BASIC RESEARCH ON SEISMIC AND INFRASONIC MONITORING OF THE EUROPEAN ARCTIC

Frode Ringdal, Tormod Kværna, Svein Mykkeltveit, Steven J. Gibbons, and Johannes Schweitzer

NORSAR

Sponsored by Army Space and Missile Defense Command

Contract No. W9113M-05-C-0224

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 two main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe and b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region. In the latter case, we plan on using the northern European seismic array network in combination with infrasonic stations either installed or scheduled for installation in the near future.

During this reporting period, we have implemented basic infrasonic processing software for the Apatity infrasonic array and for the ARCES seismic array. In the case of ARCES, there are currently no infrasonic sensors available (the plans are to install an infrasound array in 2006/2007), but the seismic sensors have proved useful as an initial substitute for detecting and processing infrasonic signals from explosions at local and regional distances. We have developed an algorithm for associating detected infrasonic phases (either by ARCES or Apatity) with regional seismic events detected and located by the on-line Generalized Beamforming (GBF) process which is currently in experimental operation at NORSAR. We searched the GBF bulletin for approximately one full year of data for seismic events at local or near regional epicentral distances to ARCES or the Apatity infrasound array. We found that 944 infrasound signals could be associated with 651 different seismic events from the GBF bulletin. The large majority of these events were confirmed mining explosions, mainly on the Kola Peninsula.

We present results from an analysis of seismic and infrasonic signals from a set of 108 surface explosions in northern Finland, carried out for the purpose of destroying old ammunition. We have used waveform cross-correlation on ARCES seismic recordings to determine very accurate origin times for the explosions. The extremely high correlation coefficients observed for this data set indicate that these explosions are all very closely spaced, probably within an area of some hundreds of meters in diameter. We have used this database to study the stability of slowness estimates for both seismic and infrasonic phases, using ARCES and Apatity array recordings. By analyzing various subconfigurations of the ARCES array, we find that the scatter (standard deviation) in the azimuth estimates for the explosions is about inversely proportional to array aperture. When carrying out a similar analysis of infrasonic data, we find that, in contrast to the case for the seismic P-waves, the azimuth scatter using our f-k estimation process does not decrease when the array aperture increases. Furthermore, the average azimuth remains essentially unbiased both with varying array aperture and with varying filter bands. This is also in contrast to the situation for seismic P-waves, where we have found strong frequency dependent and configuration dependent azimuth anomalies.

The recent upgrade of the Spitsbergen seismic array, which has included installation of five new three-component seismometers, has resulted in a significant improvement of S-phase detection. We demonstrate this improvement by presenting analysis of recent small seismic events on Novaya Zemlya, where three events (of m_b=2.2, 2.3 and 2.7) were detected by the GBF process during March 2006.

OBJECTIVE

The objective of the project is to carry out reseach 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 two main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe and b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region. In the latter case, we plan on using the northern European seismic array network in combination with infrasonic arrays either installed or scheduled for installation in the near future

RESEARCH ACCOMPLISHED

Infrasound Data Processing using Apatity and ARCES Array Data

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). For further details see Baryshnikov (2004).

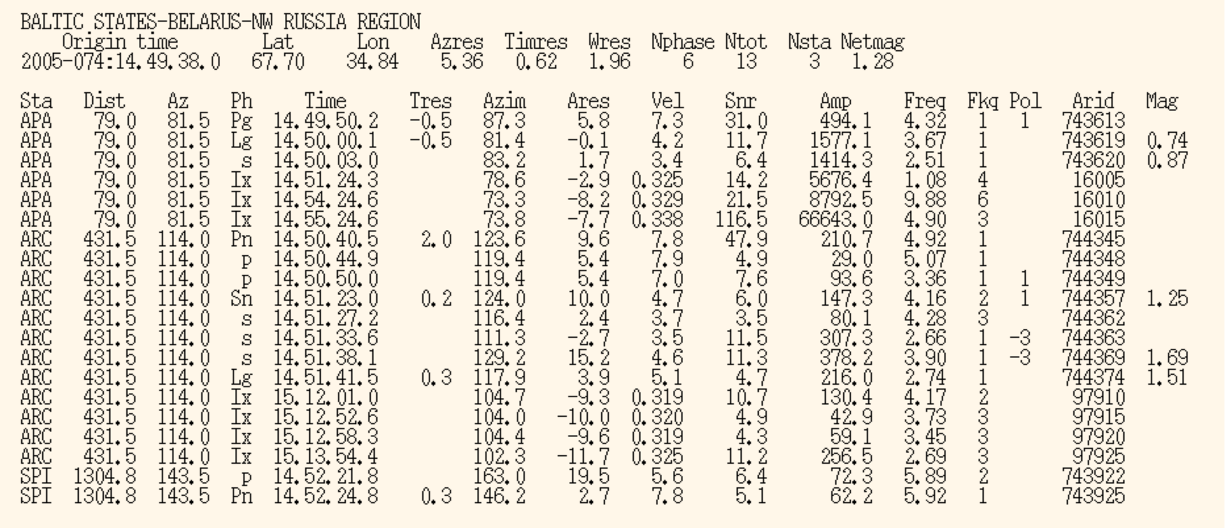
The 25 element ARCES array is a short-period regional seismic array, located in northern Norway. ARCES has no infrasound sensors, but because of special near surface installation conditions, many of its seismic sensors are also sensitive to infrasound signals. The seismic sensors have therefore proved useful as an initial substitute for detecting and processing infrasonic signals from explosions at local and regional distances (see e.g., Ringdal & Schweitzer, 2005). Current plans are to install an infrasound array near the ARCES site in 2006/2007.

