NORSAR

NORSAR Scientific Report No. 2-2003

Semiannual Technical Summary

1 January - 30 June 2003

Frode Ringdal (ed.)

Kjeller, August 2003

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS: Not applicable

2a. SECURITY CLASSIFICATION AUTHORITY: Not Applicable

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): Scientific Rep. 2-2003

5. MONITORING ORGANIZATION REPORT NUMBER(S): Scientific Rep. 2-2003

6a. NAME OF PERFORMING ORGANIZATION: NORSAR

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION: HQ/AFTAC/TTS

6c. ADDRESS *(City, State, and ZIP Code)*
Post Box 53
NO-2027 Kjeller, Norway

7b. ADDRESS *(City, State, and ZIP Code)*
Patrick AFB, FL 32925-6001

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: Defense Threat Reduction Agency/NTPO

8b. OFFICE SYMBOL *(If applicable)*: DTRA/NTPO

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Contract No. F08650-01-C-0055

8c. ADDRESS *(City, State, and ZIP Code)*
1515 Wilson Blvd., Suite 720
Arlington, VA 22209

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
R&D	NORSAR Phase 3	SOW Task 5.0	Sequence No. 004A2

11. TITLE *(Include Security Classification)*: Semiannual Technical Summary, 1 January - 30 June 2003(Unclassified)

12. PERSONAL AUTHOR(S)

13a. TYPE OF REPORT: Scientific Summary

13b. TIME COVERED: FROM 1 Jan 03 TO 30 Jun 03

14. DATE OF REPORT *(Year, Month, Day)*: 2003 Aug

15. PAGE COUNT: 96

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
8	11	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: NORSAR, Norwegian Seismic Array

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report describes the research activities carried out at NORSAR under Contract No. F08650-01-C-0055 for the period 1 January - 30 June 2003. In addition, it provides summary information on operation and maintenance (O&M) activities at the Norwegian National Data Center (NDC) during the same period. Research activities described in this report, as well as transmission of selected data to the United States NDC, are funded by the United States Department of Defense. The O&M activities, including operation of transmission links within Norway and to Vienna, Austria, are being funded jointly by the CTBTO/PTS and the Norwegian Government, with the understanding that the funding of IMS-related activities will gradually be transferred to the CTBTO/PTS. The O&M statistics presented in this report are included for the purpose of completeness, and in order to maintain consistency with earlier reporting practice.

(cont.)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION

22a. NAME OF RESPONSIBLE INDIVIDUAL: Lt. Col. William S. Jones

22b. TELEPHONE *(Include Area Code)*: (407) 494-7985

22c. OFFICE SYMBOL: AFTAC/TTS

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

Abstract (cont.)

The NOA Detection Processing system has been operated throughout the period with an average uptime of 100.00%. A total of 1996 seismic events have been reported in the NOA monthly seismic bulletin from January through June 2003. On-line detection processing and data recording at the NDC of ARCES and FINES data have been conducted throughout the period. Data from the two small-aperture arrays at sites in Spitsbergen and Apatity, Kola Peninsula, as well as the Hagfors array in Sweden (HFS), have also been recorded and processed. Processing statistics for the arrays for the reporting period are given.

A summary of the activities related to the GSETT-3 experiment and experience gained at the Norwegian NDC during the reporting period is provided in Section 4. Norway is now contributing primary station data from two seismic arrays: ARCES and NOA and one auxiliary array (SPITS). These data are being provided to the IDC via the global communications infrastructure (GCI). Continuous data from all three arrays are in addition being transmitted to the US NDC. The performance of the data transmission to the US NDC has been satisfactory during the reporting period.

Summaries of six scientific and technical contributions are presented in Chapter 6 of this report.

Section 6.1 contains a report from the meeting of the IDC Technical Experts Group on Seismic Event Location in Oslo, Norway on 4-9 May 2003. This was the fifth annual meeting of the Experts Group in support of Working Group B of the CTBTO Preparatory Commission. The purpose of the meeting was to support the ongoing calibration and screening efforts of the IDC and in particular to review progress toward developing regionalized travel times to improve the quality of location estimates of seismic events reported in the IDC bulletins.

Section 6.2 is entitled "Research in regional seismic monitoring" and contains a summary paper presented at the 25th Annual Seismic Research Symposium, describing a continued effort in regional monitoring research. 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. We have made some significant progress in automating the detection and location of seismic events from selected mining areas. We have also continued our efforts to develop and improve the site-specific threshold monitoring system for the Novaya Zemlya test site in Russia and have 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.

Section 6.3 is entitled "Energy partitioning for seismic events in Fennoscandia and NW Russia" and is an initial report from a separate US-sponsored project. The paper is included in this Semiannual Report in view of its relevance to the general tasks undertaken for the present contract. The objective of the project is to study the generation of seismic shear waves by explosions. The plan is to analyze data from close-in stations in mines to measure seismic waves within a few hundred meters of the explosions. We will combine these data with data from regional stations (out to several hundred kilometers) to characterize the mechanism of shear wave generation as a function of distance from the mine. Three-dimensional numerical (finite

difference) simulations of wave propagation (full waveform) within the mines will be compared to the data taken in the mines as an aid to interpretation.

Section 6.4 is entitled "Processing of regional phases using the large aperture NOA array". This study has been undertaken to develop a substitute for the regional NORES array (which is currently inoperational) for inclusion in the NORSAR regional processing system.Automatic detections from the prototype regional NOA processing system have been included in a test version of the NORSAR Generalized Beamforming (GBF) process. The test version has been quite successful at locating events within approximately 350 km of the array and many events which have not been detected by the GBF system since the loss of the NORES array can now be included. The NOA array can also provide a useful constraint on events which otherwise would only be detected by the Hagfors array.

Section 6.5 is a study of two seismic events associated with a recent mining accident in the Barentsburg coal mine on Spitsbergen. This accident occured at 12:27 GMT (14:27 local time) on 7 June 2003 and was caused by a collapse in the mine. The collapse generated seismic signals with a magnitude of 3.7 as reported in the CTBTO Reviewed Event Bulletin (REB). About 2 hours later, at 14:23 GMT, there was another seismic event of approximately the same size in the same area. We have on the basis of the P-phase picks at the four stations (BRB, SPITS, KBS and HSP) located the events within less than 1-2 km from the mine. The events are therefore useful as Ground Truth observations for the global location calibration program.

Section 6.6 is a study entitled "Body-Wave Magnitude Residuals of IMS Stations". The basic data set used is the set of the amplitude and period measurements of first P onsets as published since 1995 in the REBs by the prototype IDC for the GSETT-3 experiment at CMR in Arlington and later by the IDC of the CTBTO in Vienna. The IMS network of seismic stations was constantly under change. In this study, amplitude observations were only analyzed for stations which are part of the IMS as of June 2003. The REBs contain the most self-consistent database of amplitude and period observations of body waves. These data can be corrected for the mean station bias between m_b and Mw. The remaining m_b - Mw relation can simply be modeled with a 2nd order function. By applying this relation one can derive an expected m_b value for each event and calculate observed station m_b residuals. These residuals are up to about +/- 2 (and standard deviation of about +/- 0.44) magnitude units. Binning these residuals with respect to their source regions and plotting them on geographical maps clearly show a source region specific pattern. The reasons for this observation will mostly be ray-path dependent attenuation anomalies (defocusing, focusing) and source region dependent dominant double-couple radiation.

AFTAC Project Authorization	:	T/0155/PKO
ARPA Order No.	:	4138 AMD # 53
Program Code No.	:	0F10
Name of Contractor	:	Stiftelsen NORSAR
Effective Date of Contract	:	1 Feb 2001 (T/0155/PKO)
Contract Expiration Date	:	31 December 2005
Project Manager	:	Frode Ringdal +47 63 80 59 00
Title of Work	:	The Norwegian Seismic Array (NORSAR) Phase 3
Amount of Contract	:	$ 3,383,445
Period Covered by Report	:	1 January - 30 June 2003

The research presented in this report was supported by the Defense Threat Reduction Agency and was monitored by AFTAC, Patrick AFB, FL32925, under contract no. F08650-01-C-0055.

The operational activities of the seismic field systems and the Norwegian National Data Center (NDC) are currently jointly funded by the Norwegian Government and the CTBTO/PTS, with the understanding that the funding of IMS-related activities will gradually be transferred to the CTBTO/PTS.

NORSAR Contribution No. 834

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1 Summary

This report describes the research activities carried out at NORSAR under Contract No. F08650-01-C-0055 for the period 1 January - 30 June 2003. In addition, it provides summary information on operation and maintenance (O&M) activities at the Norwegian National Data Center (NDC) during the same period. Research activities described in this report, as well as transmission of selected data to the United States NDC, are funded by the United States Department of Defense. The O&M activities, including operation of transmission links within Norway and to Vienna, Austria are being funded jointly by the CTBTO/PTS and the Norwegian Government, with the understanding that the funding of all IMS-related activities will gradually be transferred to the CTBTO/PTS. The O&M statistics presented in this report are included for the purpose of completeness, and in order to maintain consistency with earlier reporting practice.

The seismic arrays operated by the Norwegian NDC comprise the Norwegian Seismic Array (NOA), the Arctic Regional Seismic Array (ARCES) and the Spitsbergen Regional Array (SPITS). This report also presents statistics for additional seismic stations which through cooperative agreements with institutions in the host countries provide continuous data to the NORSAR Data Processing Center (NDPC). These stations comprise the Finnish Regional Seismic Array (FINES), the Hagfors array in Sweden (HFS) and the regional seismic array in Apatity, Russia.

The NOA Detection Processing system has been operated throughout the period with an average uptime of 100.00%. A total of 1996 seismic events have been reported in the NOA monthly seismic bulletin from January through June 2003. On-line detection processing and data recording at the NDC of ARCES and FINES data have been conducted throughout the period. Data from the two small-aperture arrays at sites in Spitsbergen and Apatity, Kola Peninsula, as well as the Hagfors array in Sweden, have also been recorded and processed. Processing statistics for the arrays for the reporting period are given.

A summary of the activities related to the GSETT-3 experiment and experience gained at the Norwegian NDC during the reporting period is provided in Section 4. Norway is now contributing primary station data from two seismic arrays: ARCES and NOA and one auxiliary array (SPITS). These data are being provided to the IDC via the global communications infrastructure (GCI). Continuous data from all three arrays are in addition being transmitted to the US NDC. The performance of the data transmission to the US NDC has been satisfactory during the reporting period.

The PrepCom has encouraged states that operate IMS-designated stations to continue to do so on a voluntary basis and in the framework of the GSETT-3 experiment until the stations have been certified for formal inclusion in IMS. So far among the Norwegian stations, the NOA and the ARCES array (PS27 and PS28 respectively) and the radionuclide station at Spitsbergen (RN49) have been certified. We envisage continuing the provision of data from these and other Norwegian IMS-designated stations in accordance with current procedures.

Summaries of six scientific and technical contributions are presented in Chapter 6 of this report.

Section 6.1 contains a report from the meeting of the IDC Technical Experts Group on Seismic Event Location in Oslo, Norway on 4-9 May 2003. This was the fifth annual meeting of the

Experts Group in support of Working Group B of the CTBTO Preparatory Commission. The purpose of the meeting was to support the ongoing calibration and screening efforts of the IDC and in particular to review progress toward developing regionalized travel times to improve the quality of location estimates of seismic events reported in the IDC bulletins.

The meeting was attended by sixty technical experts, coming from ten signatory countries and the Provisional Technical Secretariat. Dr. Frode Ringdal of Norway chaired the meeting, which was organized into four sessions, and included Working Group discussions to address the technical issues in detail. Recommendations from the meeting will be presented to Working Group B in Vienna during its September 2003 session (CTBT/WGB/TL-2/76).

Section 6.2 is entitled "Research in regional seismic monitoring" and contains a summary paper presented at the 25th Annual Seismic Research Symposium, describing a continued effort in regional monitoring research. 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 excellent 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.

Section 6.3 is entitled "Energy partitioning for seismic events in Fennoscandia and NW Russia" and is an initial report from a separate US-sponsored project. The paper is included in this Semiannual Report in view of its relevance to the general tasks undertaken for the present contract.

The objective of the project is to study the generation of seismic shear waves by explosions. The plan is to analyze data from close-in stations in mines to measure seismic waves within a few hundred meters of the explosions. We will combine these data with data from regional stations (out to several hundred kilometers) to characterize the mechanism of shear wave generation as a function of distance from the mine. Three-dimensional numerical (finite difference) simulations of wave propagation (full waveform) within the mines will be compared to the data taken in the mines as an aid to interpretation.

Cooperation has been established with the operators of the Pyhasalmi mine in Finland, where a new in-mine network of 16 sensors has been installed (4 three-component and 12 vertical-component geophones). For the 1500 m deep Pyhasalmi mine there exists comprehensive and detailed information on the mine geometry in digital form. This information has been utilized to build up a model of the mine, using the NORSAR 3D Model Builder. The result is a three-dimensional gridded model which includes the velocity and density characteristics of the ore bodies, mined-out voids, access tunnels and surrounding rocks. An initial three-dimensional finite-difference calculation has been performed for an explosive source in the mine model and, for comparison, similar calculations have been made for a homogeneous model. These preliminary results indicate that near-source heterogeneities, like voids from the mined out region and low velocity backfilled material, play an important role in shaping the seismic wavefield.

Since the installation of the Pyhasalmi in-mine network in November-December 2002, numerous microearthquakes and explosions have been recorded and located. NORSAR has obtained both bulletin and waveform data for these events, and we have started to investigate these data in more detail for the purpose of studying the development of the seismic shear waves.

A particularly interesting event occurred in the Pyhasalmi mine on 26 January 2003. This was a felt rockburst, with a magnitude of about 1.0, which was also detected and located by the Finnish National Network operated by the University of Helsinki. Our plan is to use this event for validation of the wavefield modelling, as well as for more detailed analysis of the energy partitioning within the mine network, and at local and regional distances.

Section 6.4 is entitled "Processing of regional phases using the large aperture NOA array". This study has been undertaken to develop a substitute for the regional NORES array (which is currently inoperational) for inclusion in the NORSAR regional processing system. The NOA seismic array (originally called the NORSAR array) was designed to maximize signal coherence for teleseismic events and, at the same time, minimize the coherence of noise, therefore providing an optimal signal to noise ratio (SNR) for teleseismic phases using ordinary beamforming. With an inter-station separation of about 3 km, signal coherence is very low for seismic phases from regional events. In order to process regional phases using NOA, a special processing system is therefore required. We have developed such a system, which works by calculating the arrival times of phases at each of the short period vertical instruments in the array and by fitting a wavefront to those arrival times. The circular wavefront formulation of Almendros et al. (1999) was found to give very robust and realistic estimates of slowness and azimuth of phases at near-regional distances, an iterative process being employed to find the parameters which minimize time residuals. This iterative method could robustly be applied to all arriving wavefronts because the limiting case of the circular wavefront is a plane wavefront.

Automatic detections from the prototype regional NOA processing system have been included in a test version of the GBF process. The test version has been quite successful at locating events within approximately 350 km of the array and many events which have not been detected by the GBF system since the loss of the NORES array can now be included. The NOA array can also provide a useful constraint on events which otherwise would only be detected by the Hagfors array.

The remaining challenges to the process are to improve the determination of onset times for secondary phases and to improve the detection and processing of events at far-regional distances. The key to the first issue is almost certainly the use of the rotated horizontal components of the 3-component broadband instruments, of which one is located in each subarray. The key to the second issue is probably the use of detecting beams which cover more than one subarray: possibly with the additional use of the 3-component instruments.

Section 6.5 is a study of two seismic events associated with a recent mining accident in the Barentsburg coal mine on Spitsbergen. This accident occured at 12:27 GMT (14:27 local time) on 7 June 2003 and was caused by a collapse in the mine. The collapse generated seismic signals with a magnitude of 3.7 as reported in the CTBTO Reviewed Event Bulletin (REB). About 2 hours later, at 14:23 GMT, there was another seismic event of approximately the same size in the same area.

We have on the basis of the P-phase picks at the four stations (BRB, SPITS, KBS and HSP) located the events within less than 1-2 km from the mine. The events are therefore useful as Ground Truth observations for the global location calibration program.

The first arrivals at all of the four stations have negative polarity for the events. This suggests that it was not an earthquake that triggered the collapse. An earthquake would most likely not show the same first arrival polarity at the four stations, since the stations are located at very different azimuths from the events. On the contrary, we expect that a mine collapse would generate negative first arrival polarity for stations in all directions. We therefore believe that the mine collapses themselves are the primary seismic sources.

Section 6.6 is a study entitled "Body-Wave Magnitude Residuals of IMS Stations". The body-wave magnitude mb is important in many schemes for discriminating between natural earthquakes and man-made explosions. Observed magnitudes show a large scatter and stations often have a systematic magnitude bias, which makes it difficult to calculate magnitudes in the case of events with only a small number of observations. However, this is the scenario for seismic stations analyzed at the IDC of the CTBTO in Vienna.

The amplitude (and thereby magnitude) observations at the IMS stations must therefore be calibrated. The amplitude measurements in the bulletins of IDC (REBs) have the advantage that they follow common rules and that therefore the scatter due to the application of different digital filters, unknown transfer functions, and analysis rules is reduced compared with the amplitude data in other international catalogues. Today, for many of the IMS stations, thousands of amplitude readings are now available for a systematic analysis of the station bias.

The basic data set used is the set of the amplitude and period measurements of first P onsets as published since 1995 in the REBs by the prototype IDC for the GSETT-3 experiment at CMR in Arlington and later by the IDC of the CTBTO in Vienna. The IMS network of seismic stations was constantly under change. In this study, amplitude observations were only analyzed for stations which are part of the IMS as of June 2003.

Although the amplitude measuring procedure at the prototype IDC and the IDC was stable over time, the whole IMS network was and is still under construction. Stations were added one by one and, for some, the equipment was changed due to major refurbishment work. Station-response information was always included when it became available at the prototype IDC or IDC, which was not necessarily the same time at which the station's onset readings were included in the REBs. Therefore, the time-dependent behavior of the difference between station m_b observations and the Mw values calculated here, was chosen as an indicator for the stability of the amplitude measurements.

The REBs contain the most self-consistent database of amplitude and period observations of body waves. These data can be corrected for the mean station bias between m_b and Mw. The remaining m_b - Mw relation can simply be modeled with a 2nd order function. By applying this relation one can derive an expected m_b value for each event and calculate observed station m_b residuals. These residuals are up to about +/- 2 (and standard deviation of about +/- 0.44) magnitude units.

Binning these residuals with respect to their source regions and plotting them on geographical maps clearly show a source region specific pattern. The reasons for this observation will mostly be ray-path dependent attenuation anomalies (defocusing, focusing) and source region dependent dominant double-couple radiation.

The study recommends to investigate the application of source-station specific corrections (SSSCs) for amplitude / period observations to obtain more stable magnitude estimates. However, this will require more studies on the influence of a mixture of calibrated and uncalibrated areas / stations on network magnitudes.

Frode Ringdal

2 Operation of International Monitoring System (IMS) Stations in Norway

2.1 PS27 — Primary Seismic Station NOA

The average recording time was 100%, the same as for the previous reporting period.

There were no outages of all subarrays at the same time.

Monthly uptimes for the NORSAR on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

January	:	100%
February	:	100%
March	:	100%
April	:	100%
May	:	100%
June	:	100%

J. Torstveit

NOA Event Detection Operation

In Table 2.1.1 some monthly statistics of the Detection and Event Processor operation are given. The table lists the total number of detections (DPX) triggered by the on-line detector, the total number of detections processed by the automatic event processor (EPX) and the total number of events accepted after analyst review (teleseismic phases, core phases and total).

	Total DPX	Total EPX	Accepted Events		Sum	Daily
			P-phases	Core Phases		
Jan	10,872	833	227	51	278	9.0
Feb	12,366	1,114	228	58	286	10.2
Mar	12,777	1,122	299	68	367	11.8
Apr	8,147	832	258	52	310	10.3
May	6,184	826	309	53	362	11.7
Jun	5,670	794	298	65	363	12.1
	56,016	5,521	1,419	347	1,996	10.85

Table 2.1.1. *Detection and Event Processor statistics, 1 January - 30 June 2003.*

NOA detections

The number of detections (phases) reported by the NORSAR detector during day 001, 2003, through day 181, 2003, was 56,016, giving an average of 309 detections per processed day (181 days processed).

B. Paulsen

U. Baadshaug

2.2 PS28 — Primary Seismic Station ARCES

The average recording time was 100%, the same as for the previous reporting period.

There was one outage: 14/05 02.45.40.000 - 02.50.30.000..

Monthly uptimes for the ARCES on-line data recording task, taking into account all factors (field installations, transmission lines, data center operation) affecting this task were as follows:

January	:	100%
February	:	100%
March	:	100%
April	:	100%
May	:	99.99%
June	:	100%

J. Torstveit

Event Detection Operation

ARCES detections

The number of detections (phases) reported during day 001, 2003, through day 181, 2003, was 177,106, giving an average of 978 detections per processed day (181 days processed).

Events automatically located by ARCES

During days 001, 2003, through 181, 2003, 8,933 local and regional events were located by ARCES, based on automatic association of P- and S-type arrivals. This gives an average of 49.4 events per processed day (181 days processed). 53% of these events are within 300 km, and 82% of these events are within 1000 km.

U. Baadshaug

2.3 AS72 — Auxiliary Seismic Station Spitsbergen

The average recording time was 99.80% as compared to 99.96% for the previous reporting period.

Table 2.3.1 lists the time periods of the main downtimes in the reporting period.

Date	Time
24/01	07.47.18.000 - 07.54.51.000
24/01	09.21.10.000 - 09.28.43.000
30/03	12.25.39.000 - 12.33.12.000
06/04	11.56.31.000 - 12.04.04.000
15/04	11.17.50.000 - 11.25.24.000
16/04	11.11.44.000 - 11.19.17.000
20/04	04.05.38.000 - 04.13.11.000
21/04	10.49.51.000 - 10.57.24.000
24/04	10.37.06.000 - 10.44.38.000
25/04	10.37.37.000 - 10.45.10.000
26/04	10.31.29.000 - 10.39.02.000
28/04	10.25.23.000 - 10.32.55.000
30/04	10.16.15.000 - 10.23.47.000
01/05	10.10.07.000 - 10.17.40.000
09/05	09.21.02.000 - 09.28.35.000
10/05	09.34.55.000 - 09.42.28.000
15/05	09.26.07.000 - 09.33.39.000
17/05	09.09.59.000 - 09.17.32.000
22/05	08.51.43.000 - 08.59.15.000
09/06	09.09.00.000 - 09.34.37.000
09/06	09.40.54.000 - 09.48.29.000
23/06	12.14.40.000 - 12.24.20.000

Table 2.3.1. *The main interruptions in recording of Spitsbergen data at NDPC, 1 January - 30 June 2003.*

Monthly uptimes for the Spitsbergen on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

January	:	99.96%
February	:	100%
March	:	99.98%
April	:	99.78%
May	:	99.84%
June	:	99.90%

J. Torstveit

Event Detection Operation

Spitsbergen array detections

The number of detections (phases) reported from day 001, 2003, through day 181, 2003, was 301,965, giving an average of 1668 detections per processed day (181 days processed).

Events automatically located by the Spitsbergen array

During days 001, 2003, through 181, 2003, 36,030 local and regional events were located by the Spitsbergen array, based on automatic association of P- and S-type arrivals. This gives an average of 199.1 events per processed day (181 days processed). 67% of these events are within 300 km, and 83% of these events are within 1000 km.

U. Baadshaug

2.4 AS73 — Auxiliary Seismic Station at Jan Mayen

The IMS auxiliary seismic network will include a three-component station on the Norwegian island of Jan Mayen. The station location given in the protocol to the Comprehensive Nuclear-Test-Ban Treaty is 70.9°N, 8.7°W.

The University of Bergen has operated a seismic station at this location since 1970. An investment in the new station at Jan Mayen will be made in due course and in accordance with PrepCom program and budget decisions. A so-called Parent Network Station Assessment for AS73 was completed in April 2002. Work is now underway to prepare for the installation of a vault at a new location (71.0°N, 8.5°W) recently approved by the PrepCom. In the meantime, data from the existing seismic station on Jan Mayen are being transmitted to the NDC at Kjeller and to the University of Bergen via a VSAT link installed in April 2000.

J. Fyen

2.5 IS37 — Infrasound Station at Karasjok

The IMS infrasound network will include a station at Karasjok in northern Norway. The coordinates given for this station are 69.5°N, 25.5°E. These coordinates coincide with those of the primary seismic station PS28.

A site survey for this station was carried out during June/July 1998 as a cooperative effort between the Provisional Technical Secretariat of the CTBTO and NORSAR. Analysis of the data collected at several potential locations for this station in and around Karasjok has been completed. The results of this analysis have led to a recommendation on the exact location of the infrasound station. This location needs to be surveyed in detail. The next step will be to approach the local authorities to obtain the permission necessary to establish the station. Station installation is now expected to take place in the year 2004.

S. Mykkeltveit

2.6 RN49 — Radionuclide Station on Spitsbergen

The IMS radionuclide network will include a station at Longyearbyen on the island of Spitsbergen, with location 78.2°N, 16.4°E, as given in the protocol to the Comprehensive Nuclear-Test-Ban Treaty. These coordinates coincide with those of the auxiliary seismic station AS72. According to PrepCom decision, this station will also be among those IMS radionuclide stations that will have a capability of monitoring for the presence of relevant noble gases upon entry into force of the CTBT.

A site survey for this station was carried out in August of 1999 by NORSAR, in cooperation with the Norwegian Radiation Protection Authority. The site survey report to the PTS contained a recommendation to establish this station at Platåberget, some 20 km away from the Treaty location. The PrepCom approved the corresponding coordinate change in its meeting in May 2000. The station installation was part of PrepCom's work program and budget for the year 2000. The infrastructure for housing the station equipment has been established, and a noble gas detection system, based on the Swedish "SAUNA" design, was installed at this site in May 2001, as part of PrepCom's noble gas experiment. A particulate station ("ARAME" design) was installed at the same location in September 2001. A certification visit to the station took place in October 2002, and the particulate station was certified on 10 June 2003. The equipment at RN49 is being maintained and operated in accordance with a contract with the CTBTO/PTS.

S. Mykkeltveit

3 Contributing Regional Seismic Arrays

3.1 NORES

NORES has been out of operation since a thunderstorm destroyed the station electronics on 11 June 2002.

J. Torstveit

3.2 Hagfors (IMS Station AS101)

The average recording time was 100% the same as for the previous reporting period.

Monthly uptimes for the Hagfors on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

January	:	100%
February	:	100%
March	:	100%
April	:	100%
May	:	100%
June	:	100%

J. Torstveit

Hagfors Event Detection Operation

Hagfors array detections

The number of detections (phases) reported from day 001, 2003, through day 181, 2003, was 85,436, giving an average of 472 detections per processed day (181 days processed).

Events automatically located by the Hagfors array

During days 001, 2003, through 181, 2003, 2425 local and regional events were located by the Hagfors array, based on automatic association of P- and S-type arrivals. This gives an average of 13.4 events per processed day (181 days processed). 65% of these events are within 300 km, and 86% of these events are within 1000 km.

U. Baadshaug

3.3 FINES (IMS station PS17)

The average recording time was 100% as it was for the previous reporting period.

There were 19 outages that lasted from 2 to 10 seconds in the period.

Monthly uptimes for the FINES on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

January	:	100%
February	:	100%
March	:	100%
April	:	100%
May	:	100%
June	:	100%

J. Torstveit

FINES Event Detection Operation

FINES detections

The number of detections (phases) reported during day 001, 2003, through day 181, 2003, was 54,643, giving an average of 302 detections per processed day (181 days processed).

Events automatically located by FINES

During days 001, 2003, through 181, 2003, 2521 local and regional events were located by FINES, based on automatic association of P- and S-type arrivals. This gives an average of 13.9 events per processed day (181 days processed). 75% of these events are within 300 km, and 88% of these events are within 1000 km.

U. Baadshaug

3.4 Apatity

The average recording time was 99.62% in the reporting period compared to 99.32% during the previous period.

The main outages in the period are given in Table 3.4.1.

