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6.2 Research in regional seismic monitoring

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Abstract

This project represents a continuing effort aiming at three main topics: (a) to carry out research in regional monitoring of the European Arctic, (b) to apply experimental methods such as the site-specific threshold monitoring to target areas of interest and assess the results and (c) to contribute to the global location calibration effort currently being undertaken in Vienna, Austria by Working Group B of the Preparatory Commission (PrepCom).

We have used data from the regional networks operated by NORSAR and the Kola Regional Seismological Centre (KRSC) to assess the seismicity and characteristics of regional phases of the European Arctic. Recently, seismic instrumentation has been installed inside the mines in the Khibiny Massif of the Kola peninsula in order to provide origin times of the seismic events as well as to contribute to additional validation of the location accuracy. These recordings supplement the ground truth information that is routinely obtained by KRSC for mining explosions in the Kola Peninsula. Some interesting results are emerging from comparing underground and surface explosions. For example, two explosions, one underground and one at the surface occurred in the Rasvumchorr mine in Khibiny on 16 November 2002. These 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 stations in our network (up to 400 km distance) were remarkably different: At lower frequencies (2-4 Hz), the underground explosion was stronger by a factor of 10 in amplitude, whereas above 10Hz, the surface explosion had by far the stronger signals.

We have made some significant progress in automating the detection and location of seismic events from selected mining areas. For example, an experimental on-line detection and location system, using the ARCES array, has been implemented for the Kovdor mine in Kola, and the automatic process has been compared to the regular analyst reported bulletin. It turns out that the automated process, with appropriate calibration, can match or exceed the performance of the analyst in terms of location precision. The main reasons for this performance is the application of optimized, fixed frequency band filters together with careful application of automatic autoregressive onset estimation techniques.

We have continued our efforts to develop and improve the site-specific threshold monitoring system for the Novaya Zemlya test site in Russia. We have also developed a site-specific generalized beamforming procedure, which has proved able to detect small events at this site with a very low false alarm rate. In addition, we are attempting to optimize the automatic detector performance for Novaya Zemlya and adjacent regions by adjusting the beam set, adding specially designed filters and correcting for plane-wave anomalies in the beamforming.

A workshop was held in Oslo, Norway, during 4-9 May 2003 in support of the global seismic event location calibration effort currently being undertaken by PrepCom's Working Group B in Vienna. The workshop, which was chaired by Dr. Frode Ringdal, was attended by 54 scientists from 10 countries and the Provisional Technical Secretariat of the CTBTO. The workshop recommendations will be reported to Working Group B.

6.2.1 Objective

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. Another objective is to apply advanced site-specific seismic monitoring methods to other sites of special interest, in particular known nuclear test sites. A third objective is to support the international effort to provide regional location calibration of the International Monitoring System.

6.2.2 Research Accomplished

NORSAR and the Kola Regional Seismological Centre (KRSC) of the Russian Academy of Sciences have for many years cooperated in the continuous monitoring of seismic events in North-West 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 a detection capability for the Barents/Kara Sea region that is close to $m_b = 2.5$ (Ringdal, 1997).

The research carried out as part of 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 Fig. 6.2.1. This figure also shows some of the most active mining areas. We also briefly review the location calibration effort currently underway for the International Monitoring System (IMS).

Khibiny mine explosions

We have continued our research on rockbursts and mining explosions in the mining areas of NW Russia, in particular the Khibiny Massif. Recently, seismic instrumentation has been installed inside the mines in the Khibiny Massif of the Kola Peninsula in order to provide origin times for the seismic events as well as to contribute to additional validation of the location accuracy. These recordings supplement the ground truth information that is routinely obtained by KRSC for mining explosions in the Kola Peninsula. We are also cooperating with Lawrence Livermore National Laboratory in a DOE-funded project to carry out more detailed studies of the characteristics of recordings from mining events in northern Fennoscandia and Western Russia. That project includes the installation of additional seismometers along profiles in Norway, Finland and the Kola Peninsula, for recording over a period of one year. The station Ivalo (IVL) in Fig. 6.2.1 is one of these temporary stations.

