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6.4 Combined seismic/infrasonic processing: A case study of explosions in NW Russia

6.4.1 Introduction

This paper contains results from a continued study of combining seismic and infrasonic recordings for detection and characterization of seismic events at local and regional distances. We present results from an analysis of several recent surface explosions in the Kola peninsula near the Norwegian border. At least two of the explosions were reported felt/heard over a large area in the Varanger peninsula, northern Norway, at an epicentral distance of more than 100 km. The explosions were presumably carried out for the purpose of destroying old ammunition, and generated unusually strong infrasonic signals in addition to seismic signals. Not unexpectedly, the infrasonic signals were well recorded on the infrasound array in Apatity, but more interestingly, they were also clearly recorded on the seismic sensors at the ARCES and Apatity arrays (both at about 250 km distance from the source area). We used the recordings to make a location estimate based upon the infrasonic detections (on the seismic sensors) at these two arrays, and found that the locations matched closely the locations obtained through standard seismic data analysis. This indicates an interesting potential for joint two-array infrasonic processing, and this concept will be further developed once the IMS infrasound array near ARCES has been established (expected in 2006).

6.4.2 Data sources

The Apatity seismic array was originally installed in 1992 as a cooperative project between the Kola Regional Seismological Centre (KRSC) and NORSAR. It comprises 9 elements deployed in two concentric rings together with a center element, and has a diameter of 1 km. In 1996, KRSC became engaged in infrasonic research and development. As part of this effort, a small-aperture microbarographic array was installed in conjunction with the seismic array, with data digitized at the array site and transmitted in real time to a processing center in Apatity. A total of three infrasound sensors are installed in the innermost ring of the array, forming a triangle of approximately 500 m diameter. The sensors are differential microbarographs of model K-304-AM. The frequency working range is 0.01-10 Hz, and the sensitivity is 37.5 mV/Pa. The geometry of the combined seismic/infrasound array is shown in Fig. 6.4.1. A brief description of the Apatity infrasound system and initial results from the infrasound array operation has been presented by Vinogradov and Ringdal (2003).

The ARCES seismic array (IMS station PS28) is located in northern Norway (see Fig. 6.4.2), and will be supplemented by an infrasonic array (IS37) in the near future. Joint processing of seismic data from ARCES and Apatity has been carried out for a number of years, and has resulted in improved understanding of many topics related to two-array detection, location and characterization of small seismic events recorded at regional distances. The explosions analyzed in this paper provide the first opportunity to carry out joint two-array processing of infrasonic data, since these explosions generated unusually strong sound waves, and these sound waves were clearly recorded at the seismic sensors of the ARCES array.

The explosions forming the database for this study are listed in Table 6.4.1, which contains both the event locations from the NORSAR reviewed regional seismic bulletin and locations estimated from joint two-array infrasonic processing as described later in this paper.

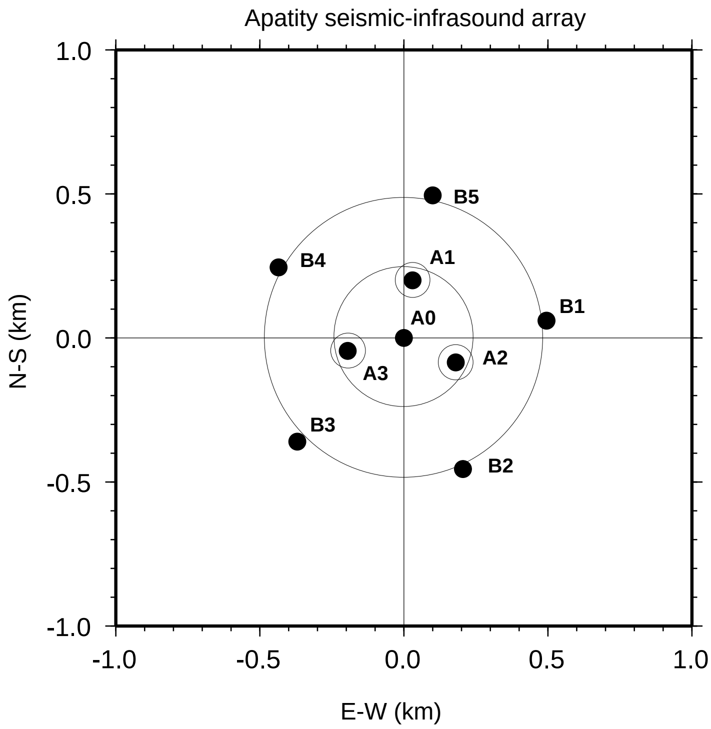

Fig. 6.4.1. *Configuration of the Apatity seismic-infrasound array. Seismometers are shown as filled circles, with the location of the three infrasonic sensors (A1, A2 and A3) marked as small circles. The two concentric circles have diameters of 500 m and 1000 m respectively.*

Table 6.4.1. List of analyzed events.

