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6.3 Infrasound data processing using Apatity and ARCES array data

6.3.1 Introduction

In this study, we have focused on developing 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), 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 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. The current status of these developments is summarized in the following.

6.3.2 Infrasound data processing using Apatity array data

The Apatity infrasound array is a three-element array co-located with the nine-element Apatity short-period regional seismic array, installed in 1992 on the Kola Peninsula, Russia by the Kola Regional Seismological Centre (KRSC). The three infrasound sensors (MB1, MB2, and MB3) are located close to the seismic array sites A1, A2, and A3 (Fig. 6.3.1).

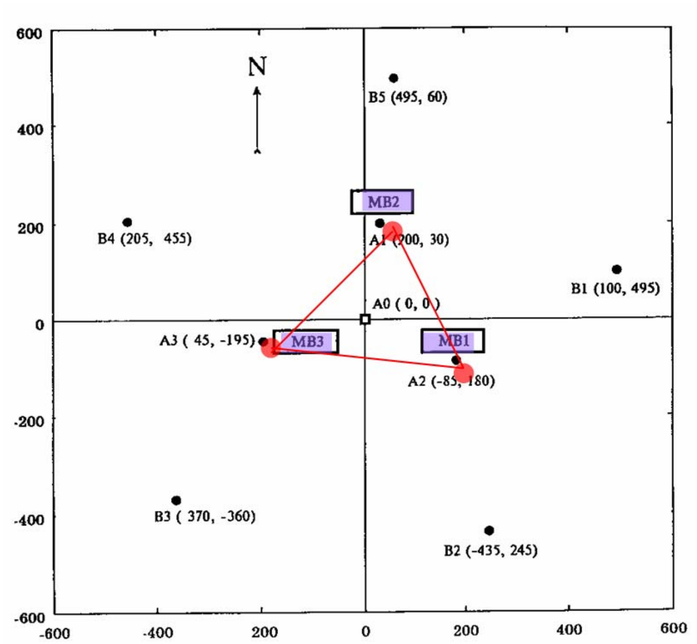

Fig. 6.3.1. Map of the Apatity seismic array with the location of the three infrasound sensors MB1, MB2, and MB3 (Baryshnikov, 2004). The axis coordinates are in meters relative to the array center.

The infrasound array was installed in June 2002, and since then, its continuous data stream has been included in the data stream from the seismic sensors transmitted to KRSC. In 2003, the originally installed K-304-AM microbarometers were exchanged with CHAPARRAL Model 5 microbarometers, for further details see Baryshnikov (2004). At all three infrasound array sites, star-like tube-systems have been installed to filter out acoustic noise.

With only 3 sensors in the array, the SNR gain by beamforming is small (√3). Nevertheless, we used beamforming and filtering in this initial study as a basis for detecting infrasound signals. Whenever an infrasound signal is observed by all three sensors, standard array techniques like fk-analysis can be efficiently used to measure backazimuth and apparent velocity of the signal. These measurements have to be interpreted very carefully, since the array-response function of a three element array has many sidelobes. Fig. 6.3.2 shows the array response of the Apatity infrasound array for a signal with a dominant period of 5 Hz, which is within the frequency range usually observed for regional infrasound signals.

