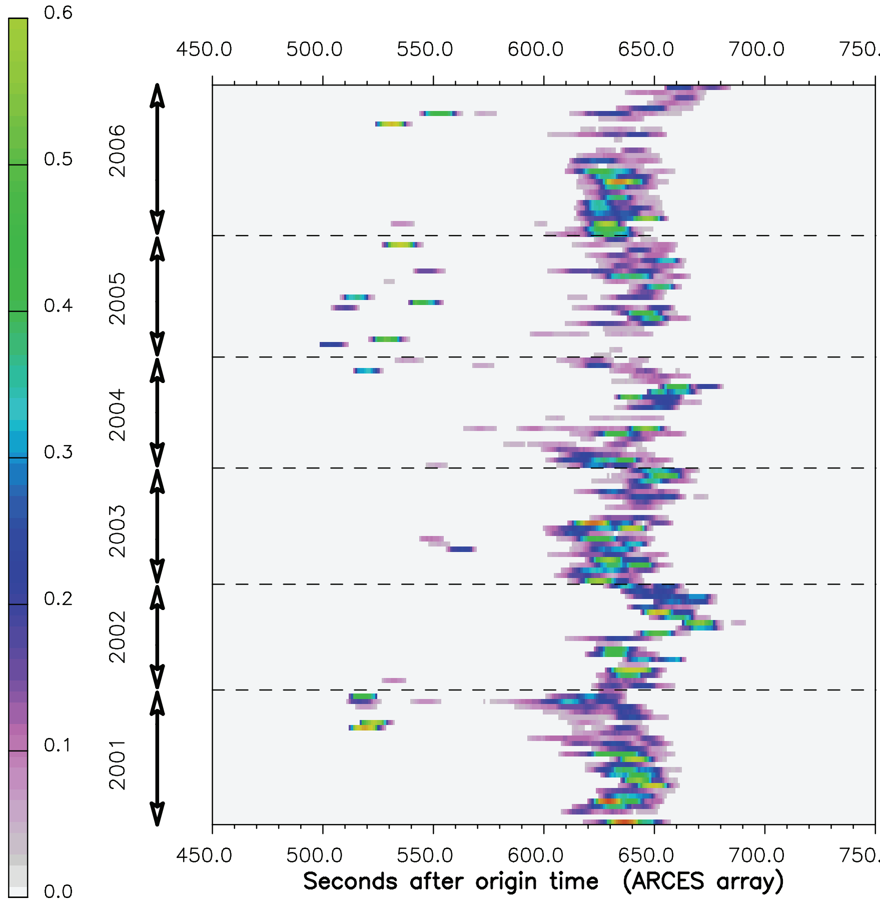

Figure 3. Detection statistics over the full ARCES seismic array within the time windows as indicated following each of the 141 identified explosions in northern Finland between 2001 and 2006. A pixel is drawn every second, at time t, for each event provided that the preferred slowness and backazimuth evaluated over the 10.0 second long window beginning at time t fall within an acceptable range for acoustic waves from the given source. The color indicates the value of the detection statistic.

Figure 4 shows spectrograms of the Spitsbergen B1 seismometer (vertical component) for the Novaya Zemlya event on 5 March 2006. The top part is the original spectrogram using 80 Hz sampling, the bottom part is converted to the response of the previous Spitsbergen system, with 40 Hz sampling. The most noticeable feature of the original spectrogram is the remarkable amount of high-frequency energy, taking into account the large epicentral distance (more than 1000 km). We note that there is significant P-wave energy even above 20 Hz. A similar observation can be made for the other events in Table 1. All of them have high SNR in the filter band 20 to 36 Hz, although the high-frequency energy is not quite as pronounced as for the event shown in Figure 4.

It is interesting to compare this original spectrogram to the bottom spectrogram in Figure 4, which shows how the same event would have been recorded with the previous array configuration (40 Hz sampling rate). It is not surprising that the high frequency information would have been lost for previous events, and we will never know whether the interesting Novaya Zemlya events in the past several years would have shown similar characteristics. It might be considered to upgrade other seismic systems located in areas of good high-frequency propagation and low noise (e.g. the ARCES array) to a higher sampling rate in the future.

