RESEARCH IN REGIONAL SEISMIC MONITORING

Frode Ringdal[1], Tormod Kvaerna[1], Elena O. Kremenetskaya[2], Vladimir E. Asming[2], Sergeij Kozyrev[2], Svein Mykkeltveit[1], Steven J. Gibbons[1], and Johannes Schweitzer[1]

NORSAR[1], Kola Regional Seismological Centre[2]

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ABSTRACT

This project represents a continuing research effort aimed at improving seismic monitoring tools at regional distances, with emphasis on the Barents/Kara Sea region, which includes the former Novaya Zemlya test site. The tasks comprise development and improvement of detection, location and discrimination algorithms as well as experimental on-line monitoring using tools such as regional Generalized Beamforming (GBF) and Threshold Monitoring (TM). It also includes special studies of mining events, for which detailed ground truth information is being provided by the Kola Regional Seismological Centre (KRSC).

Data from the regional networks operated by NORSAR and KRSC were used to assess the seismicity and characteristics of regional phases of the European Arctic. KRSC has for the past 10 years provided to NORSAR ground truth information for selected mining explosions in the Kola Peninsula. Since 2001, the project has been expanded in scope, and is currently carried out jointly with Lawrence Livermore National Laboratory (LLNL), in a Department of Energy (DOE) funded project. This ground truth information comprises accurate locations, charges and explosion characteristics, relating to large underground and surface ripple-fired explosions as well as smaller “compact” underground explosions. The Mining Institute of the Kola Science Centre has made a video recording of two large explosions (one surface and one underground) on 16 November 2002. This video has been made available to us, and the paper presents selected snapshots of the explosions.

Significant progress has been made in automating the detection and location of seismic events from selected areas. In particular, we have continued to improve the regional processing currently carried out at NORSAR for the European Arctic. The emphasis has been on automatic detection and association of phases for small seismic events in the Novaya Zemlya region, using the on-line Generalized Beamforming (GBF) process. The number of false associations can be reduced by 90 percent through relatively simple selection criteria, while still retaining the “real” seismic events. Furthermore, some possibilities for additional future improvements are discussed, including the development of a systematic automatic post-processing algorithm to be applied to event candidates produced by the GBF process currently in operation. Examples of recent small seismic events at Novaya Zemlya detected by the regional network are presented.

A study of location accuracy for seismic events near the Spitsbergen archipelago is illustrated. In cooperation with KRSC, more than 200 earthquakes occurring during the first half of 2003 with epicenters in Spitsbergen and adjacent areas have been relocated. We have compared our location results with those published in the Reviewed NORSAR Regional Bulletin, which makes use of the same station network. Additionally, we compared both of these interactive location results to the automatic location provided by the on-line GBF procedure at NORSAR. The Spitsbergen region is geologically far more complex than Fennoscandia, and multiple arrivals of P and S phases are quite common. Consequently, different phase interpretation by different analysts result in occasionally large deviations in location estimates, sometimes as much as 100 km for events located by the SPITS array alone. Some possibilities for future enhancements of the event location procedures are discussed.

OBJECTIVES

This work represents a continued effort in seismic monitoring, with emphasis on studying earthquakes and explosions in the Barents/Kara Sea region, which includes the former Russian nuclear test site at Novaya Zemlya. The overall objective is to characterize the seismicity of this region, to investigate the detection and location capability of regional seismic networks and to study various methods for screening and identifying seismic events in order to improve monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Another objective is to carry out special studies of mining events, for which detailed ground truth information is being provided by the Kola Regional Seismological Centre.

RESEARCH ACCOMPLISHED

Introduction

NORSAR and Kola Regional Seismological Centre of the Russian Academy of Sciences have for many years cooperated in the continuous monitoring of seismic events in northwest Russia and adjacent sea areas. The research has been based on data from a network of sensitive regional arrays which has been installed in northern Europe during the last decade in preparation for the CTBT monitoring network. This regional network, which comprises stations in Fennoscandia, Spitsbergen and NW Russia, provides detection capability for the Barents/Kara Sea region that is close to $m_b = 2.5$ (Ringdal, 1997).

The research carried out during this effort is documented in detail in several contributions contained in the NORSAR Semiannual Technical Summaries. In the present paper we will limit the discussions to some recent results of interest in the general context of regional monitoring of seismic events in the European Arctic. In particular our studies have focused on mining explosions in the Kola Peninsula, using data from stations shown in Figure 1. This figure also shows some of the most active mining areas.