In this study, we have developed an initial STA/LTA-based infrasonic processing system for the Apatity infrasound array and for the ARCES seismic array. We have also developed an algorithm for associating detected infrasonic phases (either by ARCES or Apatity) to regional seismic events generated in the on-line Generalized Beamforming process which is currently in experimental operation at NORSAR. Some preliminary results are summarized in the following (for details, see Schweitzer et. al., 2006).

On the average, 23.4 infrasound signals per day were observed with the Apatity infrasound array and 7.6 signals per day with the ARCES array. These numbers of observations result from applying only an initial set of infrasound signal processing rules. We want to determine how many of these infrasonic signals can be associated to sources already known from their seismic signals. To investigate this question in more detail the following test was performed:

The Generalized Beamforming (GBF) algorithm (Ringdal and Kværna, 1989) integrates automatically all observations of local and regional phases from all seismic arrays analyzed at the NORSAR data center in one common bulletin, associates these observations to their common sources, and locates these seismic sources. It can be assumed that this bulletin is quite complete and that it is representative for local and regional seismic events in Fennoscandia and the European Arctic with local magnitudes above 1.5 in on-shore regions and above 2.5 overall. At large distances from the arrays, the threshold could be higher. We searched the GBF bulletin for the first 351 days of the year 2005 (until the 17^{th} of December) for seismic events at local or near regional epicentral distances to ARCES or the Apatity infrasound array. The following association criteria were used to correlate seismic events with presumed, corresponding infrasound signals:

- The epicentral distance of the event must be within 500 km from the array.
- The possible onset time of the infrasound signals was set to be within the time window spanned by group velocities between 0.2 and 0.7 km/s.
- The difference between the event backazimuth and the backazimuth observed for the infrasound signal should not be larger than 20 degrees.



```
BALTIC STATES-BELARUS-NW RUSSIA REGION
    Origin time        Lat      Lon    Azres  Timres  Wres  Nphase Ntot  Nsta Netmag
2005-074:14.49.38.0  67.70    34.84    5.36   0.62   1.96     6    13     3   1.28

Sta   Dist    Az    Ph     Time      Tres   Azim    Ares     Vel     Snr      Amp     Freq  Fkq Pol   Arid    Mag
APA   79.0   81.5   Pg  14.49.50.2   -0.5   87.3     5.8     7.3    31.0     494.1   4.32   1   1   743613
APA   79.0   81.5   Lg  14.50.00.1   -0.5   81.4    -0.1     4.2    11.7    1577.1   3.67   1       743619  0.74
APA   79.0   81.5   s   14.50.03.0          83.2     1.7     3.4     6.4    1414.3   2.51   1       743620  0.87
APA   79.0   81.5   Ix  14.51.24.3          78.6    -2.9   0.325    14.2    5676.4   1.08   4        16005
APA   79.0   81.5   Ix  14.54.24.6          73.3    -8.2   0.329    21.5    8792.5   9.88   6        16010
APA   79.0   81.5   Ix  14.55.24.6          73.8    -7.7   0.338   116.5   66643.0   4.90   3        16015
ARC  431.5  114.0   Pn  14.50.40.5    2.0  123.6     9.6     7.8    47.9     210.7   4.92   1       744345
ARC  431.5  114.0   p   14.50.44.9         119.4     5.4     7.9     4.9      29.0   5.07   1       744348
ARC  431.5  114.0   p   14.50.50.0         119.4     5.4     7.0     7.6      93.6   3.36   1   1   744349
ARC  431.5  114.0   Sn  14.51.23.0    0.2  124.0    10.0     4.7     6.0     147.3   4.16   2   1   744357  1.25
ARC  431.5  114.0   s   14.51.27.2         116.4     2.4     3.7     3.5      80.1   4.28   3       744362
ARC  431.5  114.0   s   14.51.33.6         111.3    -2.7     3.5    11.5     307.3   2.66   1  -3   744363
ARC  431.5  114.0   s   14.51.38.1         129.2    15.2     4.6    11.3     378.2   3.90   1  -3   744369  1.69
ARC  431.5  114.0   Lg  14.51.41.5    0.3  117.9     3.9     5.1     4.7     216.0   2.74   1       744374  1.51
ARC  431.5  114.0   Ix  15.12.01.0         104.7    -9.3   0.319    10.7     130.4   4.17   2        97910
ARC  431.5  114.0   Ix  15.12.52.6         104.0   -10.0   0.320     4.9      42.9   3.73   3        97915
ARC  431.5  114.0   Ix  15.12.58.3         104.4    -9.6   0.319     4.3      59.1   3.45   3        97920
ARC  431.5  114.0   Ix  15.13.54.4         102.3   -11.7   0.325    11.2     256.5   2.69   3        97925
SPI 1304.8  143.5   p   14.52.21.8         163.0    19.5     5.6     6.4      72.3   5.89   2       743922
SPI 1304.8  143.5   Pn  14.52.24.8    0.3  146.2     2.7     7.8     5.1      62.2   5.92   1       743925
```