Some interesting results are emerging from comparing underground and surface explosions. For example, two explosions, one underground and one at the surface occurred in the Rasvumchorr mine in Khibiny on 16 November 2002. As illustrated in Fig. 6.2.2, the underground explosion was a ripple-fired explosion of 257 tons, whereas the open-pit explosion comprised four separate ripple-fired explosions, set off with approximately 1 second separation between each group of explosions, 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, e.g. at the temporary station in Ivalo, Finland at 300 km distance, were remarkably different: The vertical component of these recordings is shown in Fig. 6.2.3 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. A similar spectral difference between open-pit and underground explosions has been observed also in other cases.

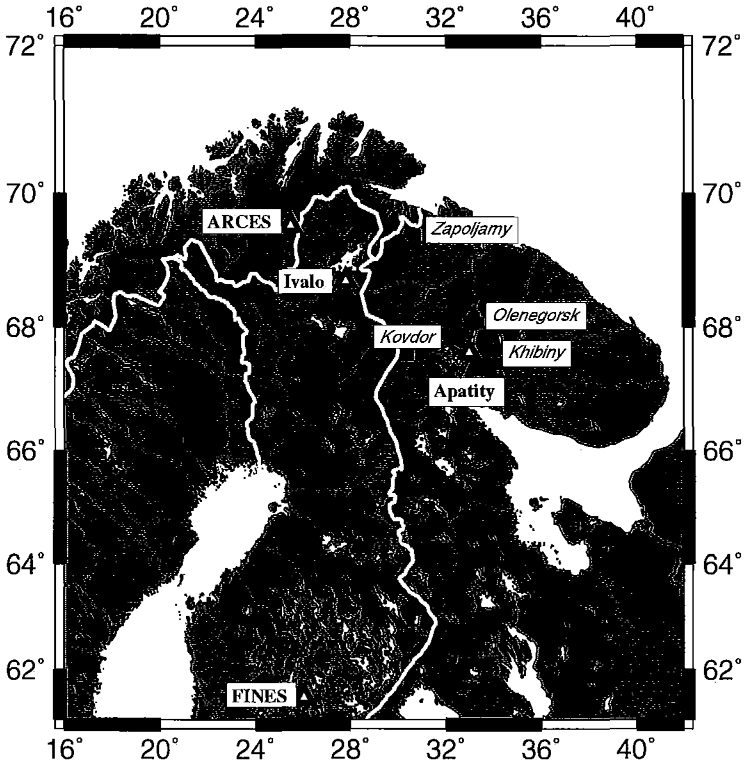

Fig. 6.2.1. Seismic stations (triangles) used in our studies of mine explosions in Kola Peninsula. The main mining sites are marked as squares.

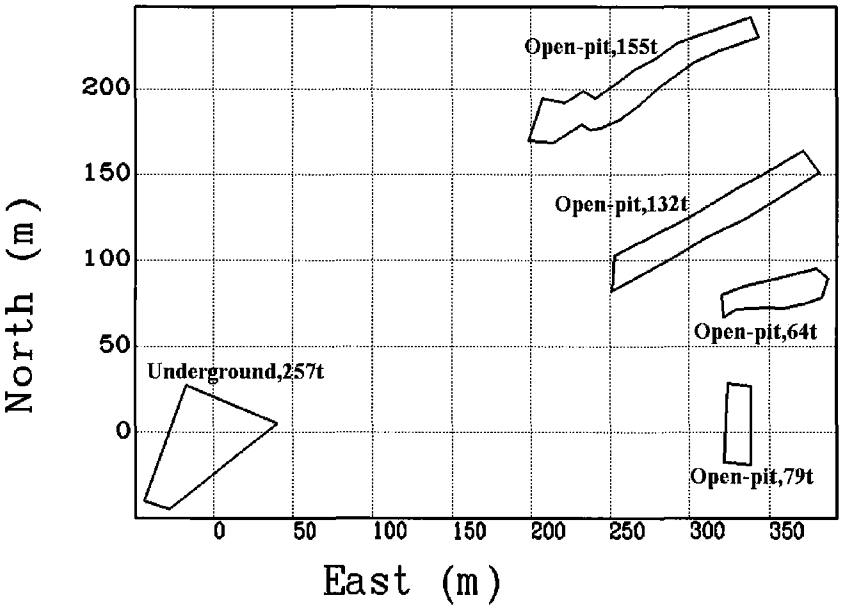

Fig. 6.2.2. Schematic view of the shot configuration for the two explosions in Khibiny on 16 November 2002. Geographical coordinates of the point (0,0) are 67.6322N 33.8565E. See text for details.