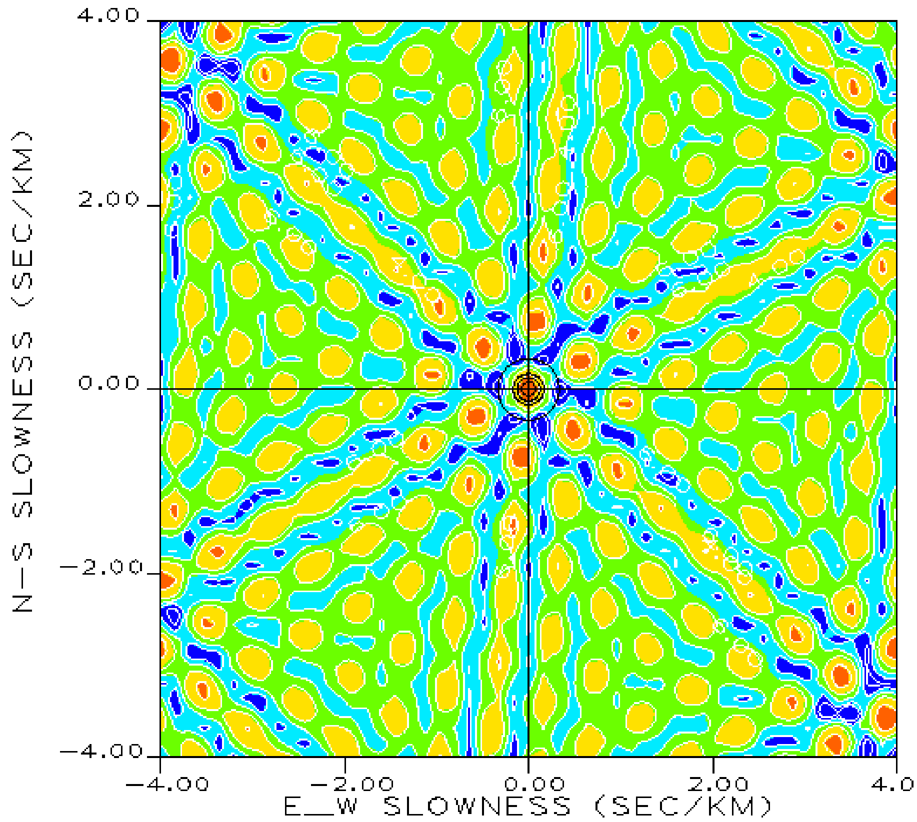

Fig. 6.3.2. The array response of the Apatity 3-element infrasound array for a signal with a dominant frequency of 5 Hz.

Signal detector for Apatity array data

Infrasound signals have usually dominant frequencies in the same range as seismic signals, and tools developed for detecting and analyzing seismic signals at seismic arrays can also be used for processing infrasound signals. This approach was used to develop an initial detector for the Apatity infrasound array:

To cover the range of incidence angles expected for infrasound signals, array beams were deployed with three different apparent velocities (0.33, 0.45, and 0.55 km/s).

For each of these apparent velocities, beams were deployed for 12 different backazimuths (0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, and 330 degrees).

Each of these 36 beams are filtered with eight different bandpass filters in the frequency ranges 0.8 – 2.0, 1.5 – 3.0, 2.0 – 4.0, 2.5 – 8.0, 3.0 – 6.0, 4.0 – 8.0, 6.0 – 12.0, and 8.0 – 16.0 Hz.

This deployment resulted in a total of 288 beams.

During testing, it became clear that larger noise bursts at one of the three sensors very often cause spurious detections on the beams. Such noise bursts are quite frequent and the number of such detections is therefore quite high. To reduce the number of such noise detections, the detection threshold of the STA/LTA detector was initially set as high as 10.0. With this setting, smaller signals will be missed, but this largely reduces the number of noise detections.

All data from 2005 were processed using these detector settings. This resulted in a total of 69,227 detections, which averages to 189.7 detections /day.

Fk-analysis for Apatity array data

As already mentioned, the largest fraction of infrasound detections is caused by noise bursts at one of the array sensors. Such detections are not of particular interest in our context and should therefore be identified and discarded. By comparing the observed amplitudes in the detection-filter band at the individual sensors, all detections based on large amplitudes at a single sensor are removed from any further analysis. Fig. 6.3.3 shows an example of such a signal.

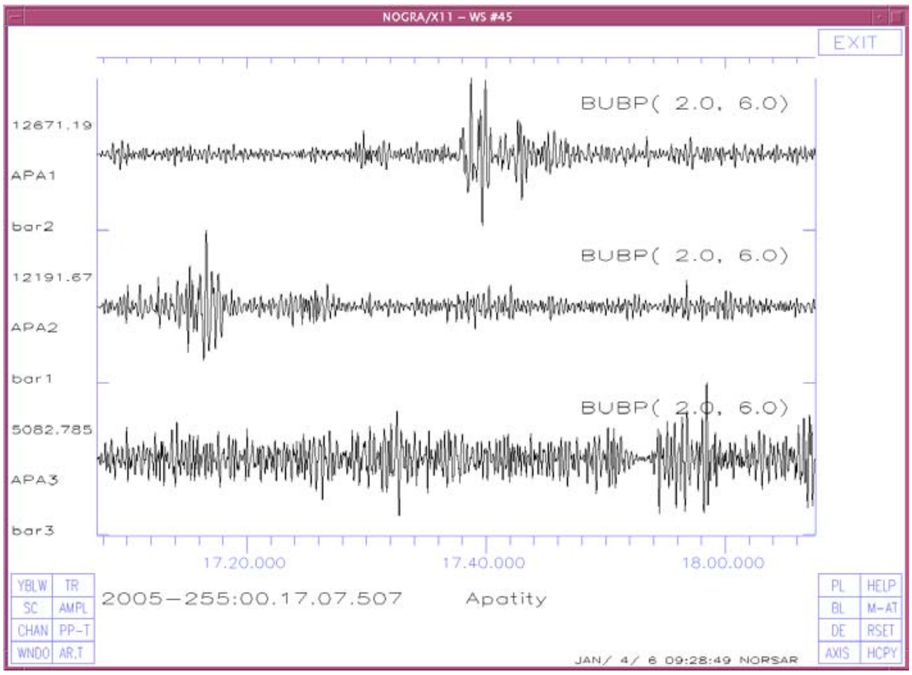

Fig. 6.3.3. Typical observation of single sensor noise bursts at the the Apatity infrasound array.