	NORSAR reviewed bulletin					This paper	
No	Date	Origin time	ML	Lat. N	Lon. E	Lat. N	Lon. E
1	2005/03/10	19.03.38.9	1.44	69.47	31.65	69.71	32.11
2	2005/03/10	19.03.38.9	1.11	69.46	31.56	69.71	32.07
3	2005/03/15	16.17.24.8	1.78	69.42	31.56	69.60	31.79
4	2005/03/15	16.44.00.6	1.21	69.52	31.75	69.62	31.79
5	2005/03/17	14.48.24.2	1.65	69.55	31.86	69.60	31.73
6	2005/03/17	15.16.09.4	1.14	69.47	31.74	69.63	31.64

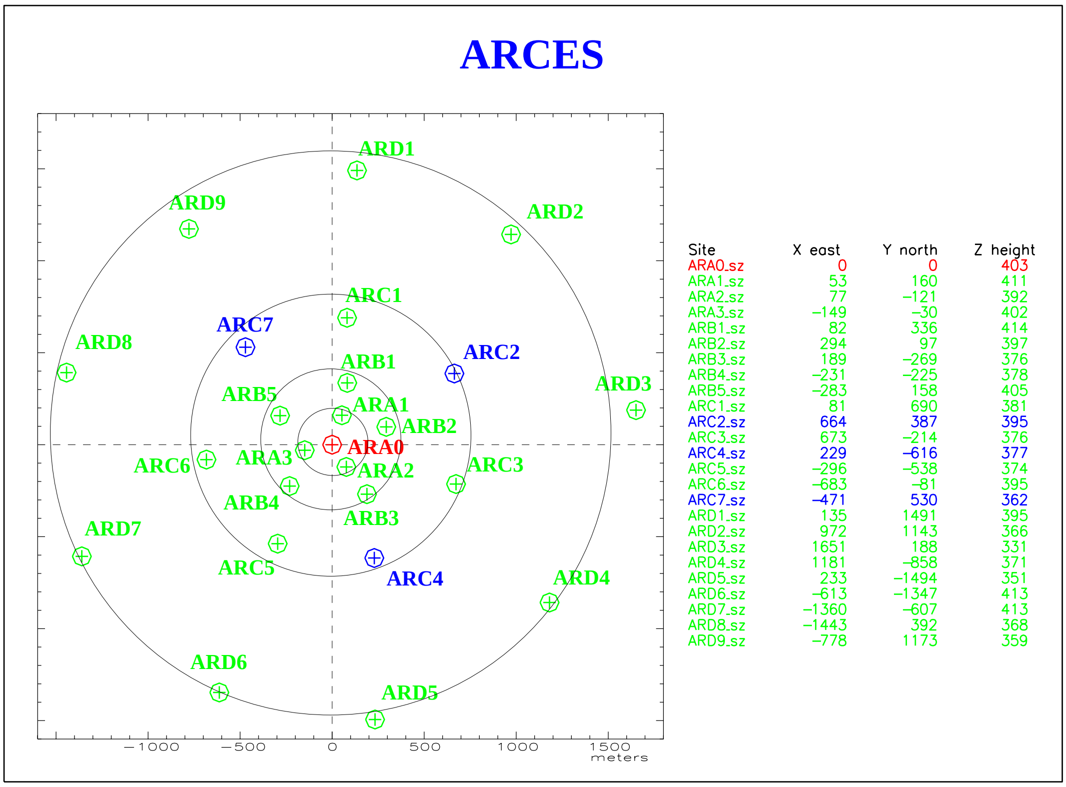

Fig. 6.4.2. *ARCES array configuration. The four circles correspond to the A, B, C and D-rings as discussed in the text.*

6.4.3 Data analysis

Detection processing

The regional processing system at the NORSAR Data Center (Ringdal and Kværna, 2004) is currently focused on seismic phases, and comprises STA/LTA detectors applied in parallel to a number of array beams in various filter bands. Although the beam set is not tuned to sound velocities, sound waves (if they are recorded with sufficient signal-to-noise ratio) will still be detected by the “incoherent” beams in the beam set.

In the present case, it turns out that the on-line detector for the ARCES array did in fact detect the sound waves from the six events. As an example, Fig. 6.4.3 shows selected individual ARCES channels for Event 5 in the data base, and we can see that the SNR of the sound waves is at least as good as for the seismic waves. Fig. 6.4.4 and 6.4.5 show the frequency-wavenumber solutions for the P-wave and the sound wave. The phase velocities are very different, 7.25 km/s for the P-wave, and 0.34 km/s for the sound wave. Thus, there is no problem in identifying the sound waves using apparent phase velocity as a criterion.