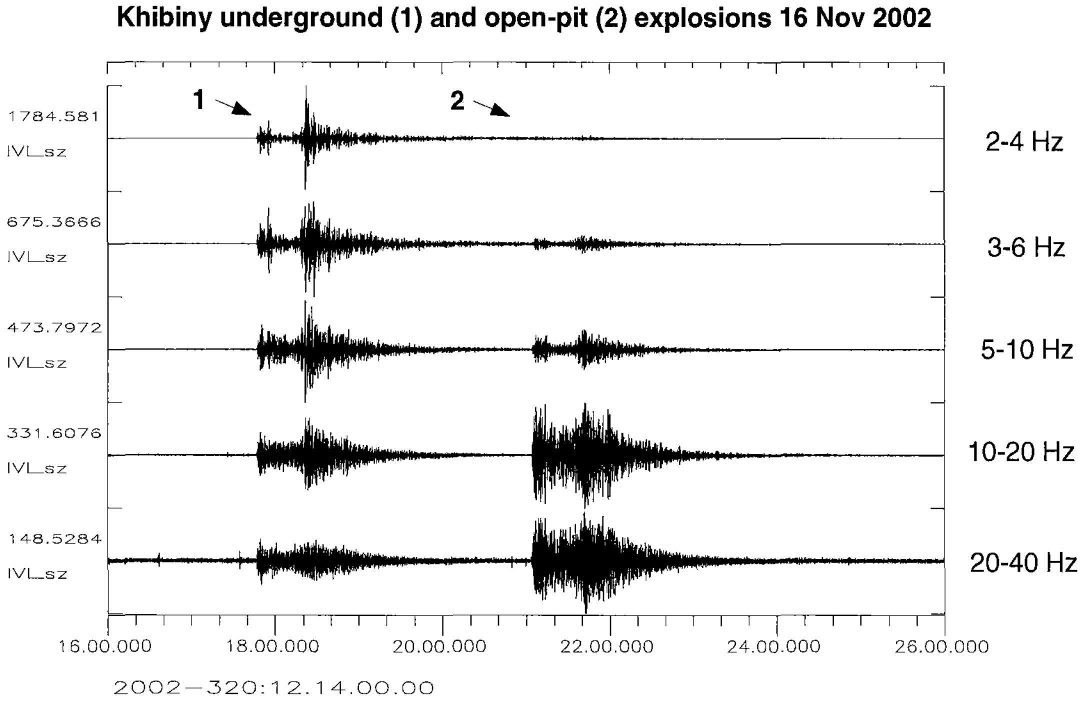

Fig. 6.2.3. Recorded SPZ waveforms at station Ivalo (northern Finland) for the two explosions in Khibiny on 16 November 2002. The data have been filtered in five different frequency bands. Note the significant difference in relative size of the two events as a function of frequency.

Kovdor mine: A single-array location study

The goal of this work is to use a single regional seismic array (ARCES) to characterize seismic signals resulting from explosions that are known to have occurred at the Kovdor open cast mine in Russia (67.557 N, 30.425 E) and use these observations to determine whether other events recorded at ARCES are the result of operations at this mine. Wherever possible, events which are deemed to be likely candidates for Kovdor events are located to the best possible accuracy. A total of 38 events within a testing period have been located in this way and the location error has been compared with that of the analyst reviewed network locations. For details, we refer to Gibbons et. al. (2003).

Fig. 6.2.1 shows the location of the Kovdor mine relative to ARCES together with the Zapoljarny, Olenegorsk and Khibiny mining regions on the Kola Peninsula. The distance between ARA0, the central seismometer of the ARCES array, and Kovdor is 298 kilometers with a receiver to source backazimuth of 135°.