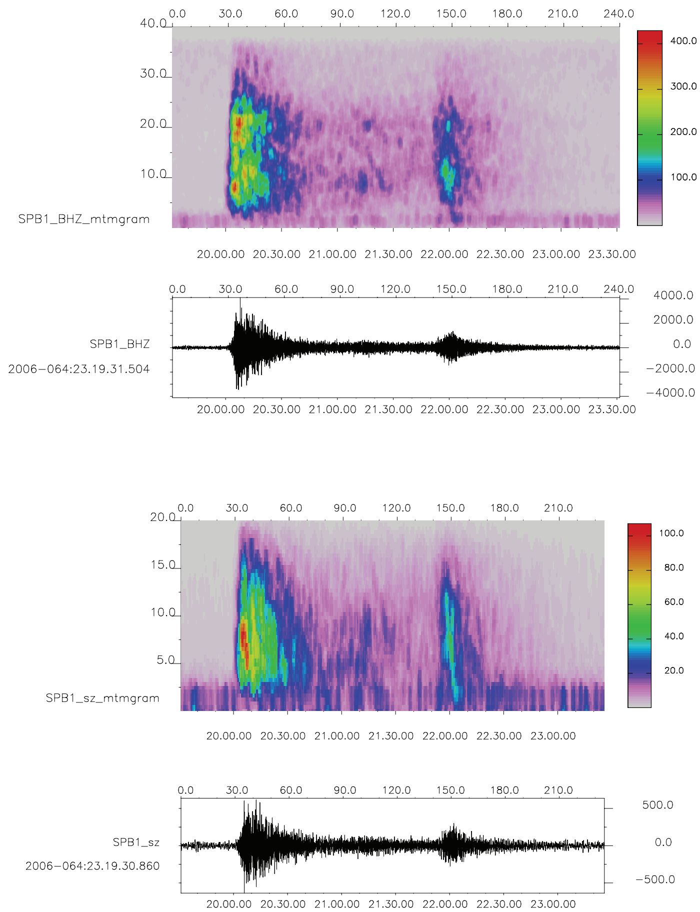

Figure 4. Spectrograms for the Spitsbergen B1 seismometer (vertical component) for the Novaya Zemlya event on 5 March 2006. The top part is the original spectrogram using 80 Hz sampling, the bottom part is converted to the response of the previous Spitsbergen system, with 40 Hz sampling.

Threshold Monitoring of the North Korean Nuclear Test Site

On 9 October 2006 the Democratic Peoples Republic of Korea (DPRK) conducted an underground nuclear explosion at a test site near Kimchaek. The explosion was detected by several seismic stations in the IMS, and was also reported by the United States Geological Survey (USGS). We have analyzed the recorded waveforms at selected seismic stations in order to investigate the capability of the global seismic network to monitor the DPRK test site for possible future explosions. Our analysis is based upon the so-called SSTM approach. Using actual seismic data recorded by a given network, SSTM calculates a continuous threshold trace, which provides, at any instance in time, an upper magnitude bound on any seismic event that could have occurred at the target site at that time.

Let us first emphasize that a large number of seismic stations world-wide recorded this event, and that many of these stations were not analyzed as part of this study. Our main reason for not including such stations is that in a site-specific capability study of the type discussed here, the resulting threshold is dominated by a few stations of exceptionally high detection capability. We have focused our analysis on these exceptional stations. In fact, as will be shown later in this study, the monitoring capability of our selected network (9 stations) for the North Korean test site is essentially defined by the best three stations in that network. Additional stations would be useful for resolving instances of excessive noise at one or more of these three stations, and would also be helpful during interfering earthquakes, but will generally have only a modest contribution to an overall lowering of the monitoring threshold.

The network selected for this study comprises in general those IMS stations which had the best signal-to-noise ratio (SNR) for the 9 October explosion plus the Chinese station at Mudanjiang (MDJ), located about 370 km north of the test site. MDJ data is openly available through the IRIS data management center. We note that data from the Korean Seismic array (KSRS) in South Korea was not operationally available from the IDC for the time period of the test. We are grateful to KIGAM for providing us with the KSRS data for our analysis.