Khibiny mine explosions

Data from the regional networks operated by NORSAR and KRSC was used to assess the seismicity and characteristics of regional phases of the European Arctic. KRSC has for the past 10 years provided to NORSAR ground truth information for selected mining explosions in the Kola Peninsula. Since 2001, the project has been expanded in scope, and is currently carried out jointly with Lawrence Livermore National Laboratory, (Harris *et. al.*, 2003). This ground truth information comprises accurate locations, charges and explosion characteristics, relating to large underground and surface ripple-fired explosions as well as smaller “compact” underground explosions.

Of particular interest are two explosions, one underground and one at the surface carried out in the Rasvumchorr mine in Khibiny on 16 November 2002. These explosions were briefly discussed in Ringdal *et al.* (2003). Additional information will be presented in this paper. As illustrated in Figures 2 and 3, the underground explosion was a ripple-fired explosion of 257 tons, whereas the open-pit explosion comprised four separate ripple-fired explosions, set off at approximately one-second intervals, from south to north. The surface and underground explosions were only 300 m apart so that differences in path effects, at the more distant stations, can be ignored. Nevertheless, the recorded signals, at the temporary station in Ivalo, Finland at 300 km distance, were remarkably different. The vertical component of these recordings is shown in Figure 4 in different filter bands. At lower frequencies (2-4 Hz), the underground explosion was stronger by a factor of 10 in amplitude, whereas above 10 Hz, the surface explosion had, by far, the stronger signals. The Mining Institute of the Kola Science Centre made a video recording of these explosions. This video was made available to us, and Figure 5 shows selected snapshots of the explosions.

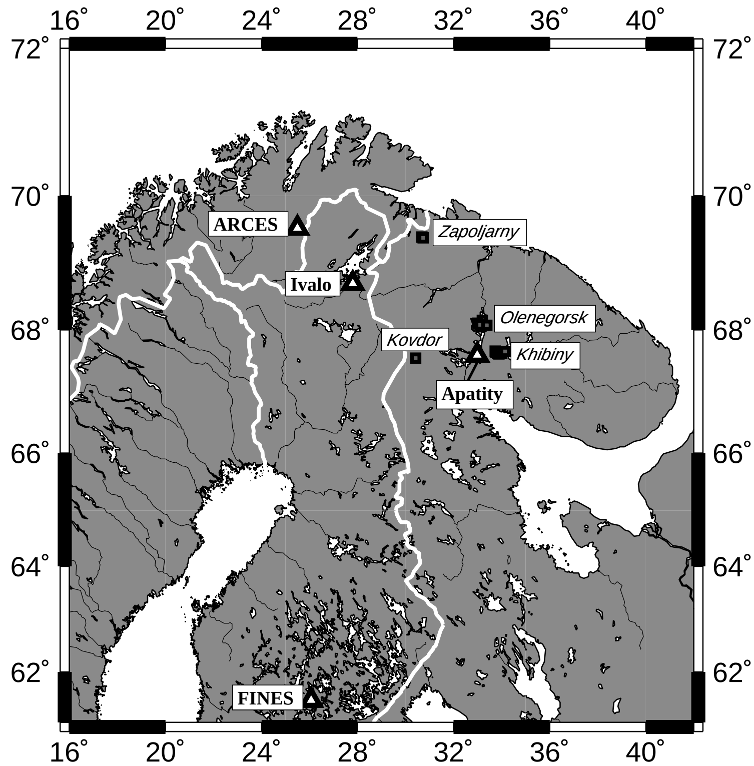

Figure 1. Seismic stations (triangles) used in our studies of mine explosions in Kola Peninsula. The main mining sites are marked as squares. The station Ivalo is one of six temporary stations established in cooperation with LLNL.