Ground Truth information for events at the mines indicated in Fig. 6.2.1 has been provided by the Kola Regional Seismological Centre (KRSC) and has been used to assemble yield information and approximate origin times for explosions at the Kovdor mine between October 6, 2001, and July 13, 2002.

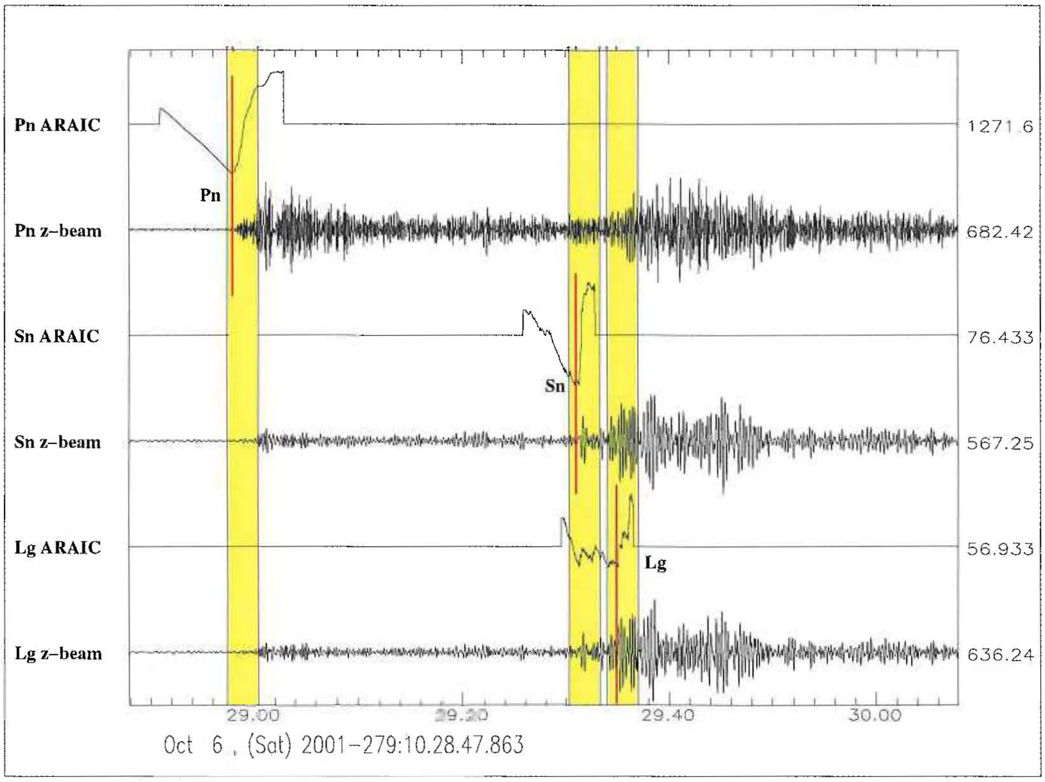

Fig. 6.2.4. Illustration of the automatic processing of a Kovdor event 2001-079 recorded at ARCES. The Pn, Sn and Lg onset picks have been made applying the autoregressive ARAIC method of Akaike (1974). We have used fixed time windows positioned relative to the Pn onset and fixed filter bands for fk-analysis of each of these phases.

We have developed a stepwise, fully automatic algorithm for identifying, processing, and locating events from the Kovdor mine, using only data from the ARCES array (see Fig. 6.2.4). Using results from the analysis of confirmed Kovdor events, we have developed a set of criteria to help determine whether or not detections from ARCES result from events at Kovdor. A detection is considered very likely to result from a Kovdor event if it passes the following three tests:

1. The automatic ARCES detection list gives velocity and azimuth values within appropriate ranges, determined from confirmed Kovdor events.
2. Velocity and azimuth values obtained from a fixed frequency band fk-analysis are consistent with a Pn-arrival from a Kovdor event.
3. There is evidence of a secondary phase (appropriate velocity and azimuth from fixed frequency band fk-analysis within a time window at a fixed delay after the first P-arrival).

The automatic process was run on ARCES data from January 1, 2002, to July 27, 2002.