Using the nuclear test for calibrating the signal propagation characteristics at the various stations, we carried out a site-specific tuning of the network stations. The details are described in Kværna et al. (2007). We then applied the methodology described in Kværna and Ringdal (1999) to obtain the threshold processing results. We will show two different types of threshold traces for the North Korea nuclear test site:

- The *detection threshold traces*, which estimate, (at the 90% probability level) the smallest seismic event that can be detected by 3 or more stations in the network (SNR>4).
- The *monitoring threshold traces,* which estimate (at the 90% probability level) the largest seismic event that could possibly have occurred.

In each of the following figures, the *detection threshold traces* are marked in red, the *monitoring threshold traces* are marked in blue.

Figure 5 shows the results for the day of the nuclear test (9 October 2006), using only those stations that were operational at the IDC during that day. We note that the detection threshold is typically around 4.0 or slightly below. At the time of the test, the detection threshold is around 3.75. The monitoring threshold averages about one magnitude unit lower than the detection threshold, i.e. close to magnitude 3.0.

Figure 6 shows a one-day plot of detection traces (red) and monitoring traces (blue) for 15 November 2006, when a large earthquake occurred in the Kurile Islands. By that time, the KSRS array was operational in the IDC, and we also extracted a full day's data from the MDJ station in China. The top panel uses the IMS network (including KSRS); the middle panel shows the effect of adding the MDJ station and the bottom panel shows results from using only the three stations KSRS, MDJ and MJAR. We can make the following observations:

- The operational IMS network (now with KSRS available) shown in red on the top panel of Figure 6 has a detection threshold of about magnitude 3.8, which is almost unchanged from the threshold observed in Figure 5 when KSRS was not available.
- In contrast, the monitoring trace (blue) on the top panel is lower by more than half a magnitude unit compared to the corresponding trace in Figure 5 where KSRS was not available.
- When adding MDJ to the IMS network (middle panel) we obtain a modest decrease (to about 3.5) for the detection trace (red), whereas the monitoring trace (blue) is now as low as 2.0 on the average. (Here we assume that detection processing is carried out for MDJ).

Finally Figure 6 gives an indication of how a regional network, comprising only the best stations, would compare to a global network. This is illustrated in the bottom panel of the figure, which shows that using the network of MJAR, KSRS and MDJ appears to perform almost as well as the "full" network. However, this does not mean that the remaining stations are unimportant. In fact, during interfering events these additional (teleseismic) stations may help lower the thresholds. This is particularly evident for the detection traces (red). Also, if one of these three stations should have abnormally high noise conditions, or (worse) being out of operation, it is important to have additional stations that can contribute to reducing the resulting decline in capabilities.

