NORSAR

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Technical Summary

1 October 2000 - 30 June 2001

Frode Ringdal (ed.)

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Abstract (cont.)

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Throughout this report the term "uptime" reflects the percentage of time that the station has been operating and providing data to the NDC. It is not equivalent with the term "data availability", which also takes into account the percentage of array elements that have been operating.

The NOA Detection Processing system has been operated throughout the period with an average uptime of 100.00%. A total of 3747 seismic events have been reported in the NOA monthly seismic bulletin from October 2000 through June 2001. On-line detection processing and data recording at the NDC of NORES, ARCES and FINES data have been conducted throughout the period. Data from 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: PS28 — ARCES and PS27 — NOA and one auxiliary array (AS72 — SPITS). These data are being provided to the IDC via the global communications infrastructure (GCI-Frame Relay). 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 array has been certified, whereas the ARCES array is in a testing and evaluation mode. 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 23-27 April 2001. This was the third annual meeting of the Experts Group in support of Working Group B of the CTBTO Preparatory Commission. At its first meeting in January 1999, the Experts Group 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 the second meeting of the Group in March 2000, and the results were presented to Working Group B in May 2000 (CTBT/WGB/TL-2/49). The third meeting had the following objectives:

- To review proposals for detailed station-specific regional corrections to be applied for IMS

stations in North America, Europe, North Africa, Asia and Australia

- To recommend a set of such corrections, including appropriate model errors, for incorporation into the next release of the IDC software
- To review progress in the general recommendations from the first and second 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 calibration information for the regions being considered, and to plan for implementing regional location calibration at the IDC, both for the next release of the IDC applications software and for implementation in the longer term. The meeting was attended by sixty-five technical experts, coming from fourteen signatory countries and the Provisional Technical Secretariat. Dr. Frode Ringdal of Norway chaired the meeting, which was organized into four sessions, including Working Group discussions to address the technical issues in detail. Topics were:

- Collection of Calibration Information
- Application of Calibration Information
- Validation of Calibration Information
- Specific recommendations for the next IDC Release
- Future work of the Experts Group

Detailed recommendations were developed for each of these subject matters, and were presented to Working Group B in Vienna during its June 2001 session (CTBT/WGB/TL-2/61).

Section 6.2 describes the results of experimental seismic threshold monitoring of the area surrounding the site of the Kursk submarine accident. On 12 August 2000, signals from two presumed underwater explosions in the Barents Sea were recorded by Norwegian seismic stations. The first of these, at 07.28.27 GMT, was relatively small, measuring 1.5 on the Richter scale. The second explosion, 2 minutes and 15 seconds later, was much more powerful, with a Richter magnitude of 3.5. These explosions were associated with the accident of the Russian submarine “Kursk”, although the exact sequence of events leading to this disaster is still unknown.

The area in the Barents Sea where the Kursk accident occurred has no known history of significant earthquake activity. Beginning in September 2000, a number of small seismic events were detected in this area. According to an official Russian announcement in November, these signals were generated by underwater explosions near the Kursk accident area, carried out by the Russian Navy. This explosion sequence, with numerous explosions ranging in magnitude from very small (about 1.5 on the Richter scale) to fairly large (about magnitude 3.0) provides a unique opportunity to investigate the performance of the threshold monitoring technique. We have implemented an experimental site-specific threshold monitoring procedure to monitor the Kursk accident area in the Barents Sea, and present some of the results in this report. In particular, we apply an automatic explanation facility to provide additional information to help the analyst determine the source of the individual peaks on the threshold traces.

The experiment demonstrates the usefulness of the threshold monitoring technique in a practical monitoring situation, and shows that for this particular site, the threshold monitoring capability is at a Richter magnitude as low as 1.5. The explosions were especially well recorded by the ARCES array (distance 500 km), but the FINES, SPITS and NORES array also detected several of the events. In addition, the Apatity array station in the Kola Peninsula (not an IMS station) provided useful recordings.

Section 6.3 is entitled “S-Velocities in the Crust and Uppermost Mantle of Northern Fennoscandia Deduced From Dispersion Analysis of Rayleigh Waves”. By means of the so-called two-station method a dispersion analysis of surface waves was carried out in northern Norway. The purpose was to investigate the structure of crust and uppermost mantle in this region with special attention to the location of the Mohorovicic discontinuity. In this study the phase velocity was calculated from the cross-correlation between the vertical seismograms of one event recorded at two stations. Since Love-wave dispersion may have large uncertainties due to interference effects, we focused in this study on observation and interpretation of the fundamental-mode of Rayleigh waves. Nevertheless, comparison between the 1D-models for the S-wave velocity from the Love wave and the Rayleigh wave dispersion may give in the future interesting results with regard to possible S-velocity anisotropy.

Although the models discussed in this paper differ in several features, they are all consistent with the observed Rayleigh-wave phase velocities. For all models a two-layer crust is common with a pronounced velocity jump at a Conrad discontinuity at about 15 km depth. The exact depth and structure of the Mohorovicic discontinuity is at the moment an open question because the resolution of the dispersion curves is not good enough to distinguish between a sharp discontinuity at about 40 km depth and a transition zone of about 20 km thickness between crust and uppermost mantle. The phase velocity curve for the receiver-function model in the frequency range between 25 and 60 mHz always lies at the lower bound of the observed dispersion curves. This might be an indication that the S-velocities are too low in the receiver-function model below a depth of about 30 km. A joint modelling of dispersion curves and receiver functions with their different model sensitivity would be needed to solve these discrepancies.

Section 6.4 is a follow-up study of work initiated at NORSAR several years ago to develop an automatic post-processing method for accurate location of seismic events recorded by a regional network. At the time, this processing was applied experimentally to seismic events in the Khibiny Massif, Kola Peninsula. However, no attempt was made to use this method in a practical day-to-day monitoring situation, and also, it was not applied to any other regions.

The aim of this contribution is to adapt the method as needed for its application in a more general context and also to investigate options for practical routine implementation of the method in an operational environment. The paper gives a summary of the method as originally developed, and attempts to set up a possible system for automatic, routine processing that could be expandable to a more general case. The work so far has been focused on recreating the processing environment used for the original post-processing studies, verifying that we can obtain results with an accuracy similar to what was achieved at that time and adapting this environment to a semi-automatic processing scheme to be applied on a routine basis. As shown in this paper, this has been successfully achieved for events in the Khibiny Massif, Kola Peninsula. The next step will be to apply the method to other nearby mines, e.g. Kovdor, Zapolyarnyi and Olenegorsk, which are also on the Kola Peninsula, and where our contacts at the Kola Regional Seismological Centre will be in a position to provide us with appropriate ground truth data. Later, we will gradually expand the area of coverage to other regions in Fennoscandia and the European Arctic.

Section 6.5 summarizes some new developments of the NORSAR Web site, including new online databases for the European Arctic. Previously, automatic bulletin information for seismic events in the European Arctic has been provided on a daily basis. From 10 November 2000 all waveform data from the available arrays (NOA, NORES, ARCES, SPITS, HFS, FINES, and Apatity) have been stored on disk for subsequent rapid access. We have also upgraded NORSAR's Web site to include both epicenter maps, event information with phase readings, and standard waveform plots of the Reviewed Regional Seismic Bulletin. For the time period preceding 10 November 2000 the waveform plots are not included. The main motivation for this work has been to facilitate the combined use of the reviewed bulletin information and online data for research purposes. The information available on the Internet is updated as events are analyzed, typically several times a month.

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Frode Ringdal

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Project Manager	:	Frode Ringdal +47 63 80 59 00
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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. 734

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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% as compared to 99.85% for the previous reporting period.

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:

October 2000	:	100%
November	:	100%
December	:	100%
January 2001	:	100%
February	:	100%
March	:	100%
April	:	100%
May	:	100%
June	:	100%

J. Torstveit

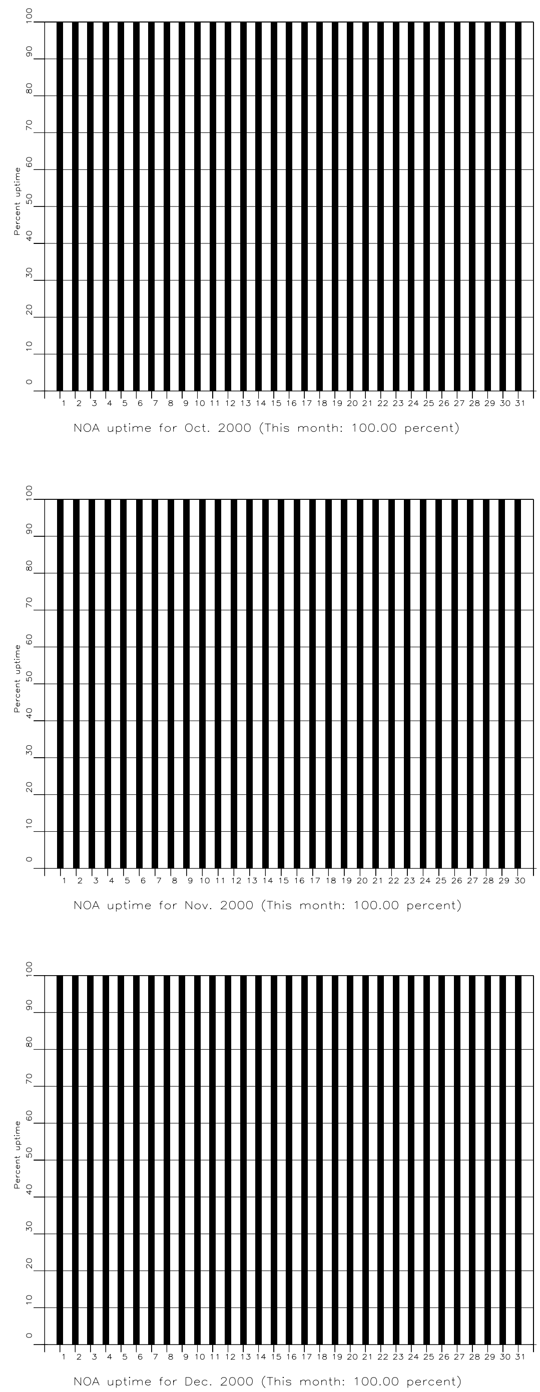
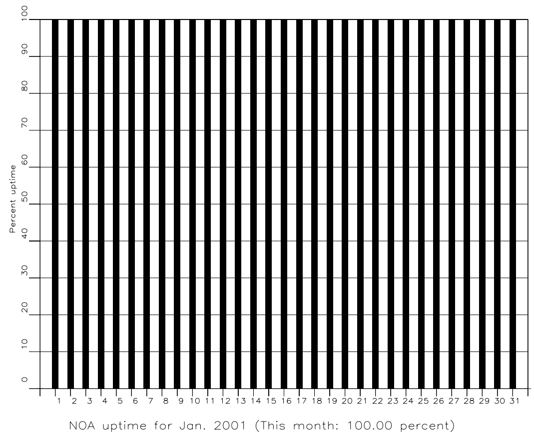
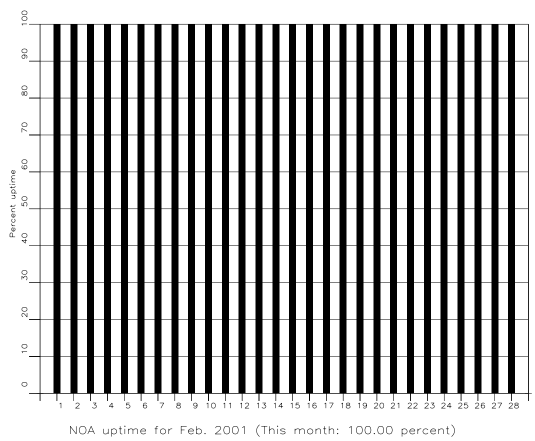


Fig. 2.1.1. *The figure shows the uptime for the data recording task, or equivalently, the availability of NOA data in our tape archive, on a day-by-day basis, for the reporting period. (Page 1 of 3, Oct-Dec 2000).*





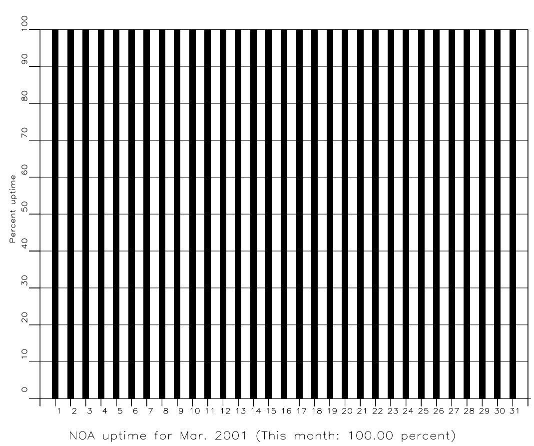


Fig. 2.1.1. *(cont.) (Page 2 of 3, Jan-Mar 2001).*

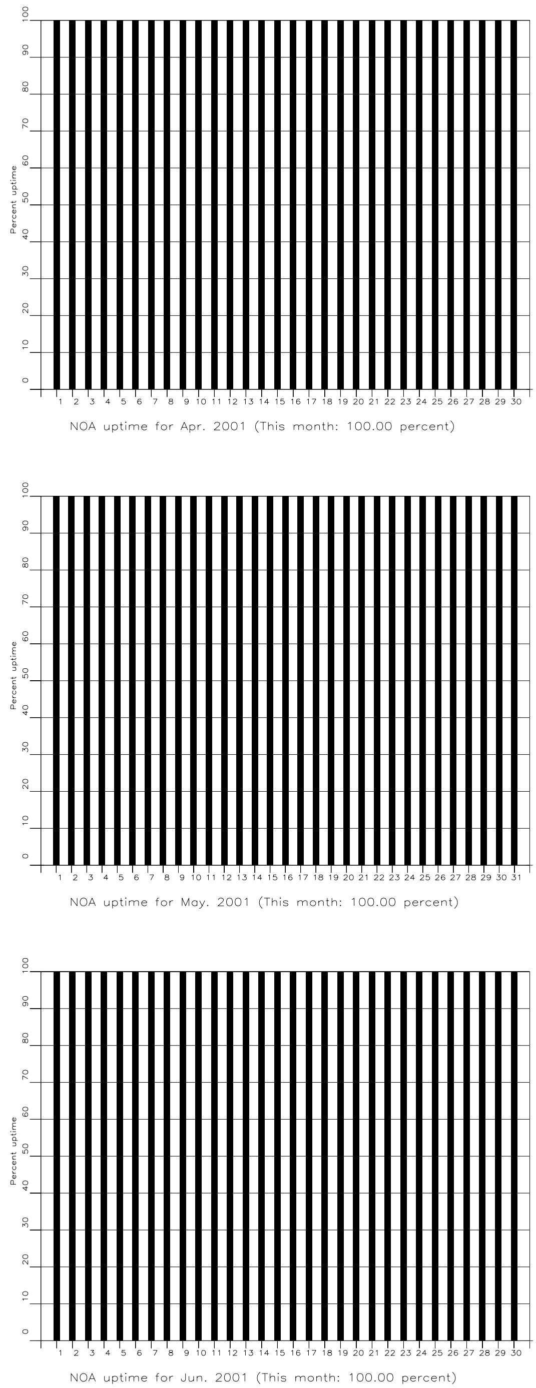


Fig. 2.1.1. *(cont.) (Page 3 of 3, Apr-June 2001).*

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		
Oct 2000	8,443	1,237	622	178	800	9.3
Nov	8,715	776	340	302	642	10.7
Dec	11,239	815	293	106	399	9.3
Jan 2001	11,951	924	246	47	293	9.5
Feb	10,791	908	180	32	212	7.6
Mar	10,780	952	255	59	314	10.1
Apr	10,472	955	284	96	380	12.7
May	4,972	726	277	77	354	11.4
Jun	6,424	758	282	71	353	11.8
	84,187	8,051	2,779	968	3,747	10.3

Table 2.1.1. *Detection and Event Processor statistics, 1 October 2000 - 30 June 2001.*

NOA detections

The number of detections (phases) reported by the NORSAR detector during day 275, 2000, through day 181, 2001, was 84,187, giving an average of 308 detections per processed day (273 days processed).

B. Paulsen

U. Baadshaug

2.2 PS28 — Primary Seismic Station ARCES

The average recording time was 99.74% as compared to 100% for the previous period. Table 2.2.1 lists the reasons for and time periods of the main downtimes in the reporting period.

Date	Time			Cause
03 Jun	1830	-		Power failure
04 Jun		-	1029	

Table 2.2.1. *The main interruptions in recording of ARCES data at NDPC, 1 October 2000 - 30 June 2001.*

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:

October 2000	:	99.88%
November	:	100%
December	:	100%
January 2001	:	100%
February	:	100%
March	:	100%
April	:	100%
May	:	100%
June	:	97.78%

J. Torstveit

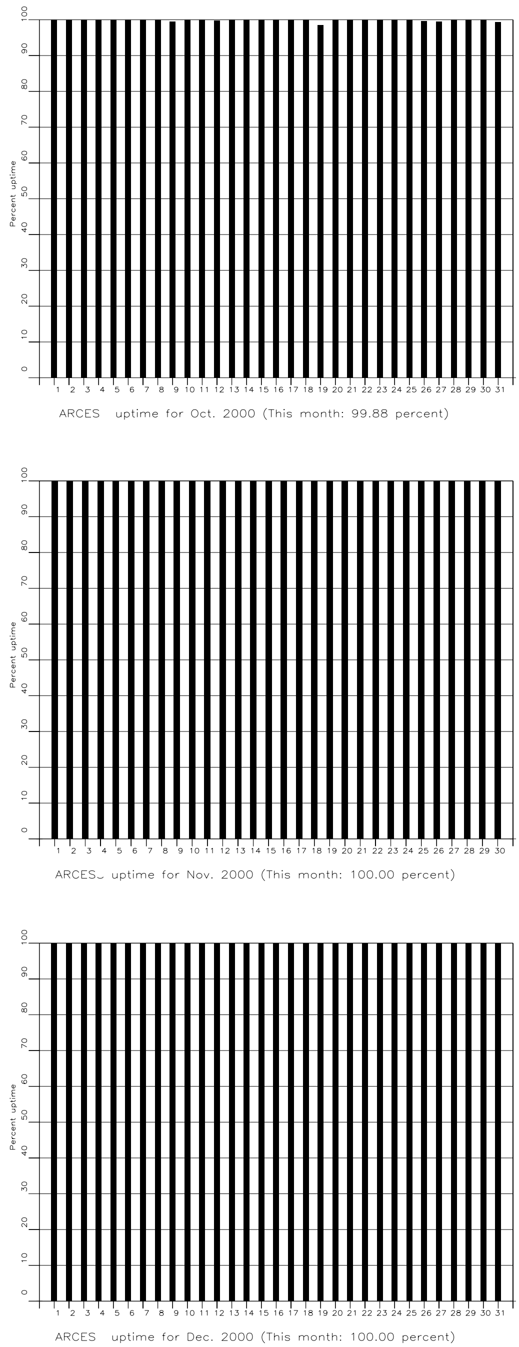


Fig. 2.2.1. *The figure shows the uptime for the data recording task, or equivalently, the availability of ARCES data in our tape archive, on a day-by-day basis, for the reporting period. (Page 1 of 3, Oct-Dec 2000)*

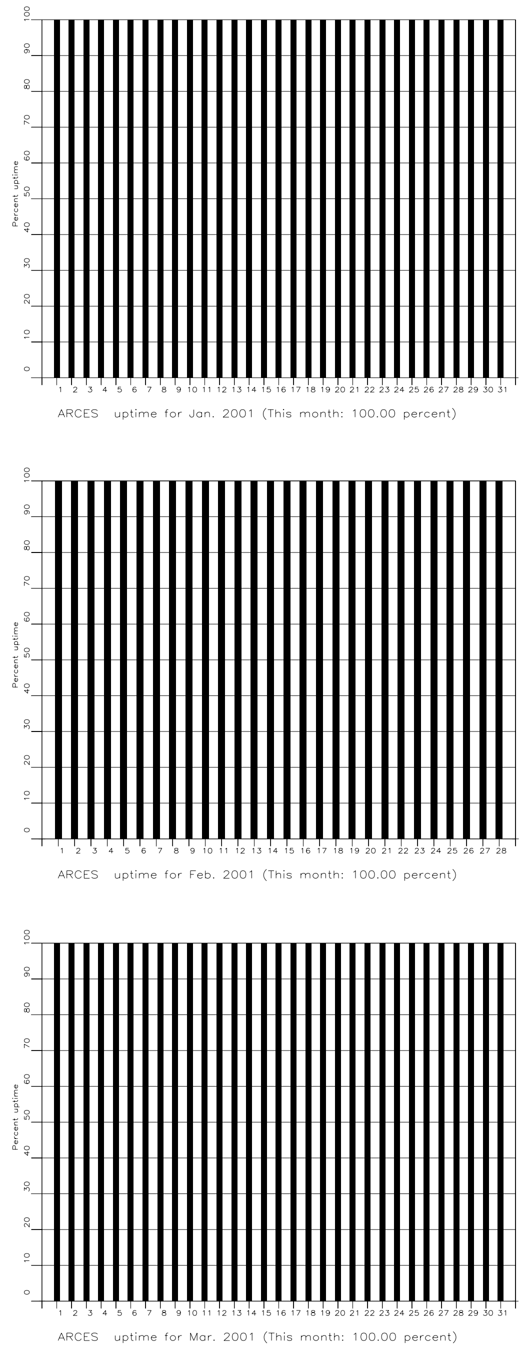


Fig. 2.2.1 *(cont.) (Page 2 of 3, Jan-Mar 2001).*

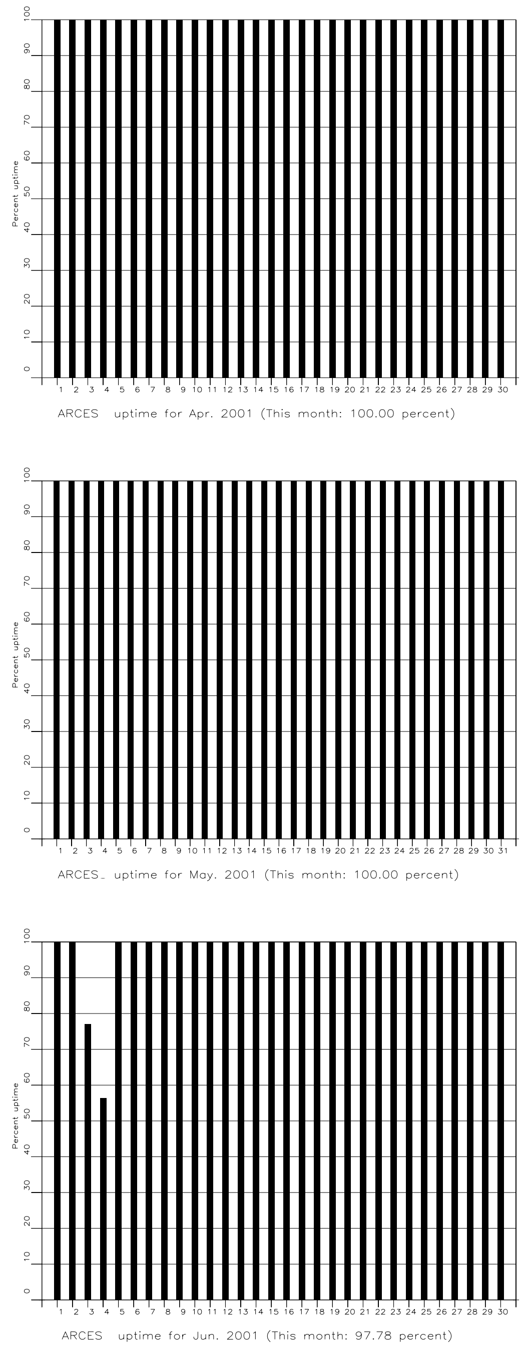


Fig. 2.2.1 *(cont.) (Page 3 of 3, Apr-Jun 2001).*

Event Detection Operation

ARCES detections

The number of detections (phases) reported during day 275, 2000, through day 181, 2001, was 185,500, giving an average of 679 detections per processed day (273 days processed).