Day No. 2003	Time	Length of outage (s)
002:	12.12.18.000 - 12.18.23.000	365.000
006:	14.39.46.000 - 14.46.29.000	403.000
007:	20.30.08.000 - 20.36.23.000	375.000
007:	20.36.35.000 - 20.46.47.000	612.000
016:	12.13.08.000 - 12.24.48.000	700.000
028:	11.48.36.000 - 11.56.31.000	475.000
030:	12.14.00.000 - 12.21.31.000	451.000
037:	02.25.33.000 - 02.32.47.000	434.000
041:	05.59.53.000 - 06.09.28.000	575.000
041:	09.27.05.000 - 09.33.08.000	363.000
043:	10.45.42.000 - 10.52.04.000	382.000
044:	12.14.24.000 - 12.21.31.000	427.000
050:	15.19.32.000 - 15.26.32.000	420.000
056:	04.28.13.000 - 05.13.03.000	2690.000
056:	15.41.44.000 - 16.22.59.000	2475.000
070:	16.15.52.000 - 16.21.58.000	366.000
076:	10.47.51.000 - 10.59.34.000	703.000
076:	11.04.06.000 - 11.11.34.000	448.000
076:	11.58.15.000 - 12.10.01.000	706.000
076:	13.51.03.000 - 13.57.32.000	389.000
076:	14.01.32.000 - 14.07.39.000	367.000
077:	07.47.36.000 - 07.59.18.000	702.000
077:	09.31.55.000 - 09.37.59.000	364.000
077:	21.29.00.000 - 21.36.35.000	455.000
077:	22.47.59.000 - 22.59.43.000	704.000
077:	23.06.09.000 - 23.59.59.000	3230.000
078:	00.00.01.000 - 04.50.02.000	17401.000
084:	16.16.40.000 - 16.22.46.000	366.000
091:	17.02.07.000 - 17.08.18.000	371.000
098:	16.17.27.000 - 16.29.09.000	702.000
109:	10.47.19.000 - 10.53.31.000	372.000
109:	18.16.42.000 - 18.29.42.000	780.000

Day No. 2003	Time	Length of outage (s)
112:	16.18.15.000 - 16.29.56.000	701.000
119:	14.38.37.000 - 14.44.43.000	366.000
119:	15.17.03.000 - 15.23.07.000	364.000
126:	02.43.56.000 - 02.51.39.000	463.000
126:	03.02.57.000 - 03.14.45.000	708.000
126:	04.38.00.000 - 04.44.02.000	362.000
126:	05.17.15.000 - 05.23.19.000	364.000
126:	05.55.57.000 - 06.02.02.000	365.000
126:	06.35.46.000 - 06.41.51.000	365.000
126:	07.15.37.000 - 07.21.44.000	367.000
126:	07.54.00.000 - 08.00.04.000	364.000
126:	08.33.48.000 - 08.39.54.000	366.000
126:	09.13.08.000 - 09.19.12.000	364.000
126:	16.18.27.000 - 16.30.07.000	700.000
134:	07.38.49.000 - 07.51.41.000	772.000
138:	01.11.24.000 - 01.43.46.000	1942.000
138:	01.45.46.000 - 01.51.42.000	356.000
139:	12.02.52.000 - 12.17.35.000	883.000
139:	15.18.15.000 - 15.29.55.000	700.000
140:	11.47.27.000 - 11.53.32.000	365.000
140:	16.19.11.000 - 16.26.42.000	451.000
142:	05.29.25.000 - 05.36.42.000	437.000
142:	09.52.24.000 - 09.58.29.000	365.000
153:	12.11.49.000 - 12.18.20.000	391.000
156:	03.10.39.000 - 03.16.44.000	365.000
168:	04.40.00.000 - 04.45.00.000	300.000
169:	06.00.00.000 - 06.05.00.000	300.000
169:	10.05.00.000 - 10.10.00.000	300.000
169:	13.35.00.000 - 13.40.00.000	300.000
169:	16.00.00.000 - 16.05.00.000	300.000
169:	16.20.00.000 - 16.25.00.000	300.000
169:	17.45.00.000 - 17.55.00.000	600.000
169:	18.35.00.000 - 18.40.00.000	300.000
169:	19.35.00.000 - 19.40.00.000	300.000
169:	20.00.00.000 - 20.05.00.000	300.000
169:	21.05.00.000 - 21.10.00.000	300.000
170:	00.05.00.000 - 00.10.00.000	300.000

Day No. 2003	Time	Length of outage (s)
170:	01.40.00.000 - 01.45.00.000	300.000
170:	04.10.00.000 - 04.15.00.000	300.000
170:	15.55.00.000 - 16.00.00.000	300.000
170:	16.50.00.000 - 16.55.00.000	300.000
170:	20.50.00.000 - 20.55.00.000	300.000
171:	03.20.00.000 - 03.25.00.000	300.000

Table 3.4.1. *The main interruptions in recording of Apatity data at NDPC, 1 January - 30 June 2003.*

Monthly uptimes for the Apatity on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

January	:	99.87%
February	:	99.68%
March	:	99.01%
April	:	99.86%
May	:	99.60%
June	:	99.74%

J. Torstveit

Apatity Event Detection Operation

Apatity array detections

The number of detections (phases) reported from day 001, 2003, through day 181, 2003, was 213,357, giving an average of 1179 detections per processed day (181 days processed).

As described in earlier reports, the data from the Apatity array is transferred by one-way (simplex) radio links to Apatity city. The transmission suffers from radio disturbances that occasionally result in a large number of small data gaps and spikes in the data. In order for the communication protocol to correct such errors by requesting retransmission of data, a two-way radio link would be needed (duplex radio). However, it should be noted that noise from cultural activities and from the nearby lakes cause most of the unwanted detections. These unwanted detections are "filtered" in the signal processing, as they give seismic velocities that are outside accepted limits for regional and teleseismic phase velocities.

Events automatically located by the Apatity array

During days 001, 2003, through 181, 2003, 2842 local and regional events were located by the Apatity array, based on automatic association of P- and S-type arrivals. This gives an average of 15.7 events per processed day (181 days processed). 34% of these events are within 300 km, and 69% of these events are within 1000 km.

U. Baadshaug

3.5 Regional Monitoring System Operation and Analysis

The Regional Monitoring System (RMS) was installed at NORSAR in December 1989 and has been operated at NORSAR from 1 January 1990 for automatic processing of data from ARCES and NORES. A second version of RMS that accepts data from an arbitrary number of arrays and single 3-component stations was installed at NORSAR in October 1991, and regular operation of the system comprising analysis of data from the 4 arrays ARCES, NORES, FINES and GERES started on 15 October 1991. As opposed to the first version of RMS, the one in current operation also has the capability of locating events at teleseismic distances.

Data from the Apatity array was included on 14 December 1992, and from the Spitsbergen array on 12 January 1994. Detections from the Hagfors array were available to the analysts and could be added manually during analysis from 6 December 1994. After 2 February 1995, Hagfors detections were also used in the automatic phase association.

Since 24 April 1999, RMS has processed data from all the seven regional arrays ARCES, NORES, FINES, GERES (until January 2000), Apatity, Spitsbergen, and Hagfors. Starting 19 September 1999, waveforms and detections from the NORSAR array have also been available to the analyst.

Phase and event statistics

Table 3.5.1 gives a summary of phase detections and events declared by RMS. From top to bottom the table gives the total number of detections by the RMS, the number of detections that are associated with events automatically declared by the RMS, the number of detections that are not associated with any events, the number of events automatically declared by the RMS, and finally the total number of events worked on interactively (in accordance with criteria that vary over time; see below) and defined by the analyst.

New criteria for interactive event analysis were introduced from 1 January 1994. Since that date, only regional events in areas of special interest (e.g, Spitsbergen, since it is necessary to acquire new knowledge in this region) or other significant events (e.g, felt earthquakes and large industrial explosions) were thoroughly analyzed. Teleseismic events of special interest are also analyzed.

To further reduce the workload on the analysts and to focus on regional events in preparation for Gamma-data submission during GSETT-3, a new processing scheme was introduced on 2 February 1995. The GBF (Generalized Beamforming) program is used as a pre-processor to RMS, and only phases associated with selected events in northern Europe are considered in the automatic RMS phase association. All detections, however, are still available to the analysts and can be added manually during analysis.

	Jan 03	Feb 03	Mar 03	Apr 03	May 03	Jun 03	Total
Phase detections	198714	140124	157067	156840	147444	170472	970661
- Associated phases	4891	4104	4717	4773	4674	5624	28783
- Unassociated phases	193823	136010	152350	152067	142770	164848	941878
Events automatically declared by RMS	1086	874	965	974	846	1221	5966
No. of events defined by the analyst	60	63	76	69	85	82	435

Table 3.5.1. RMS phase detections and event summary 1 January - 30 June 2003.

U. Baadshaug
B. Paulsen

4 NDC and Field Activities

4.1 NDC Activitities

NORSAR functions as the Norwegian National Data Center (NDC) for CTBT verification. Six monitoring stations, comprising altogether 119 field instruments, will be located on Norwegian territory as part of the future IMS as described elsewhere in this report. The four seismic IMS stations are all in operation today, and three of them are currently providing data to the IDC. The radionuclide station at Spitsbergen was certified on 10 June 2003, whereas the infrasound station in northern Norway will need to be established within the next few years. Data recorded by the Norwegian stations is being transmitted in real time to the Norwegian NDC, and provided to the IDC through the Global Communications Infrastructure (GCI). Norway is connected to the GCI with a frame relay link to Vienna.

Operating the Norwegian IMS stations continues to require increased resources and additional personnel both at the NDC and in the field. The PTS has established new and strictly defined procedures as well as increased emphasis on regularity of data recording and timely data transmission to the IDC in Vienna. This has led to increased reporting activities and implementation of new procedures for the NDC operators. The NDC carries out all the technical tasks required in support of Norway's treaty obligations. NORSAR will also carry out assessments of events of special interest, and advise the Norwegian authorities in technical matters relating to treaty compliance.

Verification functions; information received from the IDC

After the CTBT enters into force, the IDC will provide data for a large number of events each day, but will not assess whether any of them are likely to be nuclear explosions. Such assessments will be the task of the States Parties, and it is important to develop the necessary national expertise in the participating countries. An important task for the Norwegian NDC will thus be to make independent assessments of events of particular interest to Norway, and to communicate the results of these analyses to the Norwegian Ministry of Foreign Affairs.

Monitoring the Arctic region

Norway will have monitoring stations of key importance for covering the Arctic, including Novaya Zemlya, and Norwegian experts have a unique competence in assessing events in this region. On several occasions in the past, seismic events near Novaya Zemlya have caused political concern, and NORSAR specialists have contributed to clarifying these issues.

International cooperation

After entry into force of the treaty, a number of countries are expected to establish national expertise to contribute to the treaty verification on a global basis. Norwegian experts have been in contact with experts from several countries with the aim of establishing bilateral or multilateral cooperation in this field. One interesting possibility for the future is to establish NORSAR as a regional center for European cooperation in the CTBT verification activities.

NORSAR event processing

The automatic routine processing of NORSAR events as described in NORSAR Sci. Rep. No. 2-93/94, has been running satisfactorily. The analyst tools for reviewing and updating the solutions have been continually modified to simplify operations and improve results. NORSAR is currently applying teleseismic detection and event processing using the large-aperture NORSAR array as well as regional monitoring using the network of small-aperture arrays in Fennoscandia and adjacent areas.

Communication topology

Norway has implemented an independent subnetwork, which connects the IMS stations AS72, AS73, PS28, and RN49 operated by NORSAR to the GCI at NOR_NDC. A contract has been concluded and VSAT antennas have been installed at each station in the network. Under the same contract, VSAT antennas for 6 of the PS27 subarrays have been installed for intra-array communication. The seventh subarray is connected to the central recording facility via a leased land line. The central recording facility for PS27 is connected directly to the GCI (Basic Topology). All the VSAT communication is functioning satisfactorily.

Jan Fyen

4.2 Status Report: Norway's Participation in GSETT-3

Introduction

This contribution is a report for the period January - June 2003 on activities associated with Norway's participation in the GSETT-3 experiment, which provides data to the International Data Centre (IDC) in Vienna on an experimental basis until the participating stations have been commissioned as part of the International Monitoring System (IMS) network defined in the protocol to the Comprehensive Nuclear-Test-Ban Treaty. This report represents an update of contributions that can be found in previous editions of NORSAR's Semiannual Technical Summary. It is noted that as of 30 June 2003, two out of the three Norwegian seismic stations providing data to the IDC have been formally certified and thus commissioned as part of the IMS network.

Norwegian GSETT-3 stations and communications arrangements

During the reporting interval 1 January - 30 June 2003, Norway has provided data to the GSETT-3 experiment from the three seismic stations shown in Fig. 4.2.1. The NORSAR array (PS27, station code NOA) is a 60 km aperture teleseismic array, comprised of 7 subarrays, each containing six vertical short period sensors and a three-component broadband instrument. ARCES is a 25-element regional array with an aperture of 3 km, whereas the Spitsbergen array (station code SPITS) has 9 elements within a 1-km aperture. ARCES and SPITS both have a broadband three-component seismometer at the array center.

The intra-array communication for NOA utilizes a land line for subarray NC6 and VSAT links based on TDMA technology for the other 6 subarrays. The central recording facility for NOA is at NOR_NDC.

Continuous ARCES data has been transmitted from the ARCES site to NOR_NDC using a 64 kbits/s VSAT satellite link, based on BOD technology.

Continuous SPITS data has been transmitted to NOR_NDC via a VSAT terminal located at Platåberget in Longyearbyen (which is the site of the IMS radionuclide monitoring station RN49 installed during 2001).

Seven-day station buffers have been established at the ARCES and SPITS sites and at all NOA subarray sites, as well as at NOR_NDC for ARCES, SPITS and NOA.

The NOA and ARCES arrays are primary stations in the GSETT-3 network and the IMS, which implies that data from these stations is transmitted continuously to the receiving international data center. Since October 1999, this data has been transmitted (from NOR_NDC) via the Global Communications Infrastructure (GCI) to the IDC in Vienna. The SPITS array is an auxiliary station in GSETT-3 and the IMS, and the SPITS data have been available to the IDC throughout the reporting period on a request basis via use of the AutoDRM protocol (Kradolfer, 1993; Kradolfer, 1996). The Norwegian stations are thus participating in GSETT-3 with the same status (primary/auxiliary seismic stations) they have in the IMS defined in the protocol to the Comprehensive Nuclear-Test-Ban Treaty. In addition, continuous data from all three arrays is transmitted to the US NDC.

Uptimes and data availability

Figs. 4.2.2 - 4.2.3 show the monthly uptimes for the Norwegian GSETT-3 primary stations ARCES and NOA, respectively, for the period 1 January - 30 June 2003, given as the hatched (taller) bars in these figures. These barplots reflect the percentage of the waveform data that are available in the NOR_NDC tape archives for these two arrays. The downtimes inferred from these figures thus represent the cumulative effect of field equipment outages, station site to NOR_NDC communication outage, and NOR_NDC data acquisition outages.

Figs. 4.2.2-4.2.3 also give the data availability for these two stations as reported by the IDC in the IDC Station Status reports. The main reason for the discrepancies between the NOR_NDC and IDC data availabilities as observed from these figures is the difference in the ways the two data centers report data availability for arrays: Whereas NOR_NDC reports an array station to be up and available if at least one channel produces useful data, the IDC uses weights where the reported availability (capability) is based on the number of actually operating channels.

Use of the AutoDRM protocol

NOR_NDC's AutoDRM has been operational since November 1995 (Mykkeltveit & Baadshaug, 1996). The monthly number of requests by the IDC for SPITS data for the period January - June 2003 is shown in Fig. 4.2.4.

NDC automatic processing and data analysis

These tasks have proceeded in accordance with the descriptions given in Mykkeltveit and Baadshaug (1996). For the period January - June 2003, NOR_NDC derived information on 447 supplementary events in northern Europe and submitted this information to the Finnish NDC as the NOR_NDC contribution to the joint Nordic Supplementary (Gamma) Bulletin, which in turn is forwarded to the IDC. These events are plotted in Fig. 4.2.5.

Data forwarding for GSETT-3 stations in other countries

NOR_NDC continued to provide communications for the GSETT-3 auxiliary station at Nilore, Pakistan, through a VSAT satellite link between NOR_NDC and Pakistan's NDC in Nilore. The IDC now obtains data from the Hagfors array (HFS) in Sweden through requests to the AutoDRM server at this station. No requests from the IDC for Hagfors data were therefore received by the NOR_NDC in the reporting period.

Current developments and future plans

NOR_NDC is continuing the efforts towards improving and hardening all critical data acquisition and data forwarding hardware and software components, so as to meet future requirements related to operation of IMS stations to the maximum extent possible.

The PrepCom has tasked its Working Group B with overseeing, coordinating, and evaluating the GSETT-3 experiment. The PrepCom has also encouraged states that operate IMS-designated stations to continue to do so on a voluntary basis and in the framework of the GSETT-experiment until such time that the stations have been certified for formal inclusion in IMS. The NOA array was formally certified by the PTS on 28 July 2000, and a contract with the PTS in Vienna currently provides partial funding for operation and maintenance of this station. The ARCES array was formally certified by the PTS on 8 November 2001. A contract has also been signed with the PTS for operation and maintenance of this station. Provided that adequate funding continues to be made available (from the PTS and the Norwegian Ministry of Foreign Affairs), we envisage continuing the provision of data from all Norwegian IMS-designated seismic stations without interruption to the IDC in Vienna.

U. Baadshaug
S. Mykkeltveit
J. Fyen

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Kradolfer, U. (1996): AutoDRM — The first five years, *Seism. Res. Lett.*, 67, 4, 30-33.

Mykkeltveit, S. & U. Baadshaug (1996): Norway's NDC: Experience from the first eighteen months of the full-scale phase of GSETT-3. *Semiann. Tech. Summ., 1 October 1995 - 31 March 1996*, NORSAR Sci. Rep. No. 2-95/96, Kjeller, Norway.

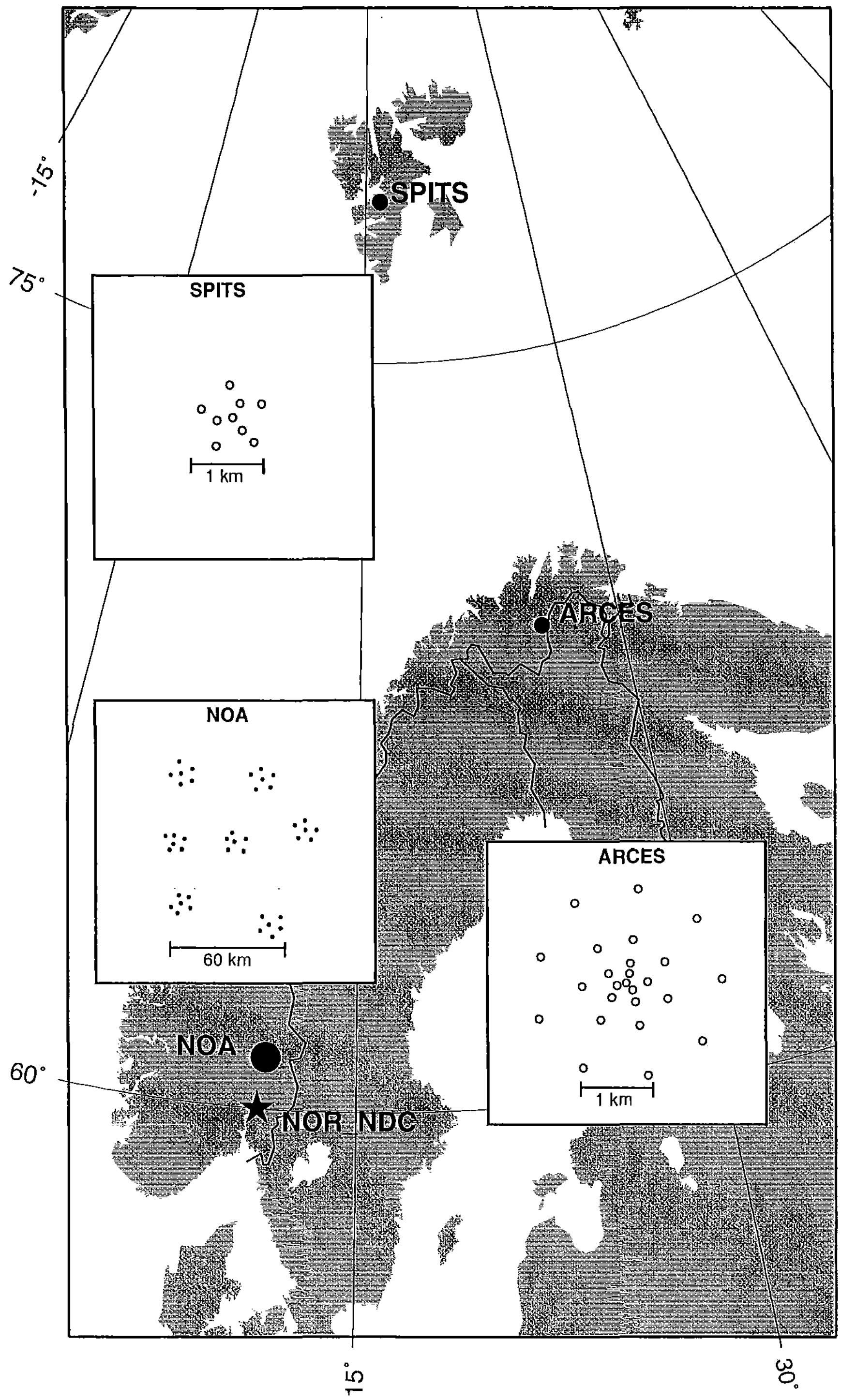

Fig. 4.2.1. The figure shows the locations and configurations of the three Norwegian seismic array stations that have provided data to the GSETT-3 experiment during the period January - June 2003. The data from these stations are transmitted continuously and in real time to the Norwegian NDC (NOR_NDC). The stations NOA and ARCES have participated in GSETT-3 as primary stations, whereas SPITS has contributed as an auxiliary station.

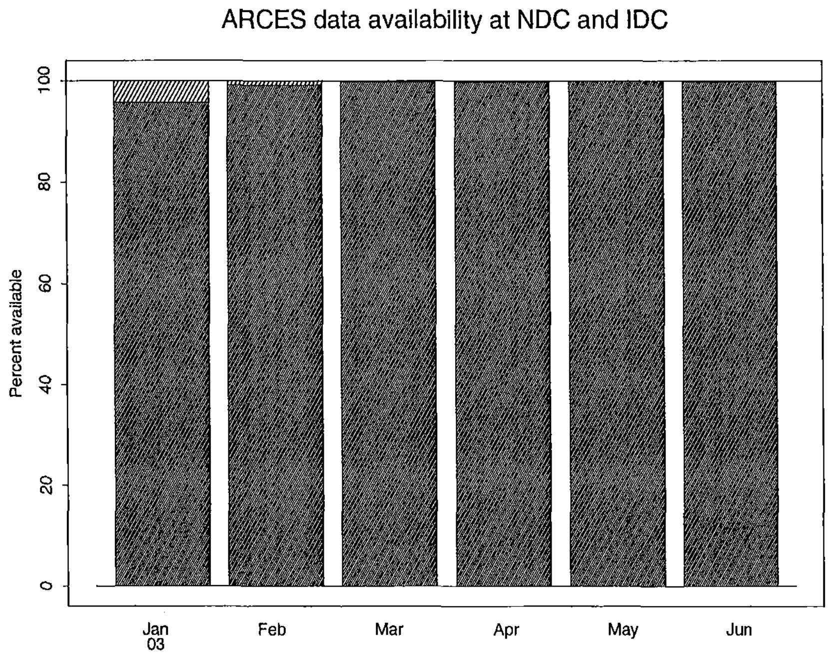

Fig. 4.2.2. The figure shows the monthly availability of ARCES array data for the period January - June 2003 at NOR_NDC and the IDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

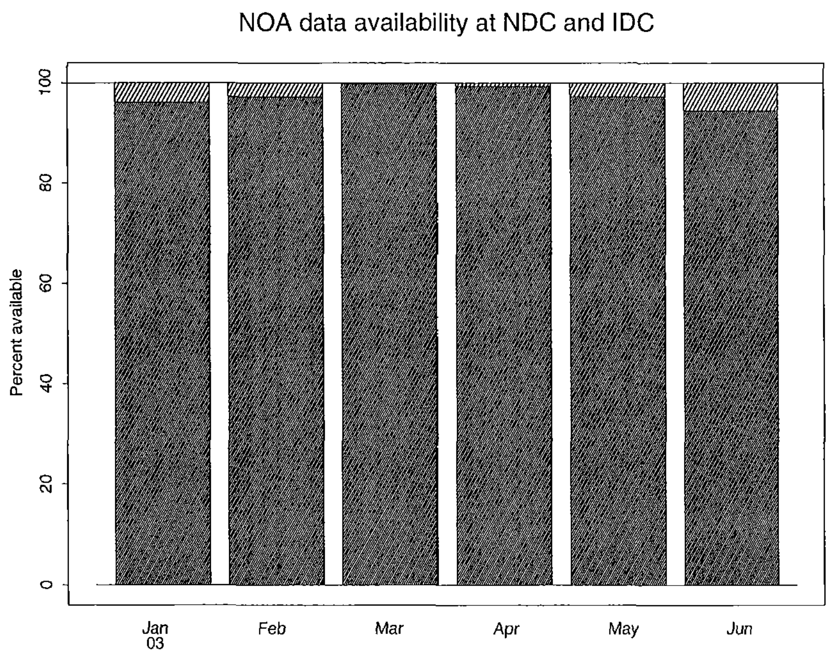

Fig. 4.2.3. The figure shows the monthly availability of NORSAR array data for the period January - June 2003at NOR_NDC and the IDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

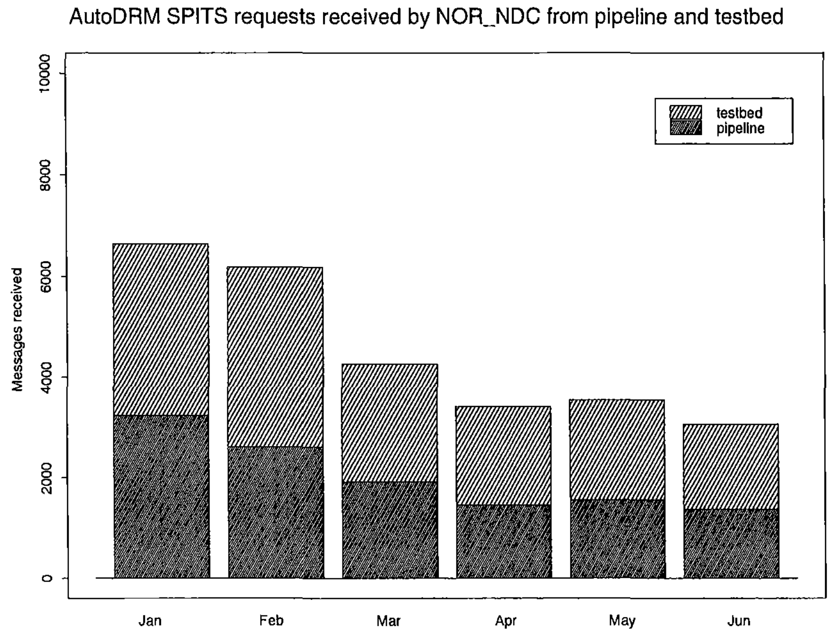

Fig. 4.2.4. The figure shows the monthly number of requests received by NOR_NDC from the IDC for SPITS waveform segments during January - June 2003.

Reviewed Supplementary events

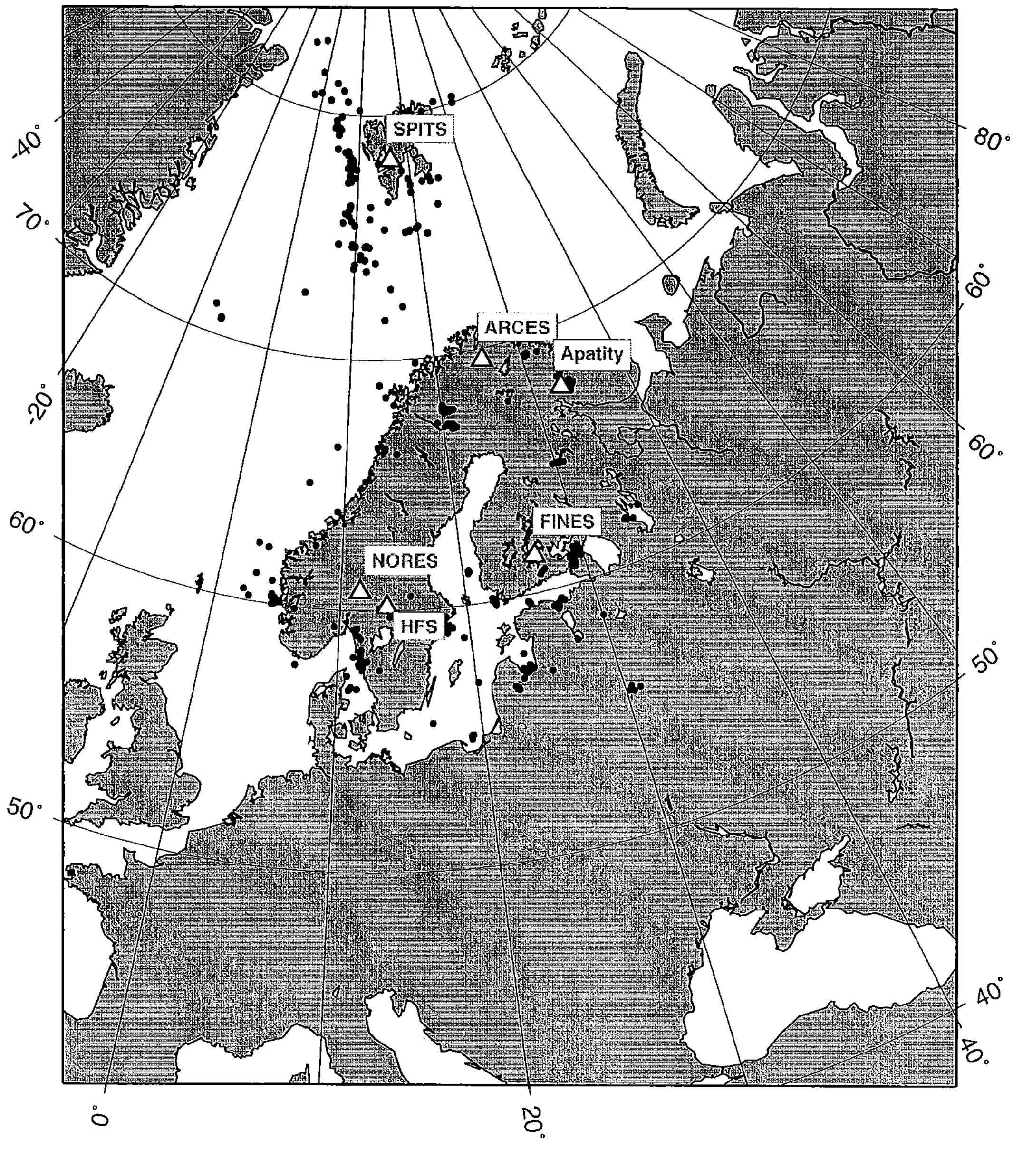

Fig. 4.2.5. The map shows the 447 events in and around Norway contributed by NOR_NDC during January - June 2003 as supplementary (Gamma) events to the IDC, as part of the Nordic supplementary data compiled by the Finnish NDC. The map also shows the seismic stations used in the data analysis to define these events.