Figure 1. GBF bulletin of an event in the Khibiny Massif, Kola Peninsula with associated infrasound signals (marked as Ix) observed at the Apatity infrasound array and at ARCES.

Applying these rules, 944 infrasound signals could be associated to 651 different events of the GBF bulletin. For these 651 events we obtained the following statistics:

- 333 events could be associated only with infrasound signals observed at the Apatity infrasound array.
- 250 events could be associated only with infrasound signals observed at the ARCES seismic array.
- 68 events could be associated with infrasound signals at both arrays, the ARCES seismic array and the Apatity infrasound array.

Figure 1 shows the GBF bulletin entry for an event in the Khibiny Massif, Kola Peninsula, for which infrasound signals were observed at both arrays. The source area is known to have numerous large explosions in open pit mines. The associated infrasound signals show quite small backazimuth residuals, the SNR of the observed infrasound signals at both arrays is of the same order as for the seismic signals, and at both arrays, the infrasound waves are arriving in different onset groups within a time window of 1 to 2 minutes.

Figures 2 and 3 show the results of the associations described above. We note that the seismic events with associated infrasound observations are concentrated around known mining areas. We further note that all of these associations are automatic, and have not been reviewed by an analyst. Nevertheless, we are confident that the vast majority of these associations are in fact real. Further work will include detailed review and statistical analysis of results from this association process.

Case Study of Explosions in Northern Finland

Each year between mid-August and mid-September, a series of explosions in the north of Finland is 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 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 a full hour, or half-hour in the middle of the day). A preliminary list of candidate events was obtained by scanning the GBF automatic detection lists for events which appeared to come from the correct region at appropriate times of day.

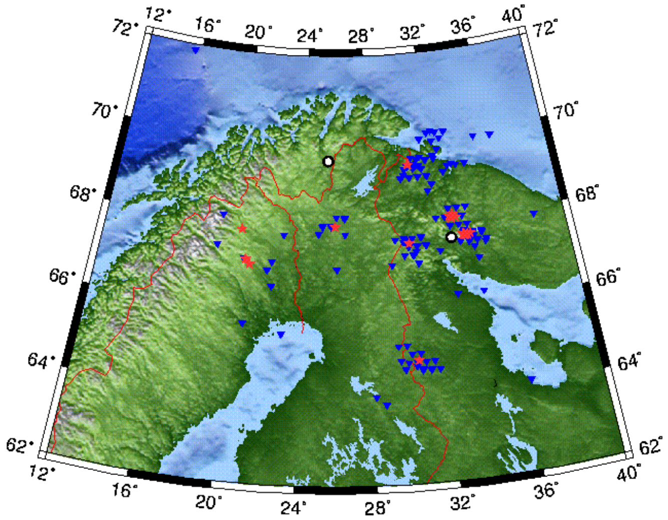


Figure 2. The map shows the 651 automatically located events (GBF) for which either the ARCES seismic array or the Apatity infrasound array observed infrasound signals. The blue triangles show the GBF event locations and the red stars show the location of known sites with explosions either at the Earth's surface or in the atmosphere. Note that the automatic GBF locations usually scatter over a larger area around these source regions. Also note that the GBF locations employ a fixed grid, and that many of the grid points shown on the map have a large number of corrsponding events.