Events automatically located by ARCES

During days 275, 2000, through 181, 2001, 12,070 local and regional events were located by ARCES, based on automatic association of P- and S-type arrivals. This gives an average of 44.2 events per processed day (273 days processed). 53% of these events are within 300 km, and 81% of these events are within 1000 km.

U. Baadshaug

2.3 AS72 — Auxiliary Seismic Station Spitsbergen

The average recording time was 93.52% as compared to 90.64% for the previous reporting period.

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

Date	Time			Cause
26 Feb	2312	-		Power failure, windmill broken
27 Feb		-	1130	
09 Mar	0520			Power failure, windmill broken
16 Mar		-	1652	
17 Mar	1536	-		Power failure, windmill broken
22 Mar		-	1247	
22 Mar	1517	-		Power failure, windmill broken
27 Mar		-	1344	

Table 2.3.1. *The main interruptions in recording of Spitsbergen data at NDPC, 1 October 2000 - 30 June 2001.*

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:

October 2000	:	100%
November	:	100%
December	:	100%
January 2001	:	99.52%
February	:	98.12%
March	:	44.11%
April	:	99.99%
May	:	99.90%
June	:	100%

J. Torstveit

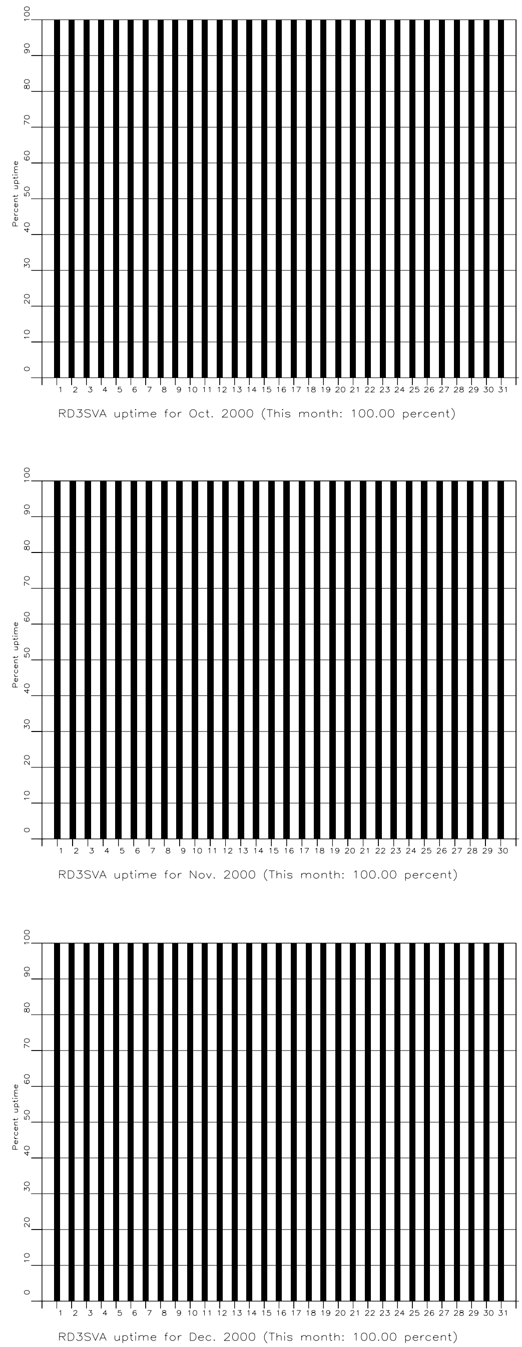
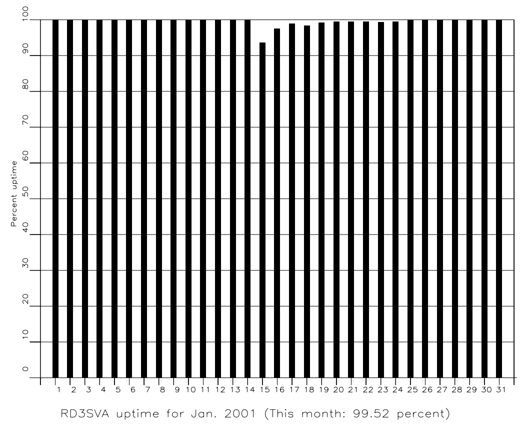
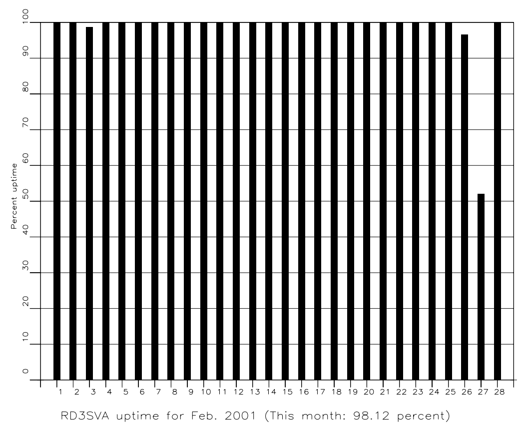


Fig. 2.3.1. *The figure shows the uptime for the data recording task, or equivalently, the availability of Spitsbergen data in our tape archive, on a day-by-day basis, for the reporting period. (Page 1 of 3, Oct-Dec 2000).*





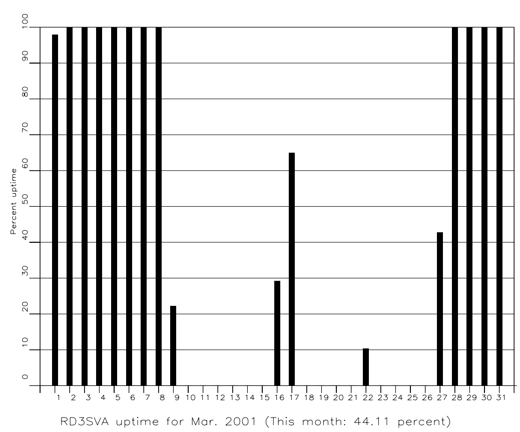


Fig. 2.3.1 *(cont.) (Page 2 of 3, Jan-Mar 2001).*

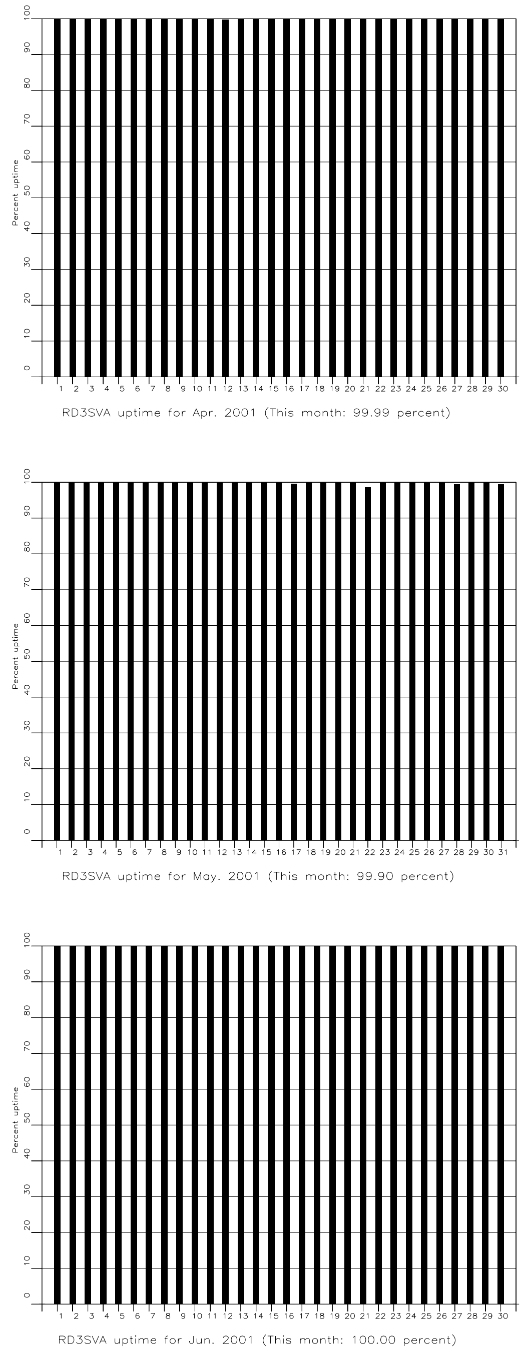


Fig. 2.3.1 *(cont.) (Page 3 of 3, Apr-Jun 2001).*

Event Detection Operation

Spitsbergen array detections

The number of detections (phases) reported from day 275, 2000, through day 181, 2001, was 329,444, giving an average of 1272 detections per processed day (259 days processed).

Events automatically located by the Spitsbergen array

During days 275, 2000, through 181, 2001, 33,565 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 129.6 events per processed day (259 days processed). 69% of these events are within 300 km, and 84% 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. In the meanwhile 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.

S. Mykkeltveit

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 lead to a recommendation on the exact location of the infrasound station. Currently, the geometry (the number of elements and the inter-sensor spacings) of the station is being assessed. Station installation is expected to take place in the year 2002.

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. A particulate station will be installed at the same location in September 2001.

S. Mykkeltveit

3 Contributing Regional Seismic Arrays

3.1 NORES

Average recording time was 99.98 as compared to 92.41 for the previous period.

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

October 2000	:	100%
November	:	100%
December	:	100%
January 2001	:	99.85%
February	:	100%
March	:	100%
April	:	100%
May	:	100%
June	:	100%

J. Torstveit

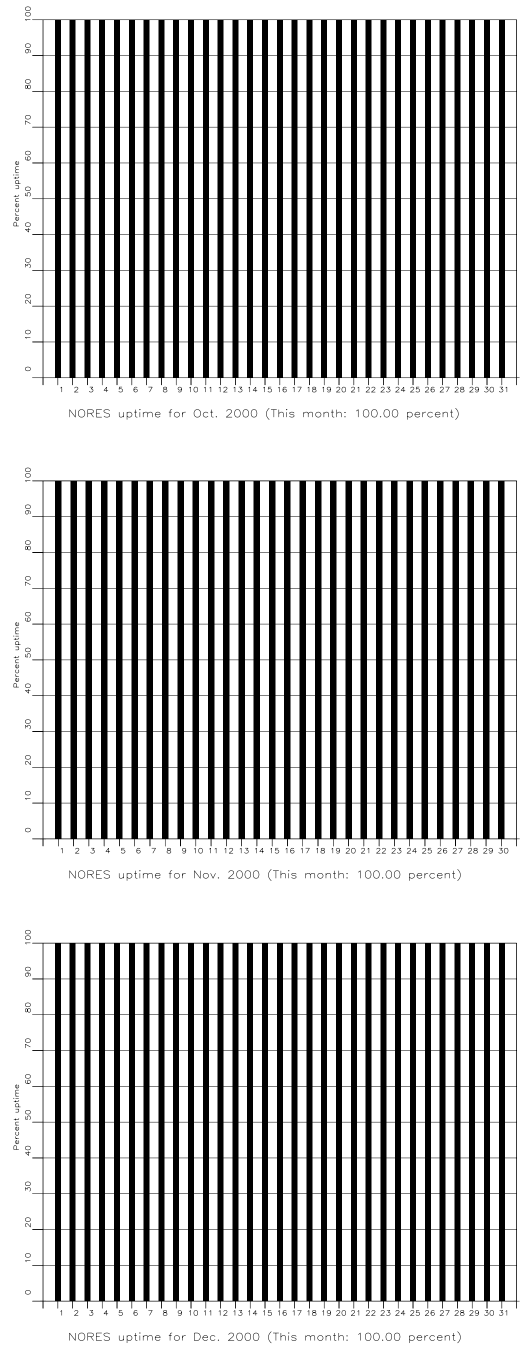
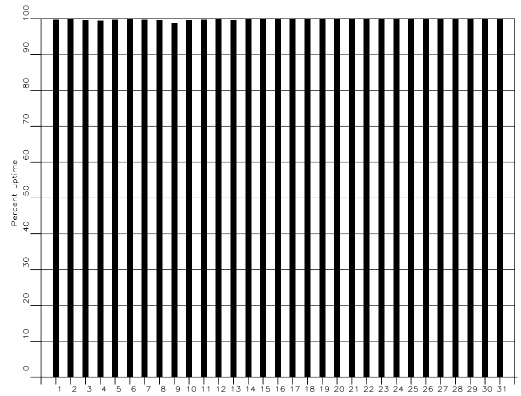
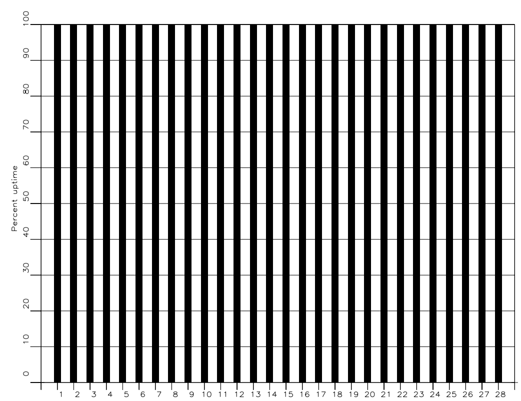


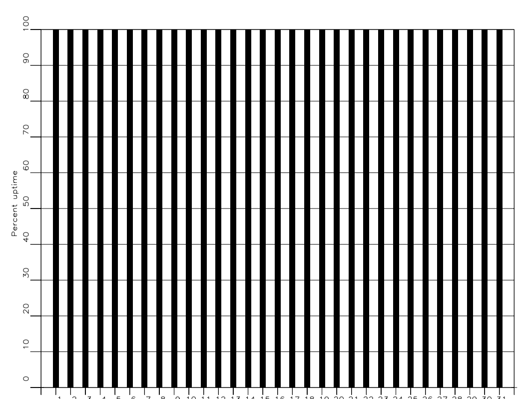
Fig. 3.1.1. *The figure shows the uptime for the data recording task, or equivalently, the availability of NORES data in our tape archive, on a day-by-day basis, for the reporting period (Page 1 of 3, Oct-Dec 2000).*



NORES uptime for Jan. 2001 (This month: 99.85 percent)

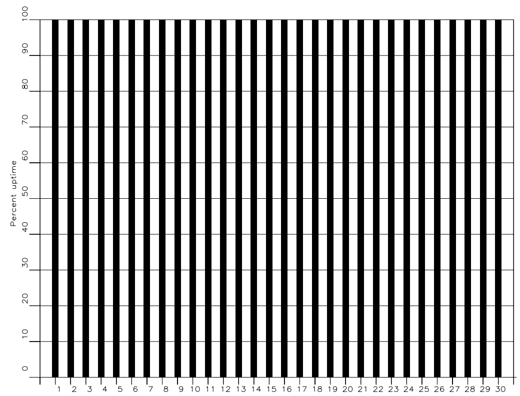


NORES uptime for Feb. 2001 (This month: 100.00 percent)

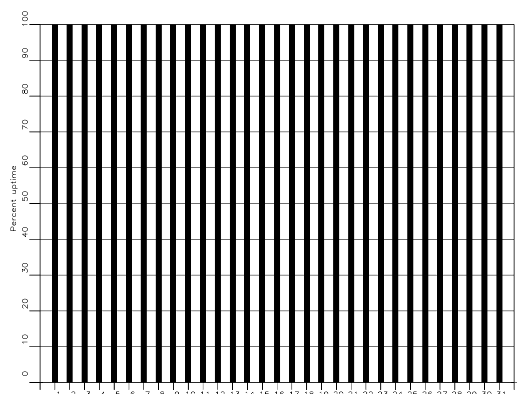


NORES uptime for Mar. 2001 (This month: 100.00 percent)

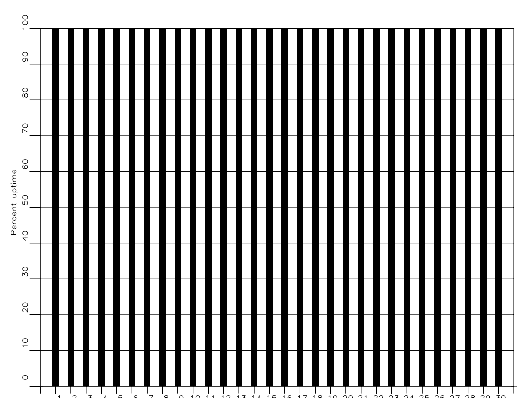
Fig. 3.1.1 *(cont.) (Page 2 of 3, Jan-Mar 2001).*



NORES uptime for Apr. 2001 (This month: 100.00 percent)



NORES uptime for May. 2001 (This month: 100.00 percent)



NORES uptime for Jun. 2001 (This month: 100.00 percent)

Fig. 3.1.1 *(cont.) (Page 3 of 3, Apr-Jun 2001).*

NORES Event Detection Operation

NORES detections

The number of detections (phases) reported from day 275, 2000, through day 181, 2001, was 120,764, giving an average of 442 detections per processed day (273 days processed).

Events automatically located by NORES

During days 275, 2000, through 181, 2001, 3526 local and regional events were located by NORES, based on automatic association of P- and S-type arrivals. This gives an average of 12.9 events per processed day (273 days processed). 57% of these events are within 300 km, and 83% of these events are within 1000 km.

U. Baadshaug

3.2 Hagfors (IMS Station AS101)

The average recording time was 99.9% as compared to 98.49% for the previous reporting period.

Table 3.2.1 lists the reasons for and times of the main outages in the reporting period.