Before fk-analysis, the data are Butterworth bandpass filtered. The frequency range of this bandpass filter is based on the detection filter, but is widened to include a larger frequency range. The amount of such widening is SNR-dependent. For the fk-analysis a signal-window length between 3 and 15 s is used, and the minimum noise-length window before the estimated onset time is set to 0.5 s.

However, even after checking the amplitudes many noise burst detections remain in the detection lists and the results of the fk-analysis must be further evaluated. It is known that infrasound signals are highly coherent across arrays. Fig. 6.3.4 shows a data example for such a highly coherent infrasound signal. This coherency can be used as an additional parameter to select reliable infrasound signals. The following evaluation procedure has been implemented:

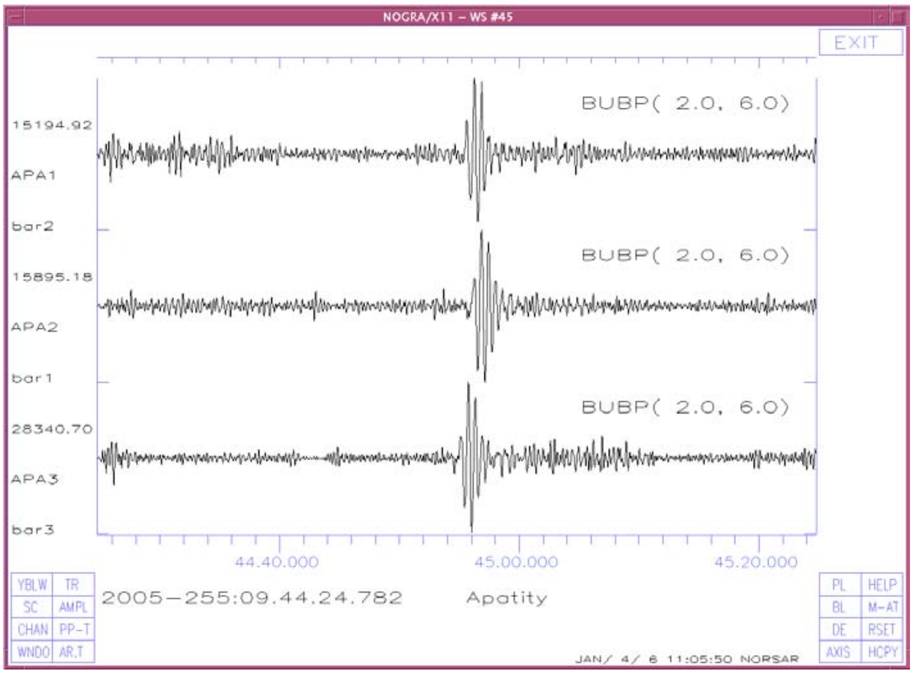

Fig. 6.3.4. A typical infrasound signal recorded at the three infrasound sensors of the Apatity infrasound array.

- The backazimuth and apparent velocity estimated by fk-analysis are used to calculate a beam trace.
- This beam trace is cross-correlated with all three single traces and backazimuth and apparent velocity are recalculated by fitting a plane-wave to the relative onset times on the single traces.
- These wavefront parameters and the cross-correlation values are then compared with the results of the fk-analysis.
- Each fk-analysis (and cross-correlation analysis) is performed for 7 slightly changed window positions/length to find the best slowness estimate, i.e., the highest relative power and cross-correlation value.
- If the highest cross-correlation values exceed a certain threshold, the corresponding plane wave fit is used to determine the wavefront parameters, otherwise the best f-k result is used.
- Following the rule used at the IDC in Vienna, whenever the apparent velocity is between 0.27 and 0.66 km/s, the phase is assumed to be an infrasound (IS) observation.

By this implementation, 8,556 infrasound signals were found for 2005, which gave on average 23.4 detections per day. For the 8,382 infrasound signals detected until the 17th of December 2005 we show histograms with the distribution of apparent velocities (Fig. 6.3.5) and the backazimuth values (Fig. 6.3.6). It is obvious that the largest number of infrasound signals correlates with pronounced backazimuth directions and that most of the signals have apparent velocities between 0.3 and 0.4 km/s.