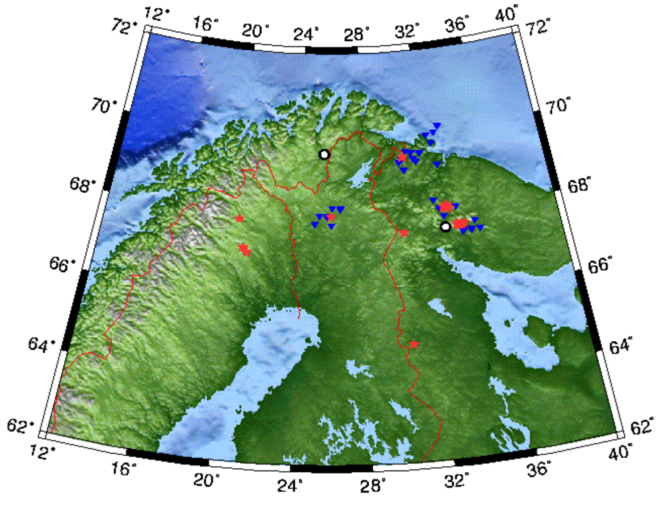


Figure 3. This map is similar to Figure 2, and shows the 68 automatically located events (GBF) for which both the ARCES seismic array and the Apatity infrasound array observed infrasound signals. The blue triangles show the GBF event locations and the red stars show the location of known sites with explosions either at the Earth's surface or in the atmosphere.

Between 2001 and 2005, a total of 108 events were found which appeared to fit the general attributes of explosions from this site; the GBF location estimates for these events are displayed in Figure 4. These fully automatic estimates display a somewhat surprisingly large geographical spread and, assuming that these events are in fact essentially co-located, the origin times will be correspondingly spurious. Before we proceed in attempting to detect and analyse infrasound signals produced from these explosions, we must first confirm that all of our candidate events are in fact from essentially the same location and then obtain the best possible origin time for each event. To this end, we applied a waveform correlation procedure, which confirmed that the explosions were indeed closely spaced, probably within an area of some hundred meters in diameter (for details, see Ringdal and Gibbons, 2006).

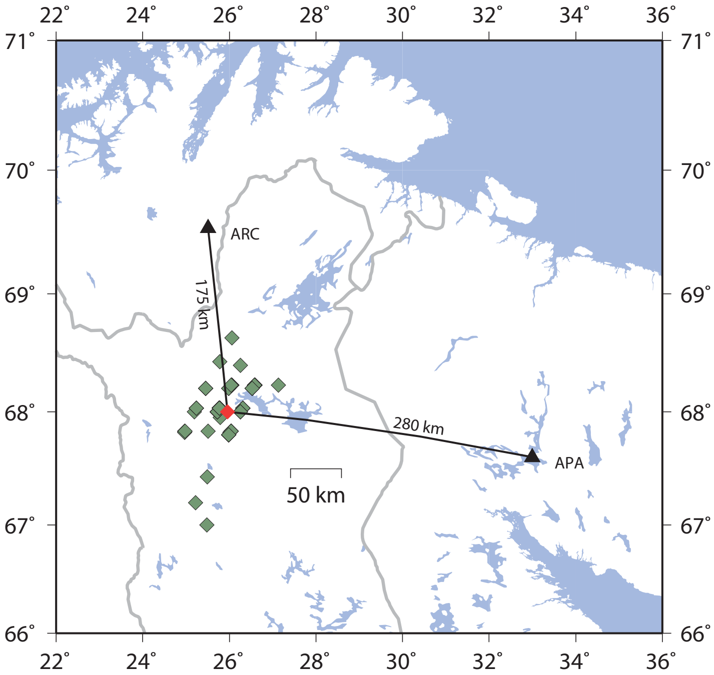


Figure 4. Estimated location of the explosion site in northern Finland (orange diamond) in relation to the seismic arrays ARCES and Apatity together with the GBF fully automatic location estimates for 108 candidate events between August 2001 and September 2005 (green diamonds). The regular pattern of event location estimates is due to the fixed-grid trial epicenter procedure employed by the GBF.

Thus, this data set of more than 100 surface explosions in almost exactly the same place recorded by the ARCES and Apatity arrays provides an excellent opportunity to investigate the stability of slowness estimates, both for the seismic and infrasonic recordings. The paper by Ringdal and Gibbons (2006) presents results on the effects of filter frequency band, array aperture and number of sensors at both the Apatity and ARCES arrays. In this paper we will focus on using various sub-configurations of ARCES to simulate array configurations of various diameters and number of sensors.

Figure 5 shows the ARCES slowness estimates for the event set as a function of various sub-configuration of vertical-component seismometers. These are, in increasing sizes:

- The 4-element A-ring configuration (seismometers A0, A1, A2, A3)
- The 9-element A,B-ring configuration (by adding the seismometers B1-B5)
- The 16-element A,B,C-ring configuration (by adding the seismometers C1-C7)

- The 25-element A,B,C,D-ring configuration (comprising the full ARCES vertical-component array)

As expected, the scatter of the estimates decreases as the array size and number of seismometers increases, and the amount of decrease in the standard deviations is about proportional to the increase in array diameter. We note that the mean azimuth estimates show significant differences among the array configurations, even if we are applying the same bandpass filter (3-5 Hz) throughout.