Date	Time	Cause
25 May	1427 - 2059	Problems at field installation

Table 3.2.1. *The main interruptions in Hagfors recordings at the Norwegian NDC, 1 October 2000 - 30 June 2001.*

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:

October 2000	:	100%
November	:	100%
December	:	100%
January 2001	:	100%
February	:	100%
March	:	100%
April	:	100%
May	:	99.12%
June	:	100%

J. Torstveit

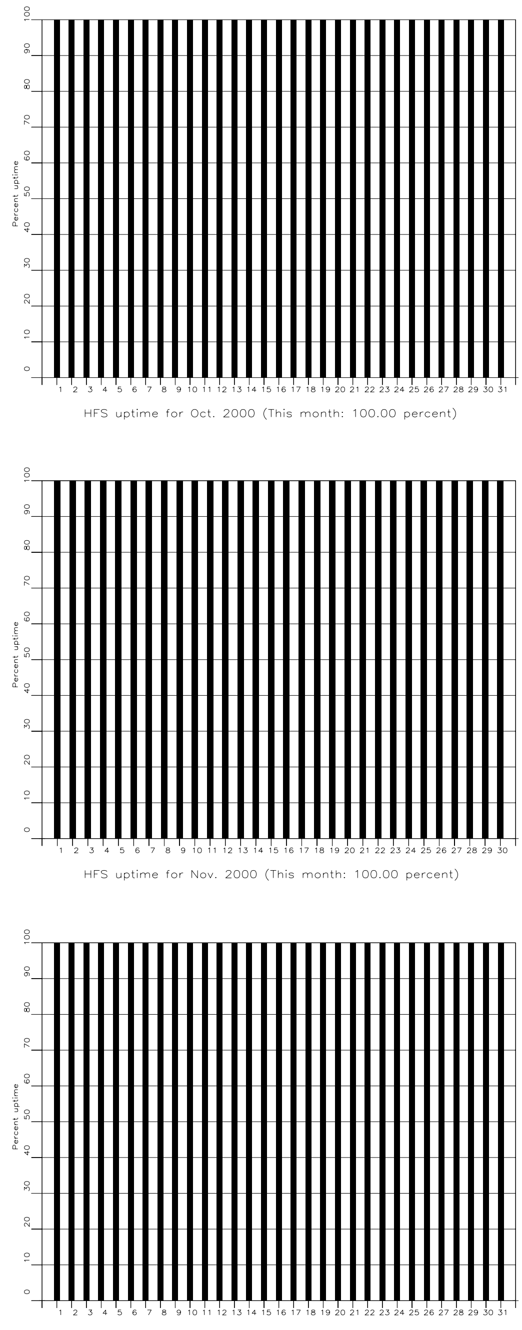
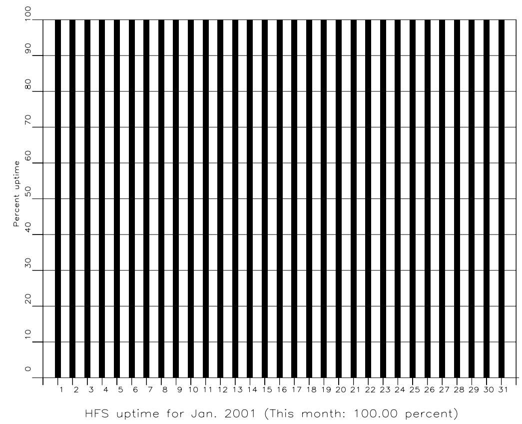
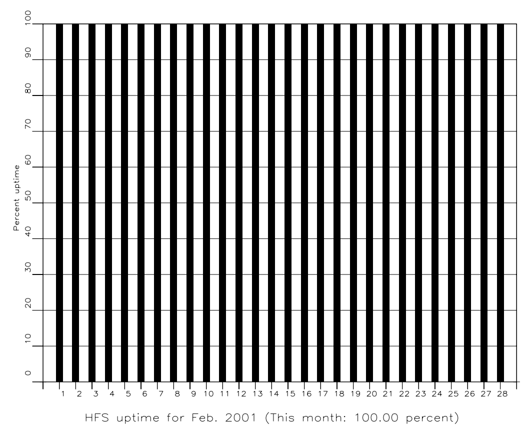


Fig. 3.2.1. *The figure shows the uptime for the data recording task, or equivalently, the availability of Hagfors data in our tape archive, on a day-by-day basis, for the reporting period (Page 1 of 3, Oct-Dec 2000).*





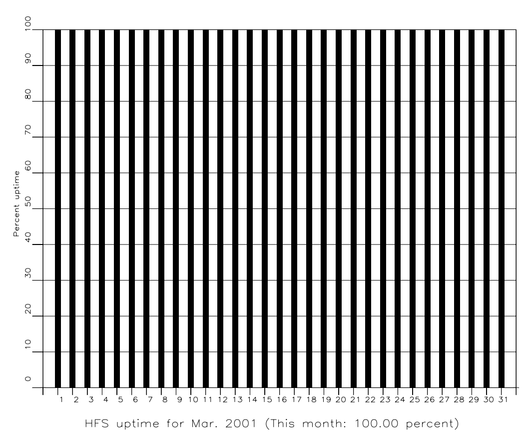
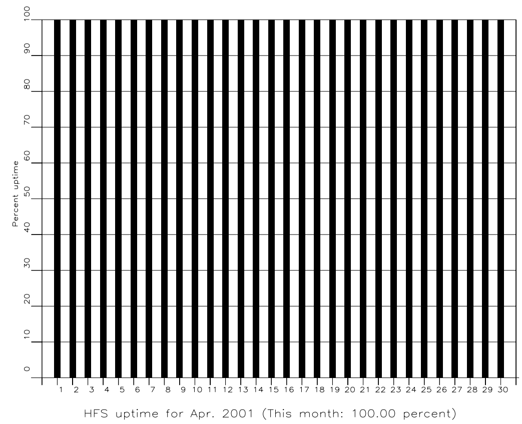
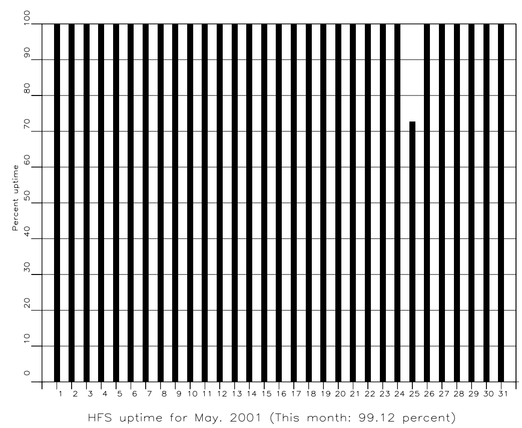


Fig. 3.2.1 *(cont.) (Page 2 of 3, Jan-Mar 2001).*





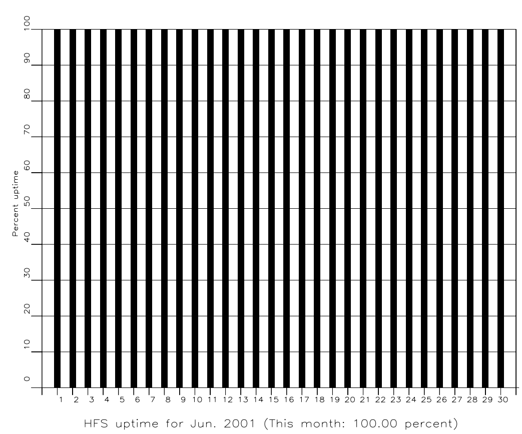


Fig. 3.2.1 *(cont.) (Page 3 of 3, Apr-Jun 2001).*

Hagfors Event Detection Operation

Hagfors array detections

The number of detections (phases) reported from day 275, 2000, through day 181, 2001, was 155,409, giving an average of 569 detections per processed day (273 days processed).

Events automatically located by the Hagfors array

During days 275, 2000, through 181, 2001, 3471 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 12.7 events per processed day (273 days processed). 52% of these events are within 300 km, and 83% of these events are within 1000 km.

U. Baadshaug

3.3 FINES (IMS station PS17)

The average recording time was 99.51% as compared to 98.94% for the previous reporting period.

Table 3.3.1 lists the reasons for and times of the main outages during the reporting period.

Date	Time	Cause
13 Feb	0944 - 1515	Software upgrade in Helsinki
25 Feb	1828 -	Power problems in Helsinki
26 Feb	- 1120	

Table 3.3.1. *The main interruptions in FINES recordings at the Norwegian NDC, 1 October 2000 - 30 June 2001.*

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:

October 2000	:	99.99%
November	:	99.95%
December	:	100%
January 2001	:	100%
February	:	95.71%
March	:	100%
April	:	100%
May	:	100%
June	:	99.95%

J. Torstveit

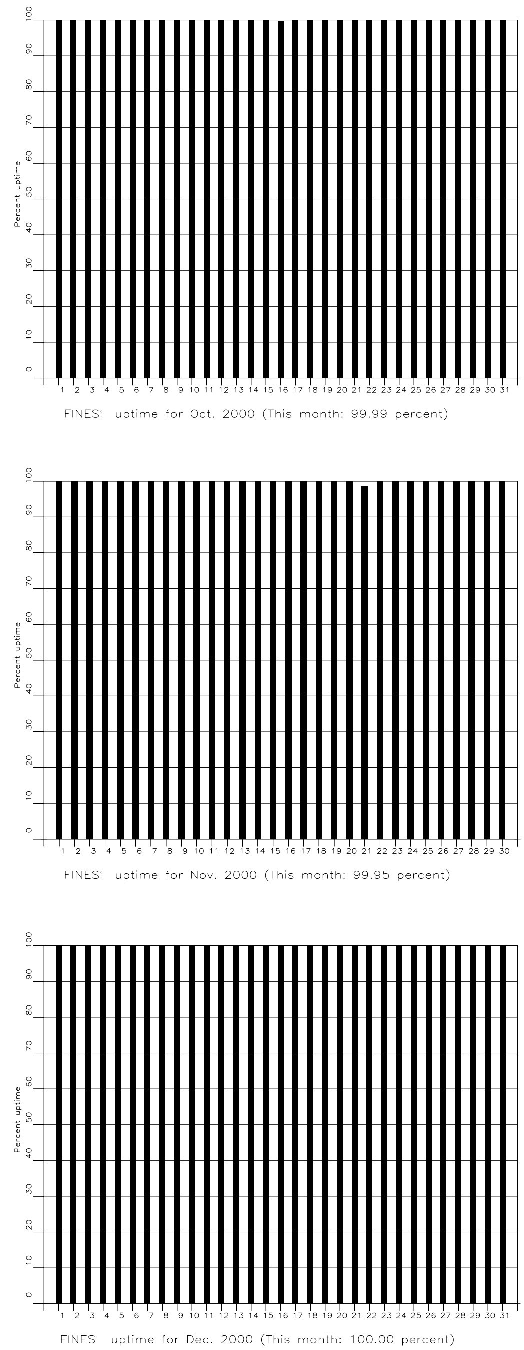


Fig. 3.3.1. *The figure shows the uptime for the data recording task, or equivalently, the availability of FINES data in our tape archive, on a day-by-day basis, for the reporting period (Page 1 of 3, Oct-Dec 2000).*

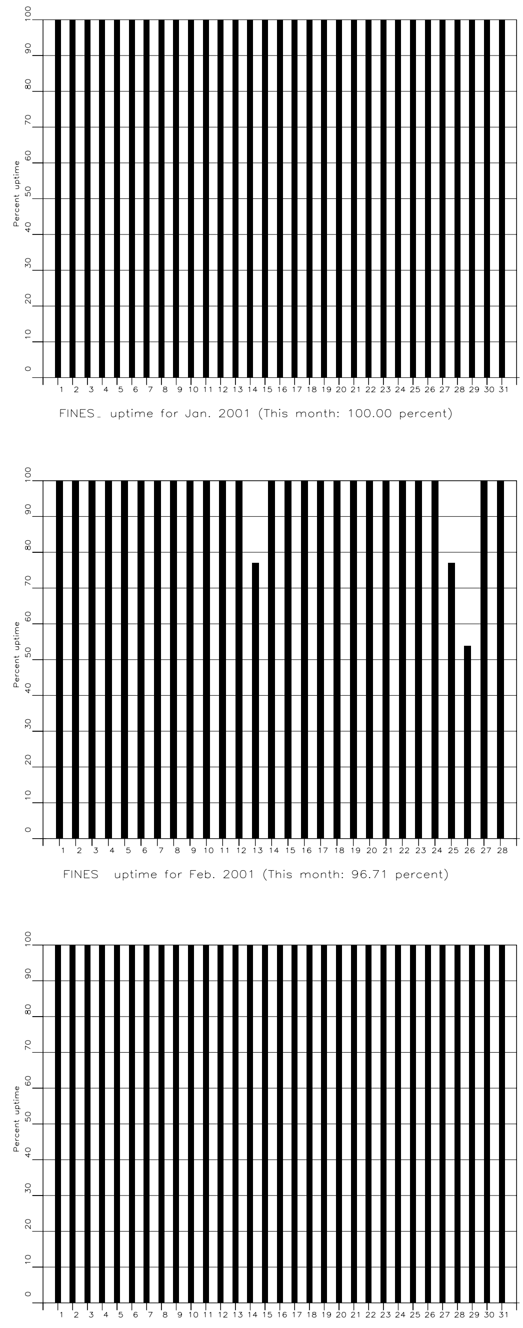
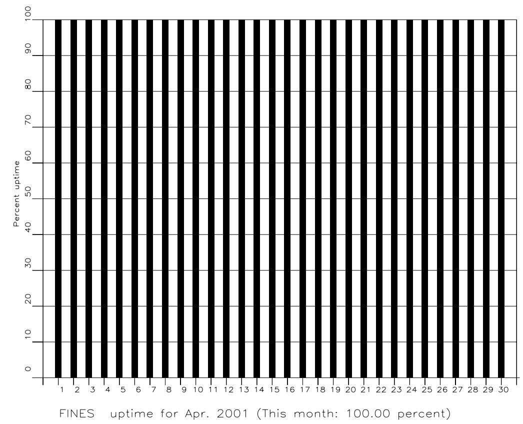
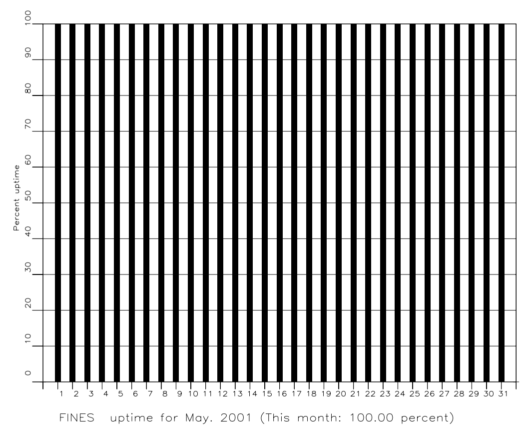


Fig. 3.3.1 *(cont.) (Page 2 of 3, Jan-Mar 2001)*





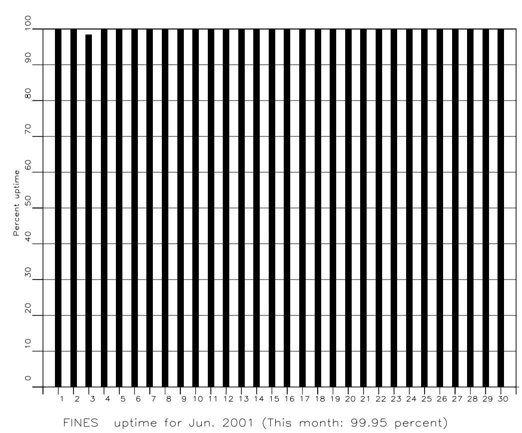


Fig. 3.3.1 *(cont.) (Page 3 of 3, Apr-Jun 2001)*

FINES Event Detection Operation

FINES detections

The number of detections (phases) reported during day 275, 2000, through day 181, 2001, was 80,766, giving an average of 296 detections per processed day (273 days processed).

Events automatically located by FINES

During days 275, 2000, through 181, 2001, 3832 local and regional events were located by FINES, based on automatic association of P- and S-type arrivals. This gives an average of 14.1 events per processed day (273 days processed). 76% of these events are within 300 km, and 89% of these events are within 1000 km.

U. Baadshaug

3.4 Apatity

The average recording time was 99.92% in the reporting period compared to 96.14% during the previous period.

Table 3.4.1 lists the reasons for and times of the main outages during the reporting period .

Date	Time	Cause
08 Nov	1350 - 1406	Stop in Apatity
14 Nov	1412 - 1755	Stop in Apatity

Table 3.4.1. *The main interruptions in Apatity recordings at the NDC, 1 October 2000 - 30 June 2001.*

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:

October 2000	:	100%
November	:	99.31%
December	:	100%
January 2001	:	100%
February	:	100%
March	:	99.99%
April	:	99.99%
May	:	100%
June	:	100%

J. Torstveit

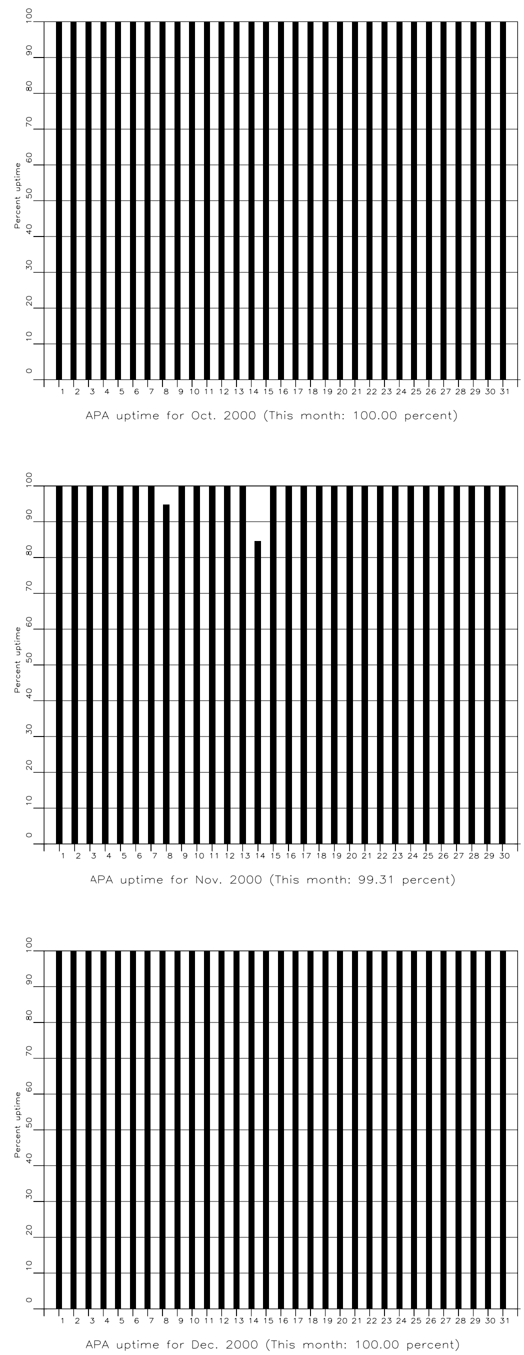


Fig. 3.4.1. *The figure shows the uptime for the data recording task, or equivalently, the availability of Apatity data in our tape archive, on a day-by-day basis, for the reporting period (Page 1 of 3, Oct-Dec 2000).*

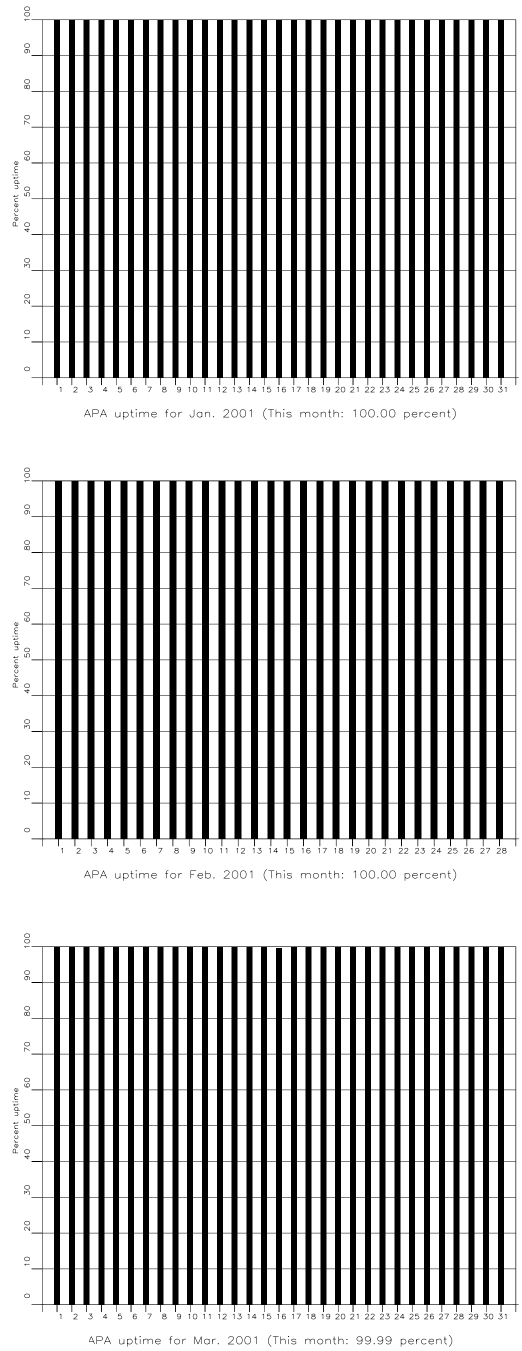
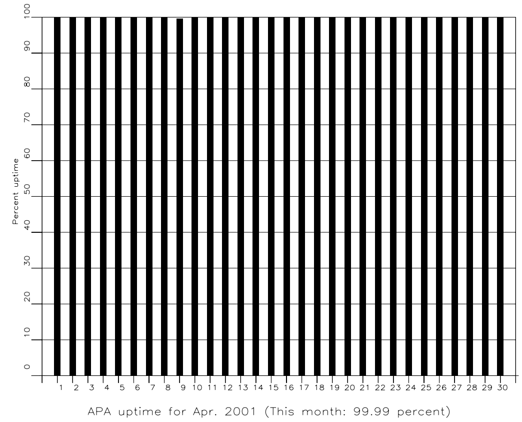
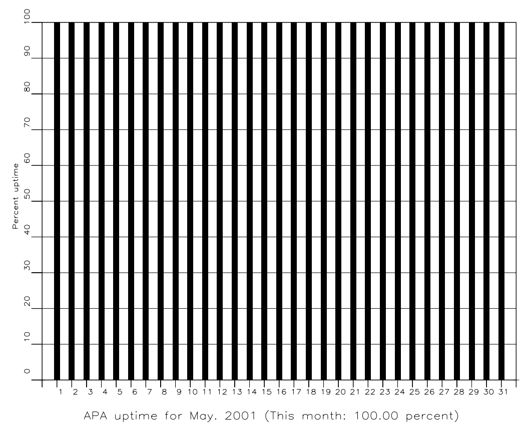


Fig. 3.4.1 *(cont.) (Page 2 of 3, Jan-Mar 2001)*





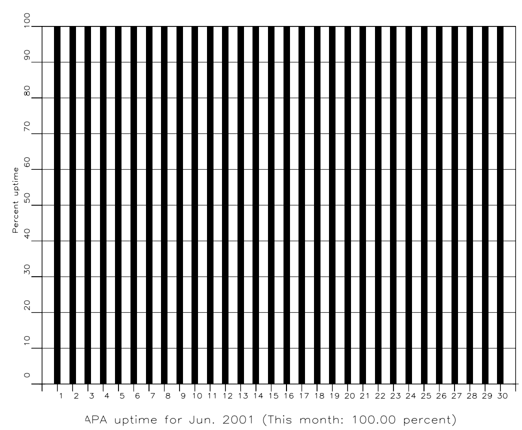


Fig. 3.4.1 *(cont.) (Page 3 of 3, Apr-Jun 2001)*

Apatity Event Detection Operation

Apatity array detections

The number of detections (phases) reported from day 275, 2000, through day 181, 2001, was 245,559, giving an average of 916 detections per processed day (268 days processed).

As described in earlier reports, the data from the Apatity array are 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 275, 2000, through 181, 2001, 2542 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 9.5 events per processed day (268 days processed). 48% of these events are within 300 km, and 78% 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 was 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 distance.

Data from the Apatity array were 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 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 to 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.

	Oct 00	Nov 00	Dec 00	Jan 01	Feb 01	Mar 01	Apr 01	May 01	Jun 01	Total
Phase detections	146151	135693	138004	114153	125081	101010	104308	106159	142500	1113059
- Associated phases	4839	6694	5486	3914	3464	3798	4335	4909	4849	42288
- Unassociated phases	141312	128999	132518	110239	121617	97212	99973	101250	137651	1070771
Events automatically declared by RMS	1021	1270	1059	663	593	553	678	781	888	7506
No. of events defined by the analyst	89	162	90	81	75	100	111	104	73	885

Table 3.5.1. *RMS phase detections and event summary.*

U. Baadshaug
B. Paulsen

4 NDC and Field Activities

4.1 NDC Activitities

NORSAR is functioning 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, with three of them contributing data to GSETT-3. The infrasound station in northern Norway will need to be established within the next few years, whereas the radionuclide station at Spitsbergen is currently being installed. 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 will require increased resources and additional personnel both at the NDC and in the field. It will require establishing new and strictly defined procedures as well as increased emphasis on regularity of data recording and timely data transmission to the IDC in Vienna. Anticipating these requirements, a new organizational unit has been established at NORSAR to form a core group for the future Norwegian NDC for treaty monitoring. The NDC will carry 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

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.