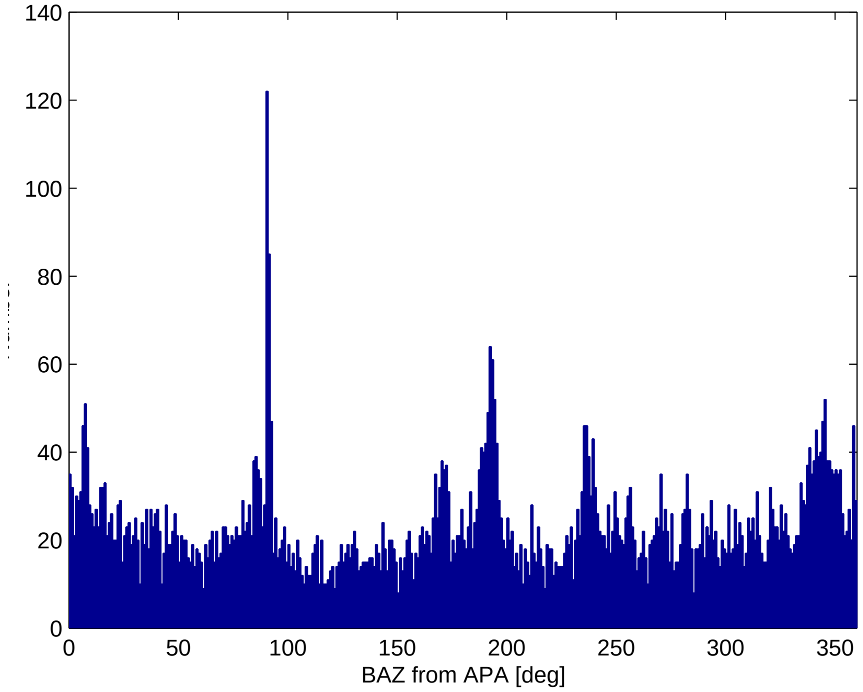

Fig. 6.3.5. Distribution of 8,556 backazimuth observations of infrasound signals observed with the Apatity infrasound array during 1st January – 17th December 2005.

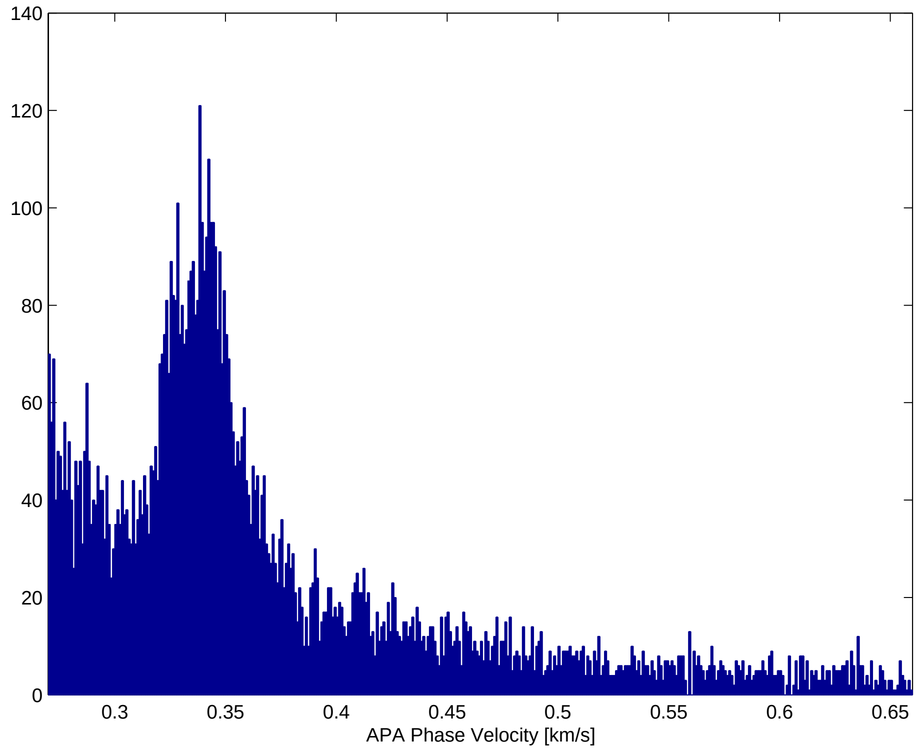

Fig. 6.3.6. Distribution of 8,556 apparent velocity observations of infrasound signals observed with the Apatity infrasound array during 1st January – 17th December 2005.