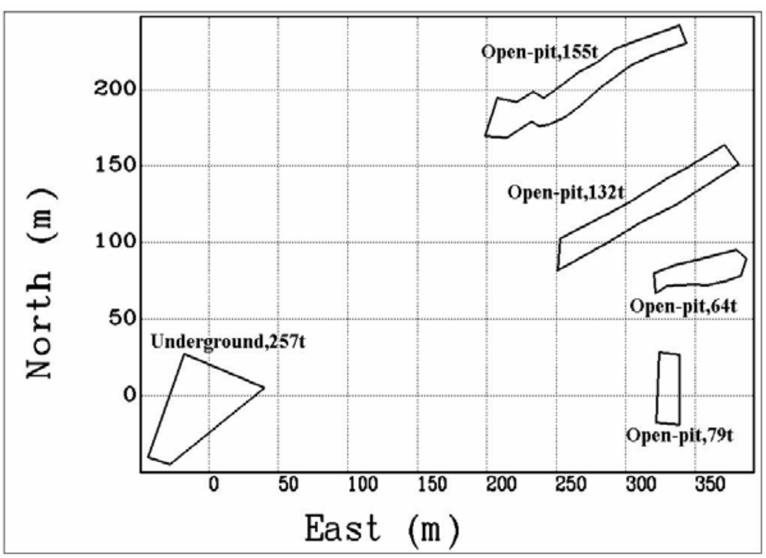

Figure 2. Schematic view of the shot configuration for the two explosions in Khibiny on 16 November 2002. Geographical coordinates of the point (0,0) are 67.6322N 33.8565E. See text for details.

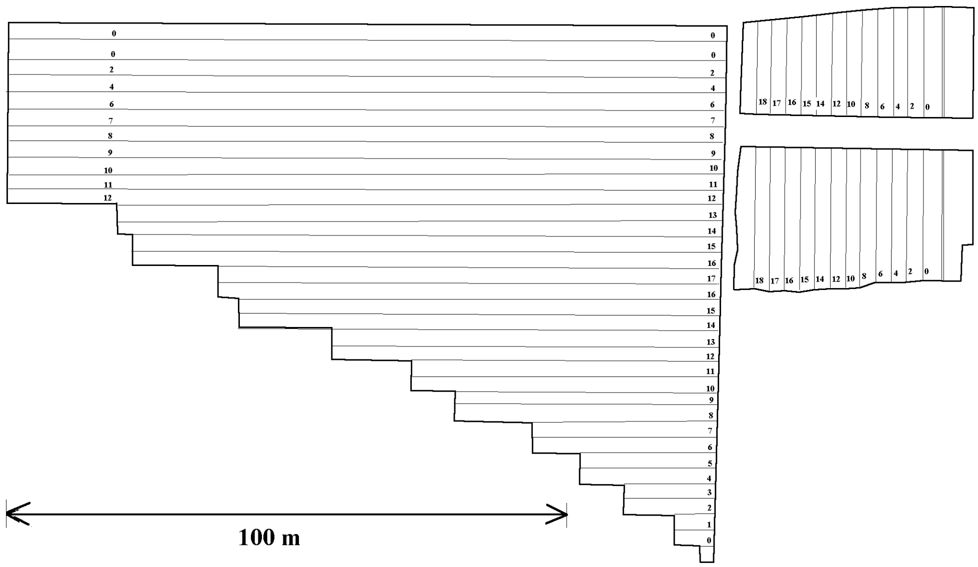

Figure 3. Geometry of the underground mining explosion in Khibiny 16 November 2002. The charges were detonated in 19 groups (delay 23 ms between each group). The sequence is indicated by the numbers, and individual charge sizes have been made available.