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.

Information received from IDC

The IDC will provide regular bulletins of detected events as well as numerous other products, but will not assess the nature of each individual event. An important task for the Norwegian NDC will 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.

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 to establish 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 continuously 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.

Certification of PS27

On 28 July 2000 the IMS station PS27-NOA was formally certified. PTS personnel visited the station in June 1998, and carried out a detailed technical evaluation. As a result of this inspection and subsequent discussions between NORSAR and the PTS, and following further discussions of the certification requirements during Working Group B meetings, it was concluded that PS27 needed the following enhancements, which all have been implemented:

- A tamper detector has been emplaced at every seismometer and at the subarray central vaults.
- A centralized authentication process in each subarray as well as at the central array recording facility has been installed.
- Connection to the GCI frame-relay link at the central array facility has been established.
- A Guralp CMG-3T seismometer has been installed at site NC602 in accordance with the certification requirements.

Communication topology

Norway has elected to use the option for an independent subnetwork, which will connect the IMS stations AS72, AS73, PS28, IS37 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.

The Norwegian NDC has been cooperating with institutions in other countries for transmission of IMS data to the Prototype IDC during GSETT-3. Details on this can be found in Section 4.2.

Upgrade of PS28

IMS station PS28-ARCES was selected by the PrepCom for hardware upgrade in 1999, and this effort has been concluded. All the digitizers and data acquisition equipment have been replaced. Data from the upgraded array are now being transmitted from the NDC to PIDC, IDC and US_NDC. PS28 is now undergoing a testing and evaluation phase, leading up to certification of this station, perhaps in the fall of 2001.

Jan Fyen

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

Introduction

This contribution is a report for the period October 2000 - June 2001 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.

Norwegian GSETT-3 stations and communications arrangements

During the reporting interval 1 October 2000 - 30 June 2001, 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 has been achieved by a land line for subarray NC6 and VSAT links based on TDMA technology for the other 6 subarrays. The central recording facility of NOA is at NOR_NDC.

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

Continuous SPITS data were transmitted to NOR_NDC using the same arrangements that have existed for several years (terrestrial line to Isfjord Radio at the west coast of Spitsbergen, and a VSAT satellite link from there to NOR_NDC). A modification to this system was made on 21 May 2001. From this date, SPITS data have 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 now being installed).

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 (central array station buffer).

The NOA and ARCES arrays are primary stations in the GSETT-3 network, which implies that data from these stations are transmitted continuously to the receiving international data center. Since October 1999, these data have been transmitted (from NOR_NDC) via the Global Communications Infrastructure (GCI) to the IDC in Vienna, whereas transmission of the same data to the Prototype International Data Center (PIDC) in Arlington, VA, was discontinued on 7 February 2000. The SPITS array is an auxiliary station in GSETT-3, and the SPITS data have been available to both the IDC and the PIDC 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 are being 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 October 2000 - 30 June 2001, 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 PIDC in the PIDC Station Status reports. The main reason for the discrepancies between the NOR_NDC and PIDC 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 PIDC uses weights where the reported availability (capability) is based on the number of actually operating channels. The PIDC receives its ARCES and NOA data via the IDC in Vienna.

Use of the AutoDRM protocol

NOR_NDC's AutoDRM has been operational since November 1995 (Mykkeltveit & Baadshaug, 1996). The PIDC started actively and routinely using NOR_NDC's AutoDRM service after SPITS changed its station status from primary to auxiliary on 1 October 1996. The monthly number of requests by the PIDC for SPITS data for the period October 2000 - June 2001 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 October 2000 - June 2001, NOR_NDC derived information on 1090 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 PIDC. 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 PIDC as well as the IDC obtain data from the Hagfors array (HFS) in Sweden through requests to the AutoDRM server at NOR_NDC (in the same way requests for Spitsbergen array data are handled, see above). Fig. 4.2.6 shows the monthly number of requests for HFS data from the two PIDC accounts "pipeline" and "testbed".

Current developments and future plans

NOR_NDC is continuing the efforts towards improvements and hardening of 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 negotiations on a contract with the PTS in Vienna for operation and maintenance of this station are in progress, and it is expected that a contract to this end will be signed in July 2001. This will formalize the responsibility of the PTS for funding of the operation and maintenance of PS27. Provided that adequate funding continues to be made available, we envisage also continuing the provision of data from other Norwegian IMS-designated stations without interruption to the IDC in Vienna.

U. Baadshaug
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J. Fyen

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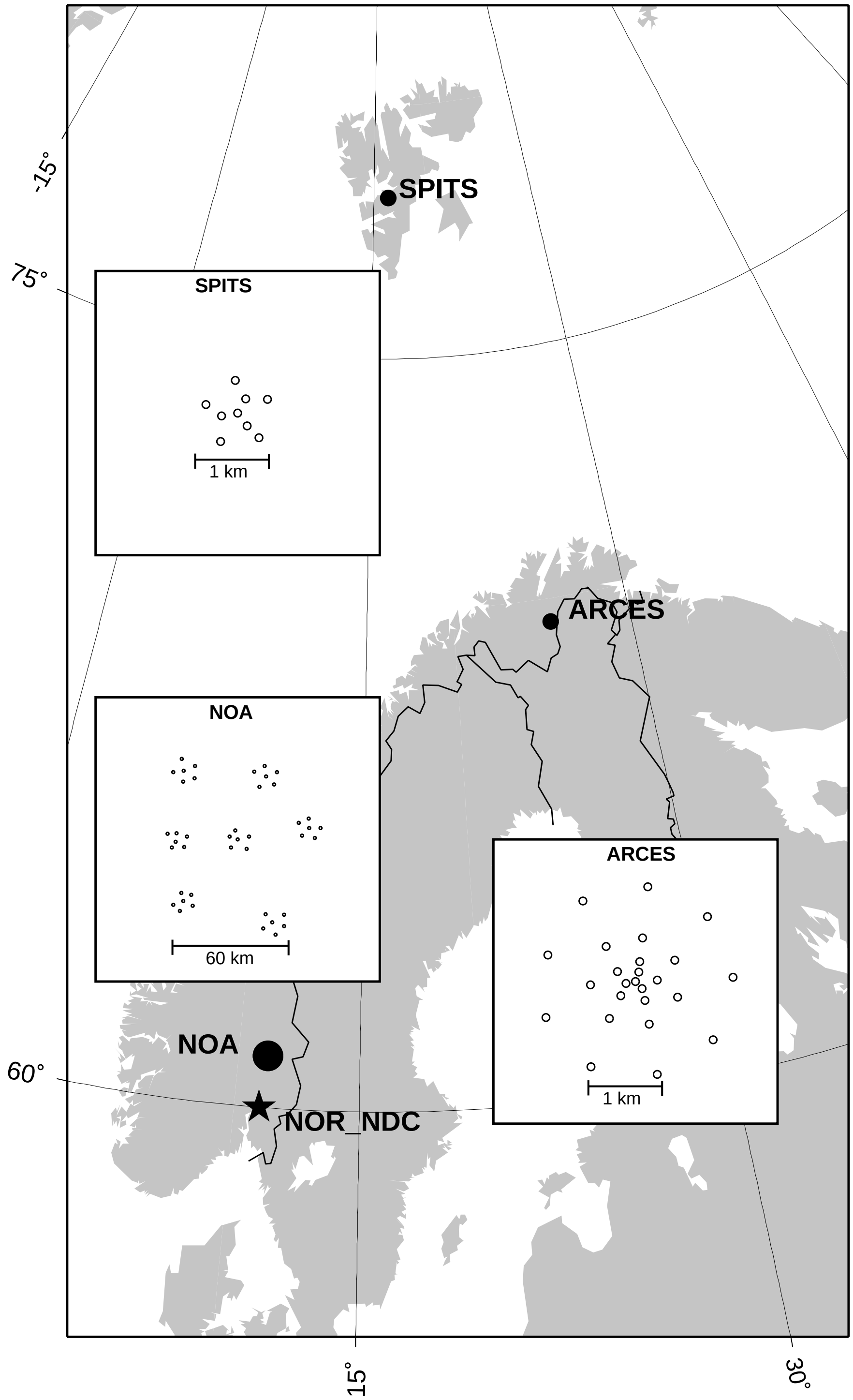

Fig. 4.2.1. The figure shows the locations and configurations of the three Norwegian seismic array stations that have provided data to the GSETT-3 experiment during the period 1 October 2000 - 30 June 2001. The data from these stations are transmitted continuously and in real time to the Norwegian NDC (NOR_NDC). The stations NOA and ARCES have participated in GSETT-3 as primary stations, whereas SPITS has contributed as an auxiliary station.

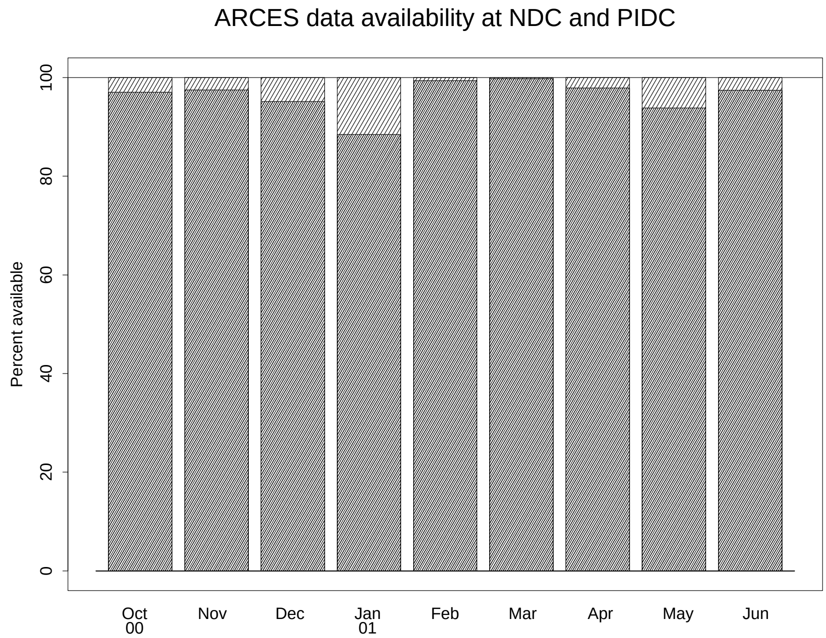

Fig. 4.2.2. The figure shows the monthly availability of ARCES array data for the period October 2000 - June 2001 at NOR_NDC and the PIDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

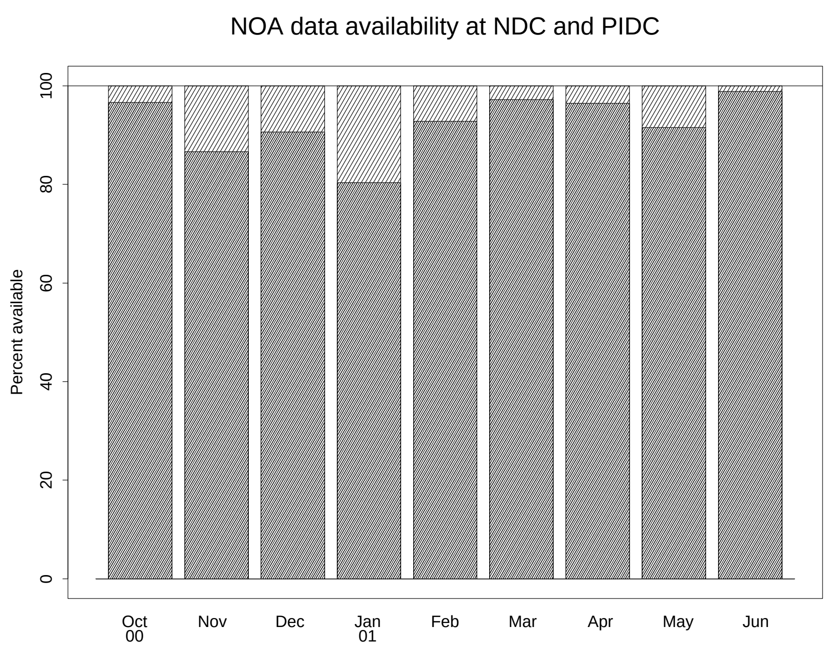

Fig. 4.2.3. The figure shows the monthly availability of NORSAR array data for the period October 2000 - June 2001 at NOR_NDC and the PIDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

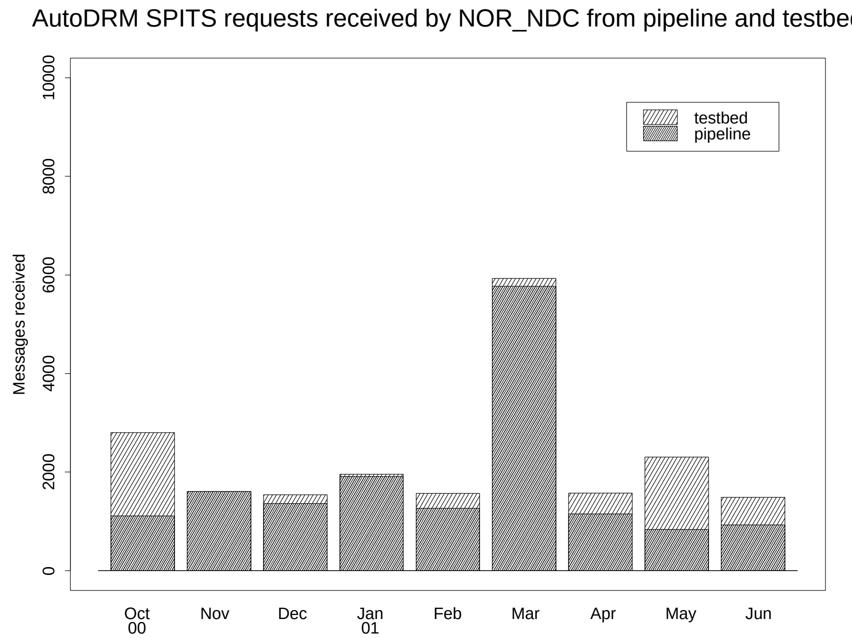

Fig. 4.2.4. The figure shows the monthly number of requests received by NOR_NDC from the PIDC for SPITS waveform segments during October 2000 - June 2001.

Reviewed Supplementary events

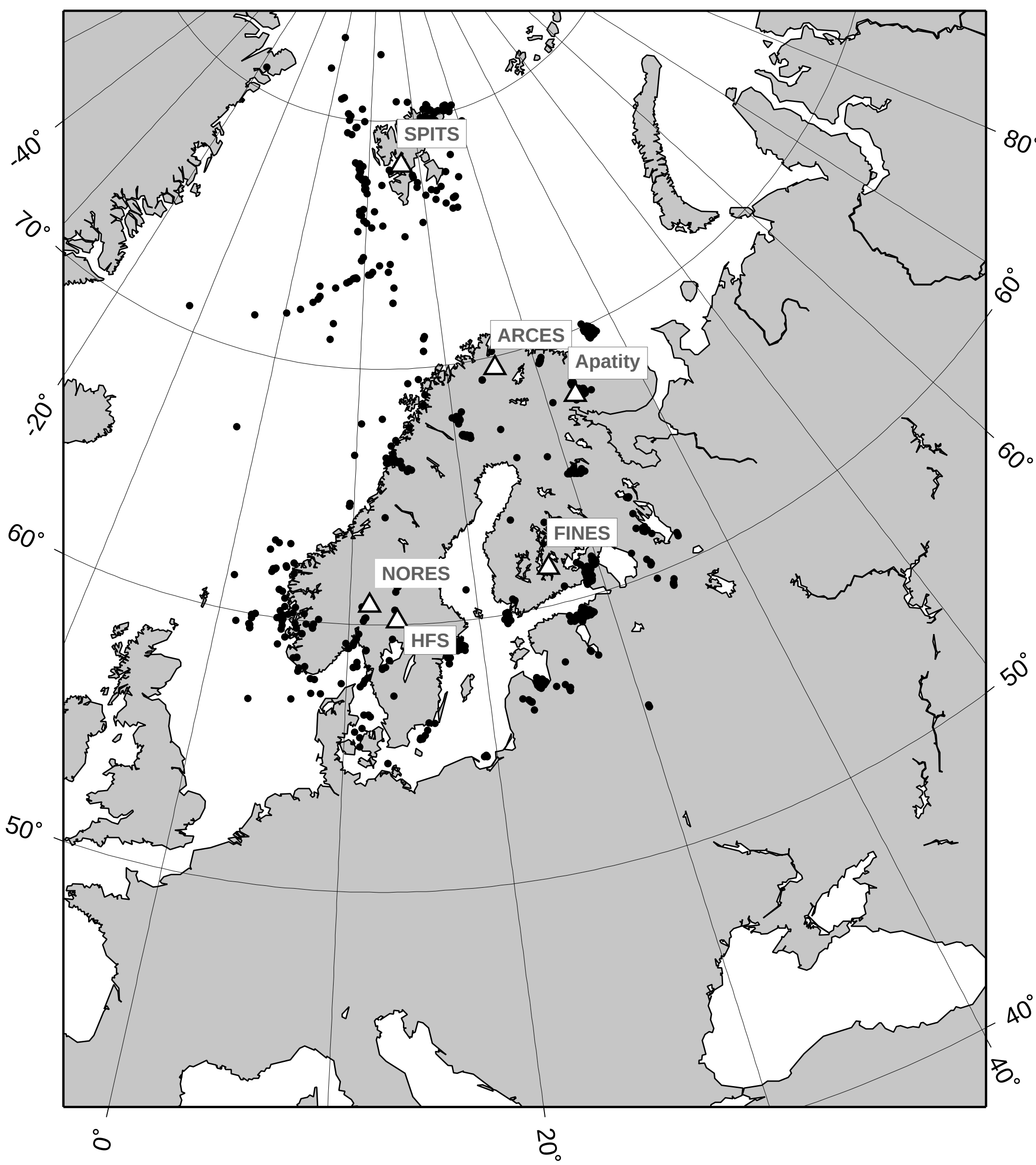

Fig. 4.2.5. The map shows the 1090 events in and around Norway contributed by NOR_NDC during October 2000 - June 2001 as supplementary (Gamma) events to the PIDC, as part of the Nordic supplementary data compiled by the Finnish NDC. The map also shows the seismic stations used in the data analysis to define these events.

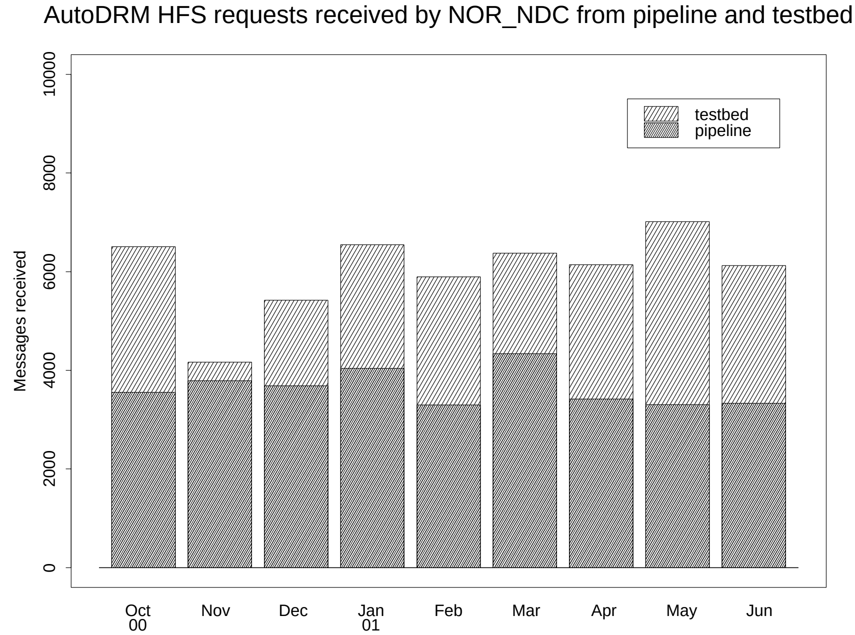

Fig. 4.2.6. The figure shows the monthly number of requests received by NOR_NDC from the PIDC for HFS waveform segments during October 2000 - June 2001.

4.3 Field Activities

The activities at the NORSAR Maintenance Center (NMC) at Hamar currently includes 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 accociated 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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Mykkeltveit, S., F. Ringdal, C. Lindholm & E.O. Kremenetskaya: Seismic calibration of the European Arctic, Conf. proc. Seismic Research Symposium, New Orleans.

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Ringdal, F., T. Kværna, J. Schweitzer & A. Hafslund: Automatic reprocessing of events from the Khibiny Massif, In: *NORSAR Sci. Rep. 1-2001*, 1 October 2000 - 30 June 2001, Kjeller, Norway.

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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 23-27 April 2001

6.1.1 Introduction

The International Data Centre (IDC) Technical Experts Group on Seismic Event Location held its third annual meeting in Oslo, Norway on 23-27 April 2001. The purpose of the meeting was to support the ongoing calibration effort 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-five technical experts, coming from fourteen signatory countries and the Provisional Technical Secretariat, participated in the meeting. In accordance with previous recommendations, the focus of the discussions was on the following geographical regions: North America, Eurasia, Northern Africa and Australia. 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 the second meeting of the Experts Group in March 2000, and the results were presented to Working Group B in May 2000 (CTBT/WGB/TL-2/49). The third meeting of the Experts Group (23-27 April 2001) had the following objectives:

- To review proposals for detailed station-specific regional corrections to be applied for IMS stations in North America, Europe, North Africa, Asia and Australia
- To recommend a set of such corrections, including appropriate model errors, for incorporation into the next release of the IDC software
- To review progress in the general recommendations from the first and second 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 such calibration information for the regions being considered, and to plan for implementing regional location calibration at the IDC, both for the next release of the IDC applications software and for implementation in the longer term. Information was provided about the CTBTO Calibration Programme initiated in 2000. Most of the scientific organizations to which contracts were awarded by CTBTO in 2000 participated at the workshop with presentations on their planned work and initial achievements.

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 general geographic regions being considered initially.

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, the prototype IDC and interested States Signatories. Countries were encouraged to continue to provide relevant calibration data for the purpose of developing accurate seismic travel-time curves for various geographical regions.