6.3.3 Infrasound data processing using ARCES array data

Description of the ARCES Array

The 25 element ARCES array is as the Apatity array a short-period regional seismic array, located in the European Arctic. ARCES has no infrasound sensors but because of special installation conditions, many of its seismic sensors are also sensitive to infrasound signals. The main reason for this sensitivity is that the seismometers of the array are standing directly on bedrock, which appears at the Earth's surface in this part of Norway. The seismometers and the associated electronic equipment are protected against the harsh arctic weather conditions by being installed inside closed vaults, but many examples can be found for which sound waves from e.g. large explosions couple into the ground and thereby produce acoustic signals recorded by the seismic sensors (e.g., Ringdal & Schweitzer, 2005).

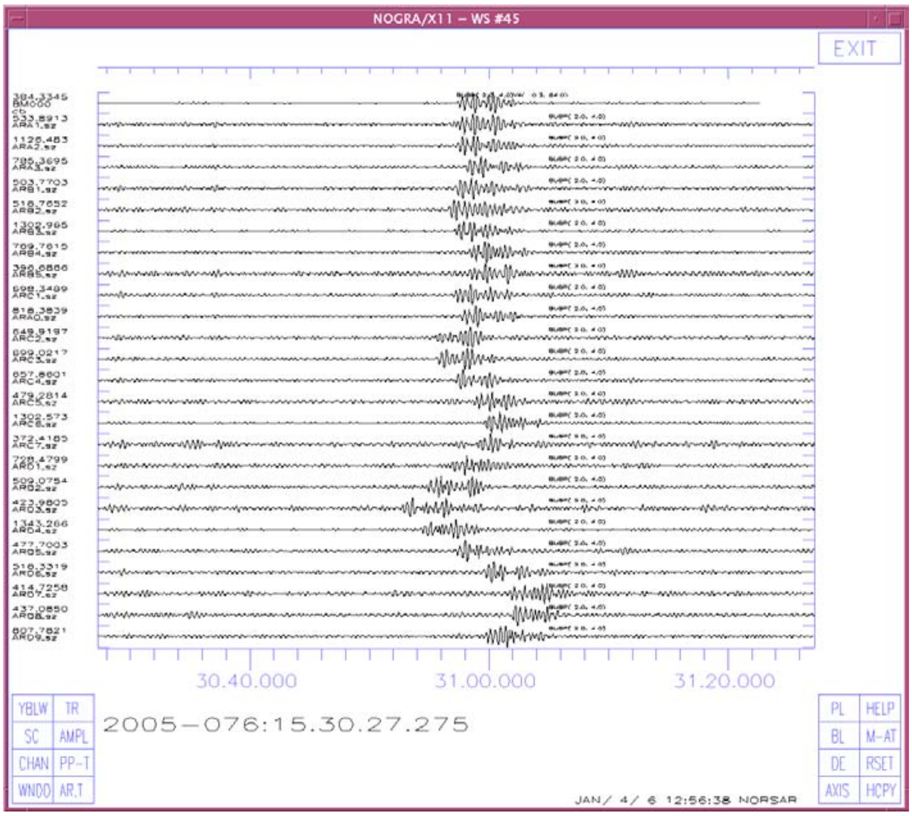

Fig. 6.3.7. An example for an acoustic signal recorded by the seismic instruments of the ARCES array.

The ARCES array consists of 25 sites located on concentric circles with a maximum aperture of 3 km. The observed coupling of acoustic signals into the ground is not equally effective for all sites and large amplitude differences can be observed. However, if recorded, the infrasound signals are highly coherent across the array just like we have observed for data from the Apatity infrasound array. Fig. 6.3.7 shows such a signal recorded at the ARCES array.

With its much higher number of sites and larger aperture, the ARCES array has much better capabilities to measure the wavefront parameters backazimuth and apparent velocity compared to the Apatity array.

Signal detector for ARCES array data

The beam deployment for an infrasound detector at ARCES has to cover the interesting apparent velocity range for all backazimuths. Because of the larger aperture of the array and thereby longer travel times needed by infrasound signals to cross the array, an enormous number of detection beams is needed to cover the whole parameter space. To keep the number of detection beams within a reasonable range, the ARCES D-ring is not used for this initial detector deployment. Two different array configurations have been defined:

- One with 16 ARCES sites comprising the center instrument, the A-, B- and C-ring.
- One with only the A-sites of ARCES (A0, A1, A2, and A3), which is similar to the Apatity infrasound array configuration. However, when comparing the array responses of the different configurations (Figs. 6.3.2 and 6.3.8), it is obvious that the additional element in the center of ARCES improves the array response by reducing disturbing sidelobes.