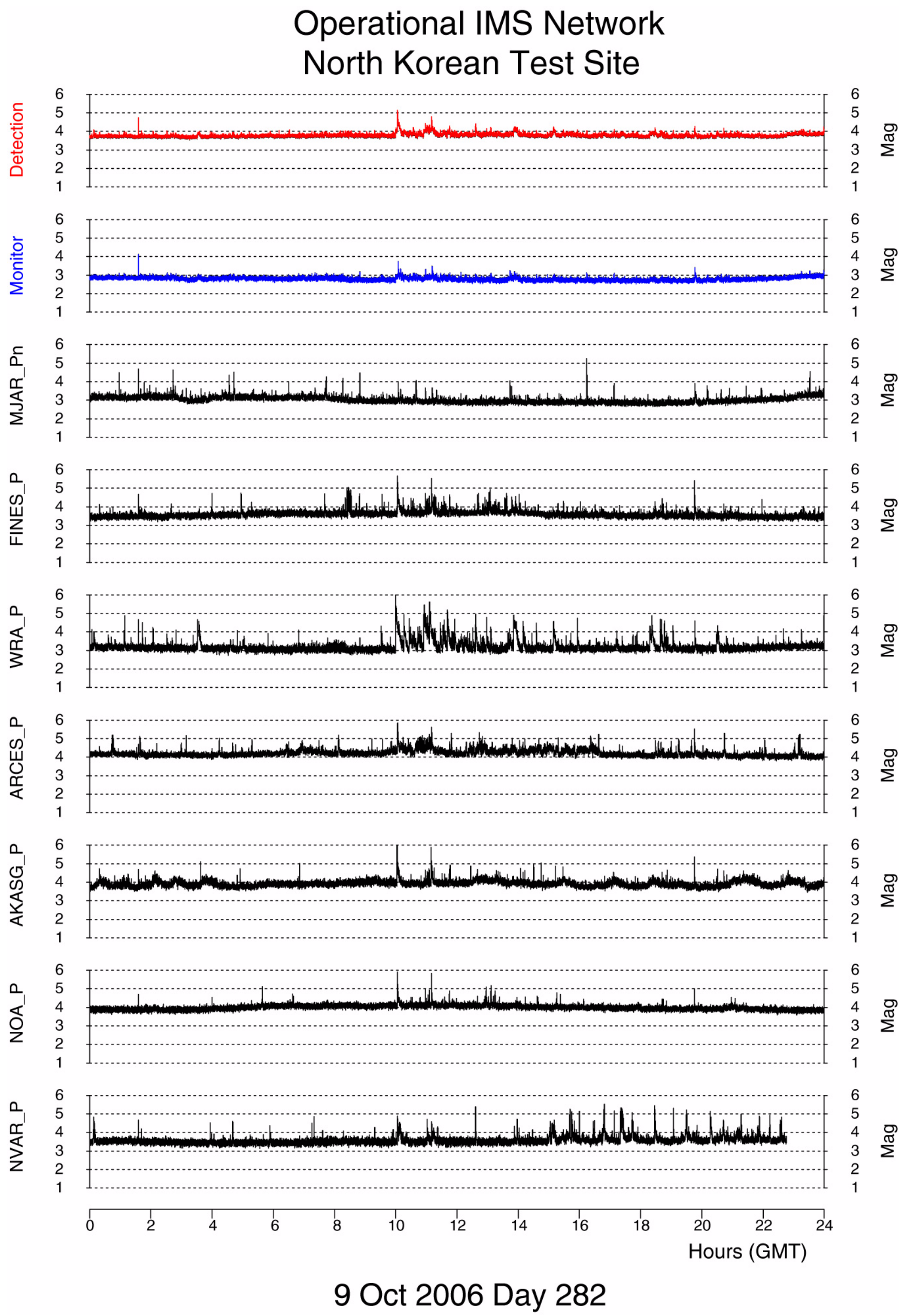

Figure 5. Threshold monitoring results for the day of the nuclear test (9 October 2006). In this figure we have used only those of our selected stations that were operational at the IDC during that day. Detection thresholds (red) are close to magnitude 4.0 or slightly below, except for occasional increases during the nuclear test (at 01.35) and during some interfering events later in the day. The monitoring thresholds (blue) average about magnitude 3.0. The individual station P-thresholds (black) are also shown.