Reports were presented on a number of modelling studies, some of which showed significant improvement in location precision when applied to test sets of seismic events. For example, one-dimensional regional Pn, Pg, Sn, and Lg travel time curves were shown to provide improvements for the Baltic shield and the Barents region. Three-dimensional models were introduced for North America and Western Russia and were found to provide considerable improvements in location accuracy compared to standard (IASPEI-91) models.

Techniques for improved regional processing using sparse seismic networks as well as improved azimuth determination for regional arrays were presented and discussed. The application of special location techniques was also addressed.

Working Group Discussions

Three Working Groups, each focusing on specific regions of the world, were established to discuss technical issues in detail during the workshop:

Working Group 1: Northern Eurasia and East Asia

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

Working Group 3: North and South America, Australia

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

Topic 1: Implementing regional corrections into the IDC operating software

Topic 2: Collection of Regional Calibration Information

Topic 3: Application of Regional Calibration Information

Topic 4: Validation of Regional Calibration Information

Topic 5: Future work of the Experts Group

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 recommendations presented below.

6.1.4 Results and recommendations

Main conclusions

The experts note with satisfaction that the work on implementing regional corrections is progressing well, and that such corrections now have been implemented for IMS stations in northwestern Eurasia and northern America. Progress was reported at the workshop by U.S sponsored consortia, by CTBTO sponsored contractors and by several other research groups.

During the course of the experts' work the importance of *validation* of ground truth data has become increasingly clear. Validation is a far more complex and time-consuming undertaking than initially expected. The experts recommend that a systematic procedure be established for the validation of ground truth data, and that this procedure be rigorously carried out before new ground truth data is accepted into the operating software for calibration usage.

The experts consider it essential that States Signatories continue to contribute actively to the calibration program by supplying relevant location calibration information for their own territories as well as for other regions where they have such information available. The relevant location information is defined in CTBT/WGB-6/CRP.26.

The experts consider that Confidence-Building Measures, especially chemical calibration explosions, are important to regional calibration, and encourage States Signatories to carry out additional such explosions or to take advantage of such explosions conducted for other purposes. The experts reiterate their recommendation that the PTS solicit from States Signatories waveform data recorded on national seismic stations of such calibration explosions.

The experts were informed about new provisons included in the Preparatory Commission Report of November 2000 on access to IMS data and IDC products by contracted scientific research organization. Still, the experts expressed concern about the current restrictions on obtaining IMS data and IDC products, and recommended that the IDC make openly available to the scientists involved in the IDC location calibration effort all of the waveform data and associated IDC products that are needed in order to successfully carry out the calibration program.

A continued full utilization of the resources of the prototype IDC, which is operated by the Center for Monitoring Research (CMR) in Arlington, Virginia, USA, will be important for future IDC development. The experts recommend that the prototype IDC should continue to act as a resource facility for the international location calibration effort, thus compiling, organizing and making openly available to the scientific community all relevant information on calibration events, travel-time curves, geological/ geophysical information and other ground truth data.

The validated information collected at the prototype IDC will be transferred to the IDC as it becomes available. The responsibility for these calibration data and the associated processing software will be transferred from the prototype IDC to the IDC on a stage-by-stage basis.

Detailed results and recommendations

Topic 1: Implementing regional corrections for the IDC operating software

Region 1

For Region 1 (Northern Eurasia and East Asia) source-specific station correction (SSSC) have previously been implemented for IMS stations in Fennoscandia. It is anticipated that a variety of SSSC estimates for many additional IMS stations in this region will be available for potential inclusion in updates to Release 3 of the IDC software, although full validation studies are not expected to be completed for another two years. These will include separate estimates from the two U.S. sponsored calibration consortia, as well as estimates from various Russian and CTBTO sponsored studies. The results of all these studies should be made available to the research community. An effort should be initiated in the coming year to define how such multiple estimates of corrections for specific stations are to be systematically compared and evaluated. The existing evaluation process used by the Configuration Control Board is not considered optimal for this purpose.

Region 2

For Region 2 (Southwestern Asia and the African/Mediterranean area) no travel time corrections are currently available. Progress was reported at the workshop by U.S. sponsored consortia at the large scale and at the smaller scale by CTBTO sponsored and other research groups. Preliminary regional travel time corrections will be available in 2002 and revised corrections will follow in 2003 as an update to the current operating software. The largest deficiencies in the region at this stage are a lack of well located validation events to demonstrate unambiguously that the proposed corrections make significant improvements in location across the region, and it is recommended that future efforts focus upon this problem. Areas of particular difficulty include the seismically active areas of North Africa along the Mediterranean and the East African Rift.

Region 3

For Region 3 (North America, Australia) there have been some recent developments. SSSCs based on 3-D modelling for all IMS stations in Canada and the USA have been generated, tested, validated, and implemented. They are in an updated version of Release 3 currently at the IDC. There are, however, currently no corrections for stations in Mexico. Corrections for IMS stations in Australia based on research sponsored by CTBTO are expected in 1-2 years. Validation is believed to be good for the U.S. stations and spotty elsewhere (there is great variability in quality).

General

The Experts Group remains concerned that there is lack of transparency in the IDC bulletin products that reflect the corrections that are being applied to travel times, azimuths, and slownesses for location purposes. The experts strongly recommend that a mechanism be developed to display the corrections used in the bulletin products. The Experts Group points out that an

IASPEI commission on seismological practise is considering extensions to IMS1.0 to distribute such information. IDC and PIDC should be encouraged to particpate in this process.

The Expert Group also points out the need for a formal procedure for validation. In addition, there should be standards for implementation and periodic checking of performance. The Group recommends that global models (large-scale regional models) continue to be tested, and points out the need for a high resolution crustal model. It is also noted that there are currently no teleseismic SSSCs available, nor are such corrections being developed within any CTBT related research so far.

Topic 2: Collection of Regional Calibration Information

Region 1

Region 1 (Northern Eurasia and East Asia): Collection of ground truth calibration data for many IMS stations in this area is progressing well. It is anticipated that high quality samples of such data for Soviet PNE events will become available at the Center for Monitoring Research (CMR) over the next 6 to 12 months from current contracts. Additional efforts are needed to collect comparable ground truth data and velocity models for other areas of this region, such as China, India, Pakistan, and Korea. Efforts by the individual NDCs/research groups to identify additional calibration and reference events from their regions should be encouraged.

The CMR Reference Event Database may be discontinued mainly due to restrictions in publishing the REB information and the delay in obtaining auxiliary data. The experts strongly support the ongoing efforts to make the IDC data available to the research community. The CMR Ground Truth Database is valuable and continued effort in maintaining this database is important. Deliveries of its updates to the IDC are expected with Release 4.

Region 2

Region 2 (Southwestern Asia and the African/Mediterranean area): The collection of many reference events of GT5 or better available in the Former Soviet Union and Europe was reported. These events are critical for model validation. The experts discussed several possible sources of additional information and recommended that research groups in the region should be queried to obtain calibration data including past refraction profiles and digital data that is not included in bulletins.

Local and national network locations are critical to developing reference events for calibration validation. WGB and the IDC should as appropriate use official diplomatic channels to encourage states signatories to support local operators to distribute calibration data. This reiterates and reinforces an important recommendation of last year’s meeting.

Region 3

Region 3 (North America, Australia): As reported last year, considerable calibration information is available, but geographical coverage is poor. Aside from where United States SSSCs have been developed, no one has seriously looked for calibration data. Additional events, preferably of GT5 or better and magnitude >3.5, should be identified. The experts recommend looking at regional PASCAL data as a source. In particular, events with good S waves and recordings beyond 5 degrees are needed. The current Ground Truth Database for this and other regions should be reviewed and revised where necessary.

The experts note that the U.S. Department of Energy has recently published detailed hypocenter information on United States nuclear explosions: http://www.nv.doe.gov/news&pubs/publications/historyreports/pdfs/DOENV209_REV15.pdf (185 pages).

General comments:

Every effort should be made to support “target of opportunity” experiments, particularly in areas such as South America which currently lacks detailed regional travel time curves. Special consideration should be given to large well-designed mine blast experiments, such as contained single blasts, that would provide unique source phenomenology information.

The number of events available for the Reference Event Database since 1994 is small, and it should be possible to analyze most of them comprehensively, given participation by the States concerned. Efforts should be made to expand the Ground Truth Database and, if possible, continue analyzing and expanding the Reference Event Database. As earlier recommended, this information, including associated waveform data, should be made available from the IDC and the prototype IDC in an unrestricted manner, through Web pages, AutoDRM, ftp, and direct electronic access to the relational databases.

Possibilities for improving the Ground Truth database include good (internal to the network) local network solutions, calibration shots, mining and construction explosions. The most useful data would be Ground Truth information for events in the REB. It may be desirable to consider some form of funding for collecting Ground Truth information on seismic events and delivering it to the IDC.

A need exists to evaluate and validate criteria for GT5 and GT10 reference events. The PIDC and others should continue to collect such events and report them to the IDC on a regular basis.

Topic 3: Application of Regional Calibration Information

The experts re-emphasized the recommendations from the previous meeting regarding the use of historic data and the further research required in developing analysis methods. In addition, some new points were made or expanded upon.

The experts consider the current plans for completion of the IMS network to be encouraging and expect that the implementation will lead to much improved location capability for events in all regions. There is some concern that the technical development of regional calibration models is being limited to some extent by the IDC software constraints. It is recommended that implementation of depth dependent SSSCs should remain as a long term goal of the IDC, independent of the current unavailability of the software needed to support their use in event location at the IDC. Development and implementation of improved databases of station parameters and locations, as well as their associated uncertainties wherever possible, are to be encouraged for use in IMS calibration studies. Additional research is needed to define optimal procedures for combining calibrated and uncalibrated data in the event location process.

The calibration program needs to help quantify both measurement and modelling errors. Our current understanding of the handling and impact of the total errors on location requires more research. Alternative location algorithms and procedures should be addressed. These algorithms include alternative norms (such as L1, uniform reduction), alternative optimization schemes (e.g. adaptive grid search, nearest neighbor algorithms), and alternative uncertainty assessment schemes (grid search, Monte Carlo methods, improved error ellipses). The calculation accuracy of travel-times using models should be high enough so that these errors are small compared to expected time pick errors.

Previously recommended work on cepstral depth estimation techniques should be continued. Positive progress was reported at the workshop that justifies the next stage of testing and validation in an operational context. Evaluation and testing of these available methods at the IDC is encouraged. Research into other methods for depth estimation need to be encouraged.

Techniques such as cepstral analysis, moment tensor, waveform modeling, and Joint Hypocentral Determination should be available, but not as isolated procedures. The experts recommend the development of a software package to present to the analyst, perhaps with depth confidence estimates.

The Experts Group note the availability of the LocSAT program on the prototype IDC ftp site. This program has the full location capability of the IDC location programs, including SSSCs, but does not require the ORACLE database; instead it uses standard files for input and output. The experts reitereted their recommendation that this program be enhanced by the PIDC developers with the capability to accommodate depth-dependent SSSCs as soon as possible.

The effects of SNR on location accuracy are known in general, but not in specific detail. It is recommended to design an experiment to evaluate the effects of onset picks by different analysts, by use of multiple frequency filters or other analyst aids, perhaps supplemented by master events. It should be recognized that timing problems associated with low SNR are ‘asymmetric’ in nature.

Topic 4: Validation of Regional Calibration Information

The experts reiterate their recommendations for establishment of a Location Calibration Board and formation and maintenance of a central database of calibation information. The IDC should use contracted services if the available resources at the IDC are not sufficient.

Multiple estimates of station corrections for individual IMS stations are expected from different research groups, and they may be submitted for consideration for implementation at the IDC. An effort should be initiated in the coming year to begin the development of the types of uniform procedures which will be needed to quantatitively compare and validate these competing SSSC estimates. Results of these validation studies should be made available to the calibration research community. Additional work directed toward the development of more reliable validation methods and acceptance criteria for ground truth events should be encouraged, especially to validate candidate GT5 events.

An appropriate mechanism for publication of calibration data needs to be developed to encourage and give credit to providers, and to provide an opportunity for review of the data. The experts reiterate their recommendation that Web and Ftp sites should be established at the IDC and the prototype IDC to receive contributed models, ground truth, and metadata (velocity models, travel time curves, phase/group velocity curves, crustal thickness, origins, arrivals, and waveforms). This would serve to encourage contributions and broaden access.

A project to establish rigorous procedures for validation of ground truth events should be initiated. This project should address all aspects of the validation problem, including the collection and storage of ‘metadata’ for future reference and comparison. It should also include procedures and validation metrics (see CTBT/WGB/TL-2/49) for documenting and demonstrating improvement to the Location Calibration Board or Configuration Control Board. The project should also define procedures for periodic updates (checks) when new Ground Truth data become available. The participants were encouraged to use procerdures for ground truth event validation as well as the metrics to access the improvement when using newly derived SSSCs as listed in the 2000 CTBTO Calibration Programme Terms of Reference.

Topic 5: Future work of the Experts Group

In its future meetings, the experts should focus on examining the status of recommendations made at earlier meetings. The experts should acknowledge those recommendations that the IDC has begun to implement. Remaining recommendations should be re-examined, reiterated, and/or prioritized.

There is some concern among the experts that the recommendations presented to the IDC and Working Group B are too technical in nature. An executive summary could highlight the high priority recommendations, which should be kept to a few well focussed items separate from those addressed to researchers.

One idea forwarded to the experts group was that a subset of the participants at the next meeting could consider serving as the Location Calibration Board for a proposed set of candidate reference events or set of corrections. Results of the discussion and review might then be published in the Experts Group's report.

The next meeting could focus and/or organize the work around specific topics such as

- discussion of Ground Truth event selection and validation criteria,
- procedures for validating SSSCs,
- better understanding of fundamental location errors,
- location algorithms,
- depth estimation,
- a summary and inventory of available information as a function of region/country.

The next meeting needs to solicit participation from under-represented areas. The experts need to identify to the meeting organizer those indiviudals and organizations that need to be invited to participate, and how their participation could be financed.

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

F. Ringdal

6.2 Experimental threshold monitoring of the area surrounding the site of the Kursk submarine accident

This research is conducted under Contract DTRA01-99-C-0107

6.2.1 Introduction

On 12 August 2000, signals from two presumed underwater explosions in the Barents Sea were recorded by Norwegian seismic stations. The first of these, at 07.28.27 GMT, was relatively small, measuring 1.5 on the Richter scale. The second explosion, 2 minutes and 15 seconds later, was much more powerful, with a Richter magnitude of 3.5. These explosions were associated with the accident of the Russian submarine “Kursk”, although the exact sequence of events leading to this disaster is still unknown.

The area in the Barents Sea where the Kursk accident occurred has no known history of significant earthquake activity. Beginning in September 2000, a number of small seismic events were detected in this area (Ringdal et. al. 2000). According to an official Russian announcement in November, these signals were generated by underwater explosions near the Kursk accident area, carried out by the Russian Navy. At the time of this report, this explosion activity is still continuing.

This explosion sequence, with numerous explosions ranging in magnitude from very small (about 1.0 on the Richter scale) to fairly large (about magnitude 3.0) provides a unique opportunity to investigate the performance of the threshold monitoring technique. We have implemented an experimental site-specific threshold monitoring procedure to monitor the Kursk accident area in the Barents Sea, and present some of the results in this report

We first note that the timing patterns of the explosions show some single explosions and some compressed sequences with explosion intervals of 1-2 minutes. The waveforms have similar characteristics, although they are not identical. These explosions, although their magnitudes were only about 2.0 on the Richter scale, were well recorded by the ARCES array (distance 500 km), but the FINES, SPITS and NORES array also detected several of the events. In addition, the Apatity array station on the Kola Peninsula (not an IMS station) provided useful recordings.

6.2.2 Automatic processing

In developing the site-specific parameters for optimized monitoring of the Kursk accident area, we have built on previous efforts to develop a fully automated tool for monitoring of a given target area. We have included additional functionality to facilitate the review of the computed threshold traces, and examples of this new functionality are shown below.

As outlined in reports under previous contracts, we have already available a robust method for detecting peaks on the threshold traces. The next step is to identify the peaks that are caused by events located outside the actual target area. We will in the following describe the procedure developed for monitoring of the Kursk accident area using data from the SPITS, ARCES, FINES, APATITY and NORES arrays.

6.2.3 Automatic explanation facility

The automatic explanation facility for threshold peaks builds on an integration of traditional detector and event information with the results of continuous Threshold Monitoring.

The first step in the automatic analysis of threshold traces is to identify significant threshold peaks. Our approach has been to develop a peak detection method based on estimates of the noise variance and the long term trend of the threshold trace. From experiments with various data sets, we have developed a method which comprises the following steps:

- Calculate the long-term-median (LTM) of the threshold trace with a typical window length of 60 minutes and a sampling interval of 5 minutes.
- Calculate the overall standard deviation (SIGMA) of the threshold trace around the long-term-median after removing the upper 5% of the data values. The removal of the upper 5% of the data values is done to reduce the influence of the threshold peaks on the estimate of the standard deviation.
- Define the peak detection limit as LTM + n * SIGMA. Optionally, the peak detection limit can be set by the user, and in this study the limit is set to approximately 0.4 m_b units above the LTM.

Fig. 6.2.1 shows a panel with threshold traces for 20 November 2000 (day 325) with the peak detection limits superimposed. Notice that several peaks are identified on the network threshold trace which we have to investigate in more detail.

In order to relate the peaks of the network threshold trace to information obtained by traditional signal processing at each array, we have to determine the time intervals associated with each network threshold peak as well as the expected azimuths and velocities from the site to be monitored (**Table 6.2.1**). The following procedure has been established:

- Detect peaks on the threshold traces calculated for each individual phase.
- For each phase considered, find the peak detection intervals overlapping the peak detection intervals of the network threshold trace, and use the union as the time interval of interest.
- The X-axes of the threshold traces show hypothetical origin times at the Kursk accident area. When searching the detection lists for signals associated with the threshold peaks, we need to shift the detection times in accordance with the expected phase travel time from the Kursk accident area to the actual array.
- We define for each phase a critical azimuth and slowness range for events in the vicinity of the Kursk accident area. Detected signals with azimuth and slowness estimates falling outside the critical ranges are assumed to be caused by events located outside the Kursk area.
- For all panels, green peaks indicate that none of the associated detections were considered critical. Yellow peaks indicate that there were no associated detections whatsoever (see the FINES-P panel in **Fig. 6.2.1** between 7:00 and 9:00). All peaks are flagged on the X-axis for easy identification.

- Each individual phase is given a weight (0 or 1) based on the sensitivity of the array and the usefulness of the phase. The P-phases from Apatity, ARCES, and FINES are given a weight of 1; all other phases have a weight of 0. Critical detections and their associated peaks will be either orange (phase weight 0) or red (phase weight 1).
- Critical peaks on the network trace are assigned a weight which is the sum of the phase weights of the corresponding individual phase peaks. These network peak weights are shown on the top of the panel. Critical peaks with a total weight of at least 2 are red (see **Fig. 6.2.1**, 7:00-9:00); otherwise they are orange (see **Fig. 6.2.1** at about 3:00 and just after midnight). The orange network peak at about 18:20 has an associated critical Lg phase at ARCES. The individual threshold traces for ARCES Lg, Apatity Lg, FINES Lg, and NORES Lg are not shown in **Fig. 6.2.1**, but these phases are all included in the calculation of the network thresholds.
- The causes of the red threshold peaks have to be investigated in more detail, e.g. by comparing to existing event bulletins or by offline analysis of the raw seismic data.

6.2.4 Comments on the Kursk TM case study (day 325/2000)

The plot in **Fig. 6.2.1** shows seven consecutive red color peaks on the network (top) trace. These peaks all correspond to real explosions from the Kursk accident area, as has been verified by interactive waveform analysis. The explosions occur between 7 and 9 GMT, and are almost equidistant in time (15 minute intervals). The software tool has the functionality to provide a higher resolution of the plot, if so desired by the analyst. **Fig. 6.2.2** shows a plot of the one-hour interval 07.00-08.00 for the same day, and it is possible to analyze the peaks in somewhat more detail.

Another new feature is the option to focus on one particular phase, and compare the results with the network trace. **Fig. 6.2.3** shows an example, focusing on the ARCES Pg phase for the day 325/2000. Together with **Fig. 6.2.4**, which is a blow-up of **Fig. 6.2.3** covering the time interval 07.00-08.00, these figures show (from top to bottom);

- The network Threshold Monitoring trace
- The TM trace using the ARCES Pg phase only
- The SNR (in dB) for the ARCES Pg detections
- The ray parameter (s/deg) for the ARCES Pg phase, with the critical interval for the Kursk accident area marked in yellow
- The calculated azimuth for the ARCES Pg phase, with the critical interval for the Kursk accident area marked in yellow
- The slowness difference (absolute value) compared to the expected ray parameter for Pg.

We note from **Fig. 6.2.3** that one red peak in the ARCES plot (at around 03 GMT) is only orange on the network trace. A closer investigation reveals that this peak corresponds to a small mining explosion near the Norway-Russia Border (The Zapolyarnyi/Nikel mine). The azimuth of this mining site from ARCES is almost exactly the same as for the Kursk accident area, and the slowness resolution is not sufficient to distinguish this phase from the Kursk phases using ARCES alone.

It is important to note that the availability of additional array data in this case provide some important contributions to the threshold monitoring results:

- They reduce the size of this “false” peak on the network trace
- They ensure that the peak is not marked in red on the network trace, because the azimuths from the other arrays do not correspond to events at the Kursk accident area.

The development of the automatic explanation facility for analysis of the threshold monitoring results is at an early stage. Our approach is to gain experience through processing of numerous different time intervals, such that as a final product we can present a tool for continuous monitoring of a given target region that requires very little human interaction.