4.3 Field Activities

The activities at the NORSAR Maintenance Center (NMC) at Hamar currently include work related to operation and maintenance of the following IMS seismic stations: the NOA teleseismic array (PS27), the ARCES array (PS28) and the Spitsbergen array (AS72). Some preparatory work has also been carried out in connection with the seismic station on Jan Mayen (AS73), the infrasound station at Karasjok (IS37) and the radionuclide station at Spitsbergen (RN49). NORSAR also acts as a consultant for the operation and maintenance of the Hagfors array in Sweden (AS101).

In addition to the above activities, which are directly related to the International Monitoring System, NORSAR's field staff are continuing, within available resources, to maintain the small-aperture NORES array, which is co-located with NOA subarray 06C. These efforts are given low priority, since there is no requirement for specific uptimes at NORES.

NORSAR carries out the field activities relating to IMS stations in a manner generally consistent with the requirements specified in the appropriate IMS Operational Manuals, which are currently being developed by Working Group B of the Preparatory Commission. For seismic stations these specifications are contained in the Operational Manual for Seismological Monitoring and the International Exchange of Seismological Data (CTBT/WGB/TL-11/2), currently available in a draft version.

All regular maintenance on the NORSAR field systems is conducted on a one-shift-per-day, five-day-per-week basis. The maintenance tasks include:

- Operating and maintaining the seismic sensors and the associated digitizers, authentication devices and other electronics components.
- Maintaining the power supply to the field sites as well as backup power supplies.
- Operating and maintaining the VSATs, the data acquisition systems and the intra-array data transmission systems.
- Assisting the NDC in evaluating the data quality and making the necessary changes in gain settings, frequency response and other operating characteristics as required.
- Carrying out preventive, routine and emergency maintenance to ensure that all field systems operate properly.
- Maintaining a computerized record of the utilization, status, and maintenance history of all site equipment.
- Providing appropriate security measures to protect against incidents such as intrusion, theft and vandalism at the field installations.

Details of the daily maintenance activities are kept locally. As part of its contract with CTBTO/PTS NORSAR submits, when applicable, problem reports, outage notification reports and equipment status reports. The contents of these reports and the circumstances under which they will be submitted are specified in the draft Operational Manual.

P.W. Larsen
K.A. Løken

5 Documentation Developed

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6 Summary of Technical Reports / Papers Published

6.1 Seismic Event Location Calibration

Report from the IDC Technical Experts Meeting in Oslo, Norway 4-9 May 2003

6.1.1 Introduction

The International Data Centre (IDC) Technical Experts Group on Seismic Event Location held its fifth annual meeting in Oslo, Norway on 4-9 May 2003. The purpose of the meeting was to support the ongoing calibration efforts of the IDC and in particular to review progress toward developing regionalized travel times to improve the quality of location estimates of seismic events reported in the IDC bulletins.

Sixty technical experts, coming from ten signatory countries and the Provisional Technical Secretariat, participated in the meeting. Dr. Frode Ringdal of Norway chaired the meeting.

6.1.2 Background and technical objectives

Working Group B has repeatedly encouraged States Signatories to support the location improvement efforts by supplying relevant location calibration information for their own territories as well as for other regions where they have such information available. The following types of calibration information were proposed in the document CTBT/WGB-6/CRP.26:

- Precise information on location, depth, and origin time of previous nuclear explosions or large chemical explosions
- Similar information on other seismic events that have been located by regional networks with sufficient precision
- Data as appropriate on seismic travel-time models
- Any other information (e.g., geologic or tectonic maps) that would be useful
- Ground truth data from chemical explosions.

At its first meeting in January 1999, the IDC Technical Experts Group on Seismic Event Location developed plans and recommendations for a global calibration program, and presented its report to Working Group B in February 1999 (CTBT/WGB/TL-2/18). This work was reviewed and updated during subsequent meetings of the Experts Group in March 2000, April 2001 and April 2002, and the results were subsequently presented to Working Group B (CTBT/WGB/TL-2/49, CTBT/WGB/TL-2/61 and CTBT/WGB/TL-2/70). The fifth meeting of the Experts Group (4-9 May 2003), reported in this paper, had the following objectives:

- To report on and review progress of ongoing research work on location calibration at national and international levels, including calibration consortia and PTS Calibration Programme Phase 1 contracts
- To discuss the development of event validation sets, using various categories of available"Ground Truth" location information

- To review proposals for station-specific regional location corrections, with particular emphasis on IMS stations in North America, Europe, North Africa, Asia and Australia
- To compare sets of such corrections, including appropriate model errors, and consider their value for incorporation into the operational IDC software
- To develop a plan for extensions and improvements of this regional correction data base, to be incorporated into IDC software in the future
- To review progress in the general recommendations from the previous meetings, and make adjustments and updates to these recommendations as required.
-

The primary task of the meeting was to assess the status and availability of regional calibration information for the geographical areas being considered, to plan for implementing such calibration information at the IDC as well as discuss the need for future research and development.

6.1.3 Technical Issues

Presentations during the meeting

A number of papers relating to the collection, application and validation of calibration information were presented by participants. Models for regionalization on a global basis were presented and discussed. Specific presentations were made by several experts describing regional velocity models and calibration data for the geographic regions being considered initially. Information was provided about the current CTBTO Calibration Programme. Progress was reported at the workshop by CTBTO sponsored contractors, by the U.S sponsored consortia which by the time of the meeting had completed their three-year calibration efforts, and by several other research groups.

As during previous meetings, it was noted that for some regions, information was incomplete or lacking, and the use of default "generic" velocity models for various tectonic regions was discussed in some detail. Valuable new data on ground truth (GT) information for seismic events was presented. These data will be organized and made available to the IDC and interested States Signatories. Countries were encouraged to continue to provide relevant calibration data to the IDC for the purpose of developing accurate seismic travel-time curves for various geographical regions, with the goal to achieve ultimately full global coverage.

Reports were presented on a number of modelling studies, some of which showed significant improvement in location precision when applied to test sets of GT seismic events. Three-dimensional models were introduced for several regions and were found to provide considerable improvements in location accuracy compared to standard (IASPEI-91) models.

Techniques for improved regional processing using single arrays or 3-component stations as well as sparse seismic networks were presented and discussed. The application of special location and depth estimation techniques was also addressed.

Working Group Discussions

Three Working Groups were established to discuss technical issues in detail during the workshop:

Working Group 1: Calibration of Northern Eurasia and East Asia

Working Group 2: Calibration of Southwestern Asia and the African/Mediterranean area

Working Group 3: Methods for detection and location

The first two Working Groups were given a mandate with a list of specific questions addressing the following topics:

Topic 1: Validation and Implementation of Regional Calibration Information

Topic 2: Collection of Regional Calibration Information

Topic 3: Application of Regional Calibration Information

Topic 4: Future work of the Experts Group

The third working group was given a special mandate to assess the quality of existing processing methods and to identify areas in which further research work is required.

The results of the Working Groups were presented and discussed in a plenary session. In some cases, previous recommendations were reiterated or amplified. These presentations and discussions provided the basis for the summary recommendations presented below. The detailed reports of these Working Groups are available on request from the Chairman of the Experts Group, Dr. Frode Ringdal, Norway.

6.1.4 Results and recommendations

Status of the calibration effort

Participants reported considerable progress in GT event data collection, GT criteria, and regional calibration. GT event lists have significantly increased over the last year. New GT category criteria to select candidate GT events proposed in the previous meetings have been applied and evaluated. Regional calibration has demonstrated reduced bias (absolute errors) and decreased uncertainty (smaller error ellipses) in accordance with the goals of the IMS calibration effort.

Preliminary regional corrections have been implemented at the IDC for IMS stations in northwestern Europe and northern America. The expert group recommended that the IDC continue their efforts to further develop and implement such corrections for the priority regions.

Northern Eurasia and East Asia

For this region, large collections of calibration data/information are becoming available from several research groups, including IDC contractors and the US-sponsored Group 1 consortia. The IDC should make plans to acquire, archive and evaluate these data, including associated bulletin data and available waveforms, within a globally consistent database. Specific data sets of GT events include, inter alia: (1) Soviet explosion database and associated bulletin data, (2) chemical calibration explosions conducted at Semipalatinsk, (3) Lop Nor nuclear explosions for which GT1 locations have been established and with regional recordings; (3) nuclear explosions during May 1998 at the Indian and Pakistani test sites; (4) clusters of GT5 events within China, Taiwan (China), Japan, Republic of Korea, and Kyrgyzstan that were established by the

Columbia University consortium; (5) clusters of GT5-10 events established by R. Engdahl for India, Tajikistan, Georgia, and Russia.

Multiple sets of SSSCs are now available for IMS stations in this region that have been shown to significantly improve location performance. It is strongly recommended that the IDC develop an initiative program with explicit plans to proactively acquire, evaluate, and install appropriate SSSCs in the routine IDC processing. This task should be the highest priority for the IDC in the area of location performance enhancement in the coming year. As an initial step in this process, the IDC should evaluate the version of SSSCs that have already been delivered to the IDC by the Russian Federation – United States Joint Calibration Programme, and implement them in the routine processing at the IDC.

Southwestern Asia and the African/Mediterranean area

For this region as well, significant progress in the last year was reported. Among the IDC contractors, Cornell University (US) and GII (Israel) have delivered GT data, velocity models, and SSSCs to the IDC/PTS for the Middle East. NORSAR (Norway) and IIEES (Iran) will deliver, by the end of 2003, GT data, models, and SSSCs for the region of Iran. The US-sponsored Group 2 consortium will soon deliver to the US DTRA/DoD a compilation of over 1900 GT events, several 3D velocity models, and computed sets of SSSCs for the region. There now exist one or more regional SSSCs for all IMS stations within the region. There now exists a body of GT events and arrivals suitable for evaluation of proposed SSSCs for the entire region.

Reports by the Group 2 Consortium on the performance of model-based teleseismic P-wave SSSCs are very encouraging and the expert group recommends that these calibrations should be considered as a next logical step for calibrating travel-times.

The existing available GT0-5 data collections will most probably constitute the bulk of the available events in this region for the near future. Efforts must continue to collect events to establish better coverage in North Africa and the Middle East. However, the existing sets of GT0-5 events will form the core of the required validation data sets.

The expert group acknowledges that GT data in this region is sparse and formal and informal data collection efforts must continue. Data for the region is still largely limited to GT5-GT10 earthquakes. The criteria for assigning GT level of location accuracy must be unambiguously documented.

Specific recommendations

Validation and Implementation of Regional Corrections for IDC

- The revised location performance metrics defined in the previous meeting of the experts group (CTBT/WGB/TL-2/70) are adequate, but consideration is needed as to which data sets to apply them to, preferably using a sparse IMS network or with suitable surrogate stations. The metrics should be considered in the context of magnitude and the number and azimuthal distribution of reporting stations.
- Validation data sets of GT events should be established at the IDC for the systematic evaluation of various sets of SSSCs that are now becoming available for common stations. Such validation data sets should consist of the highest quality events with well-balanced geographic sampling to provide objective assessment of SSSC performance.

- Validation data sets should be based on GT events of various categories, and should contain all relevant information (metadata) about the events in the data base. The data should be carefully quality controlled by the organization providing the data. Information on the quality control of origins and arrival times should be provided to the IDC along with the data.
- The Expert Group re-emphasized the need for a formal procedure for validation. In addition, there should be standards for implementation and periodic checking of performance.
- Preliminary results indicate that implementation of teleseismic travel time corrections may also be significant for improving location estimates. Such teleseismic corrections should be consistent with regional corrections.

Testing and Evaluation of Regional Calibration Information

- The IDC should test and evaluate the performance of various sets of SSSCs as an explicit function of the GT quality of available calibration data, with highest emphasis on GT0-2 explosions, where available.
- As a longer-term goal, the IDC should establish a continuing program to systematically and periodically enhance SSSCs using improved earth models and new ground-truth data as they become available and work towards a truly global coverage of the calibration programme.
- Definition of onset times for secondary regional phases is an important and difficult problem. Additional studies, processing methods, and analyst training procedures should be encouraged to enhance the utility of such phases for location estimation.
- Several new algorithms have been implemented and/or utilized in the regional calibration work by various groups that should be considered for evaluation and potential use at the IDC. Such algorithms include single and multiple event location codes (e.g., JHD, HDC, double-difference, grid search), kriging and tomographic codes for use in estimation of SSSCs, cross-correlation techniques with potential to improve phase onset times, and 3D raytracing codes. The IDC should prepare an inventory of such algorithms that are useful to their mission and prioritise plans for future evaluation on the testbed. Research groups which are using these algorithms are encouraged to provide the IDC with detailed information and/or test versions of their computer codes together with any available documentation.
- Researchers are encouraged to consider related topics and in particular the location problem in the presence of correlated errors and deviations from Gaussian statistics.

Automatic Processing Techniques

Single-array processing

Array tuning studies have shown that it is difficult to obtain general rules for improving the array processing. Different arrays have shown very different background noise conditions and signal characteristics such that general-purpose algorithms/setups are not necessarily applicable. Noise conditions are often time varying (seasonal and diurnal variations). Corrections are often frequency dependent. Use of fixed time windows and frequency bands have shown to improve stability of f-k estimates.

Future work should include investigating the possibility of multiple f-k measurements in fixed time and frequency windows. It would also be appropriate to take a new look at noise and/or signal adaptive processes. National contributions to array/station tuning at the IDC are encouraged.

Three-component processing

The experts believe that there is more room for improvements in the data processing for 3C stations than for arrays. Many ideas have been forwarded (polarization analysis, 2C detectors, etc.), but the algorithms need to be developed and tested in an operational environment. Rotation of components before picking S-onsets should be tested. For 3-component stations, unlike arrays, there is no data redundancy, and consequently quality control and data conditioning is more difficult. It is a rather complex task to retrieve reliable phase identification for a single detection at a 3C station, so several detections may need to be analyzed in context to reliably identify secondary phases.

Screening of recurring mine explosions

Adequate GT information (at least for several events for selected mines) is needed to attempt to develop a master event approach for the purpose of automatic screening of recurring mine explosions. Some promising results were reported during the workshop. A useful approach might be to aim at statements such as:

- This event is likely attributed to mine X, at a given confidence level.
- It is located within an estimated distance of Y km from the mine.
- It has certain characteristics (specified) that makes it consistent with recordings from known mining explosions in the same area.

Detection and phase association algorithms

Progress in alternative detection algorithms was noted. The experts consider as particularly promising Fisher-detectors, correlation-based techniques and noise-adaptive detection procedures. 3-C algorithms such as polarization detectors are also recommended for further evaluation. The detection of secondary phases may be aided by algorithms, which lower the required signal-to-noise threshold for detection for a certain time interval after a P-detection. Additionally, an automatic search for secondary phases could be initiated each time a P-phase is detected. The current phase association technique employed at the IDC is considered quite efficient, but requires additional tuning.

Methods for confident detection and identification of depth phases remain an important problem, and research in this area should continue. Focused discussion of selected topics such as depth estimation in the full assembly of experts is encouraged.

Data quality control and data conditioning

There is a need for improved ways to detect and handle problems with the data, such as spikes, outages, spurious noise bursts and timing problems. Improved quality control and data conditioning routines are needed. Wrong polarity and sensor orientation also sometimes cause problems. Errors must be tracked and written to a database, as part of an improved QC system.

Future work

The Experts Group should continue to review and evaluate additional GT data sets, improved models and calibration terms for IMS stations, as they become available, and should provide recommendations regarding their potential use at the IDC.

The expert group recommends that the next Location Workshop focus on a program of evaluations by NDCs and experts of existing SSSCs with the goal of making further recommendations for sets or subsets of calibrations to be installed at the IDC for routine processing. A future workshop should also address issues relevant to automatic processing method developments.

Evaluation of the regional corrections

The expert group recommends that an experimental evaluation of SSSCs should now proceed with the goal of selecting sets or subsets of proposed SSSCs for installation into routine IDC processing. It is proposed that the next Location Workshop focus on evaluation results. To facilitate the evaluation, the IDC could perform offline all available GT event relocations with available sets of SSSCs and publish the resulting bulletins with supporting database tables. The IDC could consider four (at a minimum) sets of SSSCs (with reference to the consortia efforts and the PTS calibration programme, these may be denoted "Group 2", "Group1A", "Group 1B", and PTS, respectively). At the same time, the IDC could perform offline relocation of between 3 and 12 months of the IDC REB with available sets of SSSCs and publish the resulting bulletins with supporting database tables. NDCs, experts, and the IDC could then evaluate the published results and report at the next Location Workshop.

Calibration exlosions

The expert group recommended that the PTS calibration programme be continued and if possible expanded in the future. The collection of data should expand into those areas which have not been covered so far (e.g. Africa, South America and the oceanic areas). One important aspect would be to initiate international co-operation in carrying out a series of large chemical calibration explosions on land and in water. This would allow reliable regional calibration information to be collected in regions, which are not well covered at the present time, and to validate existing calibration corrections.

Of particular importance would be to detonate such calibration explosions during the time periods of future integrated system performance testing of the international monitoring system. This would be valuable in enabling a comparison between the locations calculated by the IDC and the true event locations.

The experts also emphasized the close relation between the event calibration programme and the requirements specified in the Treaty for area to be covered by possible future on-site inspections (maximum area 1000 square kilometers with a maximum linear extent of 50 km). Improving the accuracy of event location as well as obtaining realistic location error ellipses are important in this regard. The experts noted that the accuracy of locations in the IDC bulletins will need to be improved in order to provide the high-quality locations that are required as input for such possible on-site inspections.

Collection of Ground Truth (GT) events

Collection of a set of GT events will continue to be a priority with emphasis on precise hypocenters and origin times and a good global geographic coverage. The GT events should be chosen so as to keep usage of surrogate (non-IMS) stations to a minimum. GT events should be recorded regionally and should comprise a range of magnitudes.

Need for wider participation

The experts re-iterated their concern with the unfortunate low level of participation in calibration activities in under-represented areas such as Africa. The IDC and concerned states may wish to engage in programs to encourage participation in such areas. Such activities might include professional exchanges of personnel with groups actively engaged in calibration to promote exchange of data and expertise. In recognition of the importance of aftershock surveys in the generation of valuable GT events, other activities might include support of temporary aftershock recordings (instruments and personnel) and a clearing-house to collect aftershock data and maintain an open database of aftershock metadata that can be used for calibration and GT event collection.

These recommendations will be considered before the next meeting of the Experts Group.

Frode Ringdal

6.2 Research in regional seismic monitoring

Paper presented at the 25th Seismic Research Symposium

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.

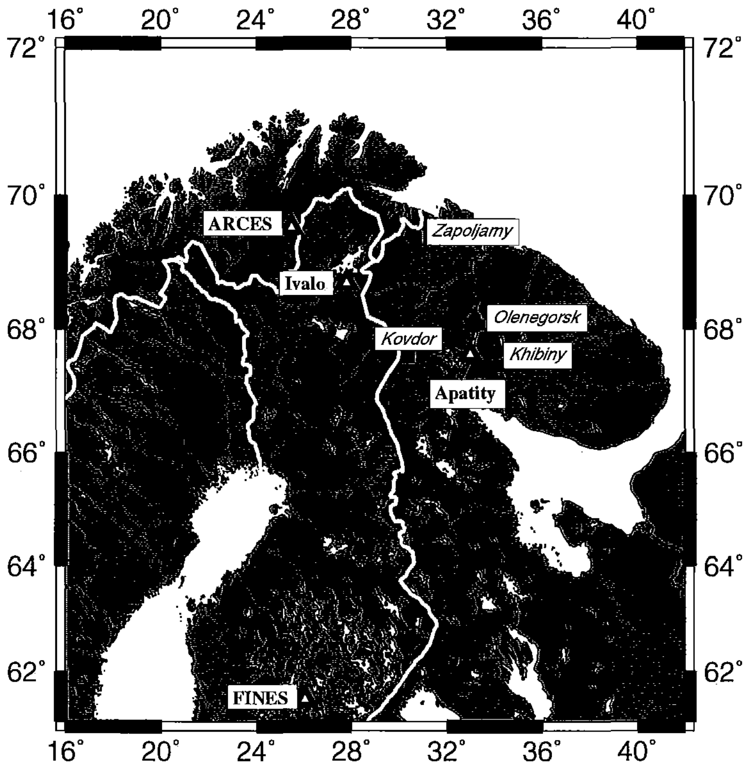

Fig. 6.2.1. Seismic stations (triangles) used in our studies of mine explosions in Kola Peninsula. The main mining sites are marked as squares.

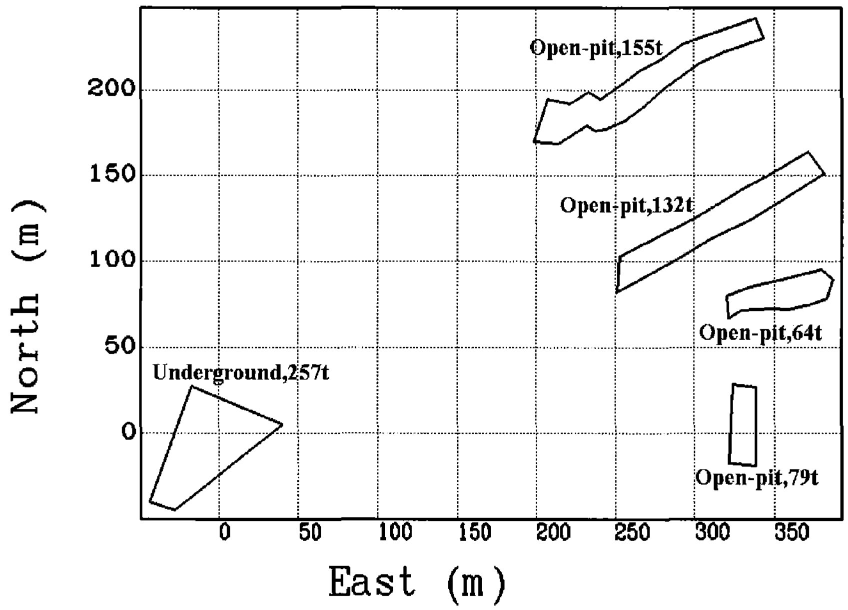

Fig. 6.2.2. Schematic view of the shot configuration for the two explosions in Khibiny on 16 November 2002. Geographical coordinates of the point (0,0) are 67.6322N 33.8565E. See text for details.

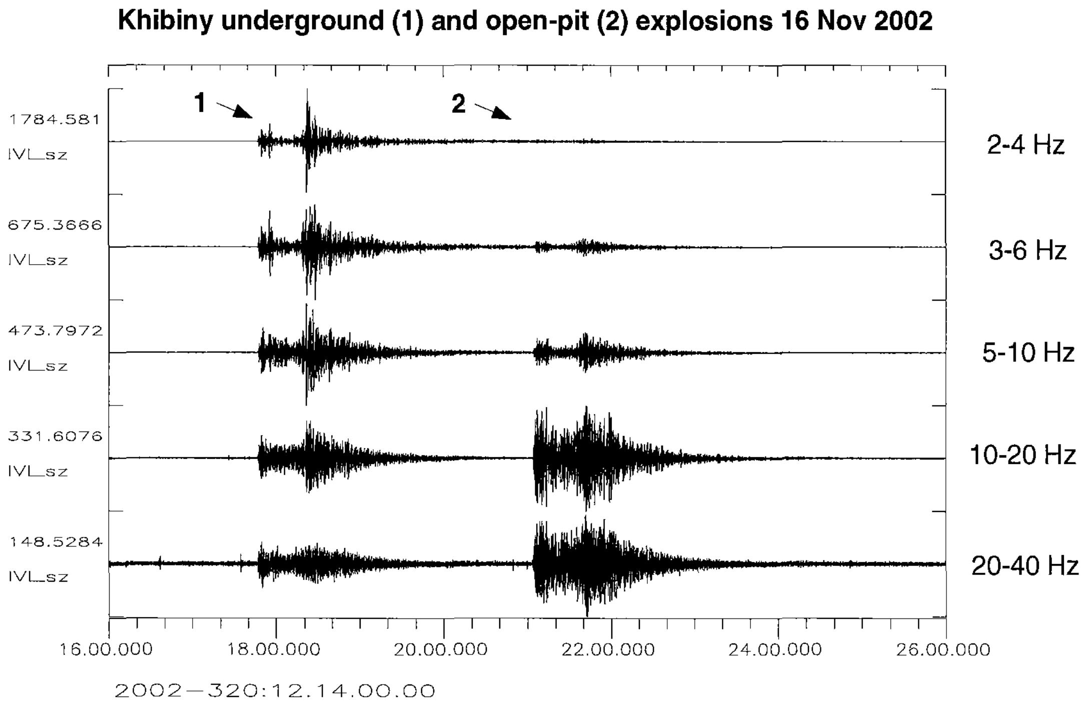

Fig. 6.2.3. Recorded SPZ waveforms at station Ivalo (northern Finland) for the two explosions in Khibiny on 16 November 2002. The data have been filtered in five different frequency bands. Note the significant difference in relative size of the two events as a function of frequency.

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.