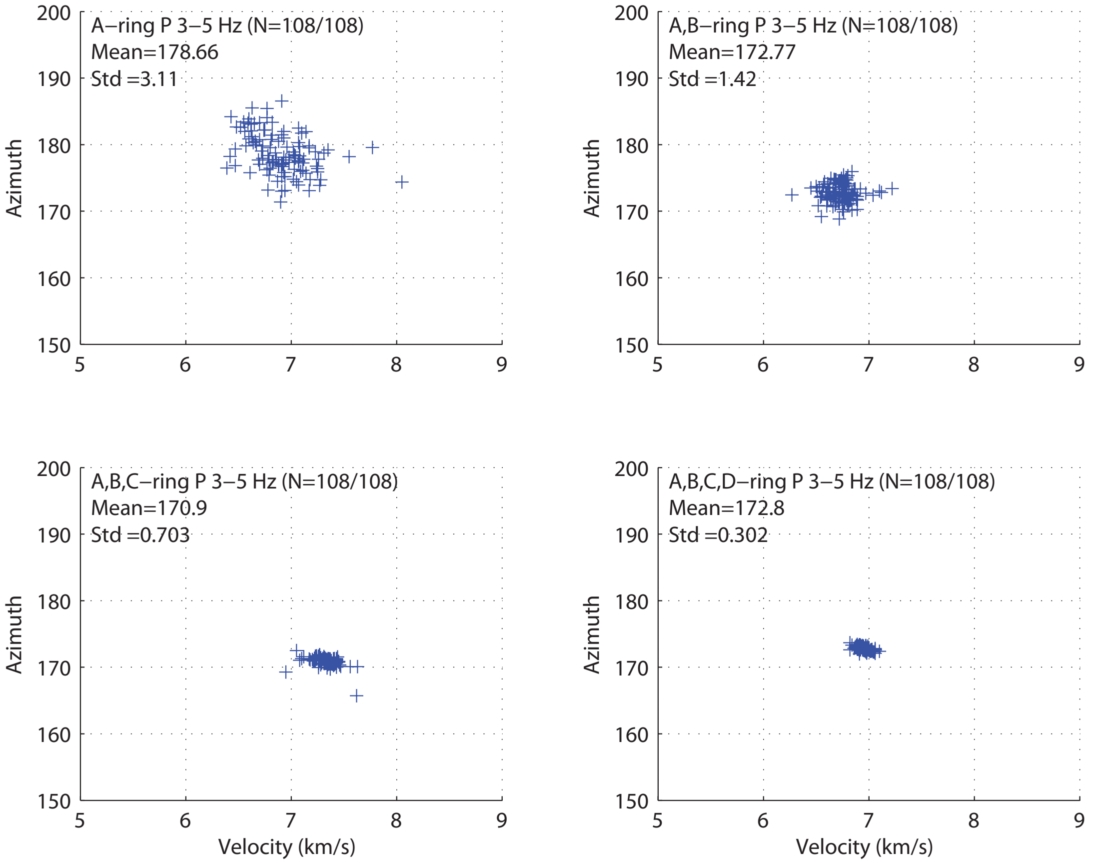


Figure 5. Seismic slowness estimates of the 108 events in the data base. The figure corresponds to estimates for the seismic P-phase (25-35 seconds after the event origin time), in the filter band 3-5 Hz. The four subconfigurations are as described in the text. For each subconfiguration, the mean and standard deviation of the azimuth estimates are indicated.

We carried out a similar study of slowness estimates for infrasonic waves recorded at the ARCES seismic array. In this case, we used throughout a 60 second window beginning 620 seconds after the event origin time. Figure 6 shows the ARCES slowness estimates for the infrasonic phases (named Ix) as a function of the same sub-configuration of vertical-component seismometers as used in our studies of P-waves described above.

In contrast to the P-wave analysis, we were not able to make reliable slowness estimates for the infrasonic phases of all the events. This is mainly due to low infrasonic SNR for a number of the events in the database. This makes a comparison between the performances of different filters and subconfigurations more complicated, and we need to consider both the number of successful estimates and the variance reduction when evaluating the results.