T. Kværna

Table 6.2.1. Definition of critical azimuth and slowness ranges for phases from events near the Kursk accident area

Array	Phase	Expected Azimuth (degrees)	Lower Azimuth (degrees)	Higher Azimuth (degrees)	Expected Slowness (sec/deg)	Lower Slowness (sec/deg)	Higher Slowness (sec/deg)
APA	Pg	50.65	25.0	65.0	13.97	10.1	22.2
APA	Lg	46.57	20.0	60.0	25.78	18.5	37.1
ARCES	Pg	88.1	75.0	100.0	13.7	10.6	15.9
ARCES	Lg	88.4	70.0	100.0	26.2	22.2	37.1
FINES	P	23.15	10.0	40.0	13.28	10.11	18.53
FINES	Lg	21.75	5.00	35.0	28.88	22.24	44.48
SPITS	P	142.70	135.0	155.0	15.27	11.12	24.71
NORES	P	33.38	20.0	45.0	12.47	9.27	15.88
NORES	Lg	29.75	20.0	45.0	32.42	22.24	55.60

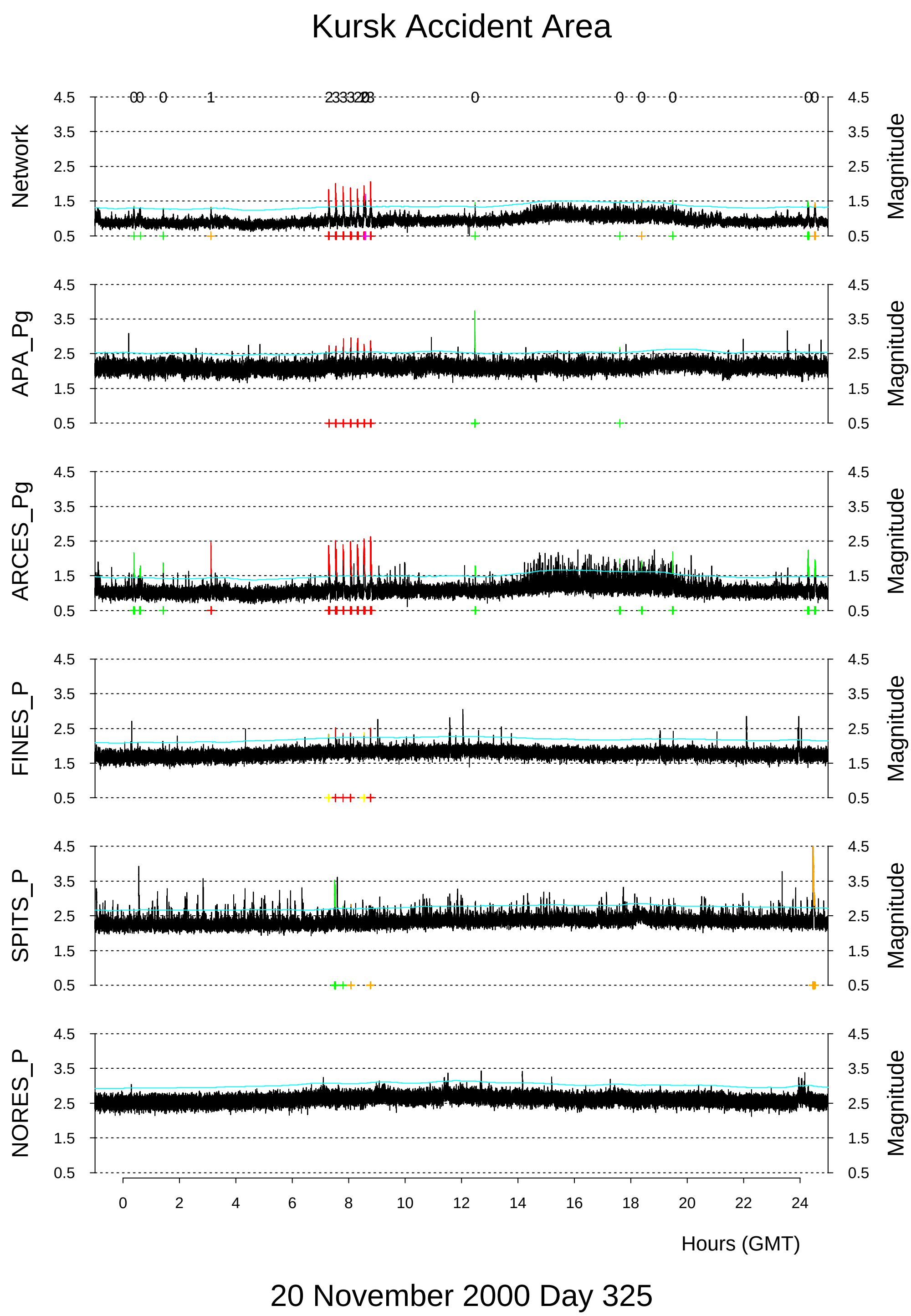

Fig. 6.2.1. *Site-specific Threshold Monitoring of the Kursk accident area for 20 November 2000 (day 325). The plot shows the 5 individual station thresholds (P-phases), with the combined threshold trace on top. Peaks which are likely to be caused by events near the Kursk accident area are shown in red.*

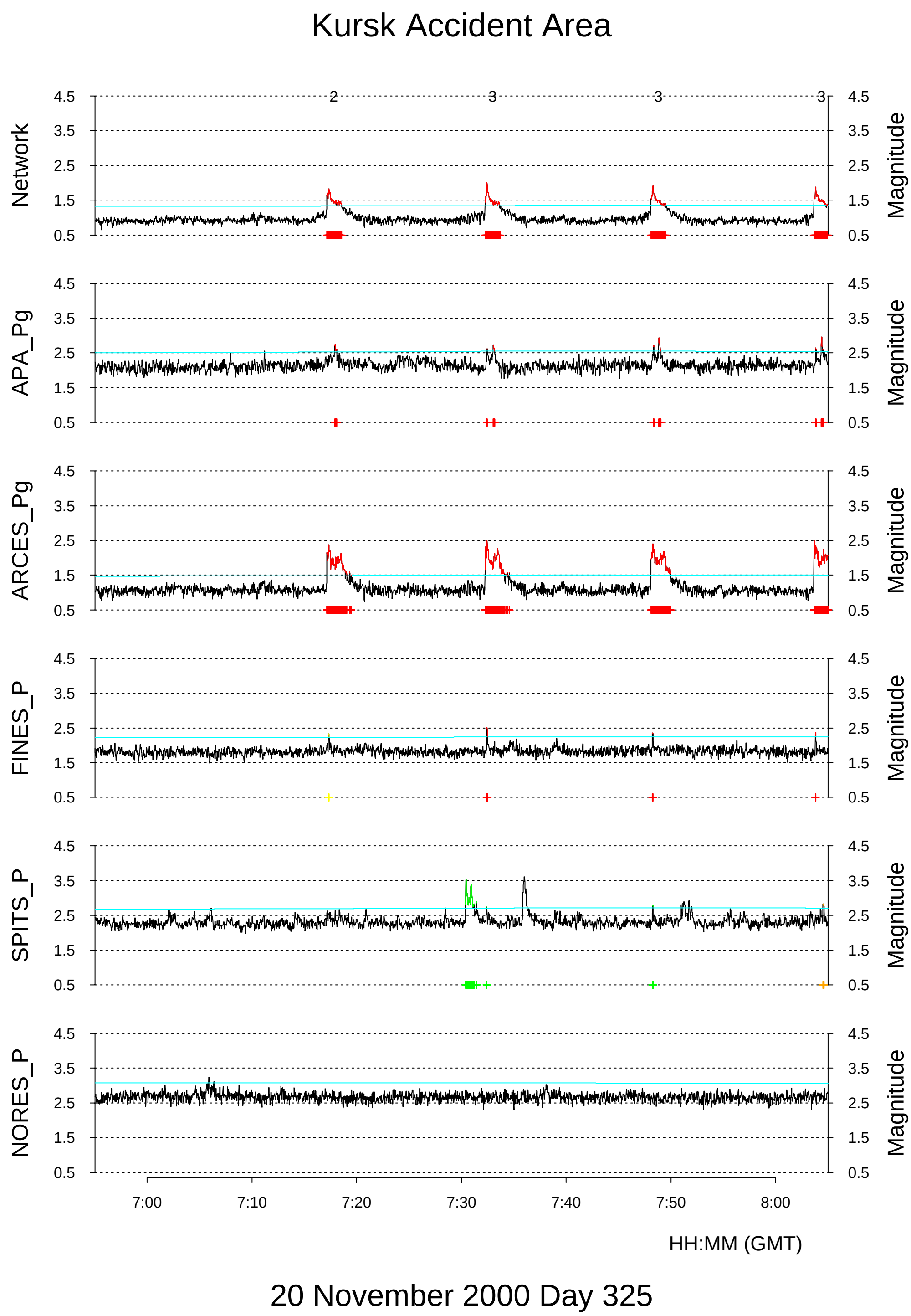

Fig. 6.2.2. *Same as Fig. 6.2.1, but covering only the one-hour interval 07.00-08.00 on day 325/2000. Note that the detailed plot for ARCES shows two peaks for each event. This corresponds to the P and S phases, and these two peaks are merged into one for each event on the network trace.*

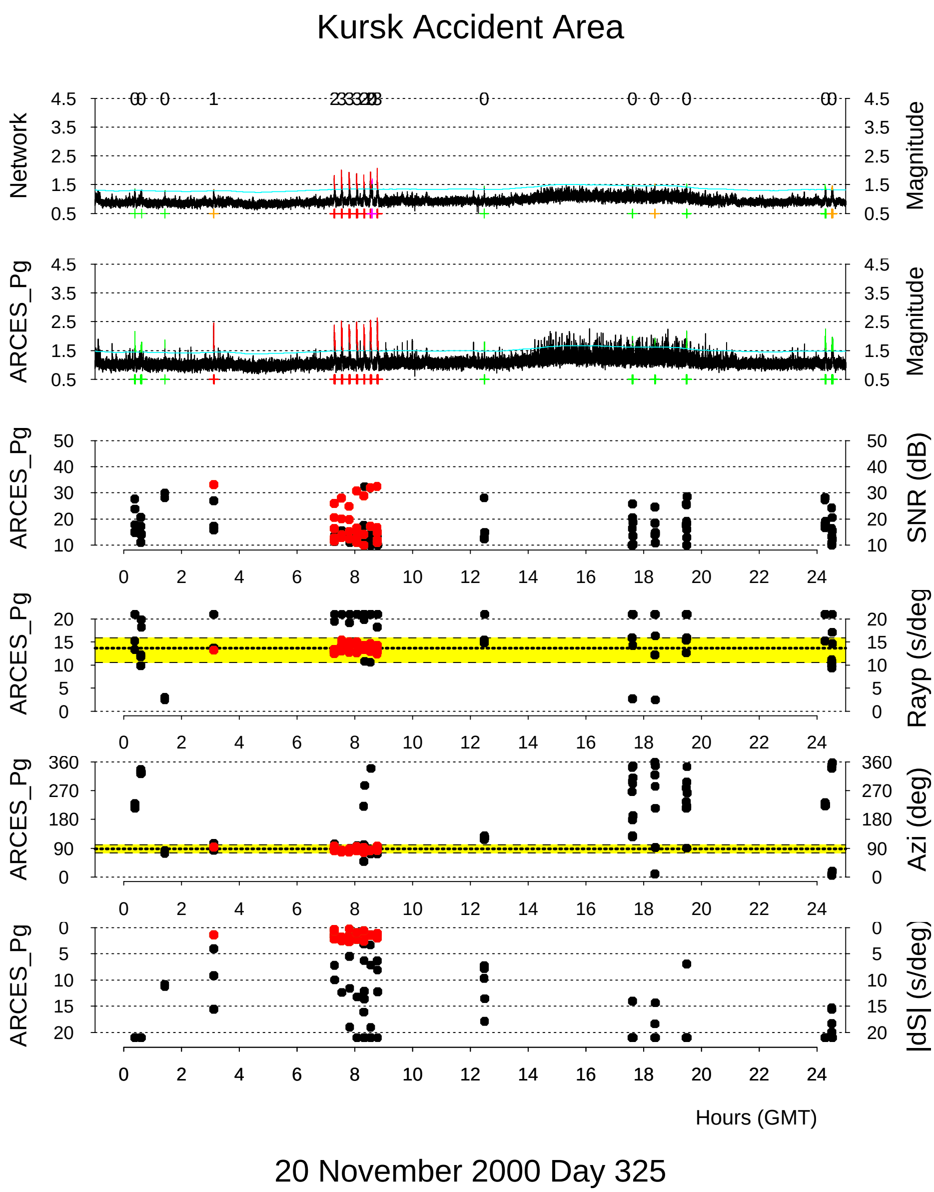

Fig. 6.2.3. *Site-specific Threshold Monitoring of the Kursk accident area for 20 November 2000 (day 325) with information from the signal detector at ARCES. The two upper panels show the threshold traces for the network and for the ARCES Pg-phase. Peaks which are likely to be caused by events near the Kursk accident area are shown in red.*
Information about the signal detections associated with the network threshold peaks is displayed in the four lower panels. The critical ranges of slowness (ray parameter) and azimuth are indicated in yellow in panels 4 and 5, and the bold dashed lines indicate the expected values of Pg-phases from the Kursk accident area.
The panel at the bottom indicates the differences in horizontal slowness estimates between the detected signals and the expected value for P-phases from the Kursk accident area (in s/deg). Signals satisfying both the azimuth and slowness criteria are shown in red.

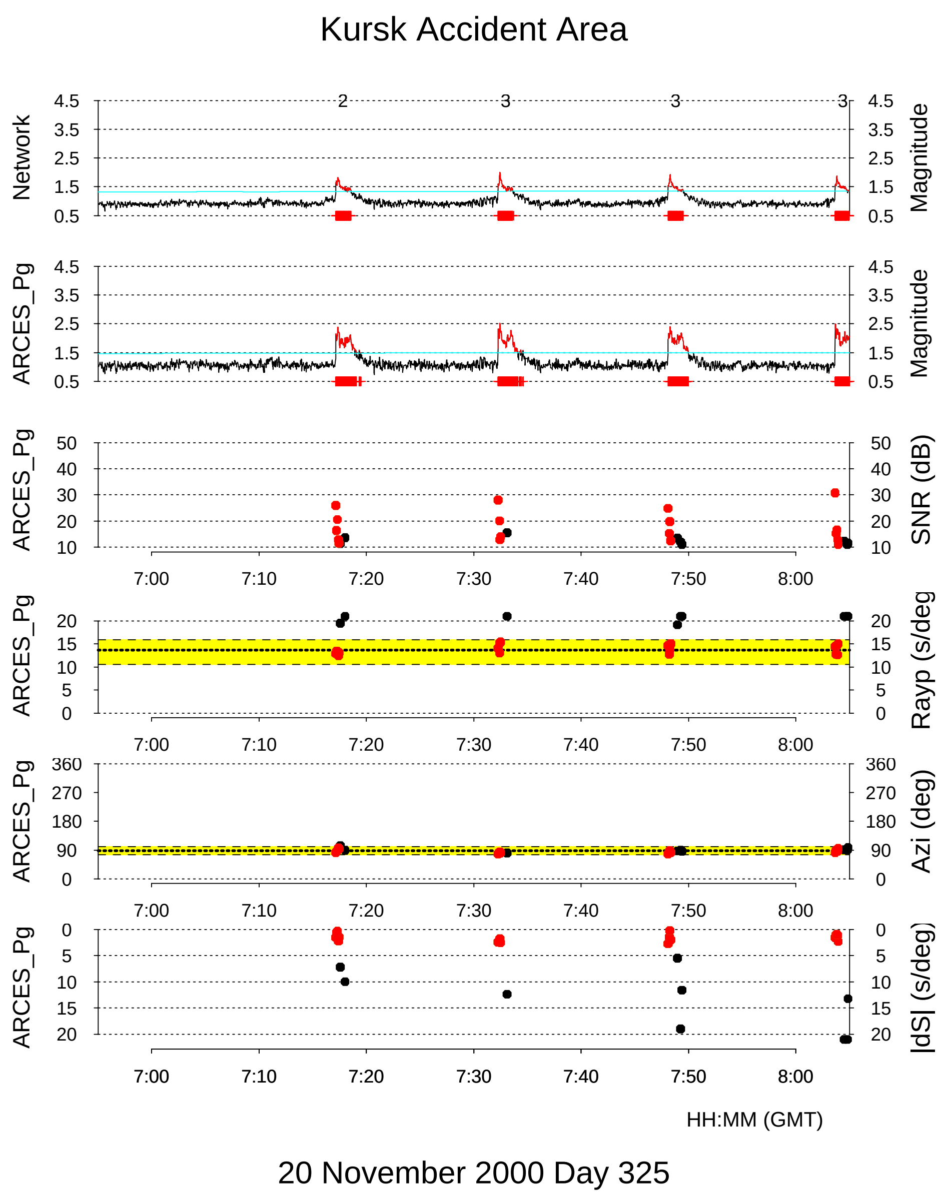

Fig. 6.2.4. *Same as Fig. 6.2.3, but covering only the one-hour interval 07.00-08.00 on day 325/2000. The red dots on the four lower panels correspond to Pg detections from events at the Kursk accident area, whereas the other (black) detections on these plots actually correspond to S-phases from the same events. Their azimuths are consistent with the Kursk accident area, while their slownesses are outside the critical area.*

6.3 S-Velocities in the crust and uppermost mantle of northern Fennoscandia deduced from dispersion analysis of Rayleigh waves

6.3.1 Introduction

The frequency dependence of phase and group velocity of surface waves can be used to invert for the S velocity in the uppermost layers of the Earth. The classical method for this inversion is the so-called two-station method in which the propagation speed of surface waves is measured between two stations along great circle paths. Measuring this velocity in different frequency bands directly results in a dispersion curve. This dispersion curve can then be inverted for a depth-dependent S-velocity structure between the two stations.

By means of the two-station method a dispersion analysis was carried out in northern Norway. The purpose for these measurements was to investigate the structure of crust and uppermost mantle in this region with special attention to the location of the Mohorovicic discontinuity (Moho). **Fig. 6.3.1** shows a map with the used network of seismic stations. Most of the stations belonged to the temporary network MASI-99, installed for about five month during summer 1999 in Finnmark in a joint project with the University of Potsdam, Germany. The MASI-99 sites were equipped with 13 mobile Lennartz MARSlite data logger and three-component LE-3D/5s seismometers (Schweitzer, 1999). In addition, we analyzed the recordings from a KS-36000 seismometer located at the center site of the ARCES array and from a CMG-3T seismometer installed at the IRIS-station KEV in northernmost Finland. For calibration reasons and to close an operational outage due to upgrade work at ARCES, one of the MASI-99 stations was temporarily co-located with the center site of the ARCES array.

6.3.2 Results with the two-station method

In this study the phase velocity was calculated from the cross-correlation between the vertical seismograms of one event recorded at two stations. Since Love-wave dispersion may have large uncertainties due to interference effects (Knopoff, 1971), we focused in this study on observation and interpretation of the fundamental-mode of Rayleigh waves. Nevertheless, comparison between the 1D-models for the S-wave velocity from the Love wave and the Rayleigh wave dispersion may give in the future interesting results with regard to possible S-velocity anisotropy.

In case of horizontally homogeneous velocities, the phase spectrum of the cross-correlogram does not depend on the epicentral distance of the actual source. Therefore, it is possible to average a number of phase-velocity curves for different events occurring at arbitrary epicentral distances but situated close to the great circle crossing the two stations (Dziewonski and Hales, 1972).

For this study, we selected 24 events with a minimum magnitude of $m_b = 5.5$ in an epicentral distance range from 10° to 120° (see **Table 6.3.1** and **Fig. 6.3.2**). Of all the data to analyze, the recordings from the 5-s seismometers of the MASI stations have the lowest resolution for long period signals. To get a homogeneous data set, the data from ARCES and KEV were converted to simulate a LE-3D/S response; all data were resampled for a common digitalization rate of 1 Hz.

For each event, the 105 possible direct lines between the 15 sites were tested if they follow the propagation direction of Rayleigh waves along a great circle from the source.

However, there were not enough data available to apply the two-station method for each of the 105 station combinations. This was mostly due to the relatively short installation period of the MASI-99 stations and due to the azimuthally uneven seismicity distribution. To solve this problem, also station combinations were analyzed where the direct connection line between the stations does not follow very closely the great circle path. In these cases a too high propagation velocity (*i.e.* an apparent velocity) will be measured. To correct for this effect, all observed phase velocities were multiplied by the cosine of the angle between the great circle direction of the surface propagation and the connection line between the two stations investigated. With this correction data could be analyzed of up to about 30° difference between wave-propagation direction and great circle path through the two stations.

Since this was on the one hand successful, there were on the other hand still too few events available for analyzing single station combination. Therefore, we combined several station combinations to four main directions as shown in **Fig. 6.3.1**, for which average phase velocity curves were calcluated. The inversions for the different directions N-S, E-W, and NE-SW lead to similar results for a Moho depth of about 40 km, only on the NW-SE profile we found indications for a slightly deeper Moho. However, these differences were close to the resolution limits of the inversion method, and we decided to invert all data together for a mean S-velocity model below Northern Fennoscandia. **Fig. 6.3.3** shows all 419 measured phase-velocity curves.

On top of **Fig. 6.3.4** the calculated mean dispersion curve of the 419 measured phase-velocity curves (red line) is shown together with its standard deviation (red dashed lines). This dispersion curve was inverted for an 1D S-velocity model. As shown in **Fig. 6.3.3** the mean dispersion curve is reliably determined in a frequency band between 25 and 100 mHz (*i.e.* in a period range between 10 and 40 s). According to Seidl and Müller (1977) the S-wave velocity has the greatest influence on the phase velocity of a Rayleigh wave c_R in a depth of $0.4 \cdot \lambda_R$ where λ_R is the wavelength of the Rayleigh wave. Assuming a mean phase velocity of about 4 km/s in the observed period range the corresponding resolvable depth range is about 15 to 60 km. The lower part of **Fig. 6.3.4** shows the two S-velocity models, the start model for the inversion (black line) and the model best explaining the observed phase velocities (in red) including an uncertainty range (blue). The resulting 1D-model for the S-wave velocities contains a clearly visible Conrad discontinuity. Moreover, the Moho is located slightly above 40 km depth, the sub-Moho S-wave velocity is between 4.6 and 4.7 km/s, and there is some indication for a low velocity channel in the lower lithosphere. As expected from the resolution estimation, the uncertainties become large below 90 km depth.

6.3.3 Comparison of the velocity model with other results

Since the single dispersion curves show a large scatter (see **Fig. 6.3.3**) the calculated mean dispersion curve have to be validated. Therefore, dispersion curves for Rayleigh waves were calculated with another method: the single stations for which the data were analyzed can also be seen as single sites of a large seismic array with a maximum aperture of about 330 km. Then array techniques can be used to measure the mean propagation velocity of the Rayleigh waves.