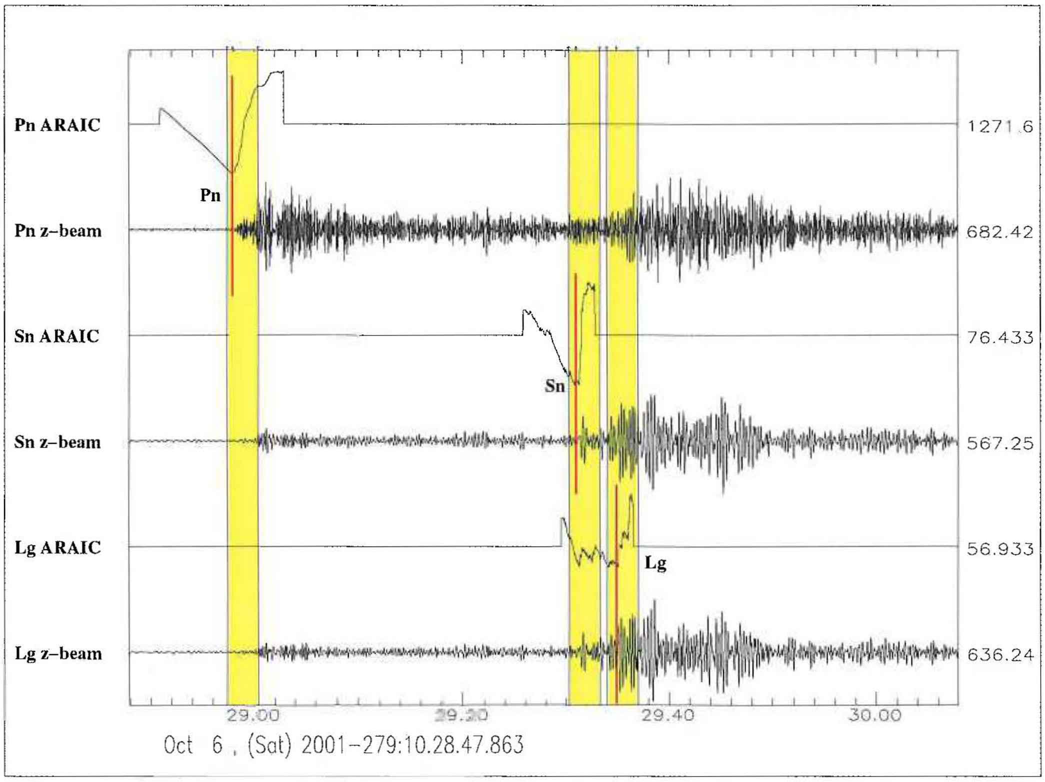

Fig. 6.2.4. Illustration of the automatic processing of a Kovdor event 2001-079 recorded at ARCES. The Pn, Sn and Lg onset picks have been made applying the autoregressive ARAIC method of Akaike (1974). We have used fixed time windows positioned relative to the Pn onset and fixed filter bands for fk-analysis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

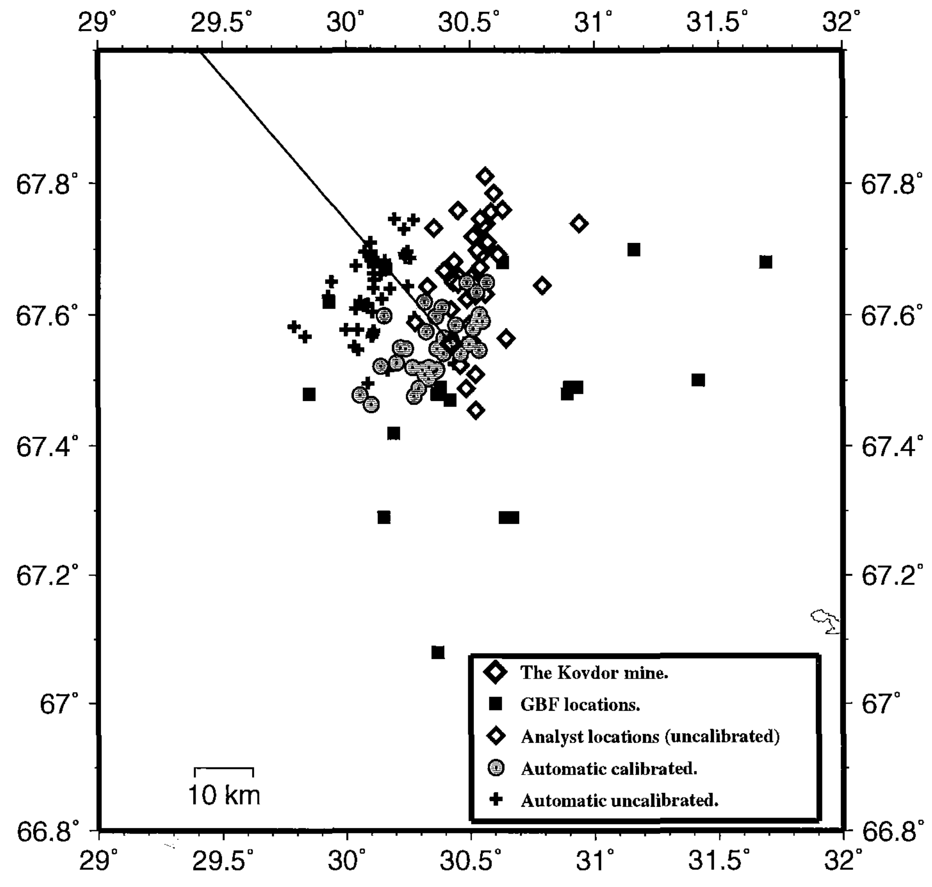

Fig. 6.2.5. Comparison of event locations by various methods for Kovdor events. The line shows the direction towards ARCES, and the true mine location is marked at the end of the line.

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.

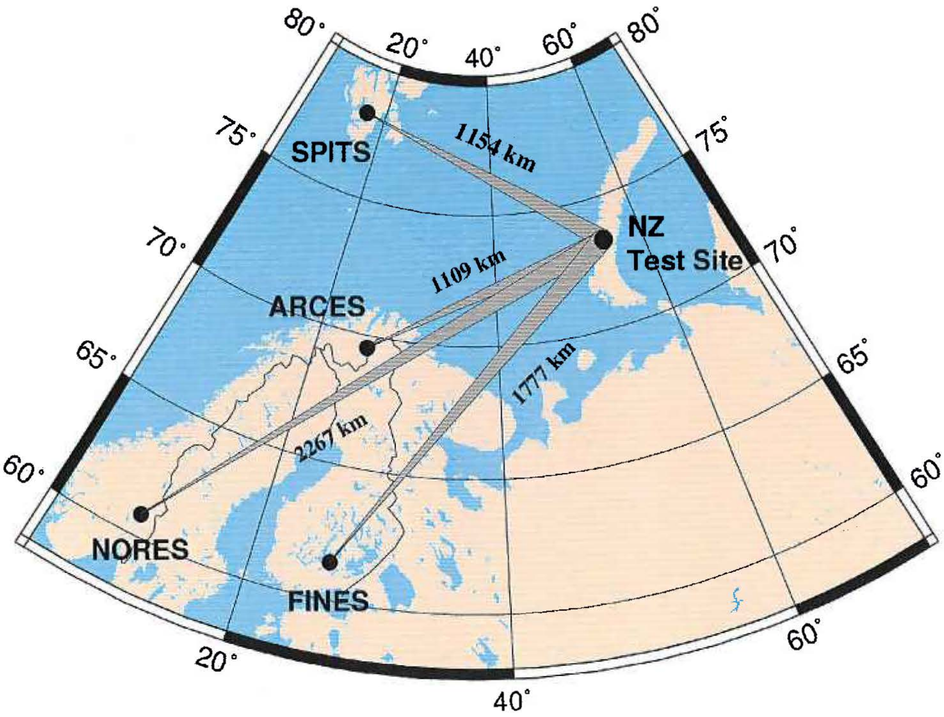

Fig. 6.2.6. Map showing the arrays used for both site-specific Threshold Monitoring and site-specific Generalized Beamforming of the former Novaya Zemlya test site.

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.

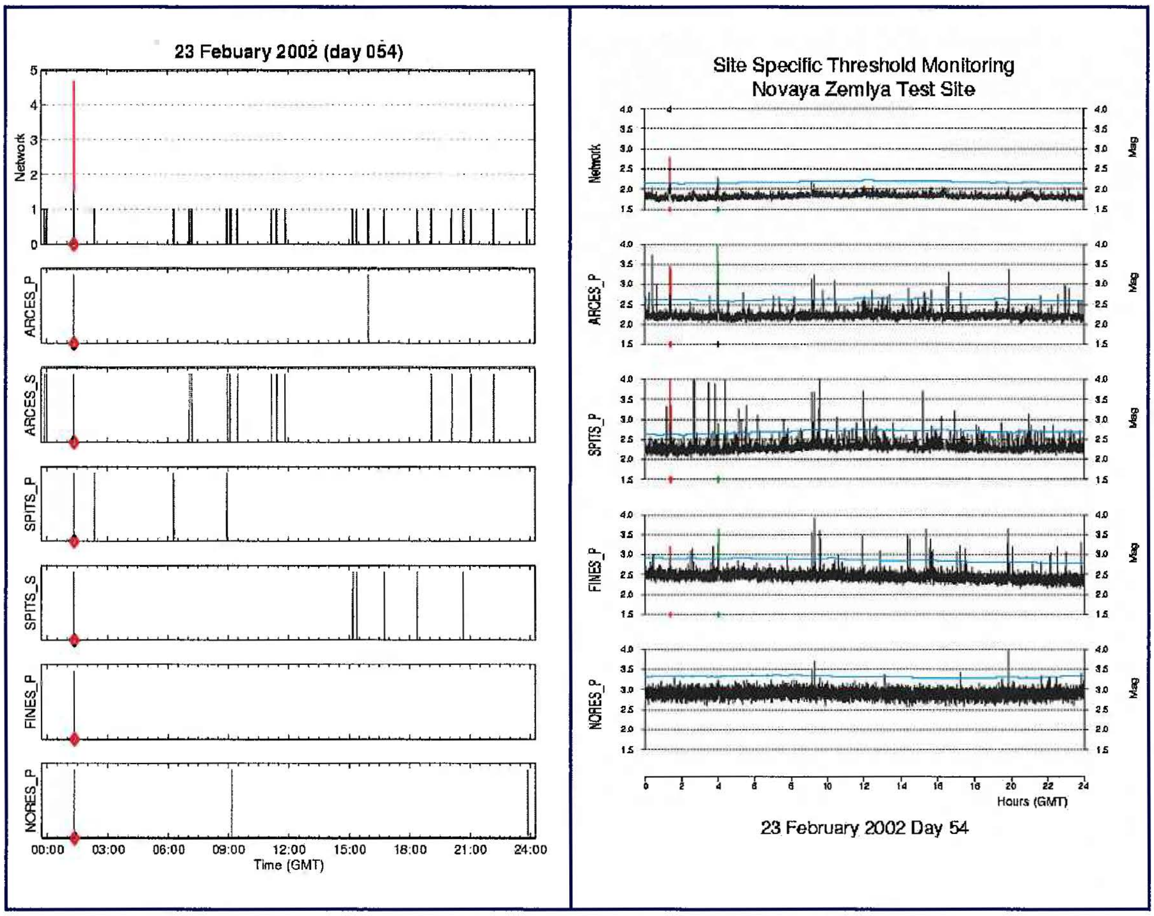

Fig. 6.2.7. SSGBF traces for 23 February 2002 are shown in the left part of the figure. The corresponding SSTM traces are shown in the right part of the figure. For detailed information on SSTM we refer to Kværna et. al., 2002b.

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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6.3 Energy partitioning for seismic events in Fennoscandia and NW Russia

Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. DE-FC03-02SF22636/A000 and W-7405-ENG-48

Abstract

We have started a project to study the generation of seismic shear waves by explosions. The plan is to analyze data from close-in stations in mines to measure seismic waves within a few hundred meters of the explosions. We will combine these data with data from regional stations (out to several hundred kilometers) to characterize the mechanism of shear wave generation as a function of distance from the mine. Three-dimensional numerical (finite difference) simulations of wave propagation (full waveform) within the mines will be compared to the data taken in the mines as an aid to interpretation.

Cooperation has been established with the operators of the Pyhasalmi mine in Finland, where a new in-mine network of 16 sensors has been installed (4 three-component and 12 vertical-component geophones). For the 1500 m deep Pyhasalmi mine there exists comprehensive and detailed information on the mine geometry in digital form. This information has been utilized to build up a model of the mine, using the NORSAR 3D Model Builder. The result is a three-dimensional gridded model which includes the velocity and density characteristics of the ore bodies, mined-out voids, access tunnels and surrounding rocks. An initial three-dimensional finite-difference calculation has been performed for an explosive source in the mine model and, for comparison, similar calculations have been made for a homogeneous model. These preliminary results indicate that near-source heterogeneities, like voids from the mined out region and low velocity backfilled material, play an important role in shaping the seismic wavefield.

Since the installation of the Pyhasalmi in-mine network in November-December 2002, numerous microearthquakes and explosions have been recorded and located. NORSAR has obtained both bulletin and waveform data for these events, and we have started to investigate these data in more detail for the purpose of studying the development of the seismic shear waves.

A particularly interesting event occurred in the Pyhasalmi mine on 26 January 2003. This was a felt rockburst, with magnitude of about 1.0, which was also detected and located by the Finnish National Network operated by the University of Helsinki. Our plan is to use this event for validation of the wavefield modelling, as well as for more detailed analysis of the energy partitioning within the mine network, and at local and regional distances.

6.3.1 Objective

The main objective of this project is to increase the (nuclear) explosion monitoring effectiveness through improved understanding of basic earthquake and explosion phenomenology. What this entails in essence is detailed characterization and understanding of how the seismic energy is generated from these phenomena (including simple and complex explosions, rockbursts, i.e. stress release in mines, and ordinary tectonic earthquakes, all at different depths and in different geological environments) and how this energy is partitioned between P and S waves.

Specific important questions here are:

- How is the generation and partitioning of seismic energy affected by properties such as source region medium and overburden, the local structure, and the surrounding tectonic structure?
- What are the significant measurable effects of the partitioning of the seismic energy into various regional P and S phases, especially at higher frequencies?
- What is the physical basis for a measurable property, such as magnitude, that can be directly related to the yield of a fully coupled explosion, and how emplacement conditions effect the observations?

6.3.2 Research Accomplished

This project is a three-year effort that started on 30 September 2002. The project is a collaboration that involves NORSAR (as the lead organization) and Lawrence Livermore National Laboratory (LLNL). This work addresses the generation of seismic shear waves by explosions. Example explosions at two mines, one in Sweden and the second in Finland, will be studied to determine where shear waves originate. The mines operate close-in stations that measure seismic waves within several hundred meters of the explosions. We will combine these data with data from regional stations (out to several hundred kilometers) to constrain the source of shear waves by range from the mine. Three-dimensional numerical (finite difference) simulations of wave propagation (full waveform) within the mines will be compared to the data taken in the mines as an aid to interpretation. These same calculations will be used as initial conditions for two-dimensional calculations. These secondary calculations will extend the numerical simulations to regional distance for comparison with more distant observations.

Mine model and 3-D finite difference calculations

Using the NORSAR 3-D Model Builder (Vinje et. al., 1999), we have completed an initial velocity model for the Pyhäsalmi mine in Central Finland, using a 4 meter equidistant grid. The three-dimensional model is visualized in Fig. 6.3.1, where green represents copper ore, grey represents zinc ore, and purple and red represent backfilled material. Based on generally available information on typical seismic velocities of different rock types, combined with measurements of the rock densities, the properties given in Table 6.3.1 were initially assigned. For the surrounding rocks, having a density of about 2.8 g/cm^3, Gardners relation was used to estimate the P-velocity. The standard $\sqrt{3}$ P/S velocity ratio was then used for estimating the S-velocity.

The gridded mine model was provided to LLNL for 3-D finite-difference calculations of the seismic wavefield, and the data format used for model exchange worked well. Very preliminary results from the modelling (Larsen and Schultz, 1995) are shown in Figs. 6.3.2-6.3.4, demonstrating that the modelling work at NORSAR and the wavefield simulations at LLNL now are ‘connected’, and that we now have the capability to do our required modelling.

The gridded model is represented by a 126x126x126 grid at 4 m spacing (i.e., 500 m on a side), with an explosive point source set near the center of the model. The source frequency is about 50 Hz (due to the coarseness of the model), and the simulation covers a duration of 0.25 s. The center of the gridded model is located in the middle of the zinc and copper ore bodies in the lower part of the mine, in the depth range 950 - 1450 meters (see Fig. 6.3.1).

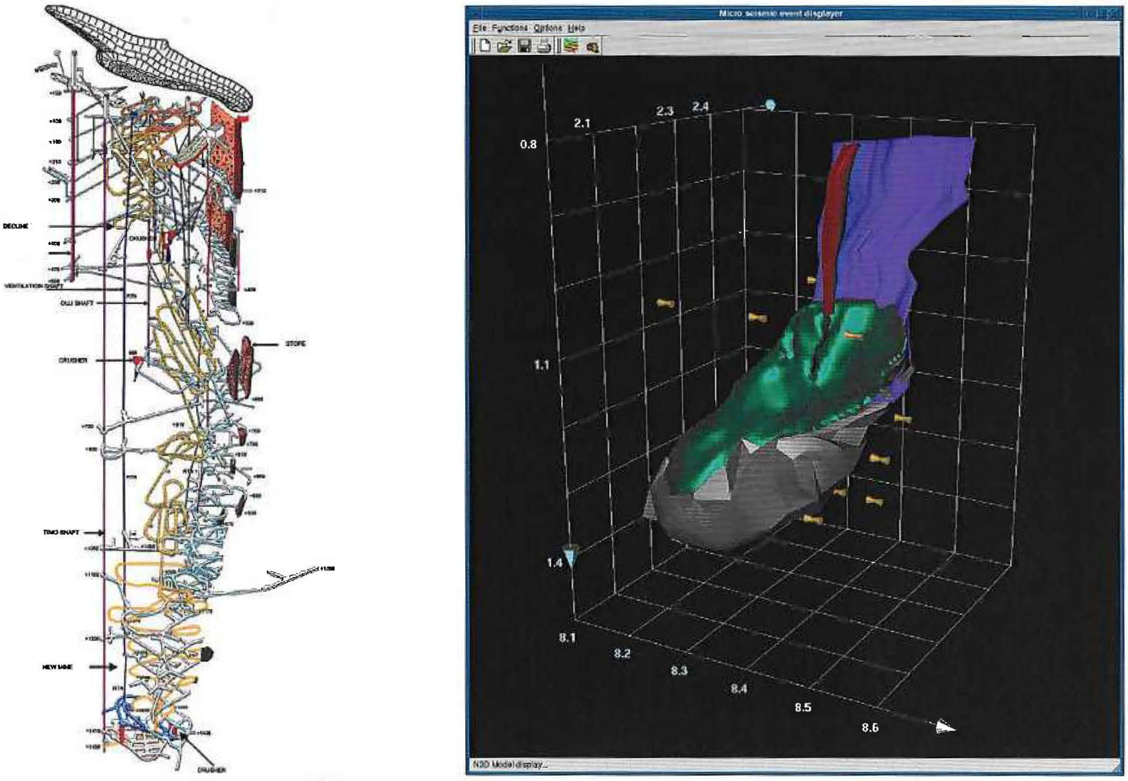

Fig. 6.3.1. The left-hand part of the figure shows the shafts and access tunnels of the Pyhasalmi mine from the surface down to a depth of 1500 meters. The right-hand part of the figure shows a three-dimensional model of the mine, for the depth range 800 - 1500 meters. Green represents copper ore, grey represents zinc ore, and purple and red represent backfilled material. Material properties assigned to the different rock types are given in Table 6.3.1. The locations of the in-mine monitoring network are indicated by the yellow symbols.

Table 6.3.1. Initial material properties assigned to the Pyhäsalmi mine

Rock type	Density (g/cm^3)	P-velocity (km/s)	S-velocity (km/s)
Copper ore	4.6	7.39	4.59
Zinc ore	4.2	5.54	2.89
Backfill	1.8	2.66	1.54
Surrounding rocks	2.8	3.84	2.22
Voids, represented as water	1.0	1.48	0.00

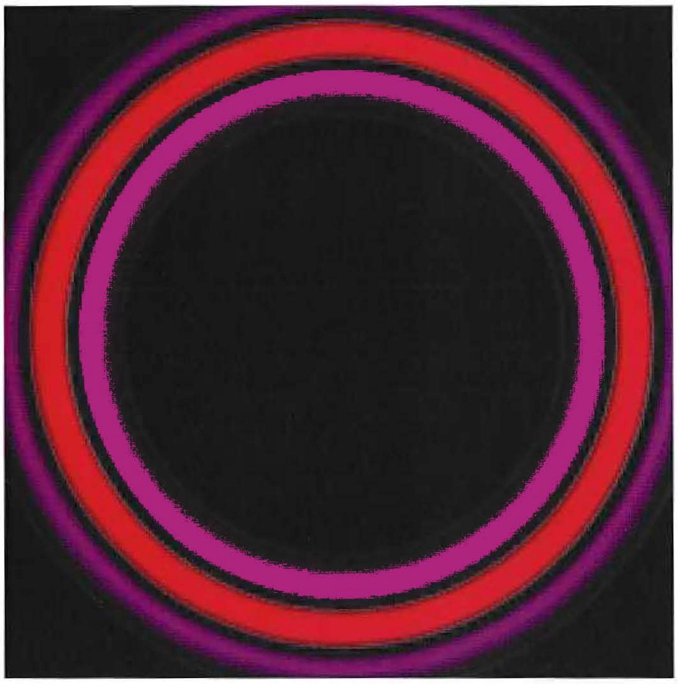

Fig. 6.3.2. The image shows a snap shot of the wave propagation in a vertical cross section cutting through the center of the model, using a homogeneous model, at a time of 0.0875 s. The red and blue-red colors represent compressional energy.

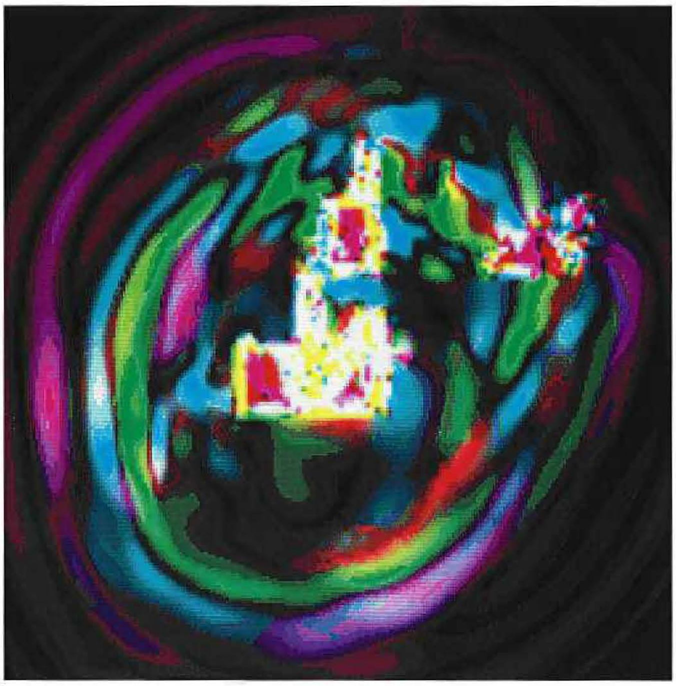

Fig. 6.3.3. The image shows a snap shot of the wave propagation in the same vertical cross section as in Fig. 6.3.2, but now calculated using the mine model. Again red and blue-red colors represent compressional energy, while green and blue-green colors mean shear energy.

When comparing the wavefield simulations in the mine model (Fig. 6.3.3) with the simulations in the homogeneous model (Fig. 6.3.2), we find that the simulated wave field is significantly perturbed when the mine model is included, and there is a significant conversion of compressional energy to shear energy in the near source region. As expected, the homogeneous model did not provide any shear energy for an explosive point source.

A different type of presentation of the modelling results is shown in Fig. 6.3.4, where the vertical component of ground velocity and the shear potential for both simulations are shown at a point near the top of the model that is directly above the source. Again, the significant conversion of compressional energy to shear energy is observed.

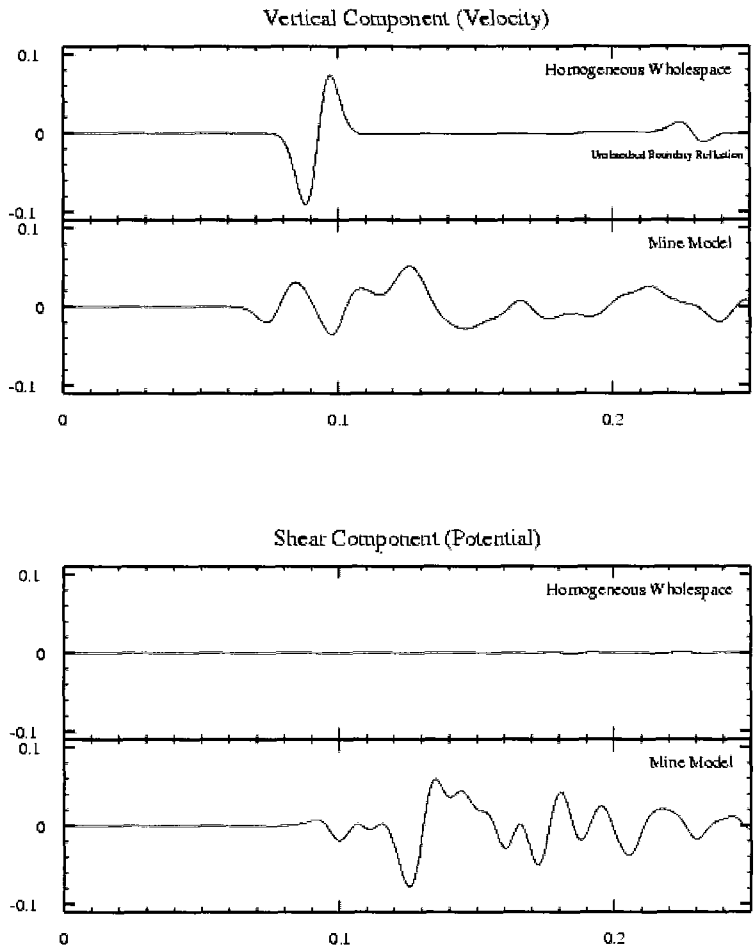

Fig. 6.3.4. The top panel shows the vertical component of ground velocity for both simulations at a point near the top of the model that is directly above the source. The lower panel shows the corresponding shear potential at the same receiver point.

Collection and analysis of in-mine recordings

An in-mine seismic network became operational in the Pyhäsalmi mine during November-December 2002. The installed network is an ISS (Integrated Seismic System) system, manufactured in South Africa, consisting of 16 sensors, out of which 4 are three-component and 12 are single-component vertical.

At the end of each month we have received bulletin and waveform data for the microseismic events located by the ISS system in the Pyhäsalmi mine. In addition, we have for a couple of one-week intervals also received waveforms for all mining explosions (mainly ripple-fired). All waveforms have been converted to CSS 3.0 format at NORSAR.

In order to analyze the Pyhäsalmi in-mine data at NORSAR, we have extended our in-house microseismic monitoring software package, called MIMO, initially written for analysis of microseismic events in oil and gas reservoirs. The extensions include reading of CSS 3.0 format data, handling of a general network configuration with both three-component and single component data, as well as handling of variable sampling rate at the different sensors. All extensions are not yet completed, but functions for waveform display, phase detection, event association, onset time estimation, and polarization analysis are in place.

As an example, we show in Fig. 6.3.5 waveforms and fully automatic processing results for a ripple-fired explosion in the mine. At this time, one three-component and one single-component sensor were disconnected from the Pyhäsalmi ISS system due to their proximity to ongoing mining activity. The left panel shows a time segment of about 8 seconds automatically stored by the ISS system. Signal detections and onset estimates of the P- and S-phases are marked by vertical bars. The results from polarization analysis of the P-phases are displayed in the two uppermost right plots (backazimuths and incidence angles). The three plots below show the automatically located hypocenters in a map view and two cross sections.

For more detailed analysis of these data in terms of energy partitioning, we plan to export the waveforms and associated processing results from the MIMO system in MATLAB format. MATLAB will then be used for measurements like amplitude spectra and spectral differences between P- and S-phases.

The microseismic activity recorded within the Pyhäsalmi mine have magnitudes usually ranging between -2.5 and 0, and thus they are not observable at other seismic stations in Finland. However, on 26 January 2003 a larger rockburst occurred in the mine, having an estimated magnitude of about 1. This felt event was caused by a pillar collapse and minor damages could be observed within the mine. The corresponding data from the in-mine ISS system is shown in Fig. 6.3.6, together with the results from polarization analysis of the four three-component sensors. This event was also observed at the network operated by the University of Helsinki, Institute of Seismology, at receiver distances ranging between 92 and 275 km. The seismograms for these stations are shown in Figs. 6.3.7 and 6.3.8. Notice the SNR increase by beamforming at the FINES array (Fig. 6.3.8) compared to the center element FIA0 of the array as shown in Fig. 6.3.8.

The 26 January 2003 rockburst is the first event for which we have recordings both in the mine and at local and regional distances. We plan to use this event for validation of the wavefield modelling as well as for more detailed analysis of the energy partitioning.

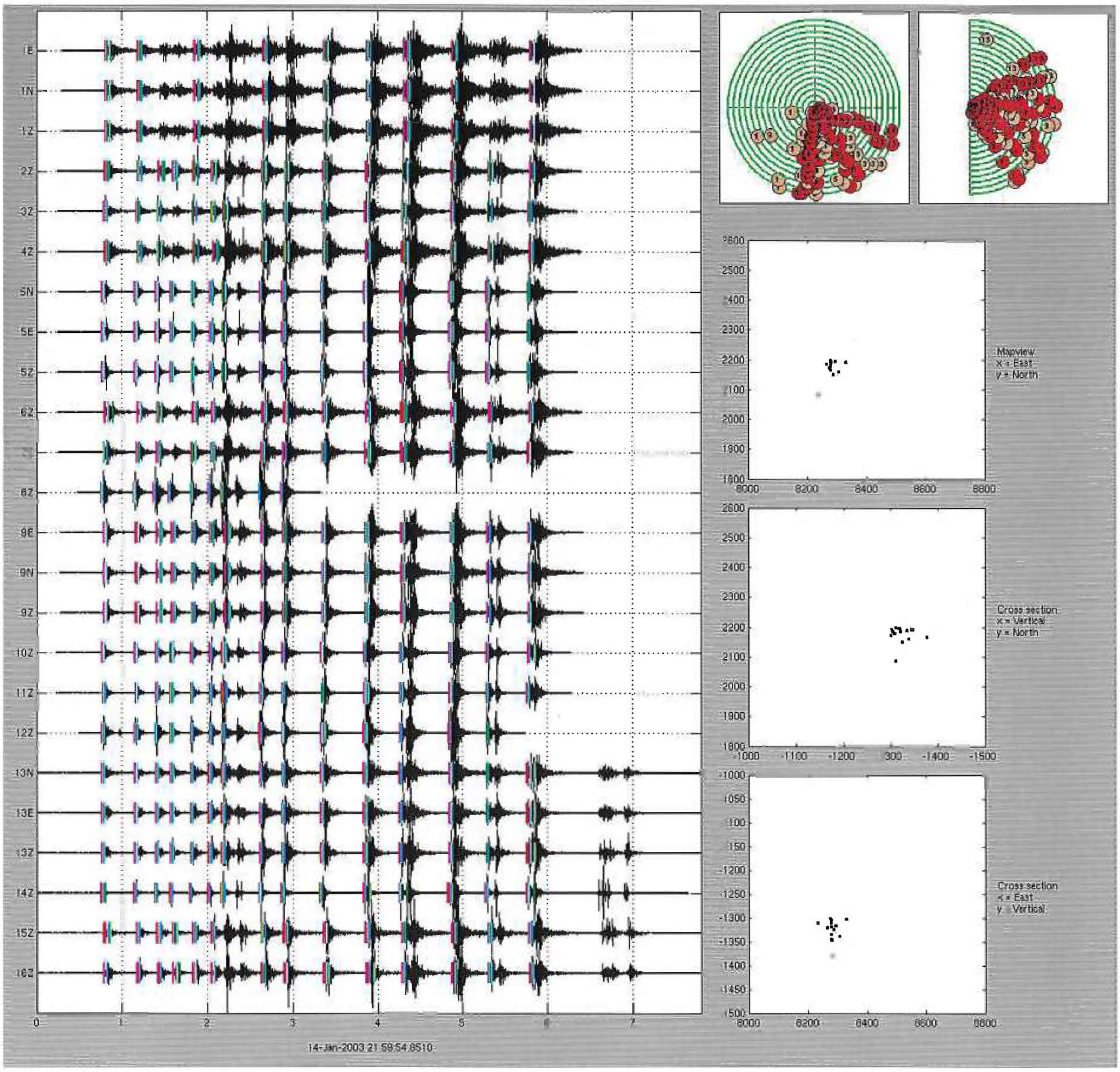

Fig. 6.3.5. Waveforms and automatic processing results for a ripple-fired explosion in the Pyhäsalmi mine. The left panel shows a time segment of about 8 seconds automatically stored by the ISS system. Signal detections and onset estimates of the P- and S-phases are marked by vertical bars. The results from polarization analysis of the P-phases are displayed in the two uppermost right plots (backazimuths and incidence angles). The three plots below show the automatically located hypocenters in a map view and two cross sections.