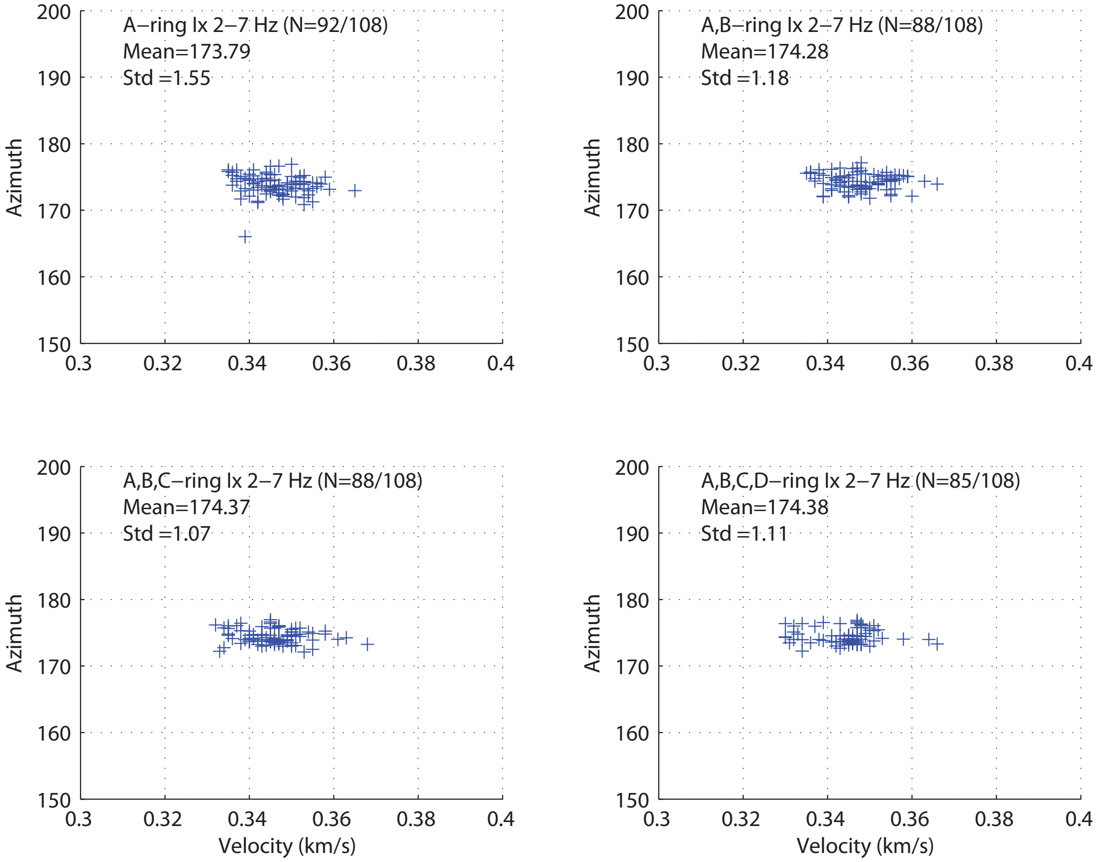


Figure 6. Infrasonic slowness estimates of the 108 events in the data base. The figure corresponds to estimates for the infrasonic phase (620-680 seconds after the event origin time), in the filter band 2-7 Hz. The number of events for which reliable estimates could be made is indicated on each plot. The four subconfigurations are as described in the text. For each subconfiguration, the mean and standard deviation of the azimuth estimates are indicated.

When comparing the infrasonic results to those obtained for seismic P-waves, we see some interesting differences. For example, we see no significant variance reduction as the array aperture and number of sensors increases. Although there appears to be a slight reduction in the standard deviations, the largest number of successful estimates were in fact made using the smallest configuration. Therefore we consider that there is essentially no difference in the stability of the slowness estimates for these four configurations. It is of course possible that other estimation techniques could show such improvements, but it may also be that the variance in estimates is dominated by factors such as varying atmospheric conditions over the 5 years covered by this study. Another important observation is that the average azimuth values are essentially independent of the subconfiguration chosen. This also contrasts to our observations from seismic P-waves.

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 a significant improvement of S-phase detection. We demonstrate this improvement by presenting analysis of recent small seismic events near Novaya Zemlya, where three events (of m_b=2.2, 2.3 and 2.7) were detected by the GBF process during March 2006 (Table 1).

Table 1. Seismic events near Novaya Zemlya detected during March 2006

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

Figure 7 shows spectrograms of the Spitsbergen B1 seismometer (vertical, radial and transverse components) for the Novaya Zemlya event on 5 March 2006. The most noticeable feature is the high SNR of the P-phase for this small (m_b=2.65) event. In fact, the SNR on the array beam is above 100, indicating that even an event at this site more than an order of magnitude smaller could have been detected. This should not, however, be extrapolated to a general statement about detection thresholds for the Spitsbergen array, since the SNR to a large extent depends upon path-specific focussing effects. Nevertheless, the amount of high-frequency energy is remarkable, taking into account the large epicentral distance (more than 1000 km). We note that the vertical and radial components have significant P-wave energy even above 20 Hz. The transverse component shows (not unexpectedly) a small P-wave and a much larger S-wave, indicating that the use of transverse components could be useful in detecting S-phases.