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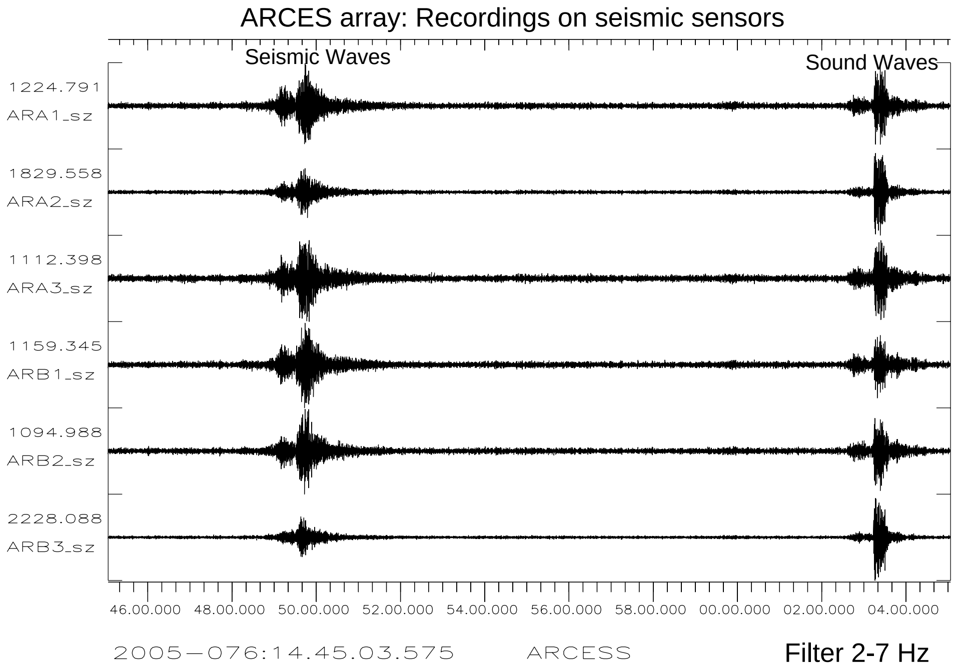

Fig. 6.4.3. *ARCES waveforms for one of the explosions discussed in the text (Event 5 in Table 6.4.1). Note the clear recording of both the seismic P and S waves and the sound waves, which appear about 14 minutes later.*

Table 6.4.2. Results from estimating the azimuth of the sound waves by f-k analysis.

Event no.	Configuration (diameter in parentheses)				
	ARCES 1 (3 km)	ARCES 2 (1.5 km)	ARCES 3 (0.7 km)	ARCES 4 (0.3 km)	Apatity (0.4 km)
1	82.91	82.45	81.92	81.59	351.67
2	83.24	82.55	82.40	82.31	351.31
3	86.58	85.34	84.76	84.27	348.14
4	85.78	84.75	84.29	83.64	348.31
5	85.79	85.47	84.69	84.25	347.48
6	85.69	84.58	83.52	82.70	346.90

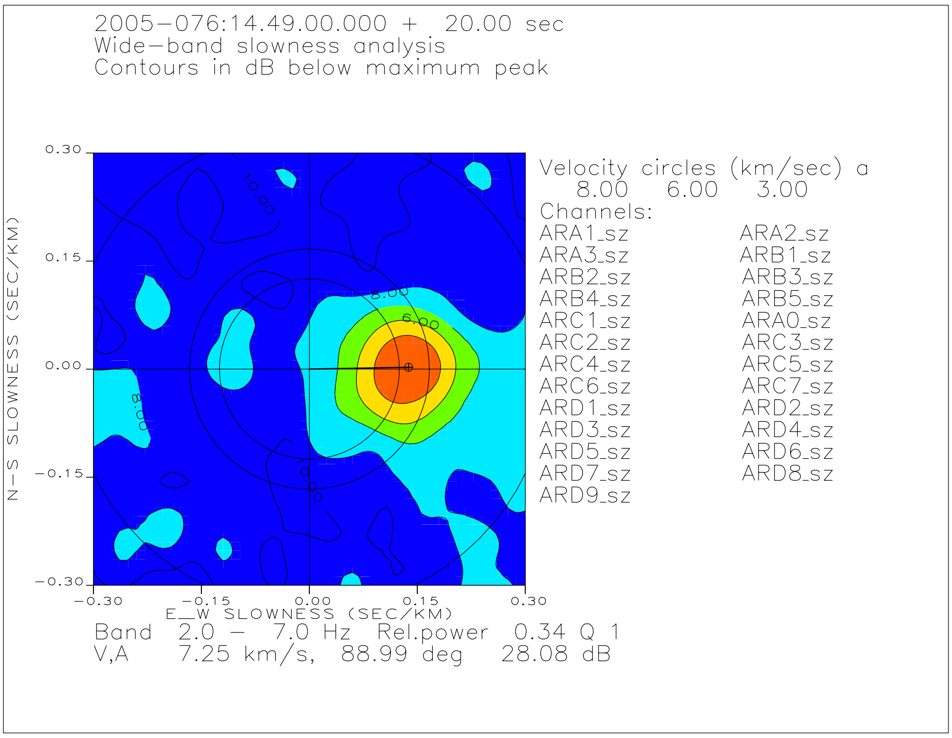

Fig. 6.4.4. *ARCES f-k plot of the P-phase for Event 5. Phase velocity is 7.25 km/s and the azimuth is 88.99 degrees.*