Eight events were selected (marked with stars in **Fig. 6.3.2** and in **Table 6.3.1**) and bandpass filtered into narrow frequency bands. For each frequency band the phase velocity was measured with the broadband f-k analysis. Whenever the corresponding backazimuth confirmed the theoretical source direction this observed phase velocity was assigned to the middle frequency of this frequency band. The such determined eight dispersion curves are shown in the upper part of **Fig. 6.3.5**. In the lower part of this figure, one can see that the mean dispersion curve estimated from all f-k results differs from that mean curve calculated from the two-station method but it still lies within the standard deviations. Some of the discrepancies may be explained by the inexact assignment of the f-k measured phase velocities to the frequency band. According to **Fig. 6.3.4** the results from the inversion of the f-k measured phase-velocity curve are shown in **Fig. 6.3.6**. The clearest difference between the two presented 1D-models for the S-wave velocity is the location of the Moho. Where the Moho lies above 40 km depth in the model calculated from the two-station method, the Moho is now deeper than 40 km.

As mentioned above, the MASI-1999 project was a cooperative experiment with the University of Potsdam, Germany. There colleagues deduced S-wave velocity models for crust and uppermost mantle by applying the receiver function method (Jens Höhne and Frank Krüger, private communication). **Fig. 6.3.7** shows on top one 1D-model for the S-velocities estimated with the receiver function analysis. This model also contains a pronounced Conrad discontinuity but in contrary to our results, the Moho now consists of a gradient zone between about 40 and 60 km depth. To check, if this model would also explain the observed phase velocities, the Rayleigh-wave dispersion curve was calculated for this model and plotted together with the above estimated mean dispersion curves (**Fig. 6.3.7**, bottom). The black lines show the mean dispersion curve from the two-station method and its standard deviations, the red line shows the dispersion curve from the f-k method, and the green line shows the dispersion curve calculated from the S-velocity model derived with the receiver-function method. The dispersion curve from the receiver-function method is nearly the same as that one from the f-k method and both lie within the standard deviation of the curve from the two-station method.

6.3.4 Discussion

*A*lthough the discussed models differ in several features, they are all in agreement with the observed Rayleigh-wave phase velocities. For all models a two-layer crust is common with a pronounced velocity jump at a Conrad discontinuity in about 15 km depth. The exact depth and structure of the Mohorovicic discontinuity is at the moment an open question because the resolution of the dispersion curves is not good enough to distinguish between a sharp discontinuity at about 40 km depth and a transition zone of about 20 km thickness between crust and uppermost mantle. The phase velocity curve for the receiver-function model in the frequency range between 25 and 60 mHz always lies at the lower bound of the observed dispersion curves. This might be an indication that the S-velocities are too low in the receiver-function model below a depth of about 30 km. A joint modelling of dispersion curves and receiver functions with their different model sensitivity would be needed to solve these discrepancies.

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Table 6.3.1. The table shows the event coordinates used for the two-station method. Events marked with a star were also chosen for the f-k method.

No.	Date	Time	Lat	Lon	Depth	mb	ms	
	year.doy	[hr.min.sec]	[°]	[°]	[km]			
1	1999.169	10.55.25.80	5.510	126.640	33.0	6.1	6.1	
2	1999.180	23.18.05.60	36.620	71.350	189.3	5.9	0.0	
3	1999.182	02.06.58.40	70.390	-15.150	10.0	4.9	5.6	*
4	1999.183	11.45.31.30	49.370	-129.200	10.0	5.4	5.7	
5	1999.184	01.43.54.00	47.080	-123.460	40.6	5.4	5.5	
6	1999.188	18.52.57.00	49.230	155.560	33.0	6.0	5.6	
7	1999.193	03.42.17.00	30.070	69.420	51.5	5.4	5.6	
8	1999.218	00.32.41.70	49.930	156.260	57.8	5.5	5.5	
9	1999.225	13.05.54.50	43.810	149.140	43.0	5.6	5.2	
10	1999.226	00.16.52.30	-5.890	104.710	101.4	6.0	5.7	
11	1999.229	00.01.39.10	40.750	29.860	17.0	6.3	7.8	*
12	1999.238	01.24.42.60	10.380	126.010	62.6	5.6	0.0	
13	1999.238	07.39.28.90	-3.520	145.660	33.0	5.6	6.2	
14	1999.238	21.38.11.90	19.120	121.150	33.0	5.5	5.2	
15	1999.241	00.46.13.50	3.100	65.860	10.0	5.8	5.6	
16	1999.250	11.56.49.40	38.120	23.600	10.0	5.6	5.8	*
17	1999.256	11.55.28.20	40.710	30.050	13.0	5.8	5.8	*
18	1999.258	03.01.24.30	-20.930	-67.280	218.0	6.0	0.0	
19	1999.263	09.32.42.70	46.330	153.460	33.0	5.6	5.1	
20	1999.263	17.47.18.50	23.770	120.980	33.0	6.5	7.7	*
21	1999.263	21.46.42.90	23.390	120.960	33.0	5.8	6.5	*
22	1999.265	00.14.39.20	23.730	121.170	26.0	6.2	6.4	*
23	1999.268	23.52.48.70	23.740	121.160	17.0	6.2	6.4	*
24	1999.271	05.00.43.00	54.590	168.260	33.0	5.4	6.1	

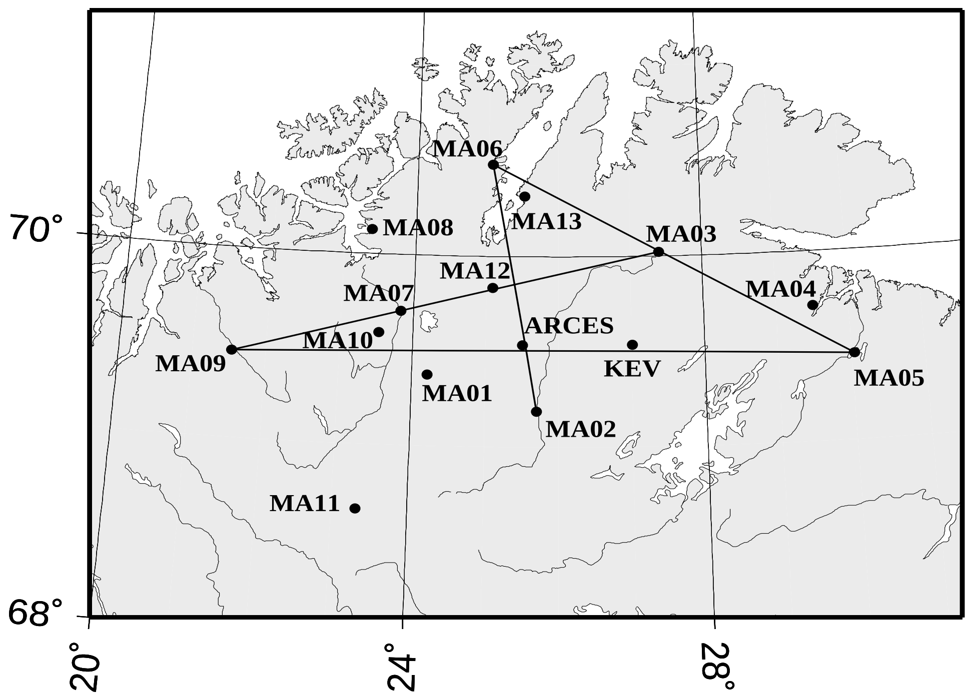


Fig. 6.3.1. Map of all seismic stations used in this study: the 13 stations of the temporary network MASI-1999 and the permanently installed ARCES array and IRIS-station KEV. The MASI-1999 station MA00 was temporarily co-located with ARCES array site ARA0. The four lines show the main profiles along which subsets of the data were interpreted.

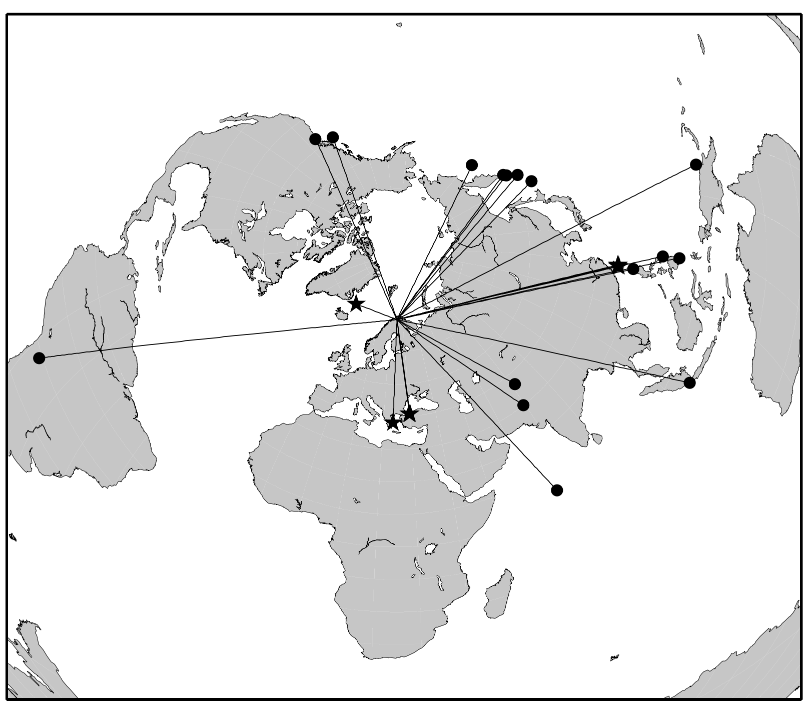


Fig. 6.3.2. A map showing the epicenters of all events used for this study. According to Table 6.3.1, data from events marked with a star were also analyzed with the f-k method.

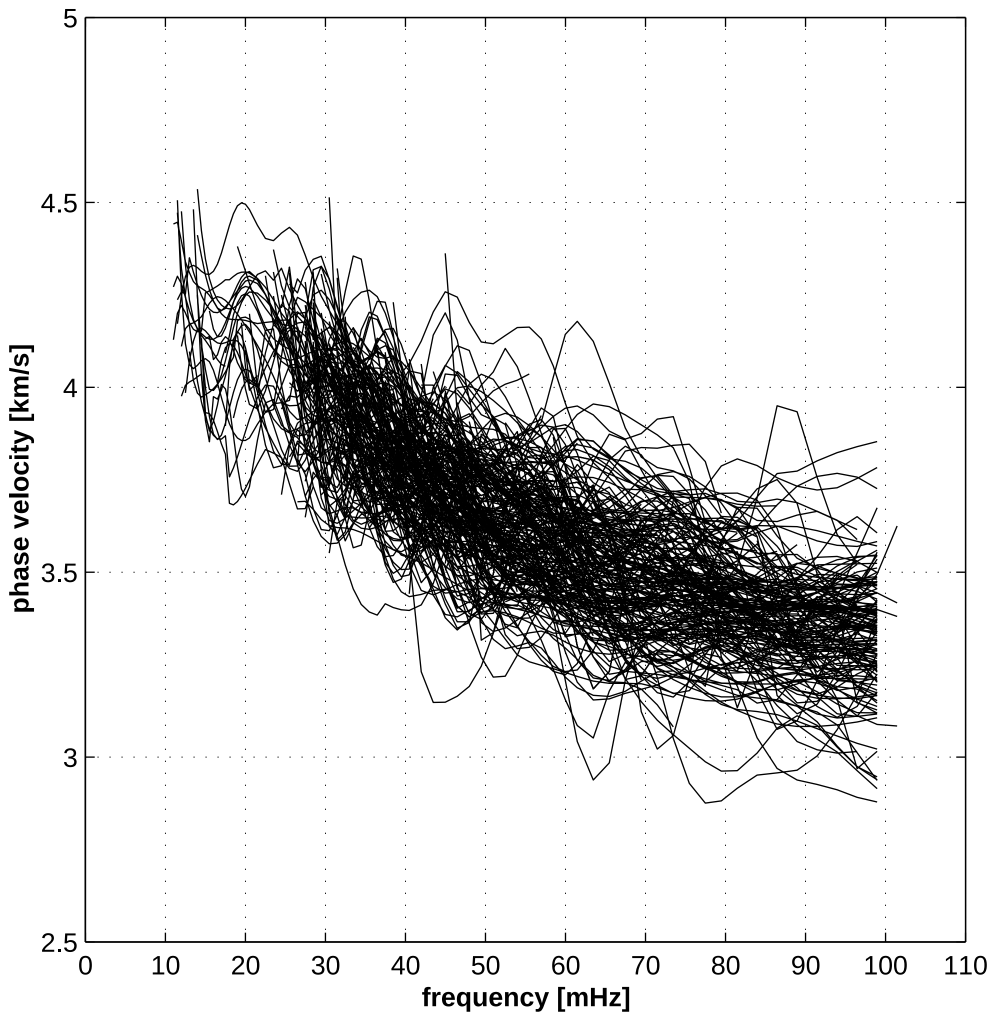


Fig. 6.3.3. All 419 dispersion curves of Rayleigh-wave phase velocities in Northern Fennoscandia determined in this study with the two-station method between. A sufficient amount of observations to invert for the S-velocity structure is available in the frequency range between 25 and 100 mHz (i.e. periods between 10 and 40 s).

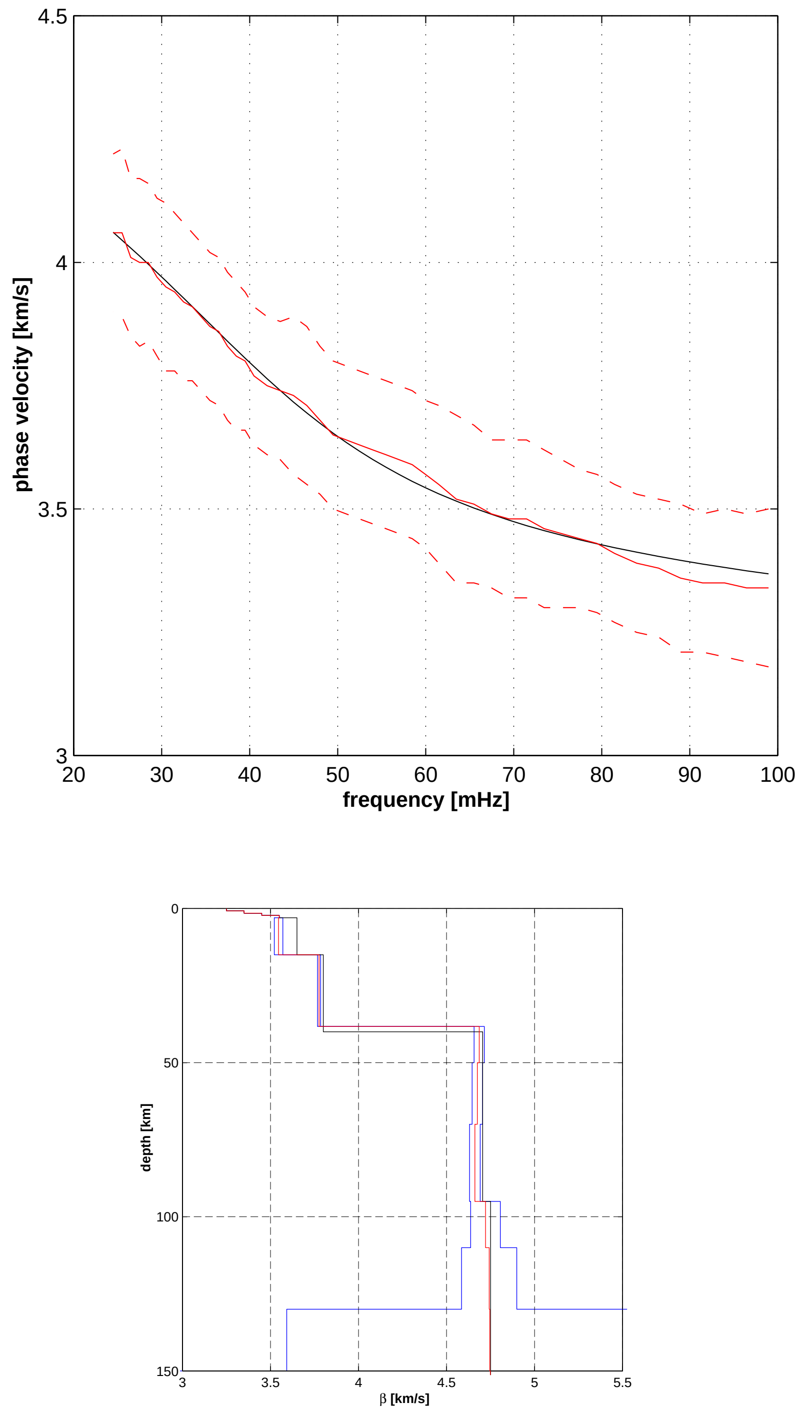


Fig. 6.3.4. On top one can see the resulting mean dispersion curve together with its standard deviations as a red line and red dashed lines, respectively. The additional black line is the fitted phase-velocity curve calculated from the resulting 1D-model for the S-wave velocity plotted at the bottom panel (red line). This also includes the reference model used for the inversion (black line) and the standard deviations (blue lines) for the calculated model.

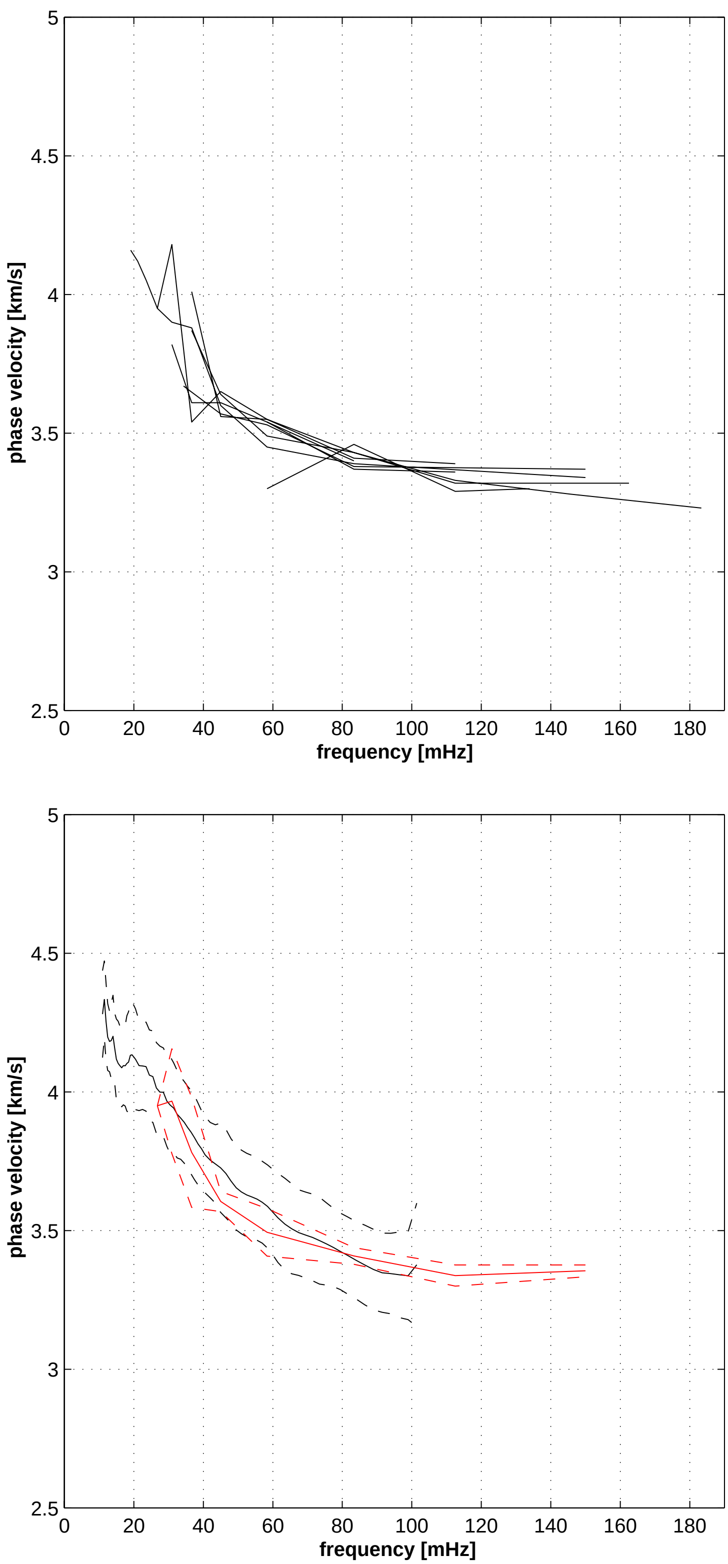
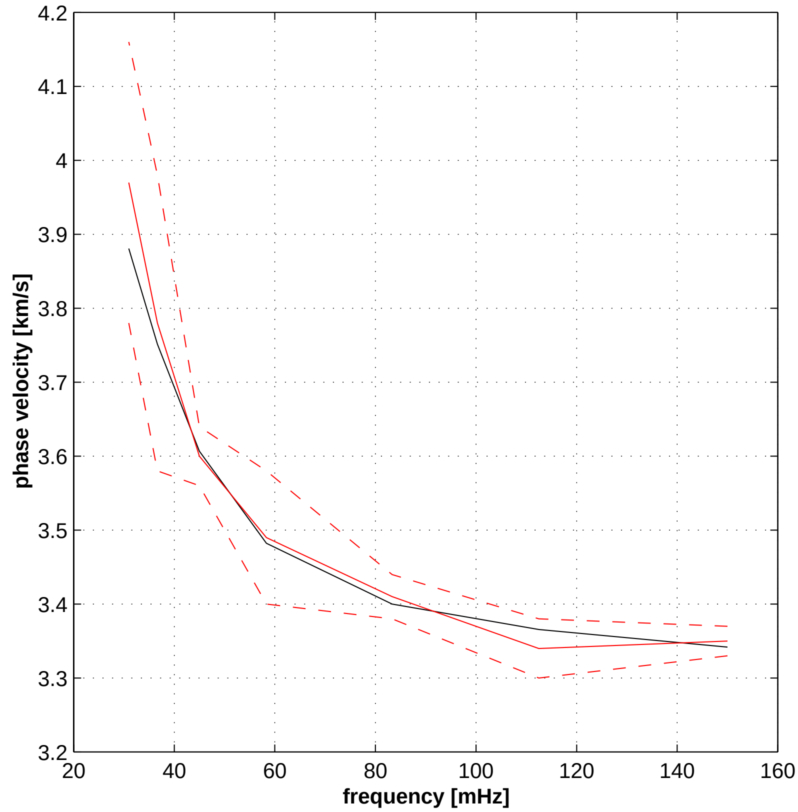


Fig. 6.3.5. The upper part of the figure shows the eight dispersion curves of Rayleigh-wave phase velocities measured by the f-k analysis. The lower part shows a comparison between the mean dispersion curves calculated from the two-station method (black) and from the f-k method (red).