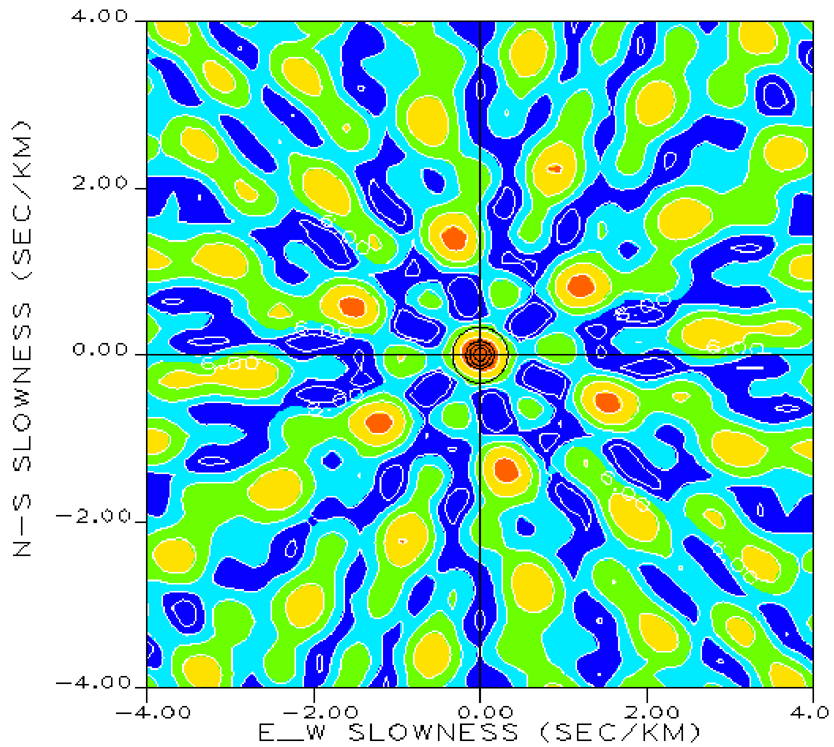

Fig. 6.3.8. The ARCES array responses for a 5 HZ signal for the four element configuration (A-sites only)

For these two configurations altogether 672 detection beams were deployed:

- To cover the range of incidence angles expected for infrasound signals, array beams were deployed with eight different apparent velocities (0.283, 0.306, 0.333, 0.365, 0.405, 0.454, 0.516, 0.599 km/s) for the larger array configuration (A0, A-, B-, and C-ring)and four different apparent velocities (0.283, 0.333, 0.405, and 0.516 km/s) for the smaller array configuration. (A0 and A-ring).
- For each of these apparent velocities, beams were deployed for 36 different backazimuths (0, 10, 20, 30, …. 340, and 350 degrees) for the larger array configuration and 12 different backazimuths (5, 35, 65, …. 305, and 335 degrees) for the smaller array configuration.

- Each of the 288 beams for the larger configuration are filtered with two different bandpass filters in the frequency ranges 2.0 – 4.0 and 3.0 – 6.0 Hz.
- Each of the 48 beams for the larger configuration are filtered with two different bandpass filters in the frequency ranges 3.0 – 6.0, and 4.0 – 8.0 Hz.
- Owing to the better noise conditions at ARCES and the better noise suppression due to the larger number of sensors, the detection threshold could be lowered to 4.0.

As for the Apatity infrasound array, all data recorded during 2005 were processed using the detector deployment for infrasound signals described above. This resulted in a total of 80,724 detections, which averages to 221.2 detections /day. However, one problem by using the seismic array ARCES for detection of infrasound signals is that many seismic signals are so strong that they still have significant onsets on the infrasound beams. These non-infrasound detections have to be sorted out during the fk-analysis.

Fk-analysis for ARCES array data

For estimating backazimuth and apparent velocity of the observed signals, the seismic array data processing as developed for ARCES with its data quality checks could be copied directly (Schweitzer, 2003). However, many sites of the seismic array are much less sensitive to infrasound signals than others. To obtain stable results, in particular also for weaker signals, data from these less sensitive sites (B5, C1, C2, C5, D2, D3, D6, D8) are not used during the further data processing.