This is further illustrated in Figure 8, which shows selected Spitsbergen array beams for the 5 March 2006 Novaya Zemlya event. The top trace is a beam steered to the epicenter with a P-wave velocity, and using a typical detection filter (3-16 Hz). Note that the S-wave on this trace is fairly small, and would give a fairly marginal detection by the automatic process. The middle trace is an “optimum” beam designed to detect the S-wave. It represents the beams of the transverse components of the six three-component seismometers in the array, filtered in the band 2-4 Hz and steered to the epicenter with an S-phase velocity. Note the greatly improved SNR gain on this trace. The bottom trace shows, for comparison, a P-beam of vertical sensors using the same (2-4 Hz) filter. Clearly, the detection of S-phases could be greatly improved by augmenting the beam deployment with several steered beams , rotated so as to provide transverse components, toward the grid points in the beam deployment system.

CONCLUSIONS AND RECOMMENDATIONS

The initial results from associating infrasonic observations to seismic events are promising. We plan in the future to compare in more detail the infrasound observations with analyst reviewed event locations. This will require a review by an analyst of each infrasound signal, in order to confirm their validity and to identify possible misassociations if appropriate. Furthermore, we will implement ant test additional infrasonic array detectors, such as the PMCC detector (Cansi, 1995).

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 to investigate the stability of slowness estimates for seismic and infrasonic recordings as a function of array geometry, number of sensors and filter frequency band. Future work will focus using this database as well as the ground truth data base of mining explosions in the Kola Peninsula to assess the detectability of infrasonic phases under various atmospheric conditions.

The new Spitsbergen array configuration has shown excellent recordings of high-frequency data from Novaya Zemlya events. The new three-component instrumentation provides a great potential for improving S-phase detection at this array, and an enhanced S-phase detector will be implemented in the near future.