- A total of 6176 detections passed test 1.
- 72 detections were still considered likely candidates after test 2.
- 48 detections were still considered likely following test 3, of which only one was found to correspond to an event located at a different site.
- All of the events confirmed by KRSC to have originated at Kovdor were successfully identified by these three tests.

Of the events which are successfully identified as likely Kovdor candidates, those satisfying a fourth condition - that at least one secondary phase has been assigned a satisfactory arrival time - may be located within the automatic process. A total of 38 events were located in this way with an error comparable to or better than that of the analyst reviewed network locations. The event locations are displayed in Fig. 6.2.5 and the statistics of these locations are given in Table 6.2.1.

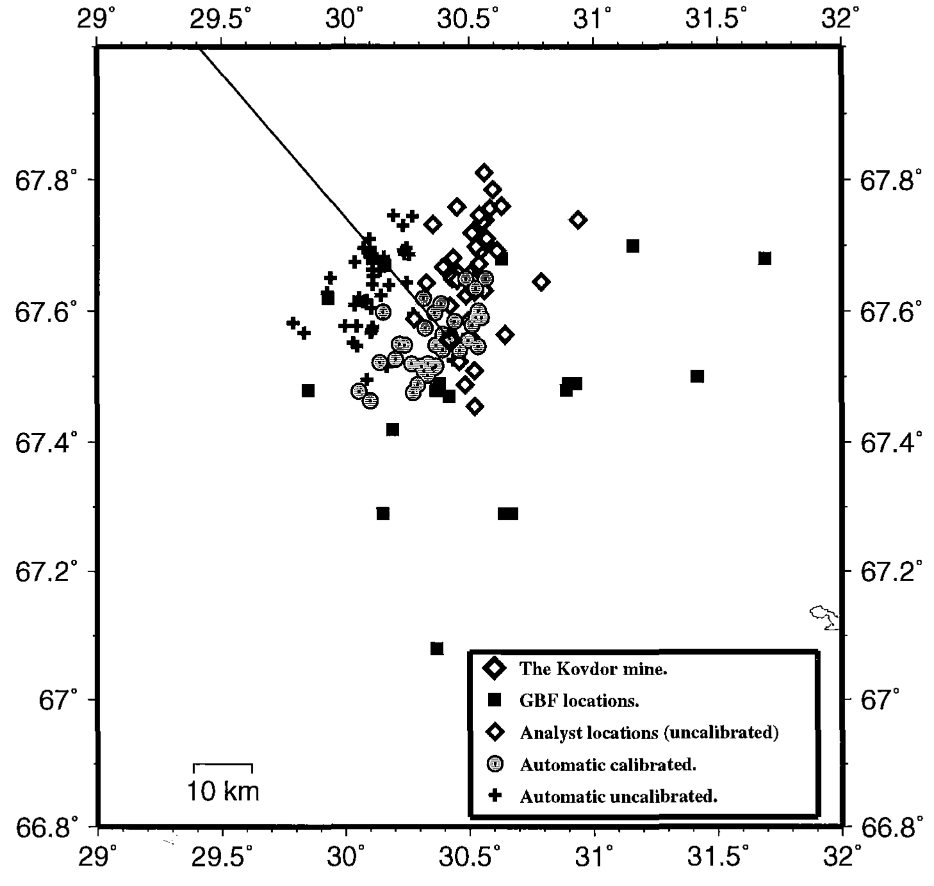

Fig. 6.2.5. Comparison of event locations by various methods for Kovdor events. The line shows the direction towards ARCES, and the true mine location is marked at the end of the line.

The results of the Kovdor study are quite encouraging. We started out with the ARCES automatic detection lists for a processing period of 208 days. During this period, we identified 6176 ARCES detections that potentially corresponded to events from Kovdor. By sophisticated automatic processing, we were able to reduce this number to 48 event candidates, out of which 47 were correct and only 1 was a false alarm. The 47 events included all of the 28 Kovdor mining explosions originally reported by KRSC during the time period, plus a number of secondary events in "double" explosions.