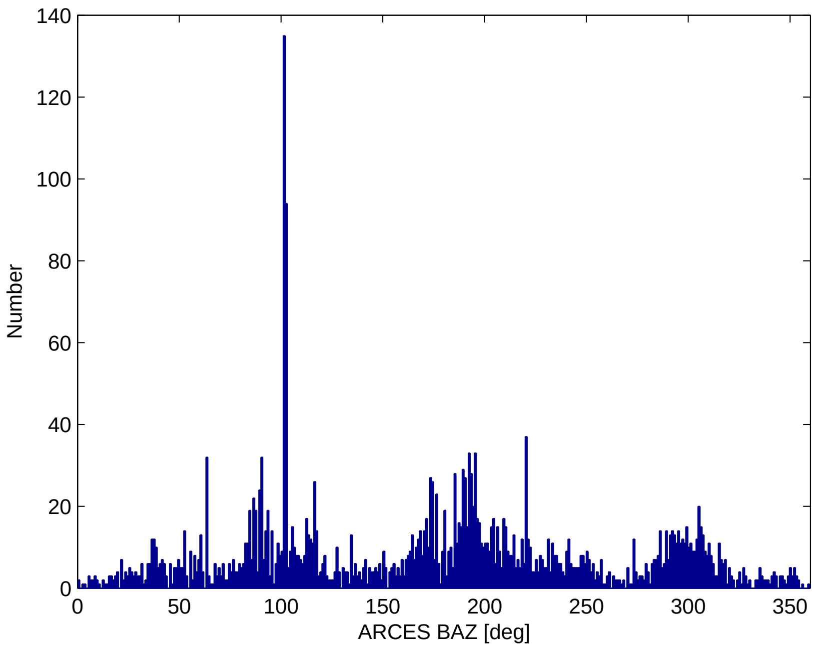

Fig. 6.3.9. Distribution of 2,768 backazimuth observations of infrasound signals observed with the Apatity infrasound array during 1st January – 17th December 2005.

The sensitivity for acoustic signals of the remaining sensors is still different and the observed signal amplitudes scatter over a large range. However, the signal coherence over the array is quite high and therefore, the most stable results are achieved by normalizing the traces before fk-analysis. The fk-analysis is performed with a window-length for the signal of between 5 and 15 s and a noise window before the estimated onset time of 0.5 s.

The major problem in searching and analyzing infrasound signals with ARCES is that many seismic signals have so large amplitudes that they are still detected due to their relatively large SNR on the infrasound beams. Therefore, each fk-analysis is performed for 7 slightly changed window positions/length to find the best slowness estimate (i.e., the one with the highest relative power), and whenever the apparent velocity is between 0.27 and 0.66 km/s, the phase is assumed to be an infrasound (IS) observation.

Applying this data processing, 2,794 infrasound signals were found in the 2005 ARCES recordings, which corresponds to 7.6 detections per day. For the 2,768 infrasound signals detected until the 17th of December 2005, we show histograms with the distribution of apparent velocities (Fig. 6.3.9) and the backazimuth values (Fig. 6.3.10). It is obvious that the largest number of infrasound signals correlates with pronounced backazimuth directions and that most of the signals have apparent velocities between 0.3 and 0.4 km/s. However, the large number of apparent velocity observations around 0.44 km/s is surprising and will be further investigated in the future.

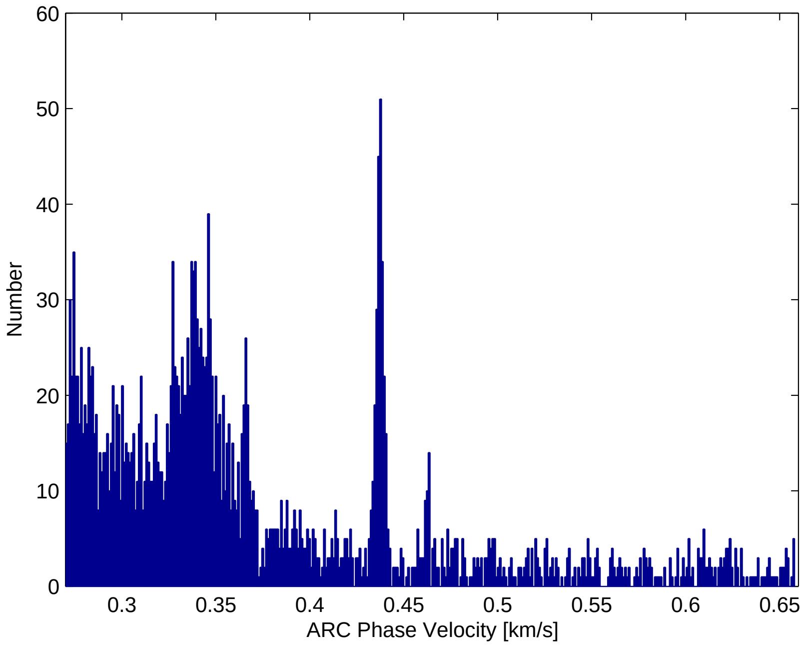

Fig. 6.3.10. Distribution of 2,768 apparent velocity observations of infrasound signals observed with the Apatity infrasound array during 1st January – 17th December 2005.