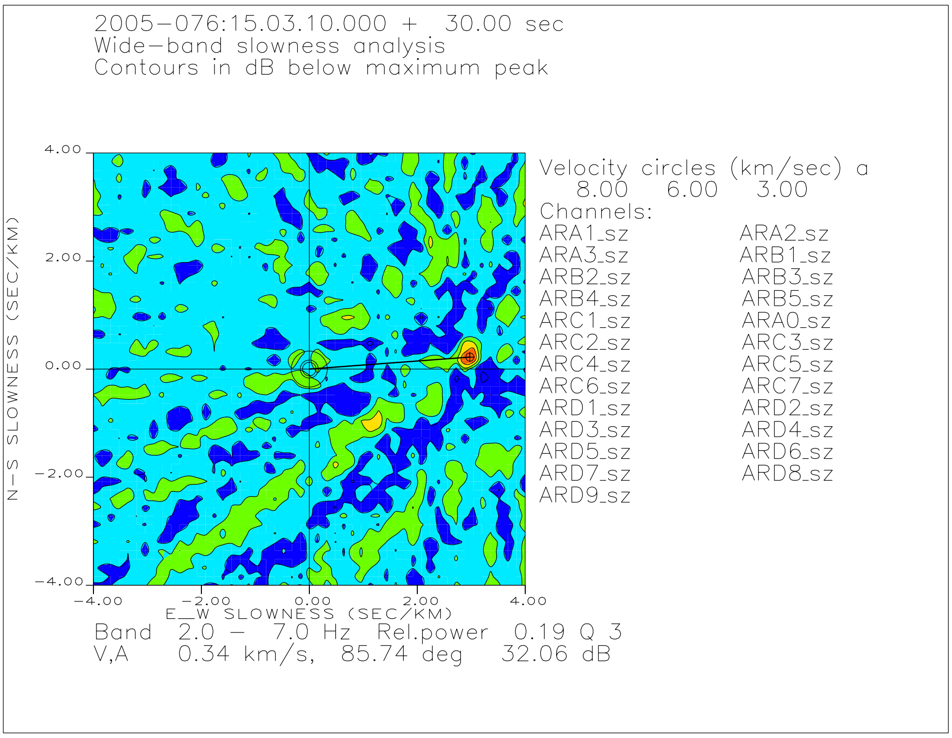

Fig. 6.4.5. *ARCES f-k plot of the sound phase for Event 5. The phase velocity is 0.34 km/s, which corresponds to sound velocity. The azimuth is 85.74 degrees.*

We also note that the azimuths of the P-phase and the sound phase are quite similar, and it would therefore be feasible to associate these phases automatically to the same event. This is currently not done in the NORSAR processing system, but is planned for implementation once the infrasonic array near ARCES is established. We will discuss the azimuth estimation of the infrasonic waves later in this paper.

Fig. 6.4.6 shows Apatity array recordings of the same event (Event 4). In this figure, we display three seismic sensors along with the three infrasonic sensors. As was the case for ARCES, the seismic sensors show both the seismic phases and the sound phase quite clearly. The infrasonic sensors show only the sound phase, and the SNR for this phase is (not unexpectedly) considerable higher than for the same phase on the seismic sensors.

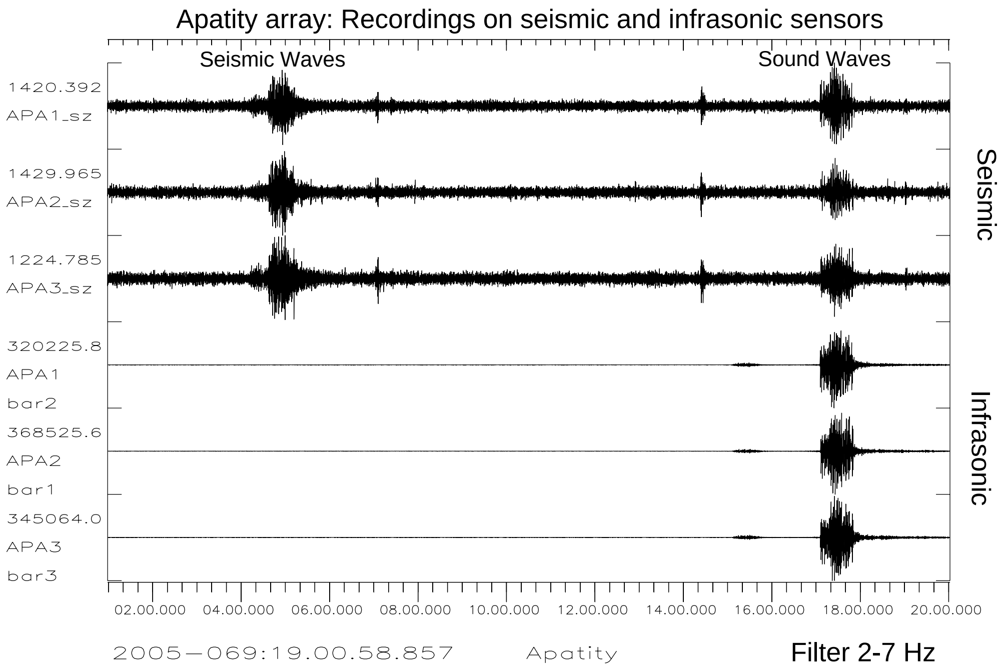

Fig. 6.4.6. *Recordings by three Apatity seismic sensors (top) and the three infrasonic sensors (bottom) for Event 5.*

Signal characteristics

When comparing the waveforms of the six events, we can make some interesting observations. In Fig. 6.4.7, we show the seismic phases for each event as recorded by the ARCES B3 sensor. These seismic recordings are quite similar, although the SNR shows some variation.