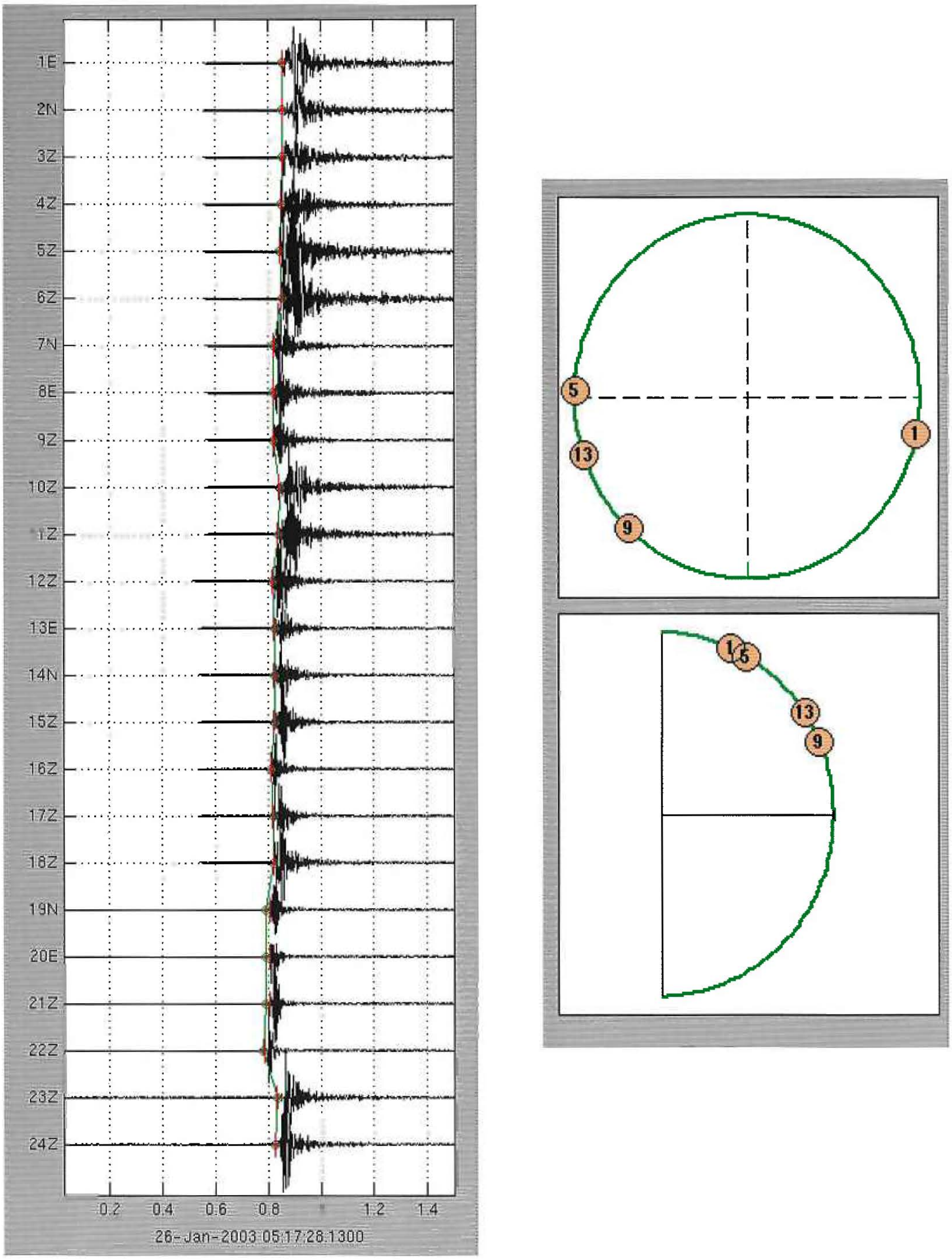

Fig. 6.3.6. The left panel shows waveforms from all 24 channels of the Pyhäsalmi ISS system for the for 26 January 2003 rockburst. Receiver distances for this event range from 30 to 370 m. The upper plot to the right shows the backazimuth estimates for the four 3-C sensors, and the incidence angles are shown below. The 3-C sensors number 1, 5, 9 and 13 are associated with the channel numbers (1, 2, 3), (7, 8, 9), (13, 14, 15), and (19, 20, 21), respectively.

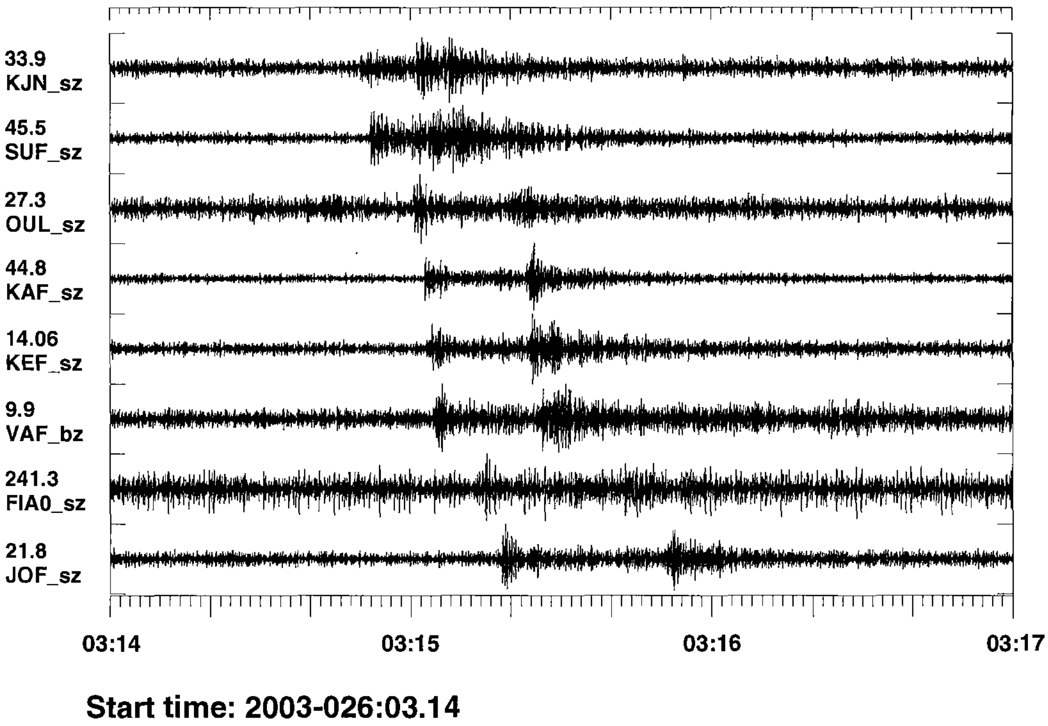

Fig. 6.3.7. Vertical component recordings at the University of Helsinki network for the 26 January 2003 rockburst in the Pyhäsalmi mine. For KJN_sz the data are bandpass filtered between 6 and 12 Hz, whereas the other traces are filtered between 8 and 16 Hz. FIA0_sz in the center element of the FINES array.

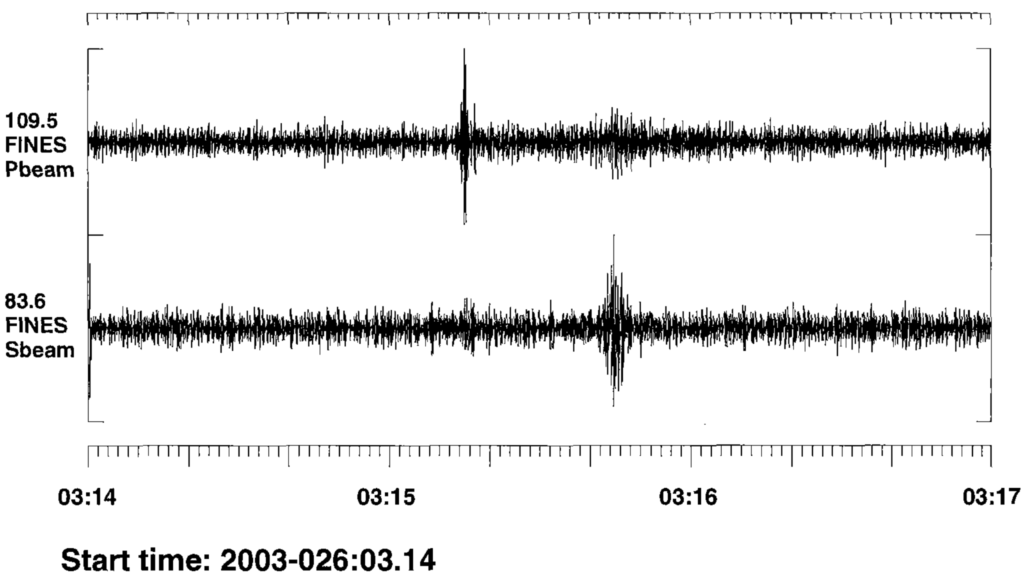

Fig. 6.3.8. FINES P- and S-beams for the 26 January 2003 rockburst in the Pyhäsalmi mine. The P-beam (azimuth 0 degrees, apparent velocity 8 km/s) is filtered between 6 and 12 Hz, and the S-beam (azimuth 0 degrees, apparent velocity 4 km/s) is filtered between 4 and 8 Hz.

Collection of regional data from explosions and earthquakes

In order to study path effects on energy partitioning, we have, in addition to the 26 January 2003 rockburst, also collected waveform data from the Finnish National Network for five additional events in the Pyhäsalmi area. Information from the University of Helsinki bulletin for these events is shown in Table 6.3.2. The magnitude 1.8 event on 24 December 2001 was a large rockburst in the Pyhäsalmi mine that was felt over a large area around the mine.

Table 6.3.2. Recent seismic events in the area around Pyhäsalmi

Date	Origin time	Latitude	Longitude	Magnitude	Number of observing stations
1999/01/31	00:33:51.8	63.51	24.81	1.2	9
1999/01/31	08:58:33.5	62.75	26.26	1.2	10
2001/12/24	01:36:18.1	63.68	26.03	1.8	17
2002/04/23	12:18:49.6	64.23	24.81	1.2	9
2002/06/13	09:22:54.4	62.84	27.31	1.9	9
2003/01/26	03:14:34.9	63.67	26.09	0.5	9

6.3.3 Conclusions and recommendations

During the first nine months of the contract period significant resources have been used for data collection and interaction with the mine operators for the purpose of preparing data sets suitable for investigation of energy partitioning. Software tools for analysis of the in-mine data have been written, and we have started to investigate the characteristics of the P- and S-waves for the in-mine data. For the investigation of path effects on energy partitioning, regional data sets have also been collected. Specifically, we have:

- Collected waveform data and bulletin information of both microseismicity and blasts from the Zinkgruvan mine in Sweden for the time interval 1 October to 9 December, 2002.
- Collected waveform data and bulletin information of both microseismicity and blasts from the Pyhäsalmi mine in Finland for the time interval 1 January to 30 June, 2003.
- Extended and adapted existing software for analysis of waveform data from the Pyhäsalmi and Zinkgruvan mine.
- Identified and retrieved regional data from the stations of the Finnish National Network from events in the Pyhäsalmi area. In addition, NORSAR array data from a set of 11 local and regional events has been made available.

Through initial 3-D finite difference calculations in the Pyhäsalmi mine model, significant conversion of compressional energy to shear energy is found in the near source region. We have to emphasize that these results are very preliminary, and that we have to look more into details like the placement of the source relative to the voids, parameterization of the voids, and the sampling density of the model. However, the results indicate that the near-source heterogeneities, like voids from the mined out region and low velocity backfilled material, may play a significant role in the seismic wavefield.

Our next step will be to calculate the 3-D wavefield for the explosion and rockburst sources, and make comparisons to the in-mine three-component data. We will also take a closer look at the material properties of the mine model, and in particular the velocities of the surrounding rocks. Concerning the study of path effects on energy partitioning, we will analyze the P- and S-waves of the local/regional data sets. This will be accompanied with modelling of P-SV conversions in 1-D lithospheric profiles using the reflectivity method (Müller, 1985) or 2-D finite difference schemes (e.g., Robertsson et. al., 1994).

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6.4 Processing of regional phases using the large aperture NOA array

6.4.1 Introduction

The NOA seismic array (originally called the NORSAR array) was conceived in the late 1960s for the detection of underground nuclear explosions at teleseismic distances. The array, completed in 1970, originally consisted of seismometers on 132 sites with a maximum spacing of over 100 km (Bungum et al., 1971, Bungum and Husebye, 1974). The array was arranged in the form of 22 subarrays, each containing 6 seismometer sites. NOA was designed to maximize signal coherence for teleseismic events and, at the same time, minimize the coherence of noise, therefore providing an optimal signal to noise ratio (SNR) for teleseismic phases using ordinary beamforming. In 1976, the array was reduced to the current configuration of 42 sites spread over 7 subarrays (Ringdal and Husebye, 1982). The configuration of the NOA array, past and present, is shown in Fig. 6.4.1.

It was, however, clear that with an inter-station separation of about 3 km, signal coherence was very low for seismic phases from regional events. In order to detect regional phases, a regional array with much smaller inter-station distances, NORES, was developed on the site of the 06C subarray of NOA (Mykkeltveit and Ringdal, 1981). The original 6-instrument experimental array was expanded to 25 instruments, arranged in four concentric rings, and was completed in 1984. This concept of regional seismic array has now been applied to many sites; e.g., GERES, ARCES, FINES, and SPITS have been based upon the NORES idea (see Mykkeltveit and Bungum, 1984; Mykkeltveit et al., 1990), FINES and SPITS having fewer sites.

The building housing the central processing systems for NORES was struck by lightning in June 2002, destroying all of the technical equipment inside. It is hoped that the array can be rebuilt, although technical and financial considerations mean that it is out of action for the foreseeable future. NORES was a key array in NORSAR's generalized beamforming (GBF) process which associates seismic phases from regional arrays and provides provisional, automatic locations for regional seismic events in the European Arctic (Ringdal and Kværna, 1989; Kværna and Ringdal, 1996). Until it is possible to rebuild NORES, or find an alternative regional array solution, it is highly desirable to try to use the NOA array for the detection and processing of regional events. This forms the motivation for the present study.

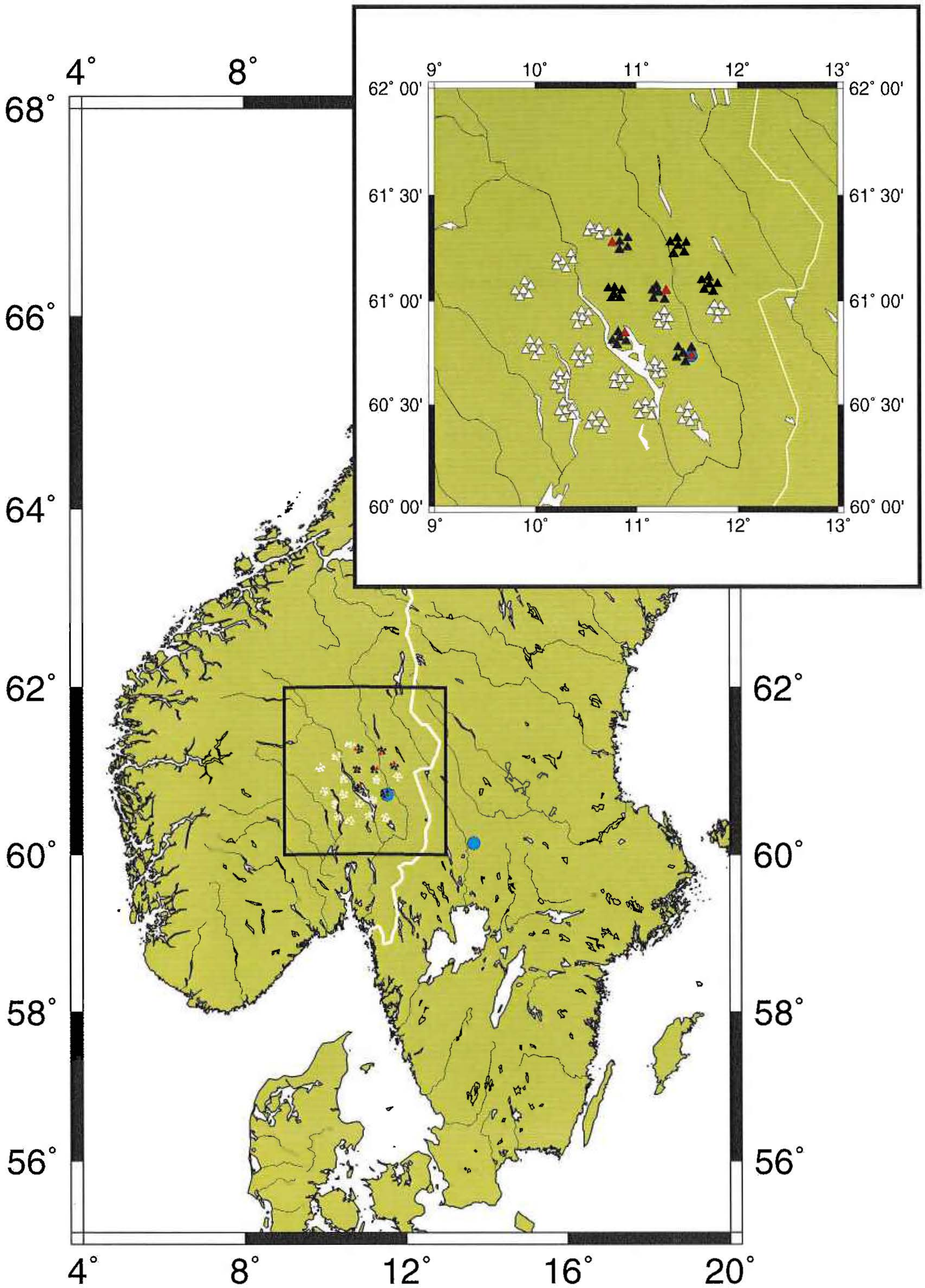

Fig. 6.4.1. The NOA seismic array. The inset diagram indicates the existing short period vertical stations as black triangles. Red triangles indicate that there is also a broadband 3-component instrument on the site and the white triangles are sites from the original array which were taken out of service in 1976. The blue circles represent the locations of the NORES and Hagfors regional arrays.

The large inter-station distances at NOA mean that traditional array techniques, such as broadband fk-analysis, are only applicable to signals with a very low frequency content. This is illustrated by the cases in Fig. 6.4.2. Although both signals have a high SNR, only the teleseismic signal (from Pakistan, a distance of 46°) has any coherence between the elements of a single subarray. This is because the signal is dominated by frequencies below 4 Hz, a frequency above which one cannot expect signals to be coherent between such widely spaced stations. The signal to the right results from a cavity explosion in Sweden at a distance of 150 km which has very little energy below a frequency of 8 Hz (see Gibbons et al., 2002).

The only way we can hope to measure slowness and azimuth from such signals is by determining the arrival time at each of the sites to the highest possible accuracy and then fitting a best fit wavefront across the array. The large size of the array means that, for most regional phases, the time taken for a wave-front to cross the array is quite large and the capability for making a good determination of slowness and azimuth is fairly good, provided that a sufficient number of sufficiently accurate arrival times are correctly associated and that spurious arrival times are successfully removed from the inversion process.

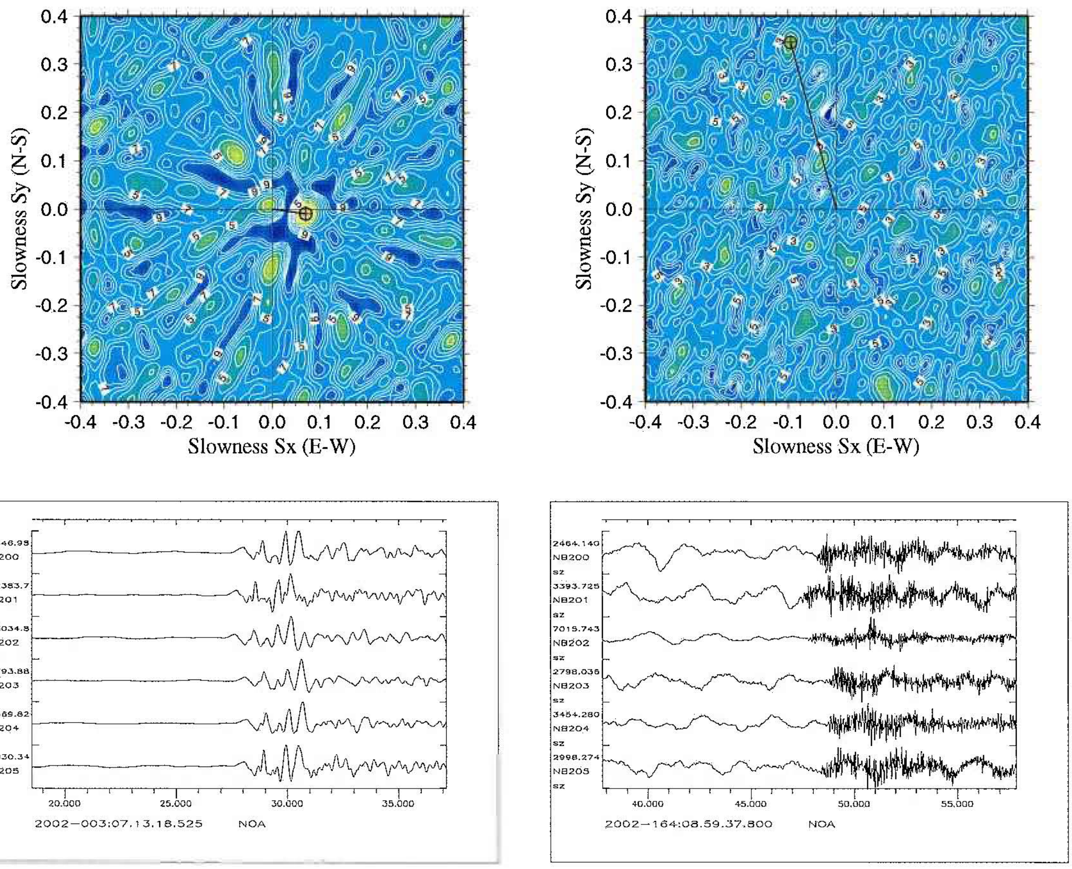

Fig. 6.4.2. Broadband fk-plots and unfiltered waveforms for a teleseismic P-arrival (Pakistan, azimuth 97°; left) and a regional Pg phase (Sweden, azimuth 71°, right). The fk-analysis was performed in a 3 second time window on waveforms filtered in the 1.5 - 4.0 Hz frequency band.

6.4.2 Detection and processing of regional events

Detection

It was pointed out by Ringdal et al. (1975) that by forming incoherent beams, i.e. the beams of the short term average (STA) or envelope of filtered waveforms, that high frequency signals could be detected on the NOA array with a high SNR, despite the incoherence of the actual waveforms. All short period vertical (sz) traces from each subarray are bandpass filtered in the frequency bands listed in Table 6.4.1. For a given frequency band, an STA trace is formed from each filtered signal and these STA traces are summed with time delays corresponding to the apparent velocity and azimuth values listed in Table 6.4.1.

Frequency band (Hz)	Azimuth values (degrees)	Apparent velocities (kms^{-1})
(2.0 - 5.0)	0, 45, 90, 135, 180, 225, 270, 335	3.8, 6.5, 9.0, 12.0
(3.0 - 6.0)		
(4.0 - 8.0)		
(6.0 - 12.0)		
(8.0 - 16.0)		

Table 6.4.1. Subarray beams used for the processing of regional events at the NOA array.

In the current prototype version of the Regional NOA processing system, all detections are made at subarray level. However, the system is designed such that a beam with arbitrary delays for any combination of sites could be introduced. Hence, travel times for a given phase from a specific site could be calculated and incorporated into a beam. An event occurring at that site would then be likely to result in a beam with a higher SNR than any of the single subarray beams.

Processing

Having made a detection, the frequency content of the signal must be estimated for each of the single traces which contributed to the detection; for all but the lowest frequency signals, the traces must be analysed individually. For each trace, a frequency band is calculated in which the SNR is a maximum; these calculations provide a trigger time which can be used as an initial estimate for a more accurate onset time determination, taking into account changes in both frequency and amplitude. For this, we use the autoregressive AR-AIC method (Akaike, 1974; GSE/JAPAN/40, 1992). The task is then to associate as many arrival times as possible (at a maximum of 42 sites in the NOA array) which correspond to the same phase arrival.

At the sub-array level, with inter-station distances of up to 9 km, most incoming wave-fronts can adequately be modelled as planar wave-fronts. However, over the full NOA array, the maximum distance between stations is almost 80 km, meaning that departures from planar geometry will be significant for events up to 250-300 km from the array's reference point. Although fitting a plane wave to a set of arrival times from such an event is likely to result in an azimuth and slowness which are approximately correct, the deviations from the best-fit wavefront will be systematic and large such that an imbalance in measurement (for example should we fail to measure any satisfactory arrival times from one or more of the sub-arrays) is likely to lead to a spurious slowness determination. Almendros et al. (1999) successfully applied a circular wave-front to seismo-volcanic sources at local distances at Deception Island, Antarctica, and we will here apply this formulation to events at regional distances arriving at the NOA array.

Using the notation of Almendros et al. (1999), we assume incoming wavefronts to travel at a constant slowness, S, from an origin a distance D from the array reference point (x_0, y_0) at an azimuth A (see Fig. 6.4.3); the time taken for the wave to reach a station k is

$$t_k = S\sqrt{(x_k - D\sin A)^2 + (y_k - D\cos A)^2} \qquad (1)$$

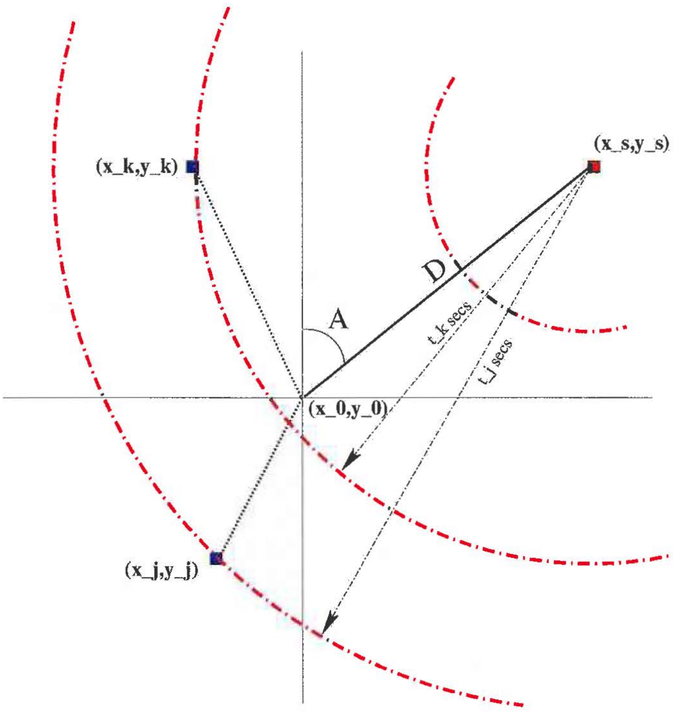

Fig. 6.4.3. The circular wave-front geometry proposed by Almendros et al. (1999).

We will have a maximum of 42 arrival times from which we must solve for the unknowns D, S, and A, along with t_0, the time at which the circular wave passes the reference point of the array. Unlike the plane wave fit, this system is non-linear and so cannot be solved by a straightforward least squares inversion. Almendros et al. (1999) used a grid search method to find the parameters best fitting the given arrival times. However, at the local distances in their study, the signals were largely coherent and the iterative process involved correlating waveforms which is not a practical solution for us. Instead, we employ a Newton-Raphson type iteration based upon the arrival times alone which minimizes the (observed - predicted) time residuals. This requires an initial estimate of the parameters, of which t_0, S, and A are available from the linear plane wave fit.