Our single-array location procedure, with adjustment for systematic bias, provided locations for the 38 events with detected P and S phases with a median error of only 5.8 km. This is significantly better than the median error (12.1 km) obtained in our regular analyst-reviewed network bulletin for the same event set. We should note that this excellent performance of the automatic processing is due to the application of consistent, fixed filter frequency bands and sophisticated onset time analysis, as well as calibration by comparison to ground-truth locations.

Table 6.2.1. Statistics of event locations

Location type	Number of events	Location difference (km)			
		90%	95%	Median	Maximum
Automatic network locations (GBF method)	36	32.1	42.9	20.3	102.7
ARCES one-array locations without bias corrections	38	22.7	23.3	16.6	27.3
ARCES one-array locations with bias corrections	38	12.0	12.8	5.8	18.0
Analyst reviewed network locations[a]	40	21.7	24.3	11.0	28.9

a. Note that the analyst-reviewed locations did not apply any bias corrections.

Development of site-specific GBF

In the two preceding NORSAR Semiannual Technical Summaries we have reported on our developments concerned with monitoring the Lop Nor test site in China (Lindholm et. al., 2002; Kværna et. al., 2002a). Using data from the global arrays and single stations having the best detection capability for the area, we developed and tested both an optimized site-specific threshold monitoring (SSTM) and a site-specific Generalized Beamforming (SSGBF) system for the Lop Nor test site.

We have now carried out a study of experimental Site-Specific Generalized Beamforming (SSGBF) applied to the Novaya Zemlya former nuclear test site (see Kværna et. al., 2003 for details). We have used data from the regional arrays ARCES, SPITS, FINES and NORES, with calibration based on available data for the Novaya Zemlya region. We present some preliminary results in applying SSGBF to the test site, using a 24-hour data set for performance testing. The data set covers the day 23 February 2002, when a seismic event near the test site occurred.

The Generalized Beamforming (GBF) technique, originally developed by Ringdal and Kværna (1989), is now widely accepted as the most efficient method for associating seismic phases from a global or regional network. In a typical implementation, a large number of generalized "beams" are steered to the points in a global or regional grid. An automatic detector is applied to each station or array in the network, and a set of "box-car" or "triangular" functions is generated for each station, such that the non-zero parts of these functions correspond to a time interval around a detection. By summing these functions with appropriate weights and with time delays corresponding to the particular phase-station-grid point combination, one obtains a "beam" that may then be subjected to a detector algorithm.

When monitoring a particular site it is possible to optimize the parameter settings to ensure the best possible detection probability for the target site. This idea was first tested by Ringdal and Kværna (1993) to monitor the aftershocks of a large earthquake sequence occurring in Western Caucasus during the GSETT-2 experiment. They concluded that the approach showed a superior performance compared with the association procedures being employed at the four experimental international data centers operating during GSETT-2. In the present paper we elaborate further on this site-specific approach to monitoring the Novaya Zemlya test site.