6.3.4 Comparing infrasound signals with seismic events in the GBF bulletin

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. This number of observations results from the application of the data processing described above, which comprises only an initial set of infrasound signal processing rules. The question still open is; can these signals 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 Kvaerna, 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 17th 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	

Fig. 6.3.11. 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 (see Fig. 6.3.12).
- 250 events could be associated only with infrasound signals observed at the ARCES seismic array (see Fig. 6.3.12).
- 68 events could be associated with infrasound signals at both arrays, the ARCES seismic array and the Apatity infrasound array (Fig. 6.3.13).

Fig. 6.3.11 shows the GBF bulletin for an event in the Khibiny Massif, Kola Peninsula, for which infrasound signals were observed at both arrays. The source area is known for 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.

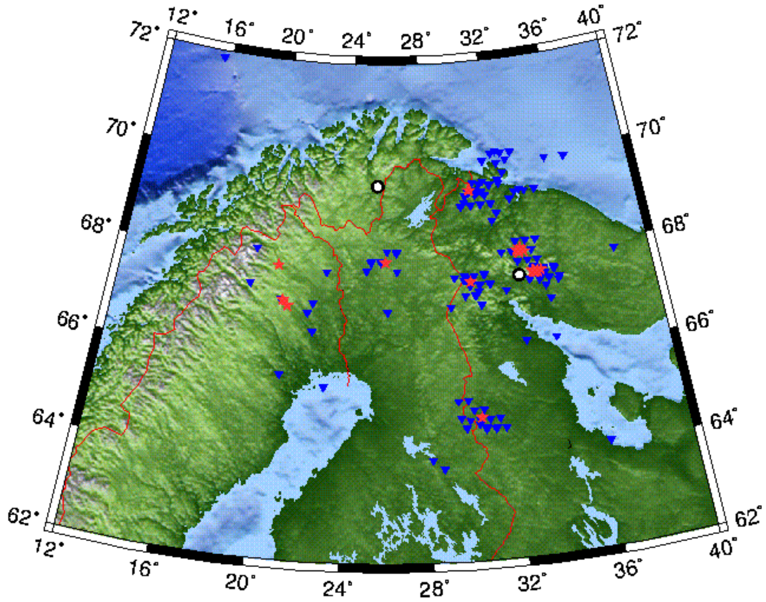

Fig. 6.3.12. The map shows automatically located events (GBF) for which either ARCES or the Apatity infrasound array observed infrasound signals. The blue triangles show the GBF event locations and the red stars show the location of known sites with explosions either at the Earth's surface or in the atmosphere. Note that the automatic GBF locations usually scatter over a larger area around these source regions.

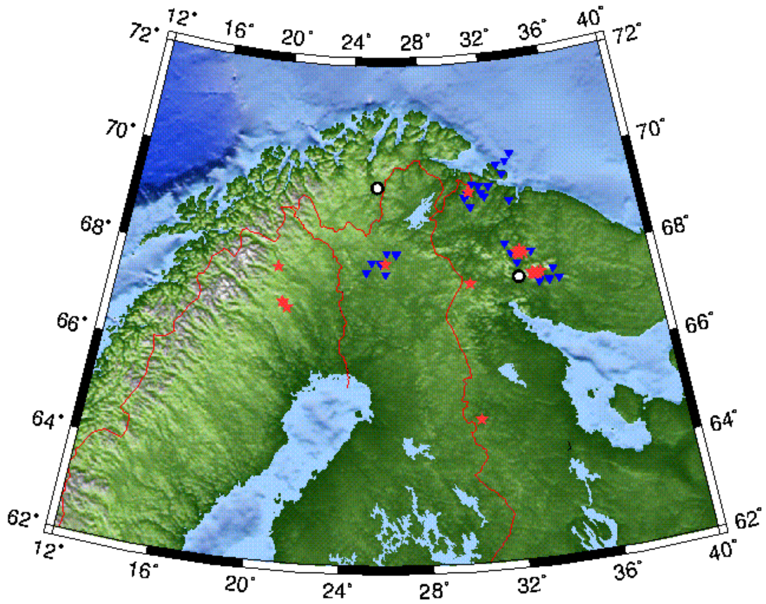

Fig. 6.3.13. The map shows automatically located events (GBF) for which both ARCES and the Apatity infrasound array observed infrasound signals. The blue triangles show the GBF event locations and the red stars show the location of known sites with explosions either at the Earth's surface or in the atmosphere.

On the map in Fig. 6.3.12 all reasonably well located GBF events for which either ARCES or the Apatity infrasound array have observed an infrasound signal are shown as blue triangles. The red stars show locations, known for regular explosions 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. Fig. 6.3.13 shows all of the 68 events for which infrasound signals were observed at both arrays.

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.

Acknowledgements

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Yuri Vinogradov, KRSC

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