The distance D is not considered to be an important parameter in this situation for two reasons; firstly, the formulation does not take into account the curvature of the Earth which will be nonnegligible over regional distances and, secondly, a circular wave travelling at a constant velocity is a gross oversimplification of the true seismic wavefield. In many cases, where the origin of the event is several times further from the array reference point than the array aperture, the curvature of the wavefront will be insignificant compared with the uncertainties in the arrival time determinations and we will not be able to solve for D. In such cases, the circular wavefront fit returns the best fit plane wavefront. The array reference point for NOA was selected to be site NB200 (coordinates 61.03972°N, 11.21475°E).

Arrival times are grouped at subarray level for a given detection. This allows for some additional screening of outliers, i.e. onset time determinations which passed the SNR tests on the individual traces, but which cannot correspond to the same seismic phase as the other picks from the subarray. The most difficult task remains; we need to associate the subarray detections which correspond to the same seismic phase. The incorrect association of subarray detections is by far the most likely cause of false alarm reporting. If a slowness and azimuth determination of a genuine seismic phase is made with onset times from a subset of NOA elements, we should obtain confidence intervals in which we can anticipate arrivals from the same seismic phase at the remaining NOA instruments. Subsequent detections which do not fall within these time intervals clearly do not belong to the same event and are readily screened out. However, there are many instances where two groupings of arrival times which do not correspond to the same seismic phase are grouped together simply because they occur in the same time window. This will may return an azimuth and slowness corresponding to a non-existent seismic phase, prevent the detection of a genuine phase, or both. Such cases will be discussed later in more detail.

6.4.3 Results from circular wavefront fitting at the NOA array

To demonstrate the validity of the circular wavefront fit to regional data, we selected a series of 12 explosions performed by the Swedish military in June and July 2001 at the Mossibränden site in Älvdalen Skjutfält (coordinates 61.566° N, 13.790° E). Details of these events are given in Gibbons et al. (2002). The explosion site is 152.40 km from the centre of the NORES array with a receiver to source backazimuth of 51.63°. The backazimuth for site NB200 of NOA is 65.85° at a distance of 149.94 km. The station to source distances vary from 119 km (NC401) to 183 km (NAO04) and backazimuths vary from 51.3° (NC603) to 79.0° (NC205).

The Pg phase is anticipated to be the first arrival from these events at those elements of the NOA array closest to the source. In southern Norway, the Pn phase replaces Pg as the first arrival at an epicentral distance of approximately 150 to 170 km (Gundem, 1984). The more distant elements of the NOA array may therefore experience the Pn phase first, with a higher apparent velocity than Pg. Given that the arrival times used for an inversion of a best fit circular wavefront will invariably be either a first P-arrival or a first S-arrival, this case study potentially illustrates a fundamental problem; we are attempting to fit a wavefront with a constant slowness to arrival times corresponding to different seismic phases.

The waveforms recorded from a typical one of these events at NOA are displayed in Fig. 6.4.4. These events were all detected with a high SNR and satisfactory automatic P-arrival times were calculated for most traces for all events. The S-phase picks were predictably poorer with many determinations being discarded as the result of low signal to noise ratio. The AR-AIC method works best for arrivals where the signal and preceding noise exhibit a large contrast in both amplitude and frequency content. In order to obtain an optimal SNR, most such traces have to be filtered in quite a narrow frequency band (typically between 2.0 and 5.0 Hz) and the contrast in the autoregressive models is consequently small.

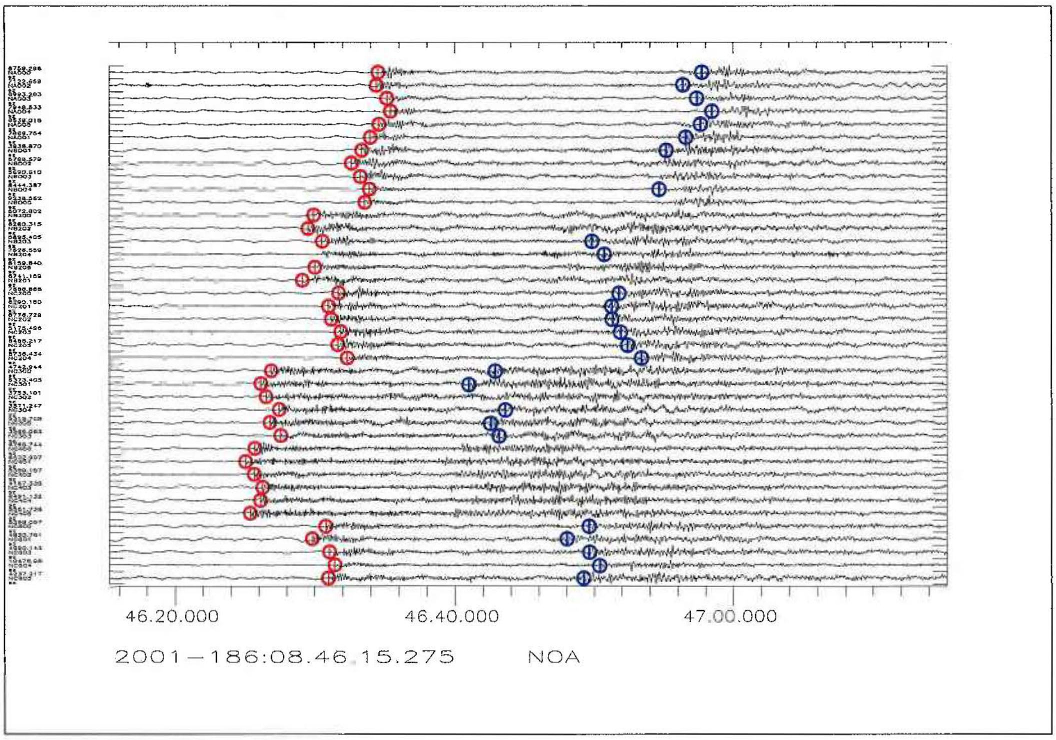

Fig. 6.4.4. Unfiltered waveform data from one of the Mossibränden explosions with the automatically calculated arrival times for P (red symbols) and S (blue symbols). An S-onset time is missing from many of the traces; this indicates that the onset picker failed, either due to a low SNR or a bad value of the Akaike Information Criterion (AIC).

Table 6.4.2 gives the azimuth values obtained for the P-arrivals from this series of events as determined by the NORES array using standard broadband fk-analysis, and by the NOA array where a best fit circular wavefront is fitted to automatically determined onset times. The azimuths determined by fk-analysis in a fixed frequency band (NORES) have a small standard deviation but a large systematic departure from the geographical backazimuth. The offset in azimuth is a function of the frequency band used for the analysis, reflecting the complicated form of the seismic wavefield resulting from the heterogeneous underlying velocity structure (see Kværna and Doornbos, 1991). The azimuths reported by the automatic event processor for NORES show a very large standard deviation but mean and median values which lie quite close to the actual values. This is due to the fact that the fk-analysis is performed in a frequency band which is not fixed but determined automatically to optimize the SNR. Fluctuations in SNR, for instance due to different levels of background noise, may lead to small differences in the selected frequency band and consequently large differences in azimuth as documented by Kværna and Doornbos (1991).

The azimuth values from the circular wavefront fits have both a small systematic offset and a low standard deviation. The large area covered by the NOA array means that many scattering effects and local wavefield properties are averaged out between the widely spaced sensors. The azimuth value returned is only a function of the measured onset times which are relatively insensitive to variations in the background noise. Although the distance parameter, *D*, is not a reliable indicator of epicentral distance in general, the closeness of these *D* values to the geographical distance indicate that there is much validity in the circular approximation to the shape of the wavefront for these events.

Origin time	Azimuth deviation from NORES from fk-analysis in a fixed frequency band (2.0 - 5.0 Hz)	Azimuth deviation from NORES automatic processing	Azimuth deviation for circular wavefront - NOA	Distance, *D*, determined from circular wavefront - NOA
2001-176:13.46.17.89	-9.65 (41.98)	-9.03 (42.6)	-0.44 (65.41)	148.07
2001-177:07.15.30.24	-9.64 (41.99)	-8.93 (42.7)	-0.72 (65.13)	156.99
2001-177:13.00.10.52	-9.38 (42.25)	-9.63 (42.0)	-0.47 (65.38)	151.13
2001-178:09.16.05.37	-9.20 (42.43)	7.77 (59.4)	-0.57 (65.28)	159.30
2001-178:13.40.12.41	-8.85 (42.78)	6.87 (58.5)	-0.51 (65.34)	171.23
2001-179:09.40.55.57	-9.84 (41.79)	2.97 (54.6)	-0.65 (65.20)	157.08
2001-179:13.50.31.67	-8.35 (43.28)	4.47 (56.1)	-0.60 (65.25)	163.52
2001-183:11.36.00.64	-8.59 (43.04)	3.17 (54.8)	-0.78 (65.07)	151.42
2001-184:07.31.03.74	-9.26 (42.37)	-9.13 (42.5)	-0.56 (65.29)	153.24
2001-184:13.01.01.21	-9.95 (41.68)	-8.03 (43.6)	-0.67 (65.18)	153.07
2001-185:09.36.06.49	-9.74 (41.89)	3.57 (55.2)	-0.71 (65.14)	158.69
2001-186:08.46.05.59	-8.94 (42.69)	7.17 (58.8)	-0.56 (65.29)	150.53
Standard deviation	0.513	7.42	0.105	6.48
Mean value	-9.28 (42.35)	-0.73 (50.9)	-0.603 (65.246)	156.2
Median value	-9.32 (42.31)	3.07 (54.7)	-0.585 (65.265)	155.1

Table 6.4.2. Azimuth values for the 12 Mossibränden explosions in June and July 2001 based upon the P-arrival. Azimuth deviation refers to the difference between the measured and known geographical azimuth values; the measured azimuths are given in parentheses. The actual azimuths are 51.63^0 (NORES) and 65.85^0 (NB200, NOA) and the distance from NB200 to the explosion site is 150 km. The corresponding apparent velocity values are given in Table 6.4.4.

The corresponding azimuth values for the S-phases are displayed in Table 6.4.3. The azimuth values obtained by the circular wavefront fit have a slightly larger offset and standard deviation than they did for the P-arrivals but, although having a higher standard deviation than the fixed frequency band fk-analysis results from NORES, still give quite accurate and consistent determinations. One crucial observation is that in most cases we failed to solve for the distance, *D*, such that most of these determinations are actually plane wave fits. Even on the occasions when a value of *D* was returned, it was generally far larger than any realistic value and so, in effect, the circular wavefront was a plane approximation.

Origin time	Azimuth deviation from NORES from fk-analysis in a fixed frequency band (2.0 - 5.0 Hz)	Azimuth deviation from NORES automatic processing	Azimuth deviation for circular wavefront - NOA	Distance, D, determined from circular wavefront - NOA
2001-176:13.46.17.89	8.92 (60.55)	11.2 (62.9)	3.32 (69.17)	-
2001-177:07.15.30.24	7.62 (59.25)	8.4 (60.1)	2.05 (67.90)	-
2001-177:13.00.10.52	8.62 (60.25)	7.6 (59.3)	2.50 (68.35)	224.8
2001-178:09.16.05.37	8.29 (59.92)	10.4 (62.1)	3.81 (69.66)	-
2001-178:13.40.12.41	7.29 (58.92)	8.0 (59.7)	-0.99 (64.86)	318.4
2001-179:09.40.55.57	8.24 (59.87)	-0.7 (50.9)	3.27 (69.12)	-
2001-179:13.50.31.67	7.33 (58.96)	10.1 (61.8)	3.21 (69.06)	202.5
2001-183:11.36.00.64	8.05 (59.68)	-0.4 (51.2)	2.18 (68.03)	-
2001-184:07.31.03.74	7.94 (59.57)	10.2 (61.9)	3.08 (68.93)	-
2001-184:13.01.01.21	6.83 (58.46)	10.6 (62.3)	1.06 (66.91)	299.6
2001-185:09.36.06.49	7.36 (58.99)	9.3 (61.0)	3.15 (69.00)	-
2001-186:08.46.05.59	7.99 (59.62)	9.2 (60.9)	2.02 (67.87)	175.69
Standard deviation	0.607	4.10	1.31	-
Mean value	7.87 (59.50)	7.87 (59.51)	2.39 (68.24)	-
Median value	7.97 (59.60)	9.32 (60.95)	2.79 (68.64)	-

Table 6.4.3. Azimuth values based upon the S-arrivals for the 12 Mossibränden events (c.f. Table 6.4.2). The absence of a *D* value indicates that this parameter could not be solved for in the circular wavefront inversion and the azimuth and slowness obtained correspond to that of a plane wave. The corresponding apparent velocity values are given in Table 6.4.4.

Finally, Table 6.4.4 lists the apparent velocities obtained by the same three calculations as provided the azimuth values in Tables 6.4.2 and 6.4.3. The circular wavefront fit for the NOA array gives very consistent values around 6.17 kms^{-1} for the apparent velocity of the P-arrival; slightly lower than those obtained by the fk-analysis at the NORES array. For the S-arrival, with the correspondingly poorer onset time estimations, the slowness determinations from NORES are more stable than the NOA circular wavefront fits. NORES and the NB200 site are essentially equidistant from the source site and so the apparent velocities should be directly comparable.

Origin time (abbreviated)	Apparent velocity: P-arrival			Apparent velocity: S-arrival		
	Fixed band fk-analysis: NORES	Automatic processing: NORES	Circular wave front fit: NOA	Fixed band fk-analysis: NORES	Automatic processing: NORES	Circular wave front fit: NOA
2001-176	6.68	6.3	6.20	3.60	3.6	3.33
2001-177a	6.73	6.3	6.15	3.61	3.3	3.23
2001-177b	6.53	6.3	6.18	3.57	3.4	3.43
2001-178a	6.62	6.6	6.16	3.54	3.6	3.34
2001-178b	6.60	6.4	6.14	3.53	3.5	2.99
2001-179a	6.61	6.7	6.18	3.57	3.3	3.44
2001-179b	6.48	6.6	6.17	3.51	3.8	3.30
2001-183	6.54	6.6	6.17	3.55	3.1	3.26
2001-184a	6.55	6.4	6.17	3.55	3.6	3.42
2001-184b	6.60	6.3	6.19	3.54	3.6	3.35
2001-185	6.68	6.5	6.17	3.56	3.5	3.27
2001-186	6.65	6.5	6.18	3.65	3.6	3.21
Standard deviation	0.0724	0.144	0.0164	0.0387	0.188	0.123
Mean value	6.61	6.46	6.17	3.57	3.49	3.30
Median value	6.61	6.45	6.17	3.56	3.55	3.32

Table 6.4.4. Apparent velocity for P and S arrivals at NORES and NOA for the events listed in Tables (6.4.2) and (6.4.3).

6.4.4 The detection and location capabilities of the NOA array at regional distances

Automatic detections from the prototype regional NOA processing system have been included in a test version of the GBF process. Fig. 6.4.5 shows the trial locations of events, from a test period of 90 days in 2003 (after NORES data became unavailable), which included at least two defining phases from the NOA array. The green symbols correspond to events which were also detected by other arrays, especially the Hagfors array in Sweden. Many of these events were also located by GBF without the NOA phases, although the additional arrival times and azimuth information provide a useful additional constraint on epicenter location.

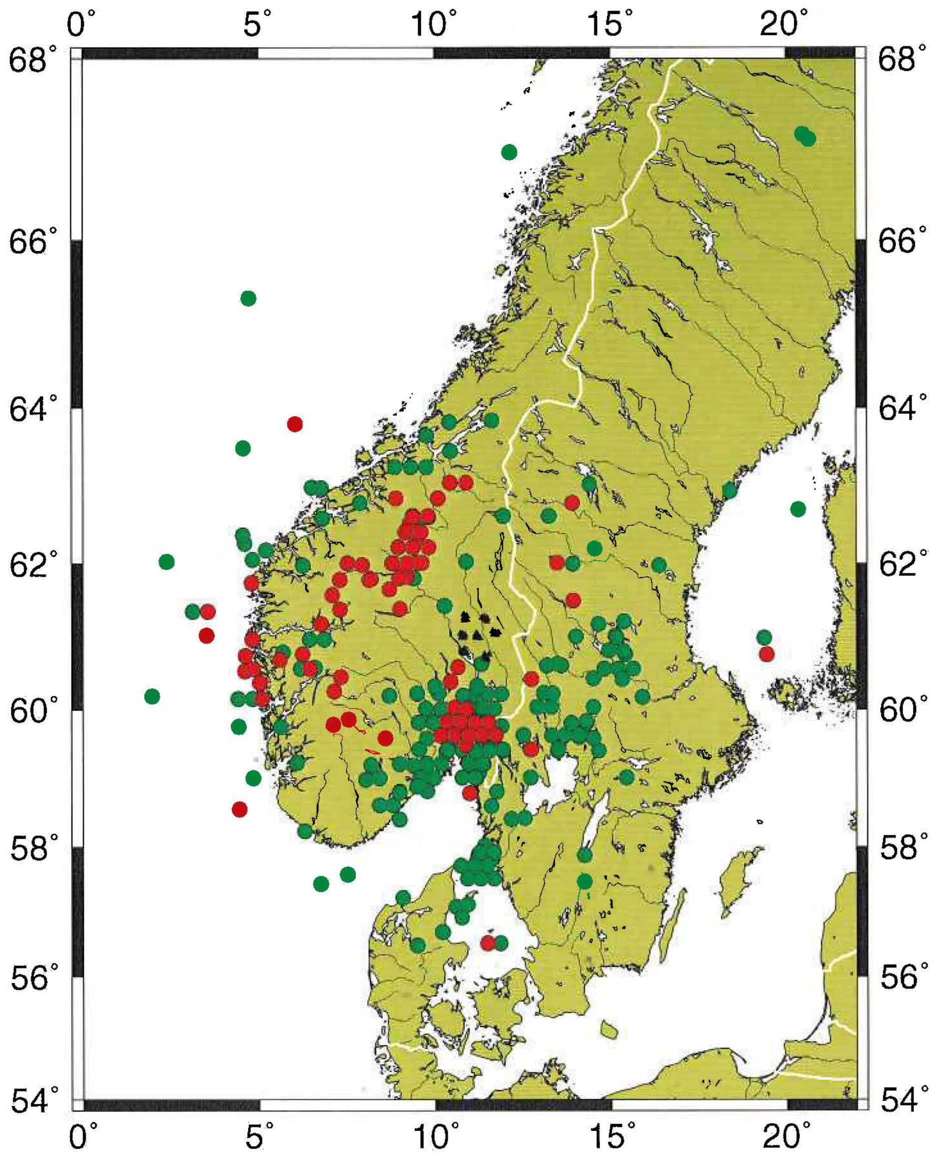

Fig. 6.4.5. Events located by the GBF system over a trial period from 2003-001 to 2003-090 which include at least two phases from the Regional NOA process. Red symbols indicate that the events were only located by phases detected using NOA; green symbols indicate that at least one phase from another array was used in addition.

Events displayed here which are only detected by NOA and which are, for example, closer to the HFS array than to NOA are very likely to be false associations, as is the red symbol in the Gulf of Bothnia in Fig. 6.4.5. Most of the symbols in Sweden correspond to events for which the directional and time observations from NOA are consistent with those from HFS. Most of the events only detected by NOA are in the range 80 - 200 km from the array and are generally associated with high frequency signals. These are ideally suited to processing with this system. Although the signals are weak, their high frequency content allows for good onset-time determinations by the AR-AIC process; the low energy content at lower frequencies mean that signal coherency is often poor, even for regional arrays such as Hagfors. The large cluster of events in central Norway (Oppland) are presumed to be industrial due to the patterns of occurrence. They are probably far more clustered than indicated in Fig. 6.4.5; azimuths from the P-arrivals fall into very narrow ranges, but the S-phases have far fewer, and poorer, onset time determinations and consequently are attributed azimuth values that are poorly constrained.

If we increase the scope of Fig. 6.4.5 to include GBF locations with only a single defining phase from NOA then we obtain many events much further away than those shown, which generally occur within approximately 350 km of the array. There are however, many more false alarms. Slowness and azimuth values have been determined from a great many P-arrivals with very small time residuals. However, in the absence of a good determination of a secondary phase, these events can not be located unless they are successfully associated with phases detected at other arrays. In its current form, there are very few events for which the process has managed to make satisfactory azimuth and slowness determinations for all of the Pn, Sn, and Lg phases.

6.4.5 Discussion and further work

We have developed a system by which seismic phases from regional events can be identified using the NOA array. The system works by calculating the arrival times of phases at each of the short period vertical instruments in the array and by fitting a wavefront to those arrival times. The circular wavefront formulation of Almendros et al. (1999) was found to give very robust and realistic estimates of slowness and azimuth of phases at near-regional distances, an iterative process being employed to find the parameters which minimize time residuals. This iterative method could robustly be applied to all arriving wavefronts because the limiting case of the circular wavefront is a plane wavefront.

The system has been quite successful at locating events within approximately 350 km of the array and many events which have not been detected by the GBF system since the loss of the NORES array can now be included. The NOA array can also provide a useful constraint on events which otherwise would only be detected by the Hagfors array.

The fundamental disadvantage of using NOA is that the signals of interest are not coherent over the array and we are thus limited to examining each trace individually. This is to say that once a detection has been made by incoherent beamforming, the elements of NOA act merely as a network and not an array. Only when we are able to determine with confidence a phase arrival time on a single trace is that data useful in identifying a phase. This somewhat defeats the purpose seismic arrays which is to improve the information which can be obtained from signals by combining data from different sites in such a way that the form of the signal is amplified and the noise reduced. Nuances of seismic signals, especially the arrival of coda phases, which are readily available from regional arrays (Mykkeltveit and Bungum, 1984), will never be discernible using the methods outlined here and a wealth of information regarding the seismic wavefield will be lost until a replacement for NORES is obtained. The best we can hope to do with the method outlined here is to obtain an arrival time, slowness and azimuth for first P-arrivals and a secondary phase; it is very seldom that more than one secondary phase can be correctly identified by the picking of arrival times on traces from such widely spaced instruments.

The principal reason for failure of the current system is an incorrect association of detections and corresponding arrival times at subarray level. For incoherent regional signals, it is generally necessary to associate detections from several subarrays to make a worthwhile estimate of the slowness and azimuth of an incoming phase. With 6 instruments in a subarray, although it is certainly possible to invert these arrival times for the parameters of a plane wavefront, the uncertainties associated with the slowness and azimuth can be large and an automatically picked arrival time needs only an error of a few samples to have a large effect on the predicted wavefront. Many single subarray determinations for P-arrivals are actually quite good due to the low error associated with the time picks. For S-arrivals, however, the error associated with each pick is usually comparable with the time delay between the stations. On the other hand, if the onset times from several subarrays are combined, the errors on individual picks become insignificant compared with the total time delays. This is beautifully illustrated in Fig. 6.4.4 where the S-arrival times from the whole array result in an azimuth determination within 2^o of the geographical value and an apparent velocity with an error less than 10%.

It takes approximately 20 seconds for a regional S-phase to cross the NOA array. Any unrelated phase arriving in this period can lead to an erroneous determination which, without a sophisticated checking mechanism, will also result in a missed determination of a genuine regional phase. An unassociated P-arrival at one subarray, combined with an S-arrival at another subarray, can result in a plausible wavefront with a far higher apparent velocity: a spurious teleseismic phase. Similarly, two detections from different segments of the coda of a teleseismic signal can combine such that a best fit wavefront gives the slowness and azimuth of a regional phase. Processing regional events on a small aperture array or teleseismic events on a large aperture array can largely be done serially; i.e. without the need to examine the history of the time series. To minimize the occurrence of spurious regional associations on the NOA array, it is probably necessary to examine a long time segment with potentially many detections on each subarray and try to deduce the most likely phase combinations. This is non-trivial.

The remaining challenges to the process are to improve the determination of onset times for secondary phases (the absence of secondary phases is the primary reason that so many events with well determined P-arrivals remain unlocated) and to improve the detection and processing of events at far-regional distances. The key to the first issue is almost certainly the use of the rotated horizontal components of the 3-component broadband instruments, of which one is located in each subarray. The key to the second issue is probably the use of detecting beams which cover more than one subarray: possibly with the additional use of the 3-component instruments. However, to prevent a prohibitively large number of beams, an optimal combination of frequency bands and time-delays must be investigated for the events of interest. Ultimately, we must accept the limitations of such a large aperture array and accept that if we have neither sufficient signal coherence (at least at subarray level) or a signal which is sufficiently strong that it can be analysed on a single component (be it short period vertical or rotated), then we have exceeded the capability of NOA and need a regional array solution.

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6.5 Seismic events associated with the Barentsburg mining accident on 7 June 2003

6.5.1 Introduction

At 12:27 GMT (14:27 local time) on 7 June 2003 there was a major mining accident, with one casualty, in the Barentsburg coal mine on Spitsbergen. This accident was caused by a collapse in the mine and generated seismic signals with a magnitude of 3.7 as reported in the CTBTO Reviewed Event Bulletin (REB). About 2 hours later, at 14:23 GMT, there was another seismic event of approximately the same size in the same area.

This Barentsburg mine is operated by the Russian company Trust Arktikugol. This mine has suffered several accidents during the last years, caused by both rockbursts and explosions of gases. We will in this contribution estimate the location and size of the 7 June 2003 events, and compare these to the known seismicity in the region.

6.5.2 Earthquakes on Svalbard

The local earthquake activity on Svalbard and in adjacent seas is significant. Larger earthquakes are reported by the Norwegian National Seismic Network, and are routinely included in international seismic bulletins. However, until recently there has not existed any systematic and detailed monitoring of the smaller seismic events that often occur in mining areas.

A recent study of the earthquake activity on Svalbard and in adjacent seas is presented in a previous NORSAR Semiannual Report (Kremenetskaya et al., 2002). Active earthquake zones are found on Heerland and on Nordaustlandet. In addition, there is significant earthquake activity on the Mid-Atlantic Ridge about 100-200 km west of Vest-Spitsbergen.The Western Barents Sea south of Svalbard also exhibits frequent earthquake activity, and on 4 July 2003, a m_b of 5.4 earthquake with several aftershocks occurred in this region.

The areas around the coal mines on Svalbard also show some seismic activity. A particularly strong earthquake (magnitude 5.9) in 1976 caused significant damage to the (now abandoned) Soviet mine in Pyramiden. But usually the events within the mining areas are small.

6.5.3 The seismic activity in Barentsburg for the time period December 2000 to June 2003

In December 2000 the Kola Regional Seismological Center (KRSC), in cooperation with NORSAR, installed a seismic station in Barentsburg (BRB). The station is located about 5 km from the mines (see Fig. 6.5.1). The motivation behind this installation was to acquire more knowledge about the increasing number of rockbursts in the mines near Barentsburg. This installation supplemented the existing seismic stations in Adventdalen (SPITS), Kings Bay (KBS) and Hornsund (HSP). The BRB data are analyzed by KSRC in Apatity, and NORSAR has access to these analyzes. The results for the time period December 2000 to April 2001 are presented by Kremenetskaya et al. (2001), and Figs. 6.5.1 and 6.5.2 give a summary of these results.

As seen from the figures (which cover a time period of 6 months), a large number of smaller events are recorded in the Barentsburg mines. Typical magnitudes for these events are between 0 and 1. Larger earthquakes are not very frequent, but occur from time to time. Dates with such events are 28 January 2001, 25 March 2001, 5 September 2002 (all with magnitudes around 2.5). Following the event on 25 March 2001, the mining activity was closed down for one month for safety reasons .