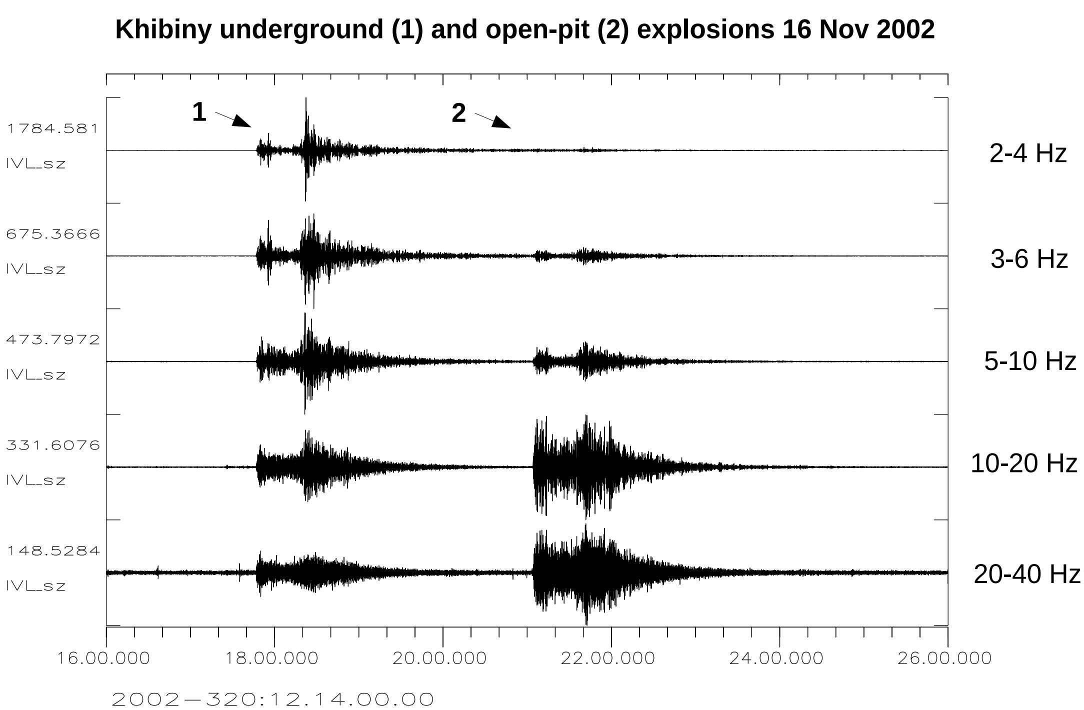

Figure 4. Recorded SPZ waveforms at station Ivalo (northern Finland) for the two explosions in Khibiny on 16 November 2002. The data have been filtered in five different frequency bands. Note the significant difference in relative size of the two events as a function of frequency.