This observation can be contrasted with Figure 6.4.8 (for Apatity) and 6.4.9 (for ARCES), which show the infrasonic phase for the six events. For Apatity, we have selected infrasound channel Bar 2, and for ARCES the seismic channel B3. The channels are lined up according to the origin time of each event. There are several striking features: First, the apparent "arrival times" are quite different (by up to 20 seconds). This may not be very significant, since we do not know the exact locations of the explosions, and a time difference in sound wave travel time of 20 seconds corresponds to only 6-7 km in epicentral distance difference. In addition, sound velocities in the atmosphere are quite variable due to changes in temperature, wind direction and air pressure. A second striking feature in the two figures is the considerable differences in signal shapes and duration. There were two explosions for each of the days 10 March, 15 March and 17 March. In each case, the first explosion is somewhat stronger, and has a long, drawn-out infrasonic signal with no clearly identifiable multiple phases. In contrast, the second explosion for each day shows two clearly distinct infrasonic phase arrivals on Apatity recordings, each with short duration. The ARCES recordings for these events are also of short duration, and show multiple phases for one of the events (Event 4).

Fig. 6.4.10 and 6.4.11 show the three infrasound sensors of the Apatity array for the two explosions of 17 March (Event 5 and Event 6). We note that the signals are extremely coherent across the array for each event. This is not surprising, and is a common feature for observed infrasound signals at this array. Furthermore, in view of the slow phase velocity, it is not surprising that the time delay of phase arrivals across the three sensors is large enough to be noticed. For this reason, f-k analysis can be expected to produce reliable velocity/azimuth estimates, even for a small array (less than 500 m in diameter).

It is interesting to note that the pairs of events for each day were separated in time by only approximately one half hour. Therefore, the atmospheric conditions would have been essentially the same for each pair. The seismic recordings displayed in Fig. 6.4.7 indicate no evidence of any significant difference in source function for the events, except that the first explosion of each pair is somewhat larger than the second explosion. We have at present no good explanation for the observed differences in the infrasonic waveforms.