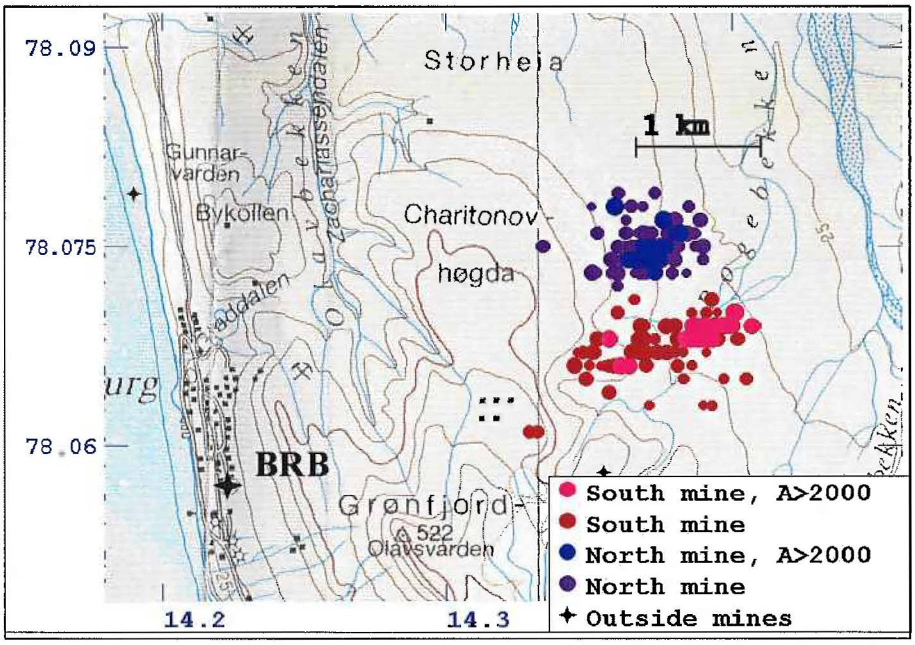

Fig. 6.5.1. The map shows the locations of seismic events in the Barentsburg area for the time period 1 December 2000 to 25 March 2001. The blue symbols show events in the northern mine, while red symbols show events in the southern mine. The largest events have lighter colors. Events located outside the mining area are shown by small crosses. The Barentsburg station (BRB) is shown by the large cross to the left. (From Kremenetskaya et al., 2001)

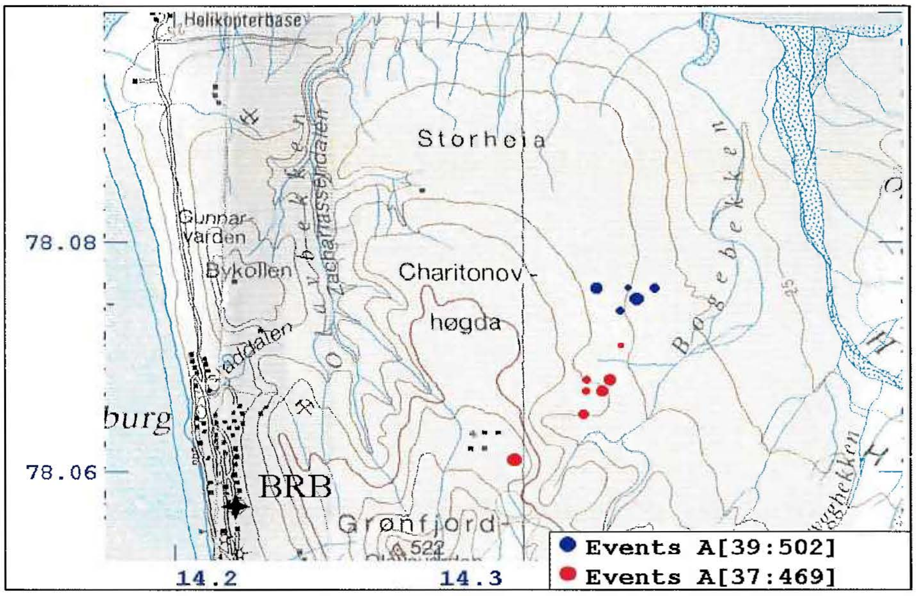

Fig. 6.5.2. The map shows the locations of seismic events in the Barentsburg area for the time period 26 March 2001 to 19 April 2001, after the mining activity was stopped due to the 25 March 2001 rockburst. (From Kremenetskaya et al., 2001)

6.5.4 Global observations

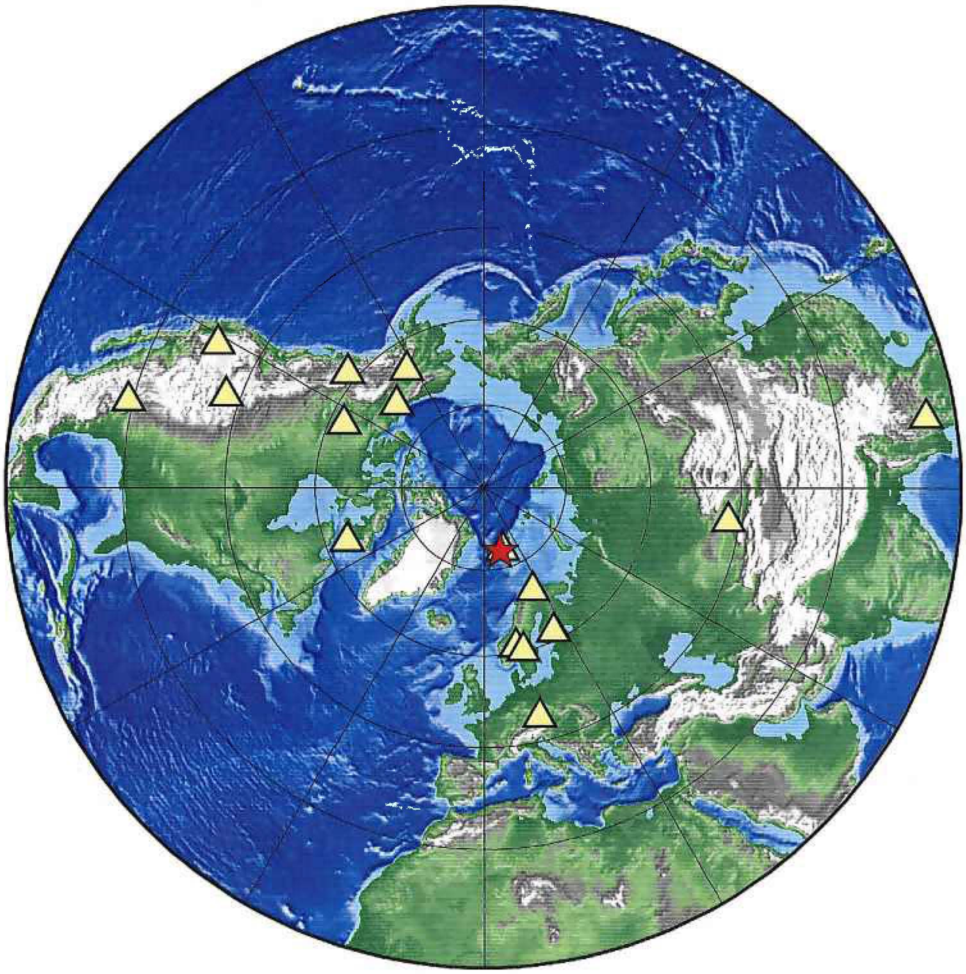

Fig. 6.5.3. Map of the IMS stations (yellow triangles) that recorded the event in Barentsburg on 7 June 2003 at 12:27 GMT (red star).

It is relatively uncommon that seismic events related to mining activity are reported in international seismic bulletins. In this case, the first event at 12:27 GMT on 7 june 2003 was reported in the CTBTO REB. The event was recorded out to 7000 km distance (see Fig. 6.5.3), and a network m_b of 3.7 was estimated for this event.

The second event, having almost the same size, was not reported in the REB. This is most likely due to the fact that a magnitude of 3.7 is close to event reporting capability of the IMS network for this region, and that the second event had a magnitude slightly below this limit.

6.5.5 Observations on Spitsbergen

The map of Fig. 6.5.4 shows the currently operational seismic stations on Svalbard, which are all used for the analysis of the 7 June 2003 events. The recordings of the two events are shown in Figs. 6.5.5-6.5.8, together with the recording of the 28 January 2001 rockburst in the Barentsburg mine. The January 2001 event was located by Kremenetskaya et al (2001), and this location was also verified by observations in the mine.

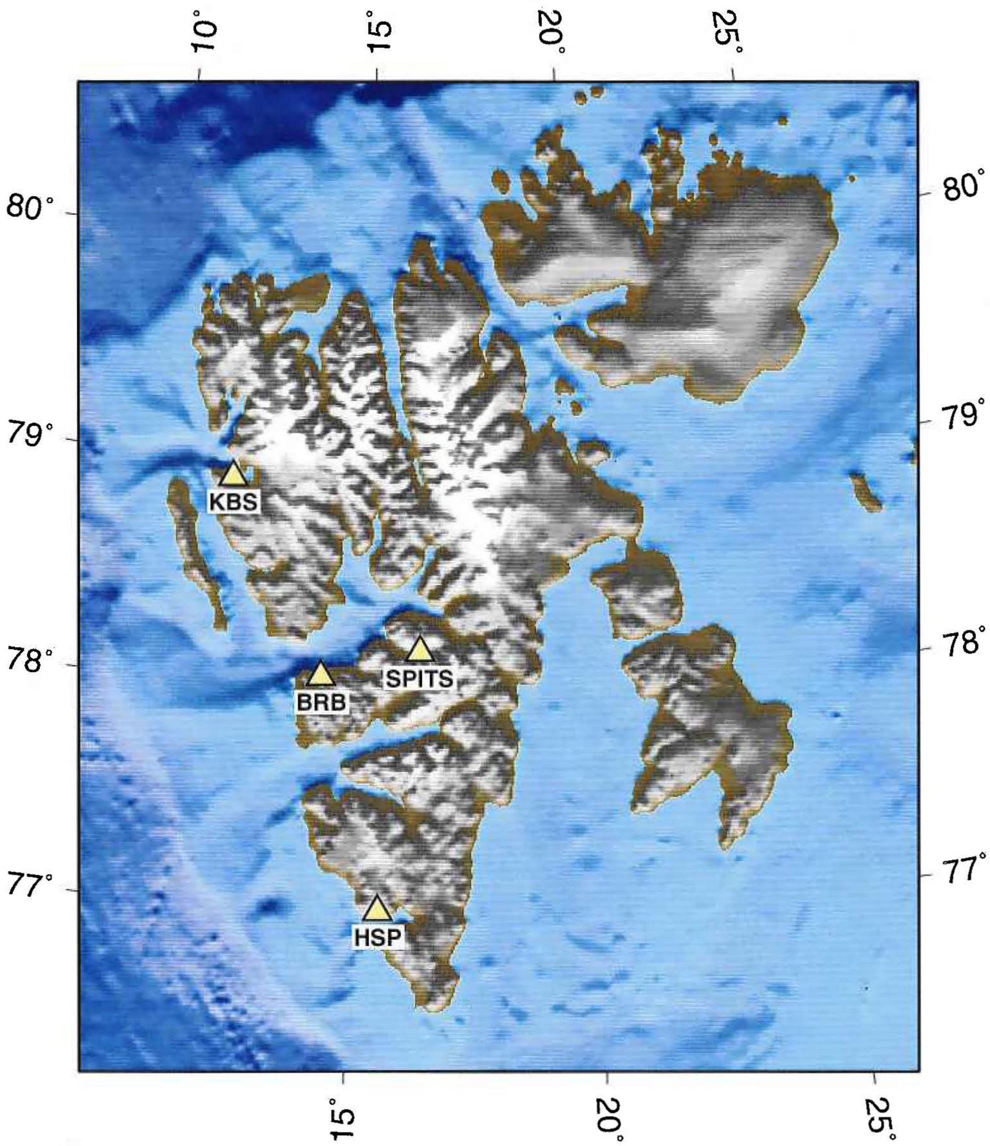

Fig. 6.5.4. Map showing the locations of the four stations on Spitsbergen recording the Barentsburg events.
SPITS - Spitsbergen arrayen (NORSAR)
KBS - Kings Bay, Ny Ålesund (University of Bergen)
BRB - Barentsburg (Kola Regional Seismological Center)
HSP - Hornsund (The Polish Polar Station)

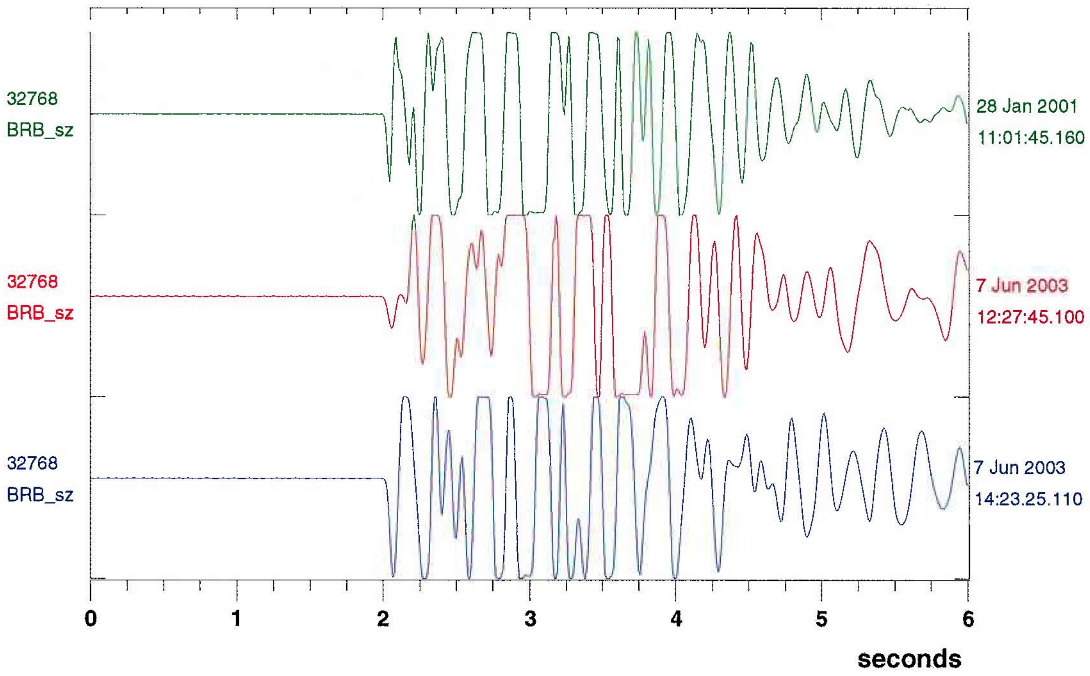

Fig. 6.5.5. Recordings at the Barentsburg station (BRB) of three different events in the Barentsburg mine. The red and blue traces show the 7 June 2003 events, while the green trace shows the 28 January 2001 rockburst.

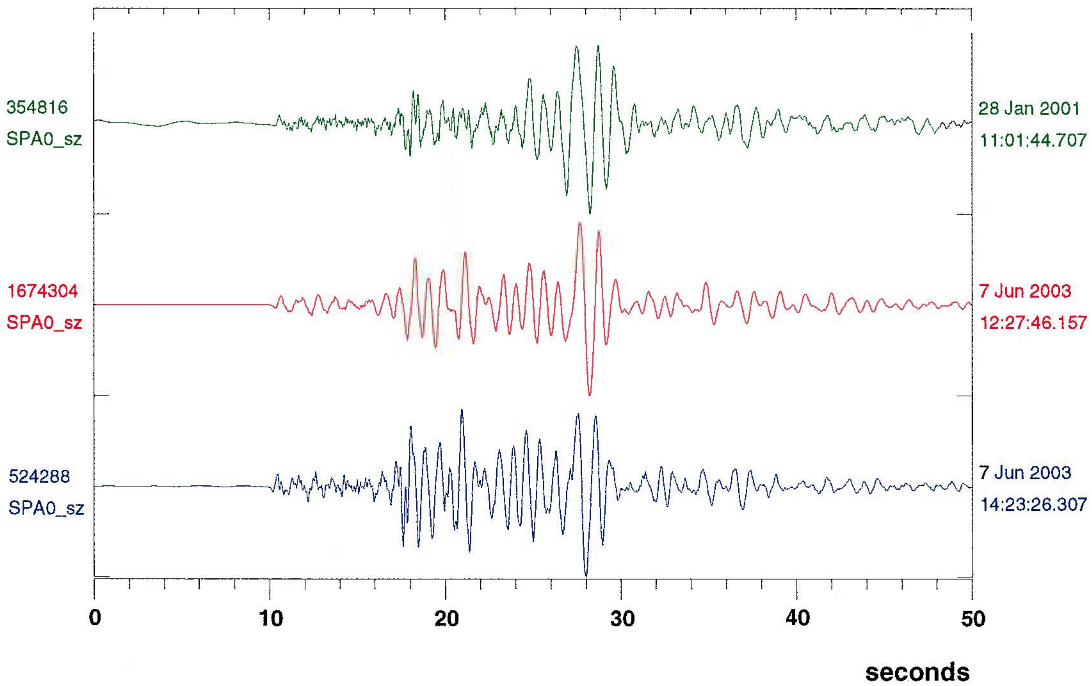

Fig. 6.5.6. Recordings at the Spitsbergen array (SPITS) of three different events in the Barentsburg mine. The red and blue traces show the 7 June 2003 events, while the green trace shows the 28 January 2001 rockburst.

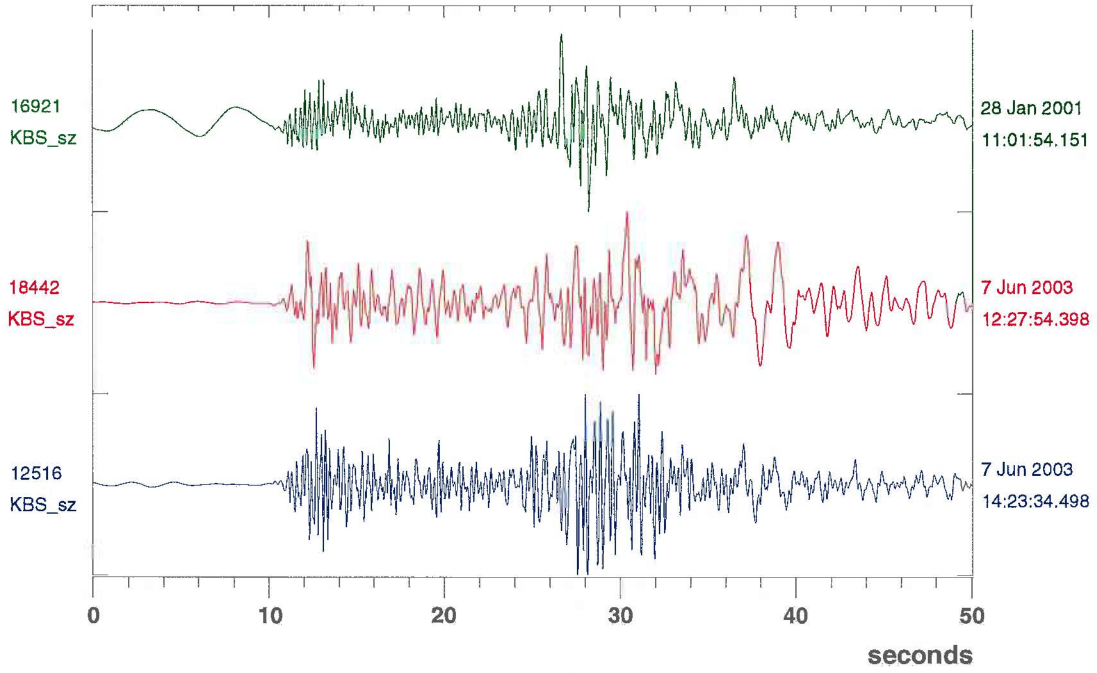

Fig. 6.5.7. Recordings at the Kings Bay station (KBS) of three different events in the Barentsburg mine. The red and blue traces show the 7 June 2003 events, while the green trace shows the 28 January 2001 rockburst.

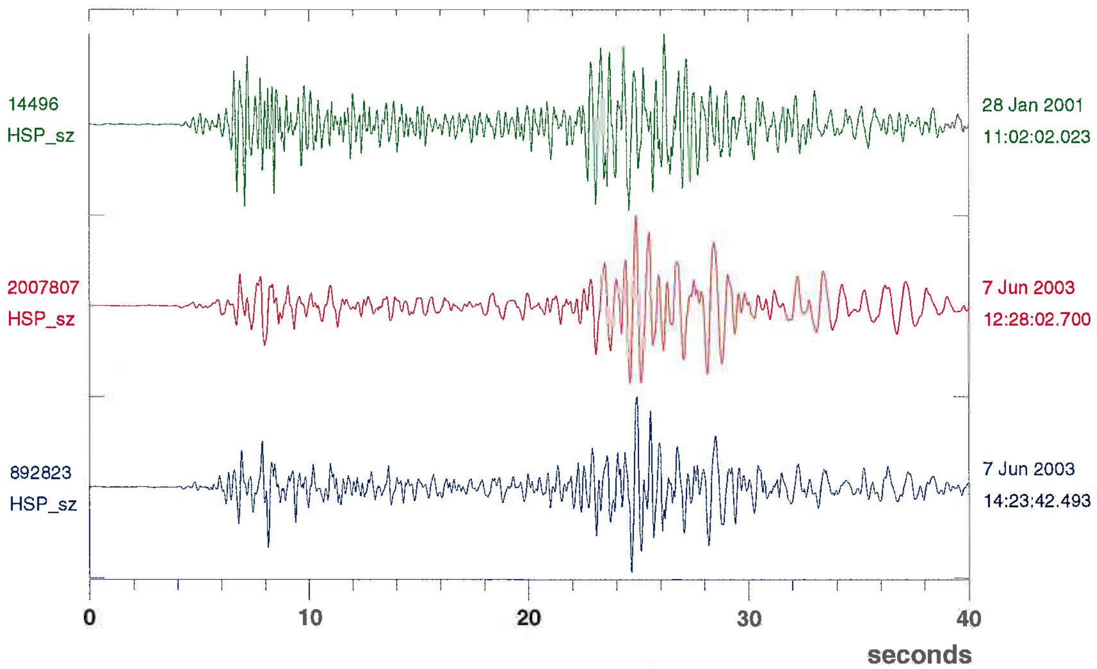

Fig. 6.5.8. Recordings at the Hornsund station (HSP) of three different events in the Barentsburg mine. The red and blue traces show the 7 June 2003 events, while the green trace shows the 28 January 2001 rockburst.

6.5.6 Locations of the seismic events on 7 June 2003

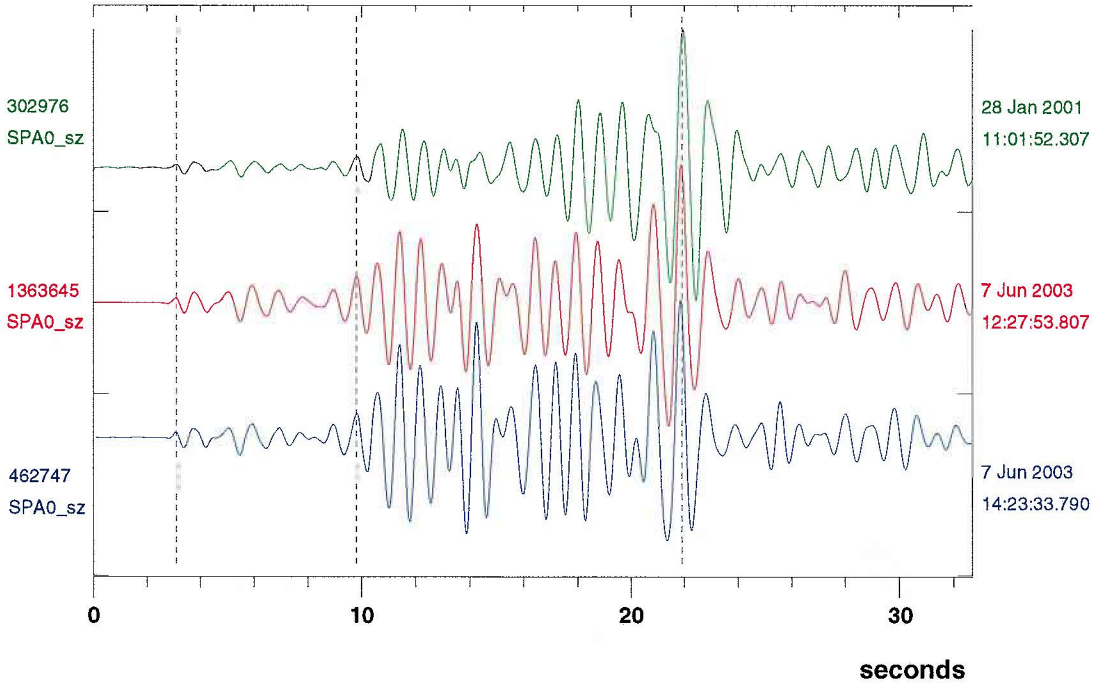

Fig. 6.5.9. Filtered recordings at the SPITS array of the three events also shown in Fig. 6.5.6. The passband is 0.8 - 2.0 Hz, and the vertical dashed lines indicate the similar time differences between the signals of these wavetrains.

Fig. 6.5.9 shows filtered SPITS recordings of the two events on 7 June and the 28 January 2001 rockburst. The data are bandpass filtered in the band 0.8 - 2.0 Hz. From the figure we can see that different seismic phases (indicated by vertical dashed lines) are very similar and that they have the same relative time difference. This suggests that all three events occurred within a very limited area (most likely within 1.5 km). For the 7 June 2003 events the two waveforms are practically identical in this frequency band.

We have on the basis of the P-phase picks at the four stations (BRB, SPITS, KBS and HSP) located the events. The locations are shown in Fig. 6.5.10, where we can see that the locations are all within 500 meters. These locations are consistent with the hypothesis that the events occurred within the mining area, but we have to emphasize that the location uncertainties are of the order 1-2 km.

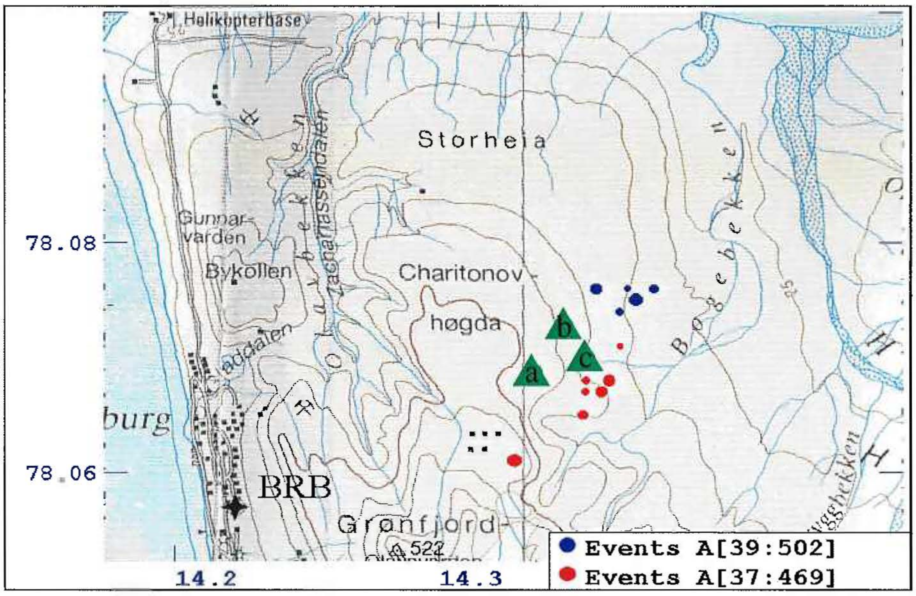

Fig. 6.5.10. Map showing the estimated locations of the events in the Barentsburg mine (green triangles).
a) shows the location of the 28 January 2001 event
b) shows NORSAR's location of the first event on 7 June 2003
c) shows NORSAR's location of the second event on 7 June 2003

Table 6.5.1. Location estimates for the events in the Barentsburg mine

Event	Latitude (N)	Longitude (E)	Comments
28/1-01 11:01 GMT	78.07	14.34	Based on observations in the mine
7/6-03 12:27 GMT	78.0742	14.3441	NORSAR's location
7/6-03 14:23 GMT	78.0716	14.355	NORSAR's location

Our data do not provide sufficient resolution for reliable estimation of the event depths. However, the relatively smaller surface wave amplitudes of the June 2003 events as compared to 28 January 2001 event, may indicate that the June 2003 events was deeper than the 28 January 2001 event.

The first arrivals at all of the four stations have negative polarity for all the three events. This suggests that it was not an earthquake that triggered the collapse. An earthquake would most likely not show the same first arrival polarity at the four stations, since the stations are located at very different azimuths from the events. On the contrary, we expect that a mine collapse would generate negative first arrival polarity for stations in all directions. We therefore believe that the mine collapses themselves are the primary seismic sources, and not a triggering earthquake.

6.5.7 Magnitude estimation of the 7 June 2003 events

For the first event at 12.27 GMT, the REB reported an m_b of 3.7. Based Pn and Sn observations at the ARCES, Apatity and FINES arrays, using the regional attenuation relation of Hicks et al (in press), we got a magnitude estimate of 3.6. For the second event, at 14.23 GMT, we obtained a slightly lower magnitude of 3.4. Tables 2 and 3 give more detailed information about the phase magnitude estimates of the different phases in two different frequency bands using the attenuation relation of Hicks et al (in press).

Table 6.5.2. Phase magnitude estimates for the first event on 7 June 2003

Station	Phase	2-4 Hz	3-6 Hz	Distance (km)
SPITS	Pg	3.03	2.69	47
ARCES	Pn	3.71	3.48	1010
Apatity	Pn	3.65	3.26	1300
FINES	Pn	3.63	3.23	1890
ARCES	Sn	3.32	2.92	1010

Table 6.5.3. Phase magnitude estimates for the second event on 7 June 2003

Station	Phase	2-4 Hz	3-6 Hz	Distance (km)
SPITS	Pg	2.97	2.83	47
ARCES	Pn	3.57	3.46	1010
Apatity	Pn	3.50	3.22	1300
FINES	Pn	3.42	3.32	1890

We note that the magnitudes estimated from SPITS array data are considerably lower than estimates from the other three arrays. We attribute this discrepancy to the much smaller hypocentral distance to SPITS. The regional attenuation relations at very close distances need to be further investigated.