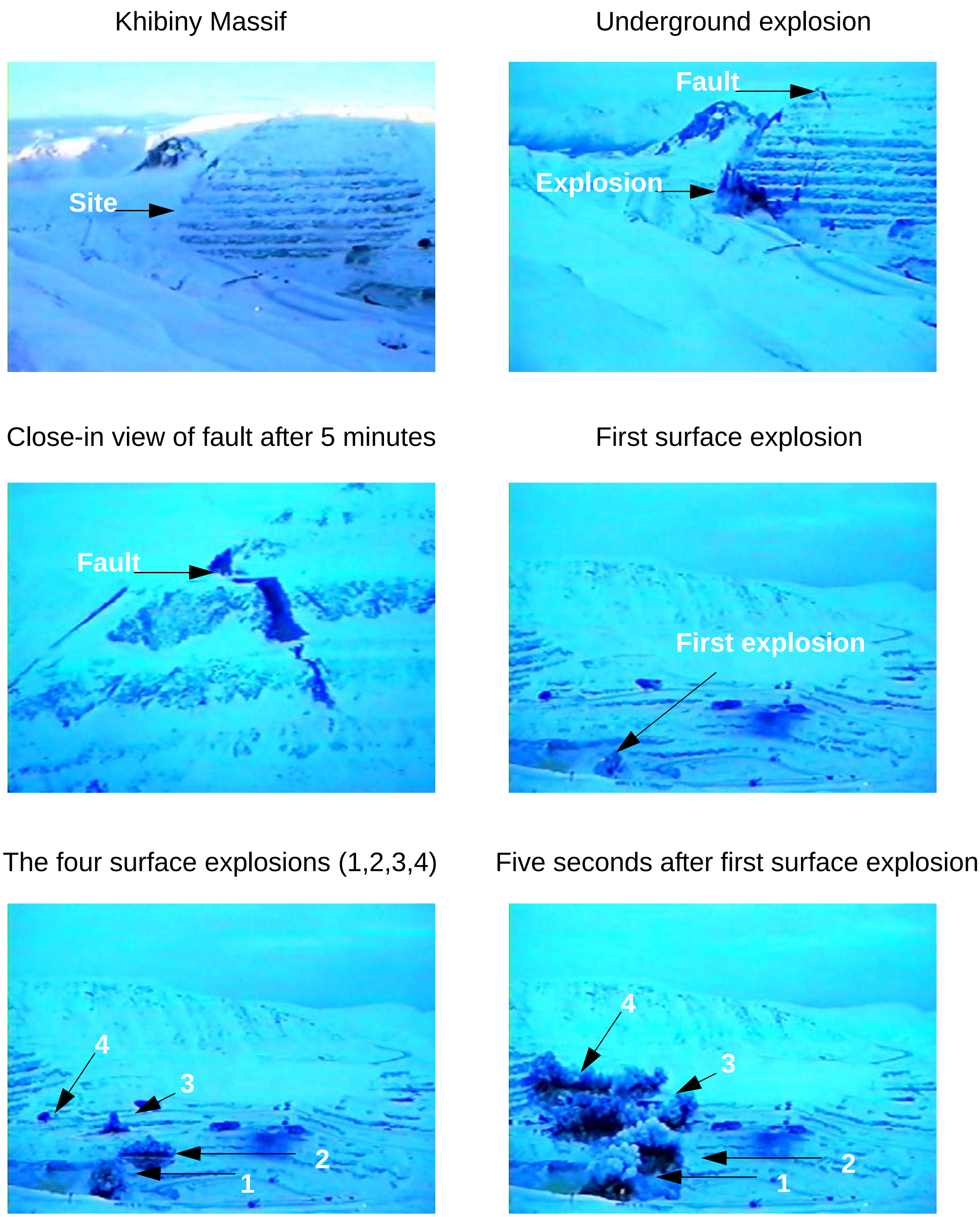

Figure 5. Snapshots of video from the sequence of Khibiny explosions on 16 November 2002. Note in particular the large crack ("fault") opening up in the mountainside at the time of the first (underground) explosion.

Developing NORSAR's regional processing system

NORSAR has for a number of years carried out processing and analysis of seismic events in the European Arctic, using the regional array network in Fennoscandia and NW Russia. The regional processing system at the NORSAR Data Center comprises the following steps:

- Automatic single array processing, using a suite of bandpass filters in parallel and a beam deployment that covers both P and S type phases for the region of interest.
- An STA/LTA detector applied independently to each beam, with broadband f-k analysis for each detected phase in order to estimate azimuth and phase velocity.
- Single-array phase association for initial location of seismic events, and also for the purpose of chaining together phases belonging to the same event, so as to prepare for the subsequent multi-array processing.
- Multi-array event detection, using the GBF approach (Ringdal and Kværna, 1989) to associate phases from all stations in the regional network and thereby provide automatic network locations for events in all of northern Europe. The resulting automatic event list is made available on the Internet (www.norsar.no).
- Interactive analysis of selected events, resulting in a reviewed regional seismic bulletin, which includes hypocentral information, magnitudes and selected waveform plots. This reviewed bulletin is also available on the Internet.

Monitoring the Novaya Zemlya region

The philosophy behind the automatic process at NORSAR is to ensure, as far as possible, that no real detectable event is lost. The penalty is that a number of false associations are generated. This problem is most significant for regions at large distances from the arrays, such as the Novaya Zemlya region. We describe below some initial steps undertaken to eliminate many of these false associations.

It is well known that the most sensitive arrays for seismic events in the Novaya Zemlya region are ARCES and SPITS. Our initial step to reduce the number of false associations is therefore to require detection by one or both of these two arrays, using a combination of the following criteria:

1. Pn and Sn detections by SPITS
2. Pn and Sn detections by ARCES
3. Pn detections by both SPITS and ARCES

In addition, we have experimented with additional constraints on Pn phase velocities for the two arrays, in order to eliminate obvious teleseismic or near-regional phases. Reasonable constraints, based on observational evidence, are:

- For ARCES: Pn velocity between 8-12 km/s
- For SPITS: Pn velocity between 7-10 km/s

Furthermore, we have considered the effects of constraining the acceptable difference in estimated azimuth for the P and S phase, by removing single-station events that have an azimuth difference (P-S) exceeding 15 degrees.

Table 1 gives an overview of the number of GBF event candidates located in the region surrounding Novaya Zemlya for the years 2002 and 2003. The geographical limits are 70-78 degrees north, 50-70 degrees east. The counts using the current on-line GBF algorithm as well as the counts requiring detection by ARCES and SPITS, and counts imposing additional constraints are given.