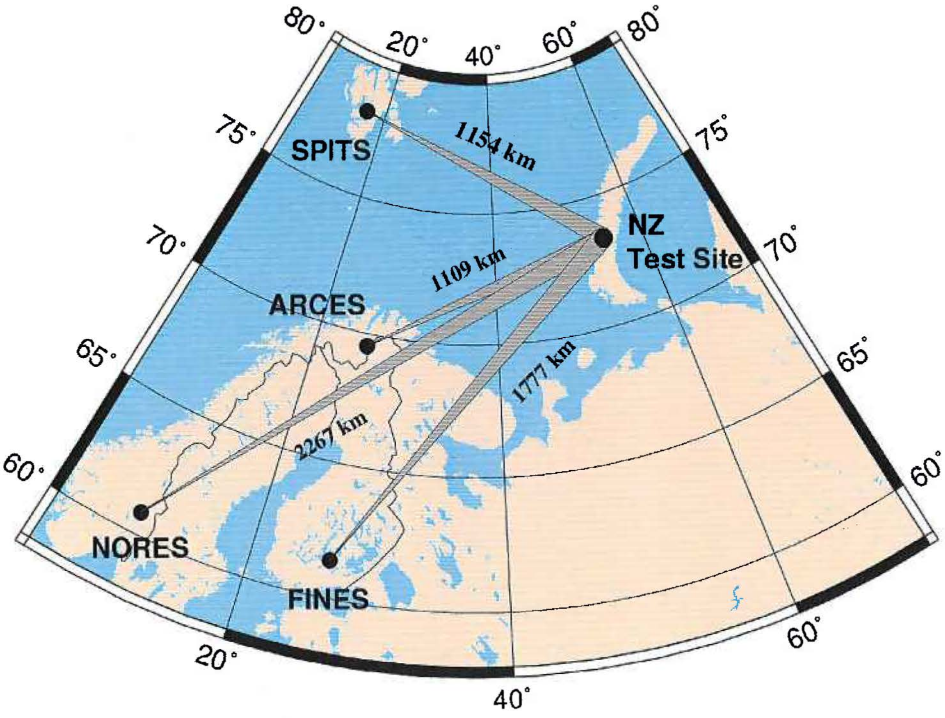

Fig. 6.2.6. Map showing the arrays used for both site-specific Threshold Monitoring and site-specific Generalized Beamforming of the former Novaya Zemlya test site.

Array network and analysis procedure

The 4-array network displayed in Fig. 6.2.6 has been shown to provide a monitoring capability for the NZ test site down to mb 2.0 for most time intervals (Kværna et. al., 2002b). Similarly, we have in the implementation of the SSGBF processing used the same 4-array network, and the processing parameters have been derived from the same events in the Novaya Zemlya region as have been used for the tuning of the SSTM process (Kværna et. al., 2002b). The beamforming procedure follows the GBF standard, except that only one generalized beam is formed in the site-specific case. The main steps are:

- Applying an automatic detector at each of the stations/arrays in the network
- Summing “boxcar” or “triangular” weight functions representing the detector outputs with the appropriate restrictions on travel time, azimuth and slowness
- Applying a thresholding procedure on the resulting generalized beam

We have used “triangular” functions centered at the expected arrival time for the beamforming in our NZ analysis. Experiments have shown that the effect of sidelobes is reduced compared with when using “boxcar” functions, while still retaining high sensitivity for detecting events in the target area.

Example: 23 February 2002

An example of SSGBF processing is shown in the left part of Fig. 6.2.7. The plots cover the day 23 February 2002. At 01:21:12.1 GMT on that day there was an event with a magnitude of about 3.2, located about 100 km north-east of the former nuclear test site. The SSGBF traces for each phase considered are shown, together with the network trace on top. To align the detections we have subtracted the phase travel-time from NZ to the respective arrays. The network trace on top is calculated by adding "triangular" functions surrounding each detection, using P and S from ARCES and SPITS, and P from NORES and FINES.