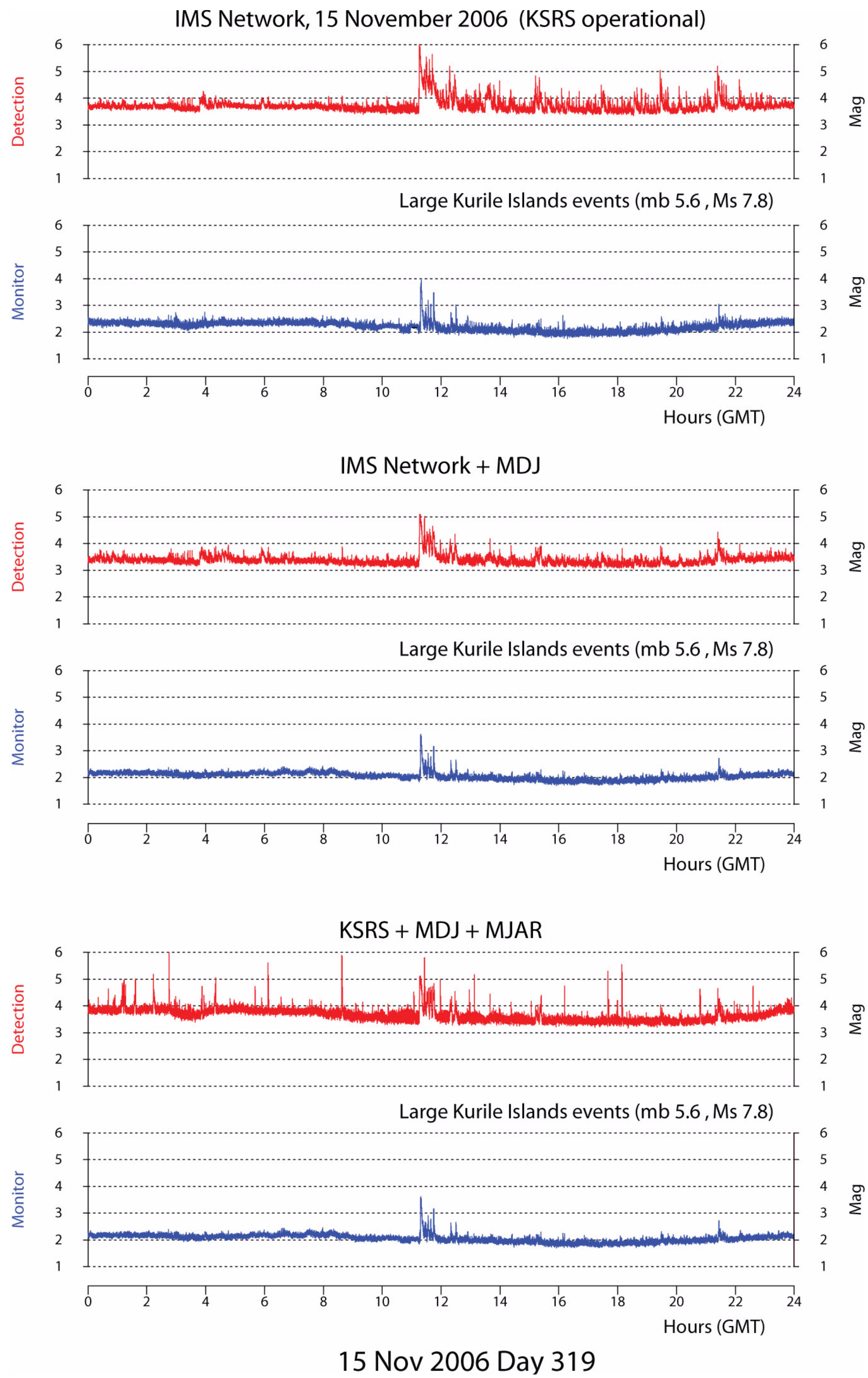

Figure 6. This figure shows a one-day plot of detection traces (red) and monitoring traces (blue) for 15 November 2006. The top panel uses IMS stations (including KSRS); the middle panel shows the effect of adding the MDJ station and the bottom panel shows results from using only KSRS, MDJ and MJAR.

CONCLUSIONS AND RECOMMENDATIONS

The Swedish infrasound array network provides a useful supplement to the seismic and infrasonic arrays in Norway and NW Russia. We have begun exploiting the data from this network, which will allow a much improved joint seismic/infrasonic regional processing at NORSAR. We continue our work towards developing and evaluating a joint seismic/infrasonic bulletin for northern Fennoscandia and adjacent regions. This bulletin would be similar to the automatic seismic bulletin that we are currently providing on the NORSAR Web pages, but it would also contain infrasonic phase associations. Furthermore, we will experimentally attempt to generate an infrasonic event bulletin using only the estimated azimuths and detection times of infrasound phases recorded by stations in the Nordic network.

The data set of more than 100 surface explosions in northern Finland in almost exactly the same place recorded by the ARCES and Apatity arrays has provided an excellent opportunity for studying infrasonic versus seismic phase propagation characteristics. Very similar waveforms and amplitudes are observed for the seismic phase arrivals, indicating a similar explosion yield and source function for each event. In contrast, the infrasonic recordings show great variation between events, both with regard to the number and amplitudes of detected infrasonic phases, as well as their travel times. A variation of several tens of seconds in travel times for corresponding phases for different events is observed at a distance of about 175 km.

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