Table 1 GBF event candidates 70-78 deg N, 50-70 deg E

Detection criterion	ARCES Pn velocity	SPITS Pn velocity	Az. diff.	Total 2002	Total 2003	Sum
All GBF	All	All	All	683	950	1733
1 or 2 or 3	All	All	All	294	382	676

Table 1 GBF event candidates 70-78 deg N, 50-70 deg E

Detection criterion	ARCES Pn velocity	SPITS Pn velocity	Az. diff.	Total 2002	Total 2003	Sum
1 or 2 or 3	8-12 km/s	7-10 km/s	All	177	211	388
1 or 2 or 3	8-12 km/s	7-10 km/s	<15 deg	66	81	147

The criteria specified in the table are conservative in the sense that they should not eliminate any potential real seismic events occurring in this region. Nevertheless, the table above indicates that the number of event candidates is reduced by about 90 percent when applying the final (strongest) test.

We note that the significant reduction in false detections when imposing the azimuth constraint is due to a wide azimuth window currently applied in the GBF processing. The GBF algorithm allows phases to be associated to the same event if they deviate less than 30 degrees from the grid point toward which the generalized beam is steered. This implies that P and S phases associated to a given event could (in extreme cases) differ by up to 60 degrees, which is clearly excessive. There is consequently a good argument for adding a more restrictive azimuth test in the second step of the on-line GBF process.

Table 2: List of seismic events in or near Novaya Zemlya (1980-2003) located outside the test site

Date/time	Location	m_b	Comment
01.08.86/ 13.56.38	72.945 N, 56.549 E	4.3	Located by Blacknest, UK
31.12.92/ 09.29.24	73.600 N 55.200 E	2.7	Located by NORSAR
23.02.95/ 21.50.00	71.856 N, 55.685 E	2.5	Located by NORSAR
13.06.95/ 19.22.38	75.170 N, 56.740 E	3.5	Located by NORSAR
13.01.96/ 17.17.23	75.240 N, 56.660 E	2.4	Approximately co-located with preceding event
16.08.97/ 02.11.00	72.510 N, 57.550 E	3.5	Located by NORSAR
16.08.97/ 06.19.10	72.510 N, 57.550 E	2.6	Co-located with preceding event
23.02.02/ 01.21.14	74.047 N, 57.671 E	3.0	Located by NORSAR
08.10.03/ 23.07.10	75.645N, 63.345E	2.5	Located by NORSAR

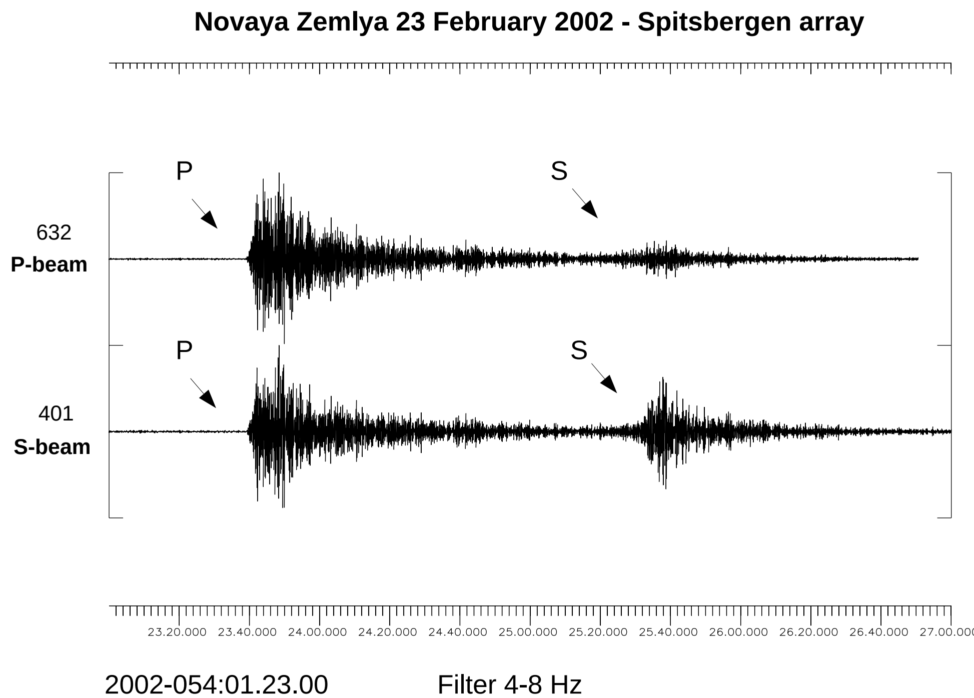

Figure 6. Spitsbergen P and S beams for the Novaya Zemlya event on 23 February 2002