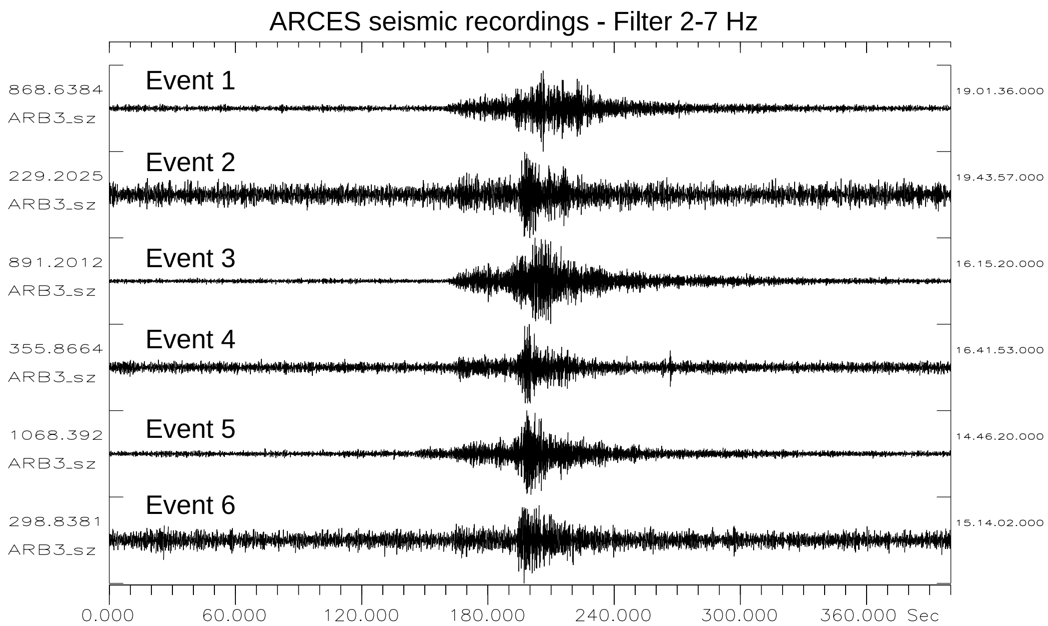

Fig. 6.4.7. *ARCES seismic recordings of the six events in the database.*

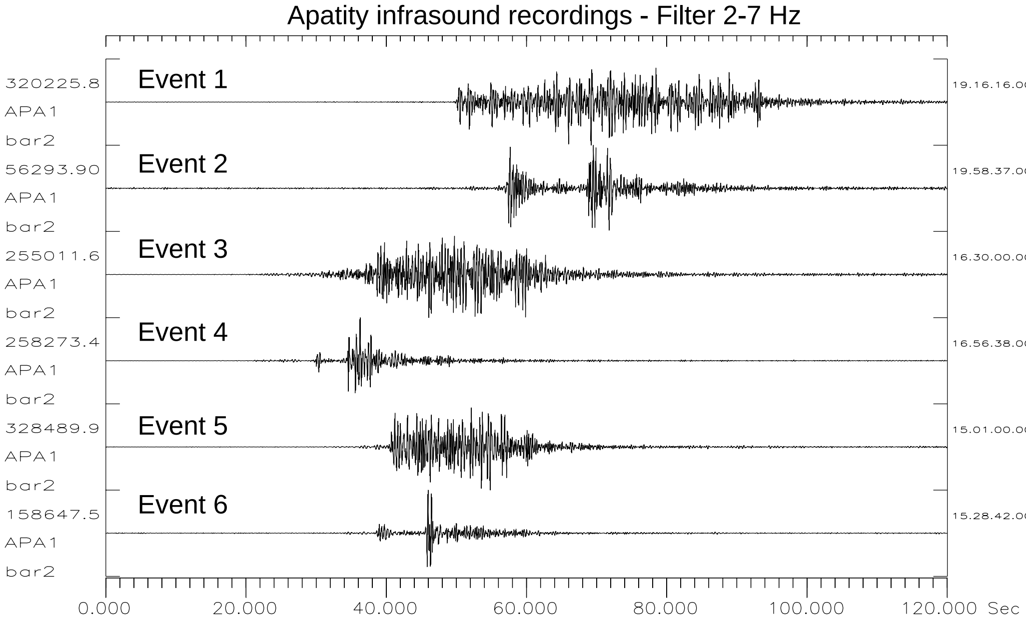

Fig. 6.4.8. Apatity infrasound recordings of the six events in the database.

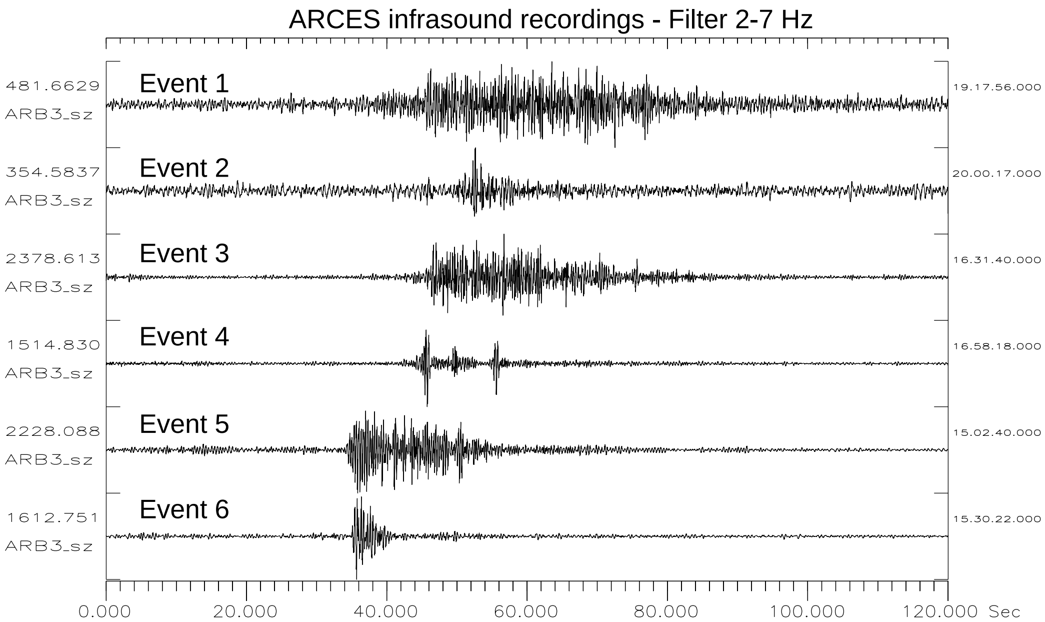

Fig. 6.4.9. ARCES recordings on seismometer B3 of the infrasound phases for the six events in the database.