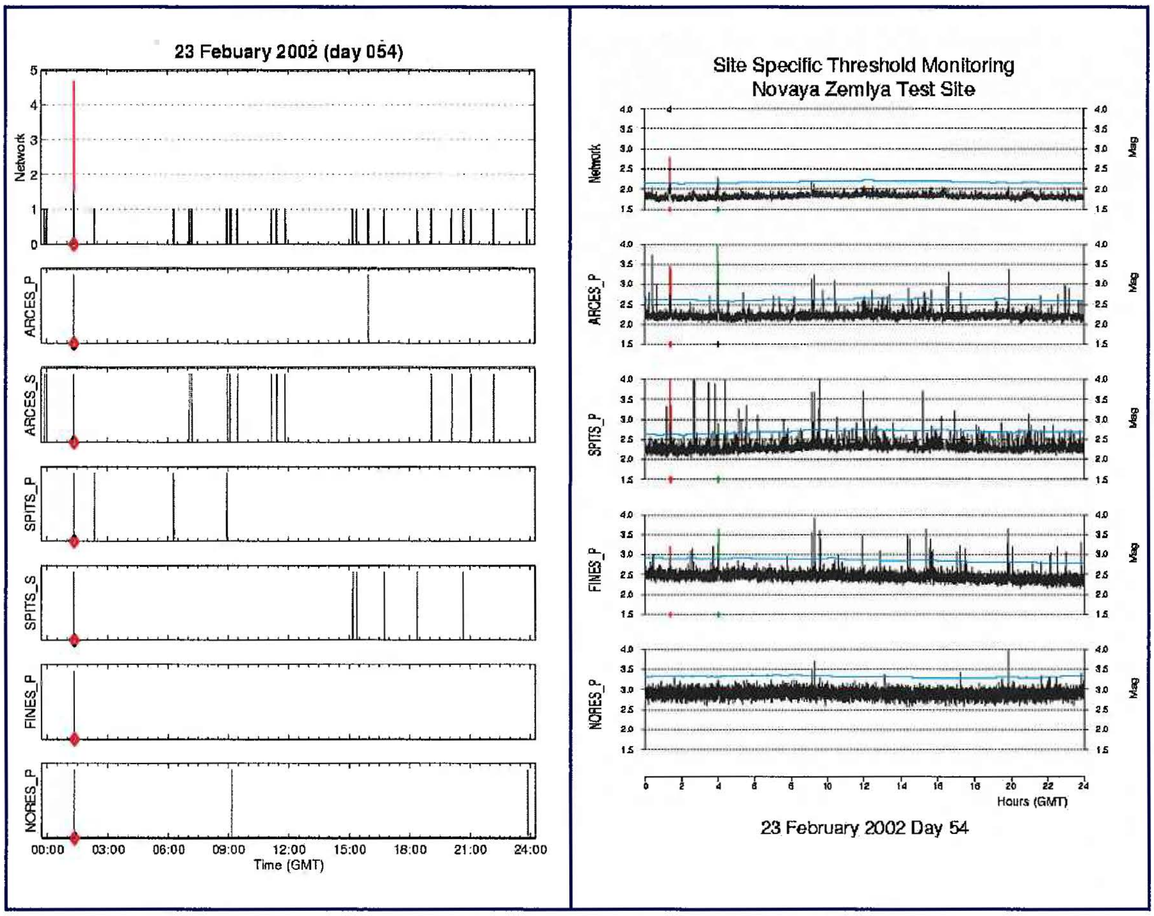

Fig. 6.2.7. SSGBF traces for 23 February 2002 are shown in the left part of the figure. The corresponding SSTM traces are shown in the right part of the figure. For detailed information on SSTM we refer to Kværna et. al., 2002b.

From the SSGBF traces of Fig. 6.2.7 we find that during 23 February 2002 there is only one significant event trigger, and this trigger corresponds to the NZ event. By summing the "triangular" weight functions of the six detected phases, we obtained a network SSGBF value of about 4.7 for the NZ event. No other peak exceeds 1 for this day. The detector performance and false alarm statistics will continue to be evaluated.

Location Calibration

Oslo Workshop on location calibration

A workshop was held in Oslo, Norway, during 4-9 May 2003 in support of the global seismic event location calibration effort currently being undertaken by PrepCom's Working Group B in Vienna. The workshop, which was chaired by Dr. Frode Ringdal, was attended by 60 scientists from 10 countries and the Provisional Technical Secretariat of the CTBTO. The workshop recommendations will be reported to Working Group B.

Conclusions and recommendations

The analysis of mining explosions in the Kola Peninsula shows significant spectral differences between surface and open-pit explosions. We recommend 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.

The automatic processing results from the Kovdor experiments shows that, at a distance of 300 km, a single array, with application of optimized processing, can locate seismic events with an accuracy comparable to or better than that of an experienced analyst, even when the analyst uses a regional network. Such performance cannot be expected at greater distances, but the possibilities and limitations of this method applied in a more general way should be investigated. Extension of the method to network processing should be considered.

The combination of the SSTM and the SSGBF methods provide a convenient tool for day-to-day monitoring of the Novaya Zemlya test site. The SSTM technique has as its main strength the ability to display the real seismic field, regardless of "station detector performance". The SSGBF technique takes advantage of the individual station detector outputs, and uses this combined information to narrow down the number of possible candidates for events in the target area. We recommend further development of this concept.

The location calibration effort will continue to be an important part of our work. The recommendations provided at the Oslo workshop should be followed up by the international community, and the progress of this work will be reviewed in future meetings.

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