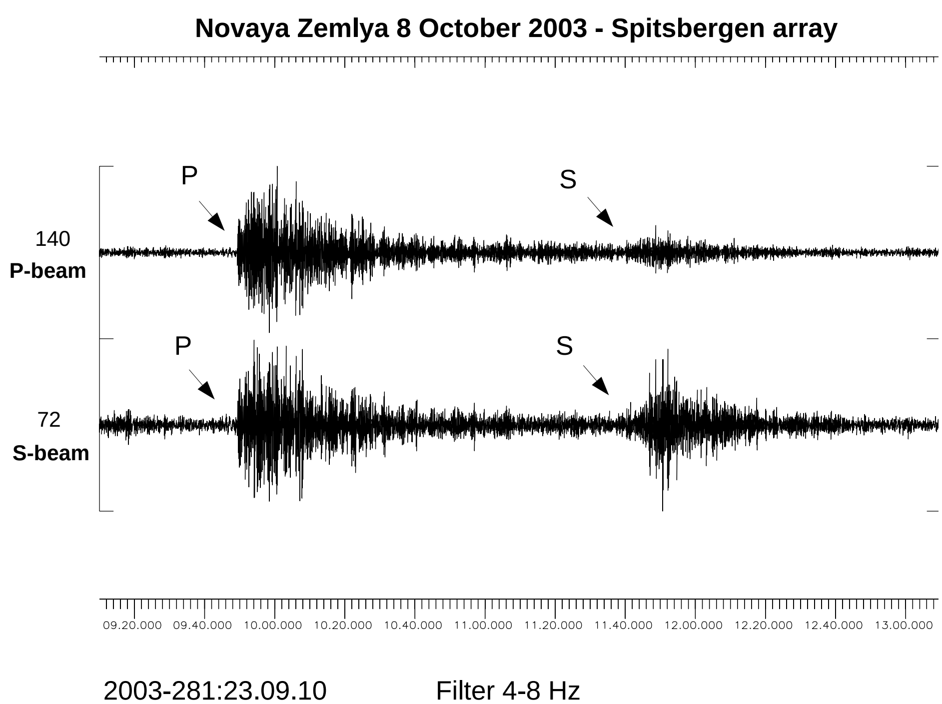

Figure 7. Spitsbergen P and S beams for the Novaya Zemlya event on 8 October 2003

Examples of recent low-magnitude events

Small events in the Novaya Zemlya region located outside the test site and detected over the years by the NORSAR regional processing are listed in Table 2. Recordings of the two most recent events are illustrated in Figures 6 and 7. The first figure shows a magnitude 3.0 event on 23 February 2002, as recorded by the SPITS array. Two filtered (4-8 Hz) array beams are displayed, corresponding to Pn and Sn velocities and directed towards the epicenter. The high signal-to-noise ratio (SNR) is noted for the P-phase and also that the S-phase is clearly detected on the S-beam. The second event (magnitude 2.5) occurred on 8 October 2003, and Figure 7 shows the SPITS Pn and Sn beams for this event. The waveforms have similar characteristics to those observed for the 23 February 2002 event. This event illustrates the importance of including, in the detection criteria, single-station detections (P and S phases detected at the same array) as well as events detected at both arrays. In fact, there was no automatic detection of this event at ARCES. However, by inspecting the ARCES waveforms visually, P and S onsets could be found, and were included in the reviewed event location in Table 2.

Locating small events near Spitsbergen

The geology of the Spitsbergen archipelago and surrounding regions is complex, and results in very complex seismograms from some areas. Multiple onsets of P and S waves are not uncommon, and can strongly increase location errors. More than 200 small earthquakes (mostly of magnitude around 2.0) occurring during the first half of 2003 with epicenters in Spitsbergen and adjacent areas were relocated. All of these events were detected by at least two stations (usually KBS and SPITS, sometimes with the addition of ARCES and other distant stations). We compared our location results with those published in the Reviewed NORSAR Regional Bulletin, which makes use of the same station network. Additionally, both of these interactive location results were compared to the automatic location provided by the on-line GBF procedure at NORSAR. Detailed results are presented in Asming *et. al.* (2004).