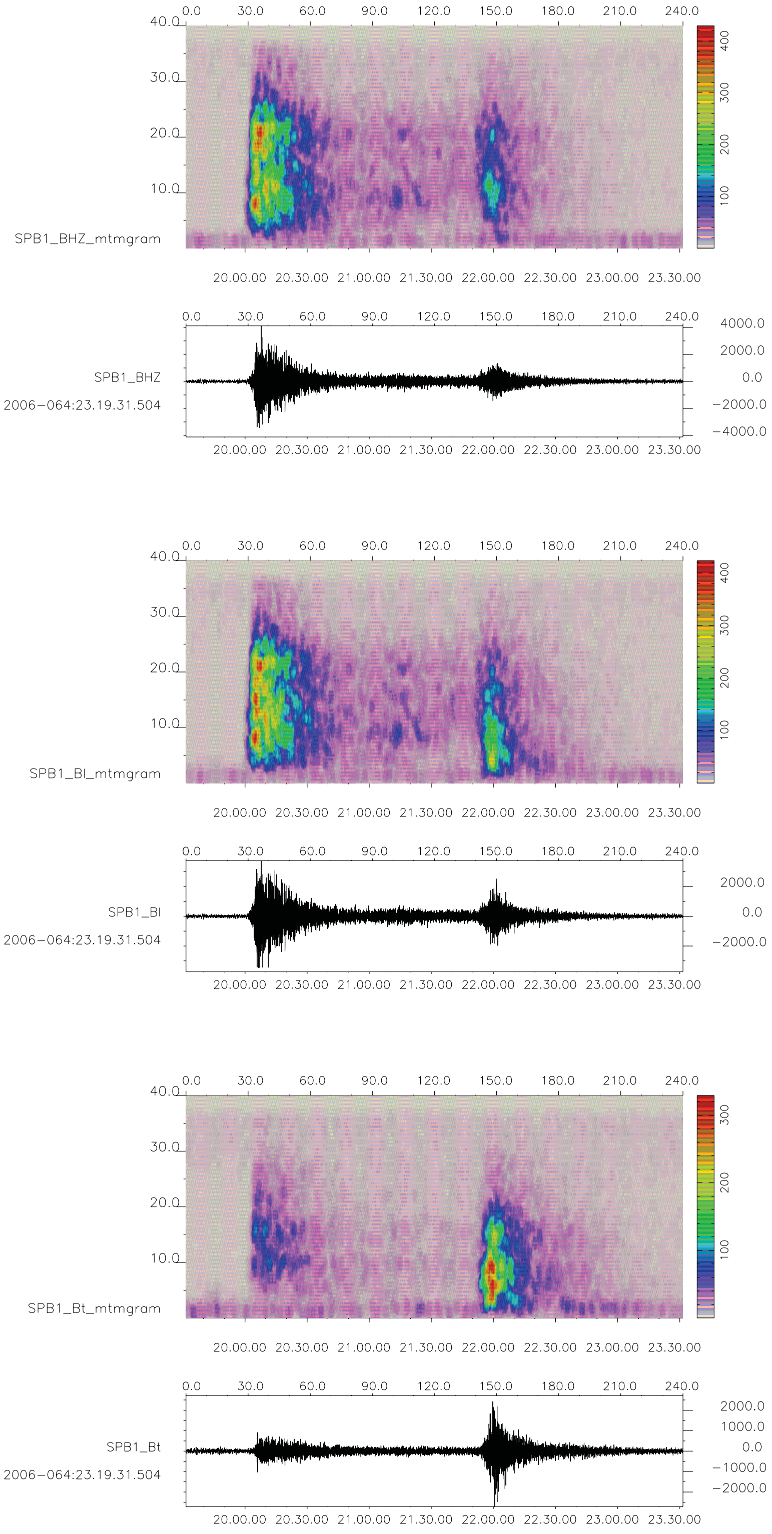


Figure 7. Spectrograms for the Spitsbergen B1 seismometer (vertical, radial and transverse components) for the Novaya Zemlya event on 5 March 2006.

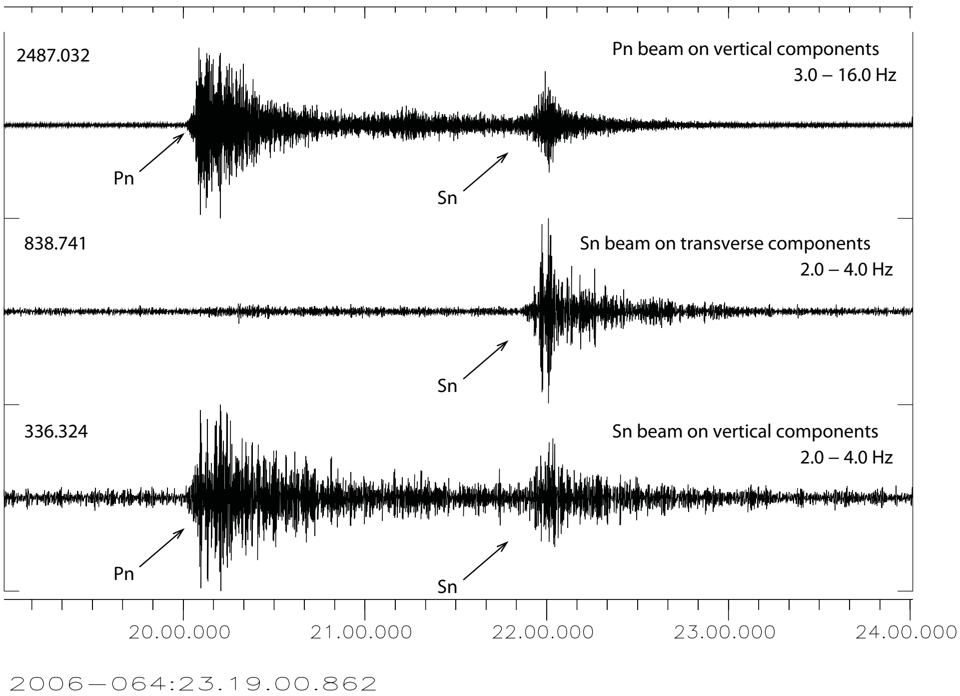


Figure 8. Spitsbergen array waveforms for the 5 March 2006 Novaya Zemlya event. Note the greatly improved SNR gain for the Sn phase shown in middle trace, which represents the beams of the transverse components of the six three-component seismometers in the array.

REFERENCES

Baryshnikov, A.K. (2004). Research of infrasound background characteristics for estimation of threshold sensitivity of infrasound method for nuclear test monitoring. Final Technical Report ISTC 1341-01 (Part 1 of total 2), International Science and Technology Center (ISTC), Moscow, 255 pp.

Cansi, Y. (1995). An automatic seismic event processing for detection and location: The P.M.C.C. method, *Geophys. Res. Lett.* 22: 1021–1024.

Ringdal, F. and S.J. Gibbons (2006). Seismic/Infrasonic Processing: Case study of explosions in north Finland. Semi-annual Technical Summary, 1 July – 31 December 2005, NORSAR Sci. Rep. 1-2006: 54–68.

Ringdal, F., and T. Kværna (1989). A multi-channel processing approach to real time network detection, phase association, and threshold monitoring, *Bull. seism. Soc. Am.* 79: pp. 1927-1940.

Ringdal, F. & J. Schweitzer (2005). Combined seismic/infrasonic processing: a case study of explosions in NW Russia. Semiannual Technical Summary, 1 January – 30 June 2005, NORSAR Sci. Rep. 2-2005: 49–60.

Schweitzer, J., F. Ringdal, T. Kværna, V asming and Yu. Vinogradov (2006). Infrasound data processing using Apatity and ARCES array data. Semiannual Technical Summary, 1 July – 31 December 2005, NORSAR Sci. Rep. 1-2006: 42–53.