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Acknowledgements

We thank Mr. Gorski for very quickly providing us with records from the Hornsund (HSP) seismic station of the three events investigated. Online data from KBS are distributed by the IRIS LISS server in Albuquerque and have been routinely received at NORSAR since August 2001. Older KBS data were retrieved from the GEOFON data center in Potsdam.

6.6 Body-Wave Magnitude Residuals of IMS Stations

6.6.1 Introduction

The body-wave magnitude mb is important in many schemes for discriminating between natural earthquakes and man-made explosions. Observed magnitudes show a large scatter and stations often have a systematic magnitude bias, which makes it difficult to calculate magnitudes in the case of events with only a small number of observations. However, this is the scenario for seismic stations analyzed at the IDC of the CTBTO in Vienna.

The amplitude (and thereby magnitude) observations at the IMS stations must therefore be calibrated. The amplitude measurements in the bulletins of IDC (REBs) have the advantage that they follow common rules and that therefore the scatter due to the application of different digital filters, unknown transfer functions, and analysis rules is reduced compared with the amplitude data in other international catalogues. Today, for many of the IMS stations, thousands of amplitude readings are now available for a systematic analysis of the station bias.

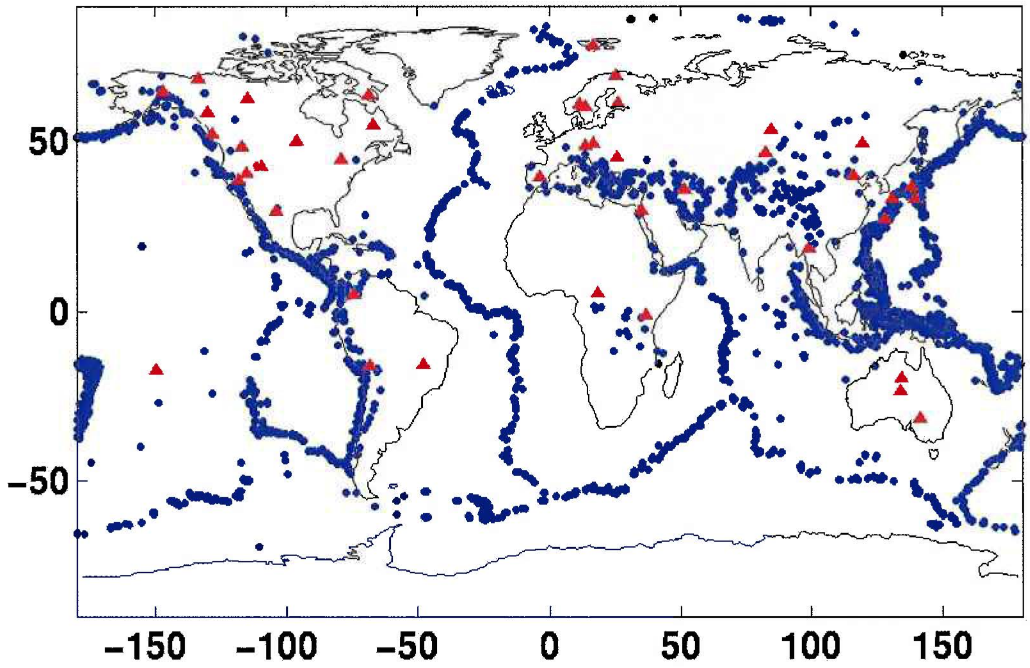

Fig. 6.6.1. Map of all crustal events between 1 January 1995 and 28 February 2003 with a reported Harvard M_0 value (blue points) and of all IMS stations investigated in this study (red triangles).

6.6.2 Data Base

The basic data set used, is the set of the amplitude and period measurements of first P onsets as published since 1995 in the REBs by the prototype IDC for the GSETT-3 experiment at CMR in Arlington and later by the IDC of the CTBTO in Vienna. The IMS network of seismic stations was constantly under change. In this study, amplitude observations were only analyzed for stations which are part of the IMS as of June 2003; these stations are plotted on the map in Fig. 6.6.1 as red triangles.

As an independent measure for the size of the analyzed events the seismic moment M_0 is used as published in the Harvard CMT catalogues. For this, all the CMT solutions of events between 1 January 1995 and 28 February 2003 were retrieved from the Harvard CMT web-page (http://www.seismology.harvard.edu/CMTsearch.html). To remove all depth dependent factors in this study only crustal events with a CMT depth <= 33 km were analyzed; all events used in this study are plotted on the map in Fig. 6.6.1 as blue points. Using the known relation between the seismic moment M_0 in [Nm] and the moment magnitude Mw (Kanamori, 1977),

$$Mw = 2/3 (\log M_0 - 9.1), (1)$$

the magnitudes Mw were calculated for all selected events and compared with the observed body-wave magnitudes m_b. Fig. 6.6.2 shows a histogram of the calculated Mw values of all events used in this study; note that Harvard uses a lower magnitude threshold of about Ms = 5.0 for calculating a CMT solution.

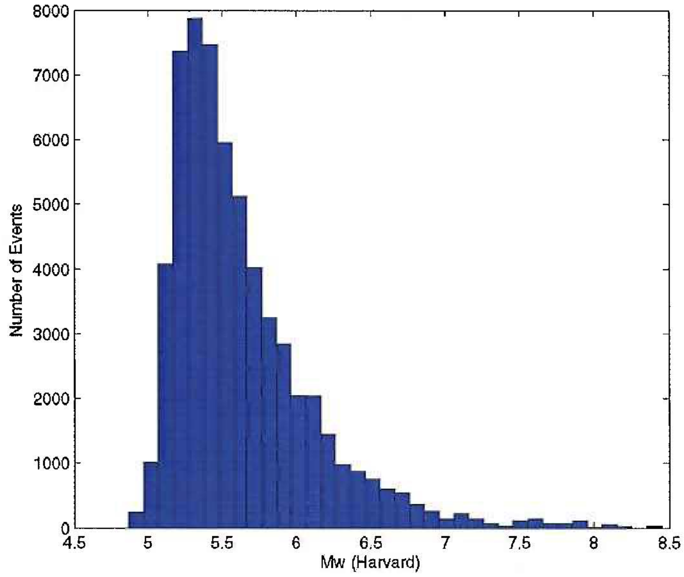

Fig. 6.6.2. Histogram for Mw of the analyzed events calculated from Harvard M_0.

The amplitude-period pairs of the first P onsets reported in the REBs, were used to calculate body-wave station magnitudes m_b for all events with a known M_0. For this, the epicentral distances between the CMT sources and the stations were recalculated and the attenuation relation of Veith and Clawson (1972) was applied.

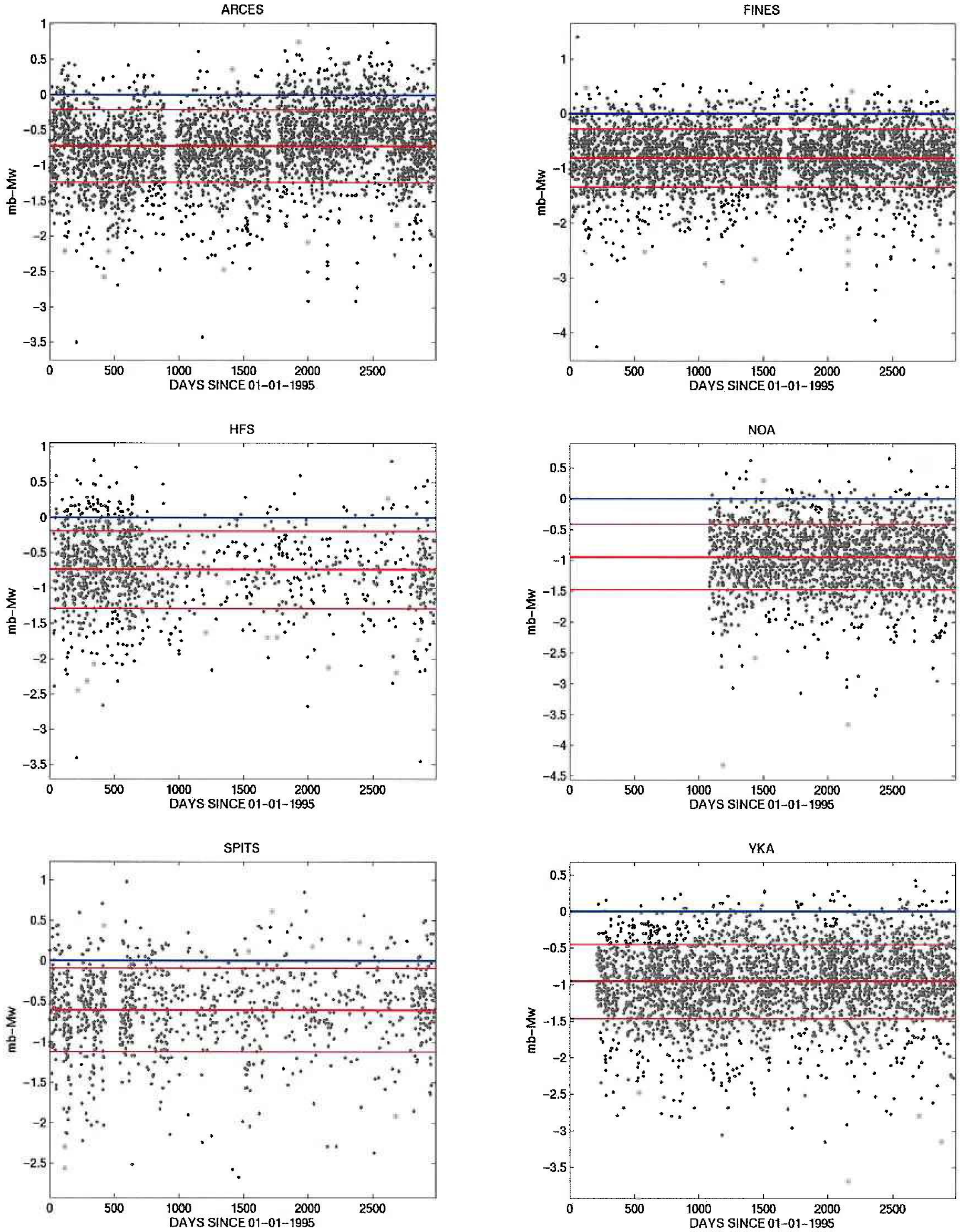

Fig. 6.6.3. Time dependent behavior of station mb observations minus event Mw for some of the stations investigated. The thick red line represents the mean mb bias and the two thin red lines are the +/- one standard deviation limits. The time axis shows days since start of the GSETT-3 experiment on 1 January 1995.

6.6.3 Stability of Magnitude Measurements Over Time

Although the amplitude measuring procedure at the prototype IDC and the IDC was stable over time, the whole IMS network was and is still under construction. Stations were added one by one and, for some, the equipment was changed due to major refurbishment work. Station-response information was always included when it became available at the prototype IDC or IDC, which was not necessarily the same time at which the station's onset readings were included in the REBs. Therefore, the time-dependent behavior of the difference between station m_b observations and the Mw values calculated here, was chosen as an indicator for the stability of the amplitude measurements.

Fig. 6.6.3 shows the result of this analysis for some of the IMS stations. The time scale was chosen to be the number of days since start of the GSETT-3 experiment on 1 January 1995. The thick red line represents the mean m_b bias with respect to Mw and the two thin red lines are the limits of +/- one standard deviation. The calculated bias in the order of about -1 magnitude units is the cumulative effect of the principal offset between the m_b and the Mw scales, and the observed bias between the amplitudes as reported in the REBs and other amplitude reporting stations or institutions (*e.g.*, Granville *et al.*, 2002). However, the m_b-Mw bias is very stable at most stations but shows some jumps at some stations often connected with known refurbishment periods. Assuming that the newest amplitude measurements are free of errors, only data showing the same offset as the newest data were used for further analysis. For ARCES, for example, data were used only from the last 350 days, for FINES, HFS, NOA, and SPITS all shown data were used, and for YKA data from the first 212 days were not used. The data from all other stations were checked and corrected in the same manner.

6.6.4 Distance-Dependent Behavior of Amplitude Measurements

Calculating an event's magnitude involves measuring the amplitude of a seismic phase and correcting this measurement for the attenuation of seismic waves on the path from source to receiver. Different, phase-dependent attenuation relations exist and are used to estimate magnitudes. The relation of Gutenberg and Richter (1956a, b) is most often used for first P onsets. However, this relation does not provide corrections for core phases, which are the first short period P-type onsets beyond about 105 deg epicentral distance. This is not the case for the more modern attenuation relations of Veith and Clawson (1972), who also published amplitude corrections for the PKP range. Therefore, the Veith-Clawson corrections are used to calculate m_b in the REBs and also in this study. With the collection of thousands of amplitude data presented here, it can now be proved that the estimated magnitudes depend on the epicentral distance.

The body wave magnitude m_b is defined as:

$$m_b = \log_{10} (A / T) + \text{corr (delta, depth)}, \quad (2)$$

with the measured amplitude A, period T, and distance and depth dependent attenuation correction corr (here from Veith-Clawson). Plotting the difference between Mw and $\log_{10}(A/T)$ for each station will then provide station dependent attenuation values.

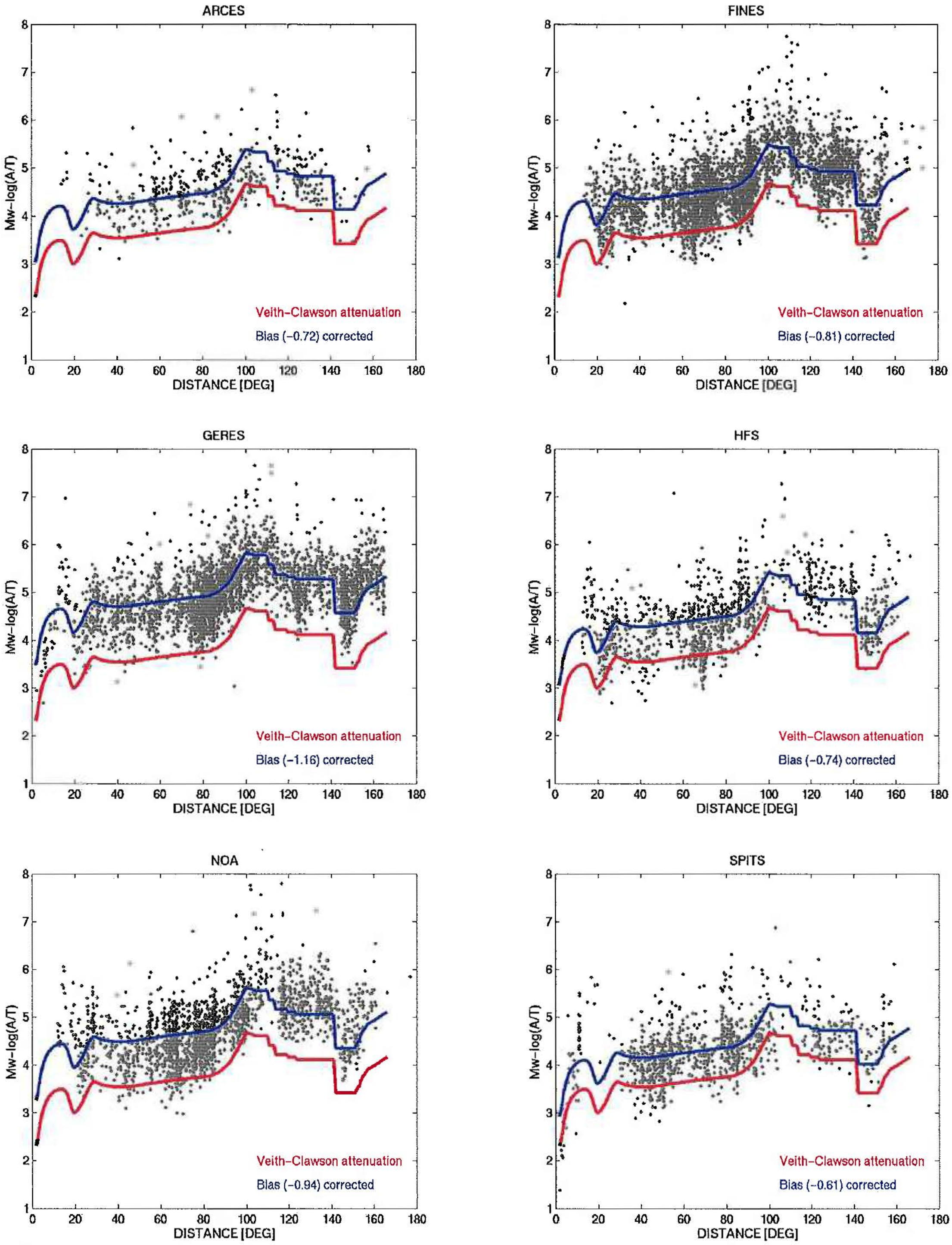

Fig. 6.6.4. Mw - log(A/T) observations for a subset of investigated stations. The red curve is the Veith-Clawson attenuation curve for a surface event (Veith and Clawson, 1972). The blue curves show for each station the Veith-Clawson attenuation after adding the mean station bias.

Fig. 6.6.4 shows a panel with six such observed data sets of (Mw - log(A/T)) for the seismic stations ARCES, FINES, GERES, HFS, NOA, and SPITS. The red curves are always the

Veith-Clawson attenuation curve for a surface event (Veith and Clawson, 1972). Obviously, the observed data do not follow this curve. However, after calculating a mean bias between observations and the Veith-Clawson curve and correcting the attenuation by this constant value of about one magnitude unit, the correspondence becomes quite good for all stations (see the blue lines). The scatter of the data is still large and at some distances very large (*e.g.*, FINES at ca. 90 deg or GERES at about 120 deg) but the general correspondence between the blue lines and the observed data is quite good.

6.6.5 The m_b - Mw Relation

A known phenomenon is that the m_b scale saturates for magnitudes above about 6.5. Therefore, m_b residuals for events with larger magnitudes are not only the effect of station and ray-path anomalies but also of this saturation effect. To define an upper magnitude limit, all station m_b values defined in equation (2) were corrected with the constant bias (stcorr) as calculated for Fig. 6.6.4:

$$m_b = \log_{10} (A / T) + \text{corr (delta, depth)} + \text{stcorr} \quad (3)$$

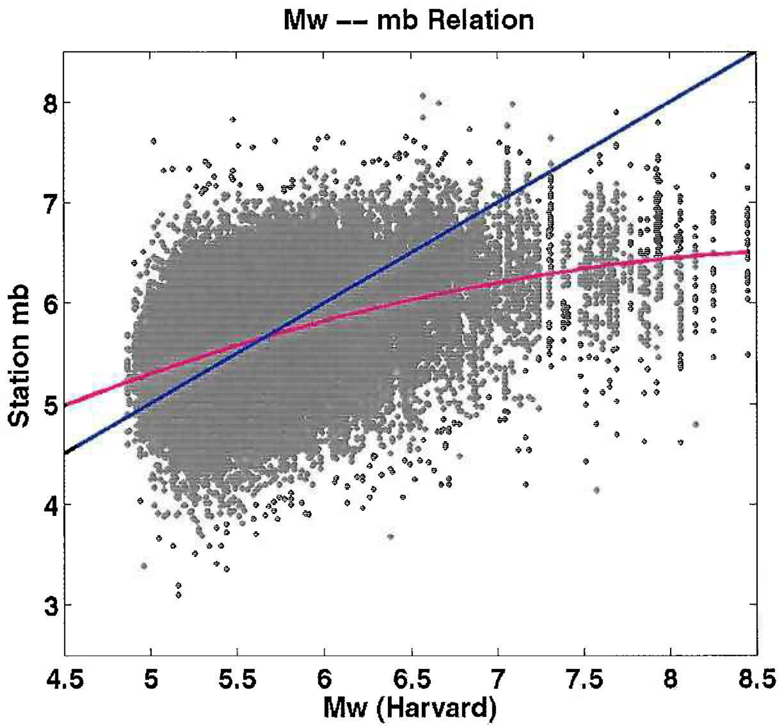

Fig. 6.6.5. All station bias corrected mb values plotted with respect to Mw as calculated from the Harvard CMT solutions. The blue line represents identity between mb and Mw, the mangenta line follows the calculated 2nd order polynomial describing the relation between m_b and Mw.

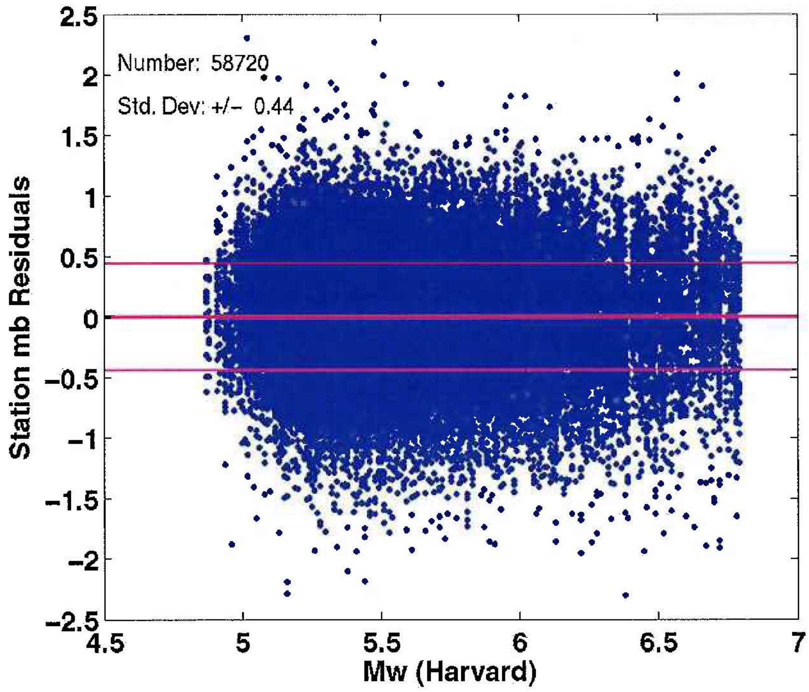

Fig. 6.6.6. Station mb residuals after removing the fitted 2nd order polynomial. The two thin man-genta lines give the +/- one standard deviation range.

These 60 273 new m_b values are plotted in Fig. 6.6.5 with respect to the corresponding Mw values. The saturation effect is clearly visible, as is the fact that m_b is not identical to Mw for magnitudes below 6.5. In the latter case, the data should be scattered around the blue line. Therefore, the m_b - Mw relation was fitted by a second order polynomial:

$$m_b = -0.0716*Mw^2 + 1.3138*Mw + 0.5171 (4)$$

Because of the saturation effect, which cannot be modelled, only m_b observations for which the event magnitude Mw was <= 6.8, were used for the final analysis. Fig. 6.6.6 shows the remaining residuals for these 58 720 m_b observations. The standard deviation of +/- 0.44 magnitude units for all m_b observations can be attributed to a number of different effects: focusing and defocusing structures along the ray paths between source and receiver, wrong hypocenter determinations (in particular uncertainty of focal depth), the influence of the radiation pattern on P-wave amplitudes as shown in Schweitzer and Kværna (1999), distance depending modelling errors of the applied Veith-Clawson attenuation curve (*e.g.*, recently Rezapour (2003) published new attenuation values for teleseismic P onsets), some still not detected instrumentation errors, and other data-analysis errors such as incorrect phase associations.

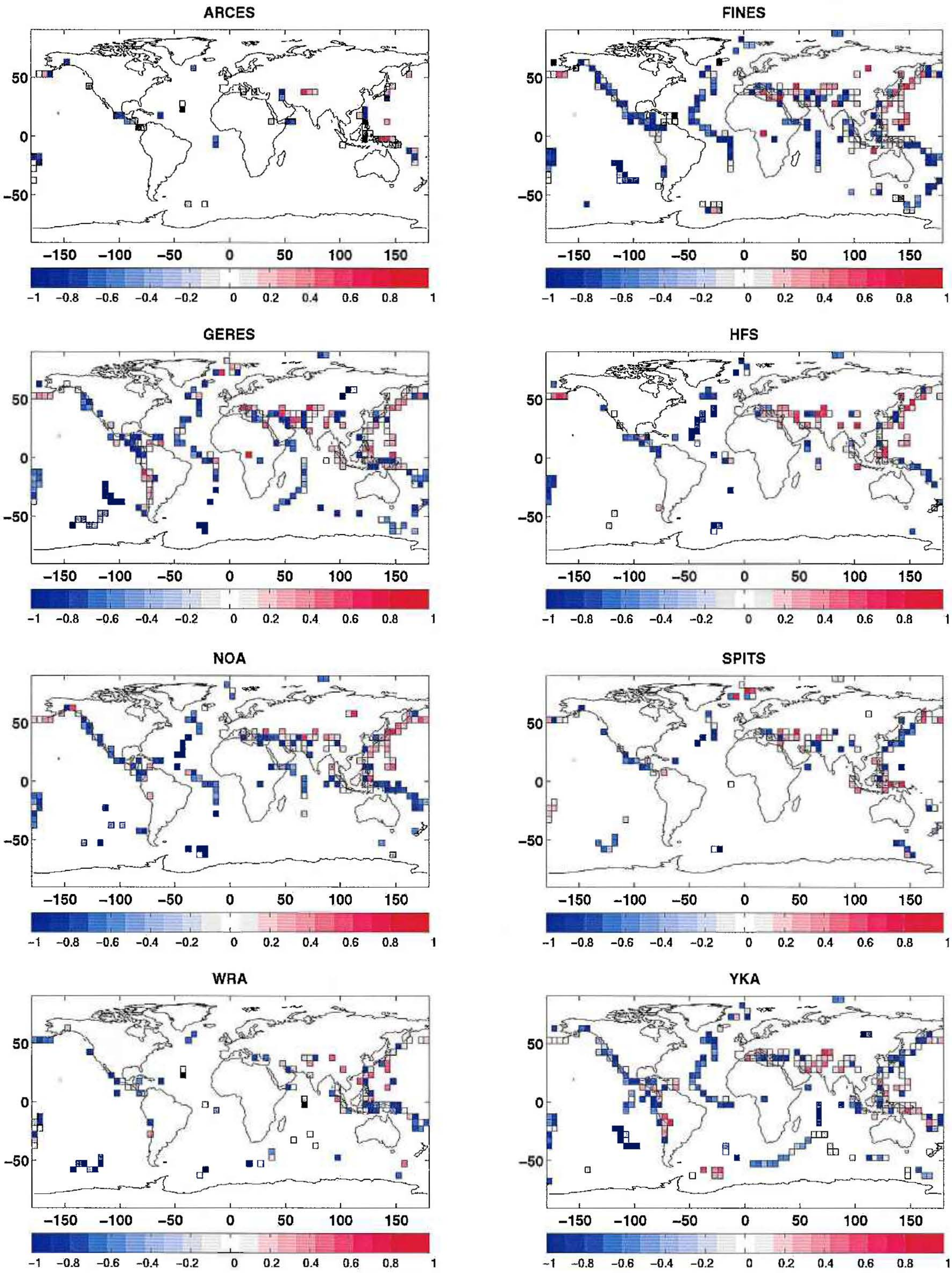

Fig. 6.6.7. Geographical distribution of mean m_b residuals for a subset of the investigated stations.

6.6.6 Geographical Distribution of the Residuals

If systematic effects like ray path and double couple radiation have a major contribution the residuals as derived in Section 6.6.5 and plotted in Fig. 6.6.6, the residuals should show some systematic geographical distribution. Therefore, the observed residuals were binned in 5 deg x 5 deg bins with respect to their epicenter for each station separately and mean values were plotted on maps. Fig. 6.6.7 shows such maps for eight of the investigated stations. The mean m_b residuals are only plotted for bins with at least three observations. The distribution of bins reflects the sensitivity of the different stations with respect to specific source regions and the usage of auxiliary stations like SPITS and HFS. However, for all stations, the regions with positive (red) and negative (blue) magnitude residuals show systematic patterns. This pattern is not identical for the different stations; *e.g.*, the subduction zones north of Australia have dominantly blue colors at WRA but red colors at SPITS and YKA, the South Sandwich events have negative residuals at GERES and NOA but positive residuals at YKA.

In general the mid-oceanic ridges have a tendency to display negative m_b residuals with respect to the reference magnitude Mw but contrary, mb seems to overestimate the event's size in subduction zones. This is in agreement with the dominant double couple radiation of the different tectonic regions, in particular for the mid-oceanic ridges systems with strike-slip movements and thereby low P-wave radiation down into the mantle.

6.6.7 Conclusions

The REBs contain the most self-consistent database of amplitude and period observations of body waves. These data can be corrected for the mean station bias between m_b and Mw. The remaining m_b - Mw relation can simply be modeled with a 2nd order function. By applying this relation one can derive an expected m_b value for each event and calculate observed station m_b residuals. These residuals are up to about +/- 2 (and standard deviation of about +/- 0.44) magnitude units.

Binning these residuals with respect to their source regions and plotting them on geographical maps clearly show a source region specific pattern. The reasons for this observation will mostly be ray-path dependent attenuation anomalies (defocusing, focusing) and source region dependent dominant double-couple radiation.

The application of source-station specific corrections (SSSCs) for amplitude / period observations is recommended and will result in more stable magnitude estimates. However, this will require more studies on the influence of a mixture of calibrated and uncalibrated areas / stations on network magnitudes.

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