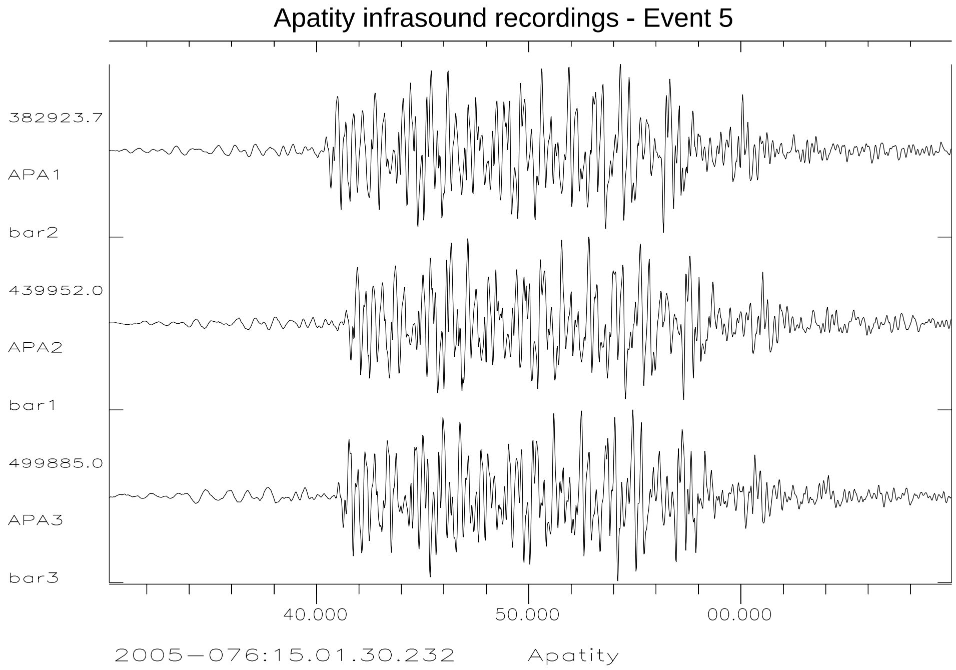

Fig. 6.4.10. *Apatity infrasound recordings of Event 5 in the database. The data are filtered in the frequency band 2-7 Hz.*

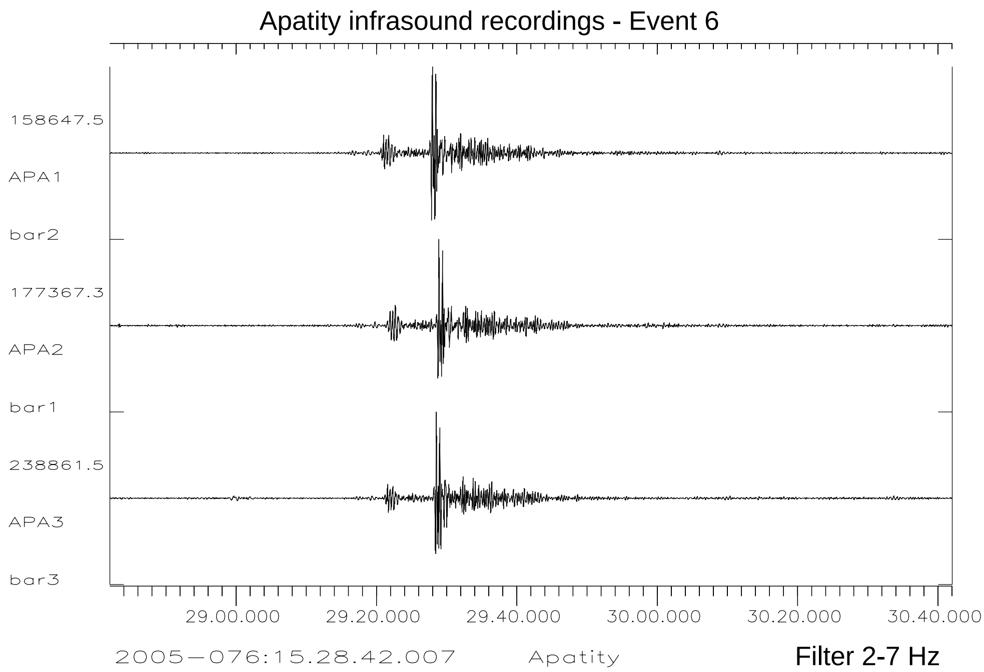

Fig. 6.4.11. *Apatity infrasound recordings of Event 6 in the database. The data are filtered in the frequency band 2-7 Hz.*

Location estimation

Although we do not know the exact coordinates of the explosion site, we have used this opportunity to investigate the stability of azimuth estimates of sound waves, using various subconfigurations of the ARCES array. These subconfigurations were:

1. The full ARCES array (A0, A,B,C and D-ring). 25 sensors. Diameter 3 km.
2. A0, A,B, and C-ring. 16 sensors. Diameter 1.5 km
3. A0, A,B ring. 9 sensors. Diameter 0.7 km.
4. A0, A-ring. 4 sensors. Diameter 0.3 km.

Table 6.4.2 shows the results of this analysis, as well as the corresponding results for the array of infrasound sensors at the Apatity array (3 sensors, diameter 0.4 km).

From the table, we see that the estimates were very stable, even for the smallest subset of the array (configuration 4, with a diameter of only 300 m). The estimates ranged from about 82 to about 86 degrees, with no significant change in the stability with the size of the selected array subset. For the 3-element APATITY infrasound array, (diameter 400 m), the estimates were likewise stable, ranging from 346 to 351 degrees.