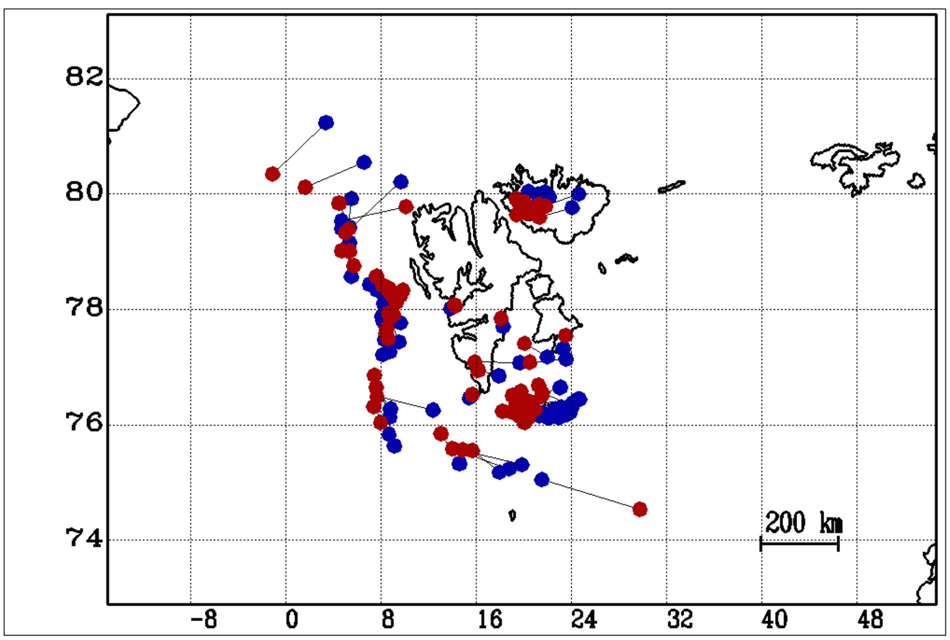

Figure 9. Location comparison: Relocated events (red) vs. NORSAR reviewed bulletin (blue)

Figure 9 compares the two sets of analyst reviewed locations (marked NORSAR for the results in the NORSAR Regional Bulletin and KRSC for the relocated solutions). In general, they are quite consistent, but a systematic shift in the locations of groups of events is noted, with the KRSC locations generally being shifted in westerly directions compared to those of the NORSAR analyst. Mostly, the location differences are small (a few tens of kilometers), but for a few events the difference exceeds 100 km, and in one case it is more than 200 km. The smaller differences can be attributed, at least in part, to the different velocity models used at KRSC and NORSAR (KRSC uses the SPITS0 model, whereas NORSAR uses a general Fennoscandian model). The cases with large differences are a direct consequence of the difficulties in phase interpretations, and demonstrate that locations of small earthquakes in this region can be associated with significant uncertainties.

CONCLUSIONS AND RECOMMENDATIONS

The accumulation of detailed ground truth for mining explosions in the Kola Peninsula is a significant step towards improved understanding of the waveform characteristics of various types of mining explosions. Our analysis shows significant spectral differences between surface and open-pit explosions. It is our recommendation to pursue this work as more ground truth data of mining events is accumulated, and a larger database of recordings from near-field stations becomes available.

We have demonstrated that a set of relatively simple post-processing criteria can significantly reduce the number of false associations in the automatic GBF process. Nevertheless, there is still room for considerable improvement. A promising approach is to use fixed-frequency filter bands for the broad-band f-k estimation. In this way, one can obtain more stable azimuth estimates, thereby enabling a much lower tolerance than the currently used threshold of 15 degrees for the difference in P and S azimuths. Our work will continue on reducing the false alarm rate in the automatic GBF lists, while retaining as many as possible of the real seismic events. Additionally, the automatic detector algorithms could be further improved, and work towards this is continuing.

By studying a set of more than 200 earthquakes in the Spitsbergen region, we have shown that analyst reviewed locations (as processed by different analysts) can have occasional large deviations, in several cases exceeding 100 km. This is due to the complexity of the seismograms, which sometimes results in ambiguous phase identification. Detection of S-phases using the SPITS array is often problematic, and improvements in this area is a topic of current research. With the planned refurbishment of SPITS, several three-component sites will be included in the array, and this should improve the detection potential for S-phases in the future. In particular, attention should be given to high-frequency processing of data for phase identification and velocity/azimuth estimation purposes.

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