We used the estimated azimuths (from the infrasonic waves) for the two arrays to locate the six events, using the HYPOSAT program (Schweitzer, 2001). For the Apatity array, we used the three infrasonic sensors, and for the ARCES array we used subconfiguration 2 above, which has a diameter close to that of the planned IS37 infrasound array. Fig. 6.4.12 shows the location results compared to those obtained using standard seismic analysis. As can be seen from the figure, the locations match quite closely. At this stage, we have not attempted to combine the seismic and infrasonic information to provide joint location estimates, since it is not clear how the individual observations should be weighted in order to obtain the best solution.

6.4.4 Conclusions and future plans

We have obtained some interesting results when comparing location estimates based on seismic and infrasonic recordings of surface explosions at local and regional distances. Using ARCES and Apatity array recordings of a set of explosions near the Norwegian-Russian border, we have found that the infrasonic locations (using azimuths only) match closely the locations obtained through standard seismic data analysis. This indicates an interesting potential for joint two-array infrasonic processing, and we recommend that this concept be further developed once the IMS infrasound array near ARCES has been established (expected in 2006).

An important task which we have not yet addressed is the development of an infrasonic real time signal detector. Several such detectors are available in various institutions, and we intend to build on this experience when designing the detector. Among the topics to be considered are which detection algorithm to select (e.g. Fisher detector, correlation detector, STA/LTA). We also need to find one or more filter bands for optimum processing, and define time windows for processing and f-k analysis.

The detector output will be similar to what is produced today for the seismic detectors. A phase association procedure will be implemented, attempting to associate the detected phases to seismic events detected by the regional network. The Generalized Beamforming (GBF) algorithm

(Ringdal and Kværna, 1989) will be used in the phase association procedure. We expect to have a number of unassociated detections, (i.e. detections by infrasound data only), and it will be a challenging task to combine these detections so as to define new “infrasonic” events.

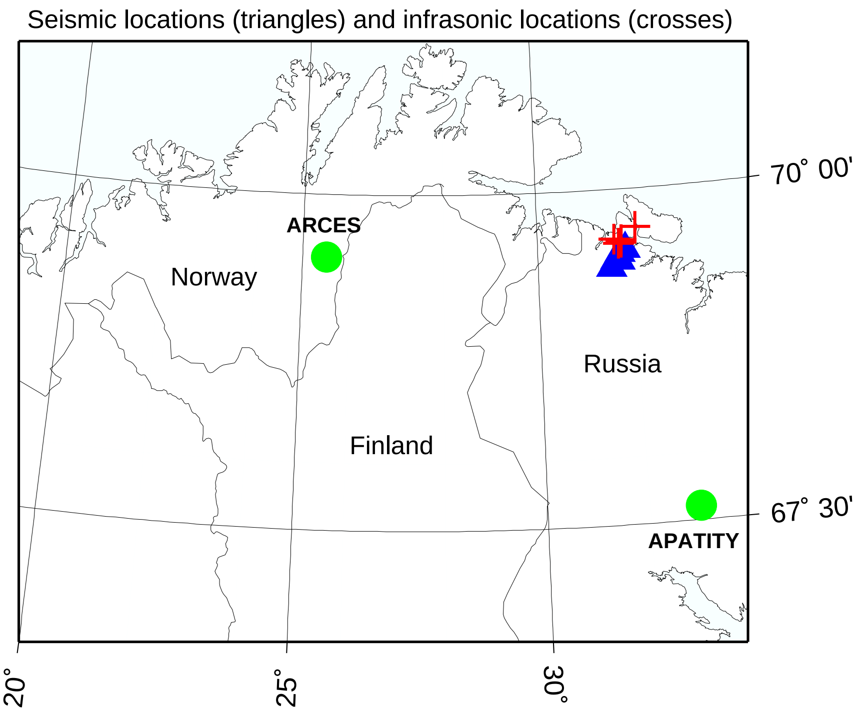

Fig. 6.4.12. *Map showing the location of the Apatity and ARCES arrays (marked as green), together with results from locating the six explosions described in the text. The triangles are locations based on standard interactive analysis of the seismic data from the ARCES and APATITY arrays, whereas the crosses are locations obtained using only the estimated azimuths of the sound waves recorded by the two arrays.*

Finally, it will be important to establish an interactive analysis tool and integrate the analysis with that currently done for the seismic data. Our preliminary aim is to augment the existing NORSAR regional seismic bulletin (analyst reviewed) with infrasound observations.

After the projected infrasonic array (IS37) in Karasjok, northern Norway, is installed, we plan to carry out joint processing of data from these two arrays. Further perspectives include cooperation with colleagues in Sweden, Netherlands and Germany for more extensive joint processing.

Acknowledgement

The Kola Regional Seismological Centre operates the Apatity seismic/infrasound array, and provided seismic and infrasonic waveforms from the array for this study.

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