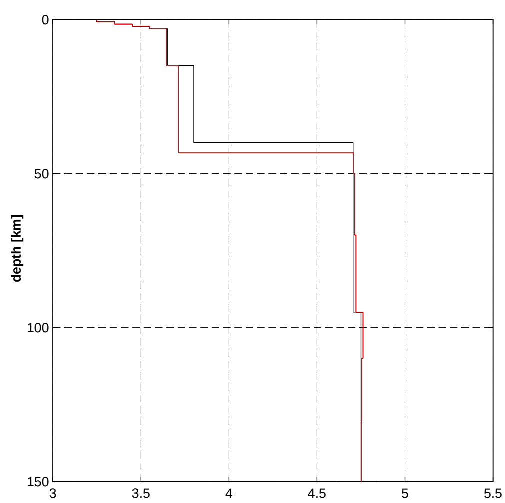
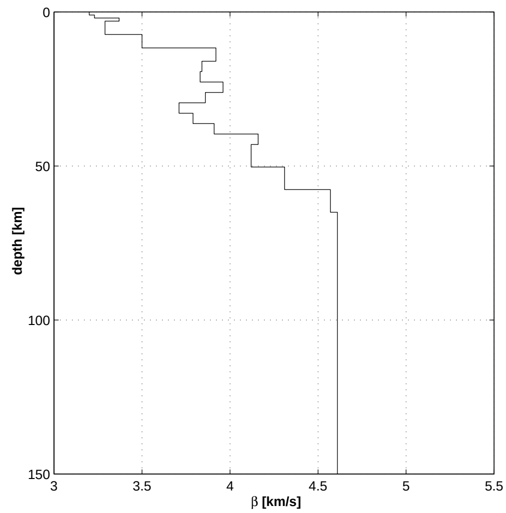


Fig. 6.3.6. The figure shows the results of the dispersion-curve inversion as in ***Fig. 6.3.4*** *but with the mean curve resulting from the f-k analysis used as input for the inversion. The main difference in the estimated model is the Moho depth, which is now below 40 km.*



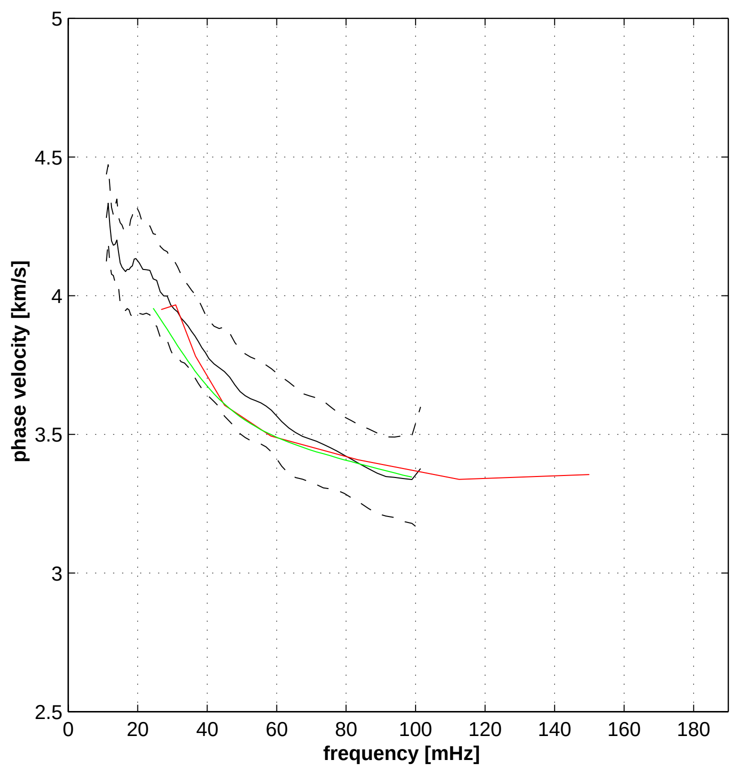


Fig. 6.3.7. The upper panel shows the 1D-model for the S-wave velocity from one of the receiver-function inversions. The lower panel shows a comparison of different dispersion curves: the mean dispersion curve from the two-station method and its standard deviations (black), the mean dispersion curve from the f-k method (red), and the dispersion curve calculated from the S-velocity model estimated from the receiver function.

6.4 Automatic reprocessing of events from the Khibiny Massif

6.4.1 Introduction

In the early 1990's NORSAR scientists developed and tested a procedure for two-step location of seismic events recorded by a regional network (see e.g. Kværna and Ringdal, 1994). At the time, this processing was applied experimentally to seismic events in the Khibiny Massif, Kola Peninsula. However, no attempt was made to use this method in a practical day-to-day monitoring situation, and also, it was not applied to any other regions.

We have recently made an effort to return to this location procedure, with the aim to apply it in a more general context and also to investigate options for practical routine implementation of the method. This paper gives a summary of the method as originally developed, and attempts to set up a possible system for automatic, routine processing that could be expandable to a more general case.

We first note that in order to obtain an accurate location of a seismic event by using a regional network, we need as precise as possible estimates of onset times, azimuths and slownesses, of the different seismic phases at each station or array.

In this study we first investigate the use of an onset-picker to be used for different seismic phases. The onset-picker is based on an autoregressive (AR) model to express the seismic signals, and Akaike's information criterion (AIC) for identifying arrival times for seismic waves, see GSE/JAPAN/40 (1992) for details. Further we will apply FK-analysis to derive more consistent azimuth and slowness values for the new onset time (see Kværna and Doornbos, 1986), and then we will do a relocalization of the event (see Schweitzer, 2001).

At NORSAR, a two-step procedure has been in use since 1985, to determine onset times for different seismic phases, see Mykkeltveit and Ringdal (1981) and Mykkeltveit and Bungum (1984) for details. A fully automated processing, from onset picking to localization, has since then been developed by Ringdal and Kværna (1989) and is now routinely applied to the seismic signals available at NORSAR. This Generalized Beamforming (GBF) system for processing of seismic events gives a daily bulletin with origin times, onset times, location and so on. We will refer to this daily bulletin as the GBF-list, see Kværna (1990, 1994) for details about the GBF system.

The GBF system provides us with initial signal processing information of the stations available at NORSAR, with phase association and localization of seismic events. To obtain more accurate locations, we have to improve the accuracy of the onset times, slowness and azimuth estimates. We also need to have a more correct phase identification, and a more accurate local velocity model for the different seismic phases. In addition, systematic biases in azimuth, slowness and traveltimes of the different seismic phases will be removed by introducing corrections for events in the actual region. For events in the Khibiny Massif, we would also like to include data from the Apatity three-component station (APZ9), which is currently not being used by the GBF system.

Region-specific application

We want to apply the approaches described in the previous paragraph to a specific area with recurring seismicity. From this area we will select a dataset with typical features for the seismicity, analyze it with respect to the methods, and then find characteristics which can be used later to monitor this specific area. In the monitoring, the region-specific methods will be activated when an event in the GBF-list is located close to this area. Then the special characteristics will be used to improve the onset times and the FK-analysis, and thus hopefully improve the relocalization.

The Khibiny Massif events

We will consider seismic events from the mining region in the Khibiny Massif in the Kola peninsula of northwestern Russia (See Kremenetskaya, 1992, Kremenetskaya and Trjapitsin, 1995). This is an alkaline intrusion occupying about 1300 square kilometers (36 by 45 km) and rising about 1000 meters higher than the surrounding plain of the Kola peninsula. Six large mines are operated by the Apatit Joint Stock Company in the Khibiny Massif to supply products to the superphosphate and aluminum industries. Through our contact with the Kola Regional Seismological Centre, we have been provided with the exact locations of 36 seismic events in this region. The 36 mining events are described in more detail in Kværna (1993), otherwise we refer to Mykkeltveit (1992) and Kværna and Ringdal (1994) for more background information.

From the GBF-list we have derived initial locations, onset times, phase associations, azimuth and slownesses for all the 36 events. In a time window around the initial onset time, we will use the onset-picker to find a new onset time. The time window is based upon the initial onset time from the GBF-list, and/or predicted travel times for seismic phases from the mining region. Thus we search for a new onset time in a small time window where we assume the different seismic phases will arrive. We can then avoid erroneous phase associations. Around this new onset time, we will make a new FK-analysis to derive better azimuth and slowness values.

From this processing of our 36 events, the "ground truth" data, we establish local corrections for the travel times of the different phases, and also for the slowness and the azimuth. Then we do a relocalization of the seismic events, and compare them to the known locations.

6.4.2 Processing flow

The processing steps involved in picking new onset times are given in Fig. 6.4.1.

For each day we will search through the GBF-list to find the events initially located in the relevant region (the mining area of the Khibiny Massif). From the GBF-list we derive initial onset times for the different phases, azimuth and slowness/velocity. The data processing is done with the EP program, see Fyen (1989), and the relocalization is made by Hyposat, see Schweitzer (2001). For each phase the general processing is:

For the Apatity and the ARCES arrays, the first step is to form a beam in accordance with the initial parameters from the GBF-list. For signals from the Apatity three-component station, we will rotate the seismic traces in accordance with the parameters from the GBF-list if we are searching for a S-phase, else we will only use the z-component trace.

In a next step we will define a bandpass filter for the processing. This filter is phase dependent, and is found from initial testing of different signals from the Khibiny Massif. Further we will define a SNR computational interval, and the search interval for the AR-AIC method. All these intervals are based on initial testing and viewing of the data.

The data are filtered in the bandpass filter band, and the SNR is calculated. If the SNR is lower than 30, we will decimate the sampling rate of the signal to obtain better performance of the AR-AIC method.

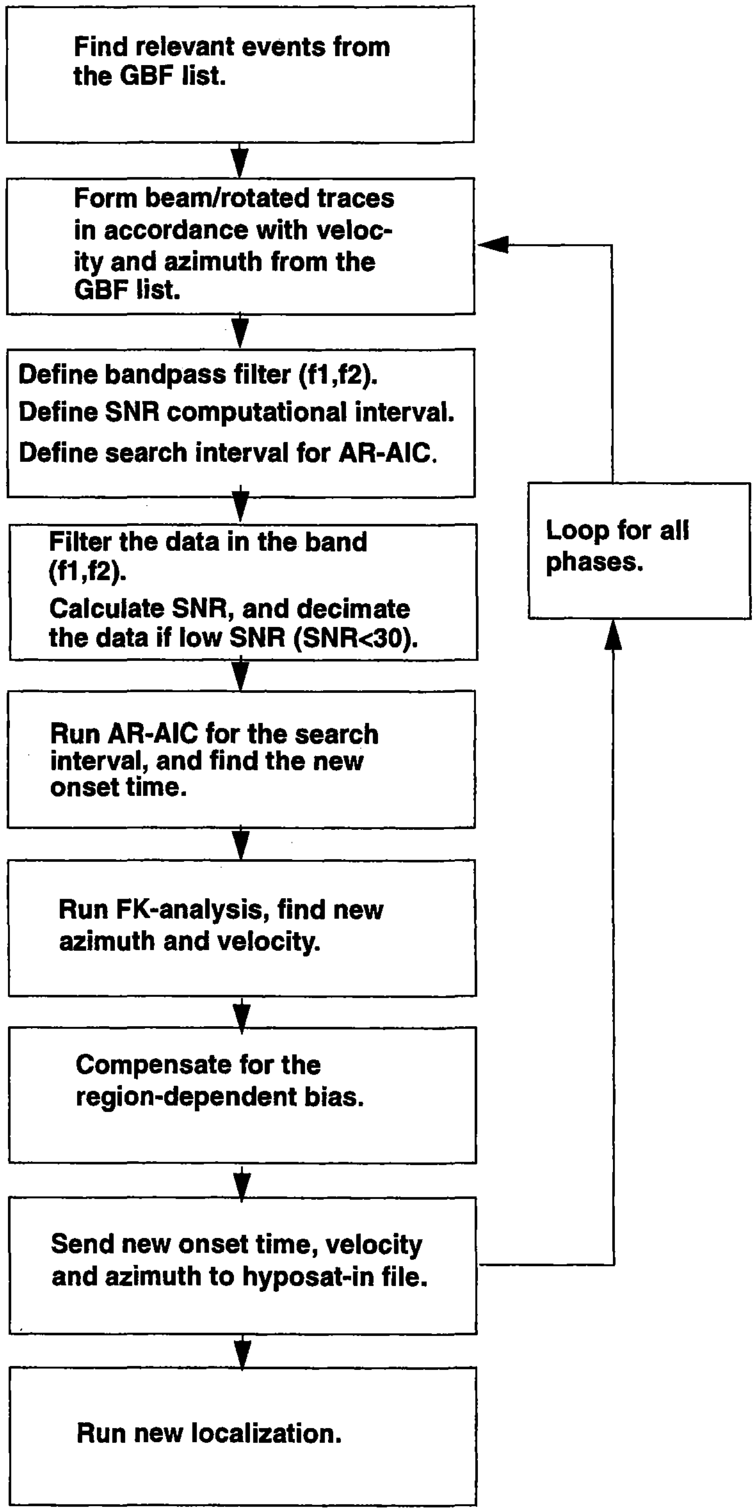


Fig. 6.4.1. Flowchart of steps involved in the automatic time picking algorithm.

The AR-AIC method is run in the search interval, with the onset from the GBF-list as an initial value. The new onset is picked.

Around the new onset, we run an FK-analysis, and new slowness/velocity and azimuth are derived.

A local model for corrections of traveltime, slowness and azimuth are introduced.

The new onset time, slowness and azimuth are sent to a Hyposat input file. When we have processed all phases for the three stations, the relocalization is made using Hyposat (Schweitzer, 2001), and the Hyposat output file gives the new localization, with an error ellipse.

6.4.3 Autoregressive model for determining onset times for seismic phases

In the processing we have used an autoregressive (AR) model for determining the different onset times of the different seismic phases. The method is described in GSE/JAPAN/40 (1992) and Yokota et al (1981), and thus we will not go into details about it in this text.

The seismic waves are described by an autoregressive (AR) model. Then Akaike's information criterion (AIC) is used to find the order and criterion for identifying onset times. The Akaike's information criterion is given by the equation:

AIC = - 2 (logarithmic likelihood) + 2 (number of parameters)

From the GBF-list we find an initial onset time for the different phases. Then the AR coefficients for both the noise and the seismic signal are derived from data in two different windows. The noise window is located in front of the initial onset, and the seismic signal window is located within the signal. We filter the data with two prediction error filters, and then the AIC criterion is derived from the filtered signal. The minimum of the AIC curve is taken to be the optimal division point between the noise and the seismic signal, and will thus be the new onset time for the seismic phase.

In the processing we have to decide the order of the autoregressive model (usually set to 8), the initial starting time (from the GBF-list), the length of looking back from the starting time (to find the AR-noise model), the length of window for deriving the AR-coefficients, and the total length of the AR-AIC window.

6.4.4 Derivation of processing recipes from the "ground truth" data

The "ground truth" data

The "ground truth" data come from underground explosions in six mines in the Khibiny Massif (the Apatity area on the Kola Peninsula of Russia). See Mykkeltveit (1992) for a detailed description of the mines and the mining activity. The center location of the mines are given in Table 6.4.1, and the locations can also be seen in Fig. 6.4.5 (the map). Mine no. I consists of both an underground part and an open-pit part.

Table 6.4.1. Center location of Khibiny mines

Mine	Latitude	Longitude
I, under-ground	67.670	33.728
I, open-pit	67.665	33.744
II	67.647	33.761
III	67.631	33.835
IV	67.624	33.896
V	67.632	34.011
VI	67.665	34.146

The exact sizes of these mines are not exactly known, but are assumed to be about 1 km^2. From a list of mining explosions, we have chosen 36 events with locations in the six mines, but where we do not know the exact origin time. The distance range from the mining region to the Apatity array (APA0), and the Apatity three-component station (APZ9), is from 18 to 49 km. The distance range to the ARCES array is about 400 km for all mines.

For each of the events we see clear Pg, Lg and Rg arrivals in the seismograms from both the Apatity array (APA0) and the Apatity three-component station (APZ9). For the ARCES array, we see clear Pn, Sn and Lg phases in the seismograms for all the mining events. Typical seismic signals from the Khibiny Massif at the different stations are given in Figs. 6.4.2 to 6.4.4.

The Khibiny Massif events

We have selected 36 events from the mining region in the Khibiny Massif. The initial locations of the events are found from the GBF-list, and are shown in Table 6.4.2, and seen in Fig. 6.4.5.

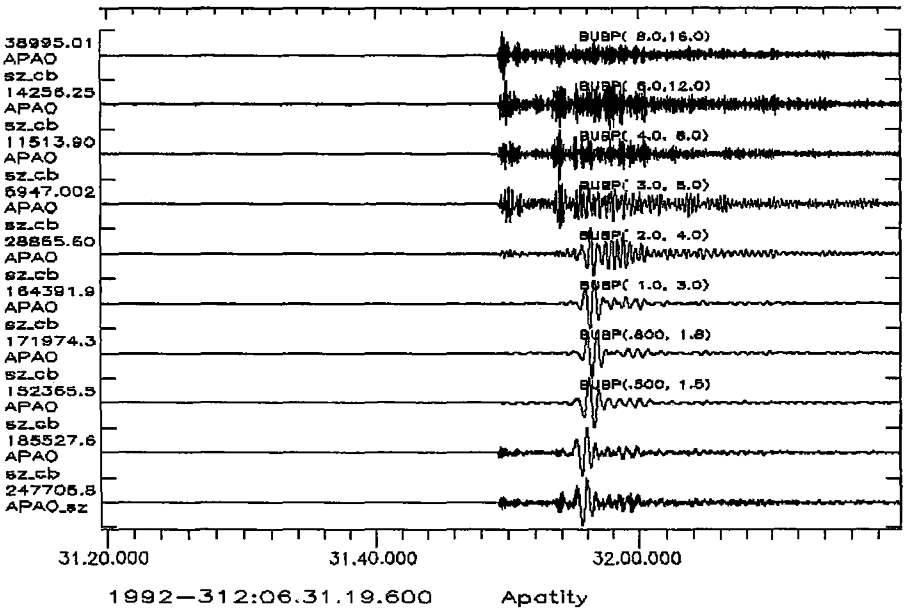


Fig. 6.4.2: The figure shows signals from the Apatity array. We have formed a P-beam in accordance with the parameters from the GBF-list for this event. The trace at the bottom is the unfiltered APA0_sz seismogram, and the one above is the unfiltered beam from all the z-component traces in the array. We have filtered the beam in different bandpass frequencies; 0.5-1.5, 0.8-1.8, 1.0-3.0, 2.0-4.0, 3.0-5.0, 4.0-8.0, 6.0-12.0, 8.0-16.0 Hz.

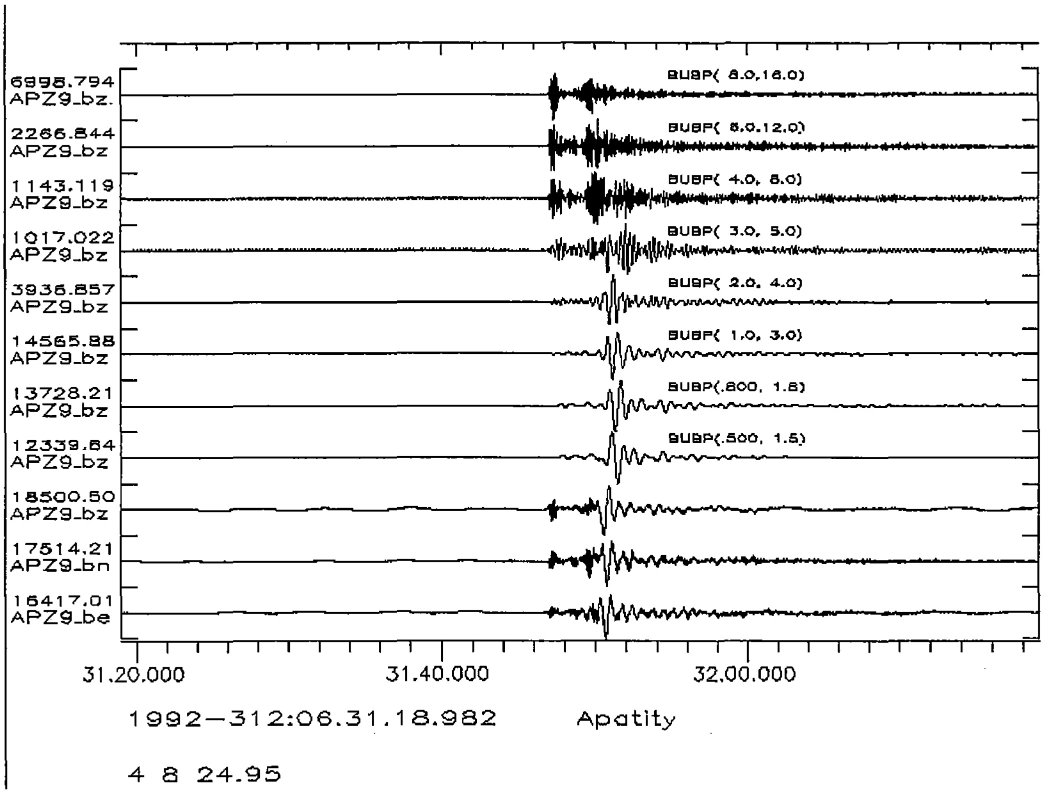


Fig. 6.4.3: The figure shows seimograms from the Apatity three-component station, APZ9. The three bottom traces show the unfiltered signal from the APZ9_bz, APZ9_be and APZ9_bn components. The remaining traces show the APZ9_bz seismogram filtered in the same set of frequency bands as in the previous figure (6.4.2).

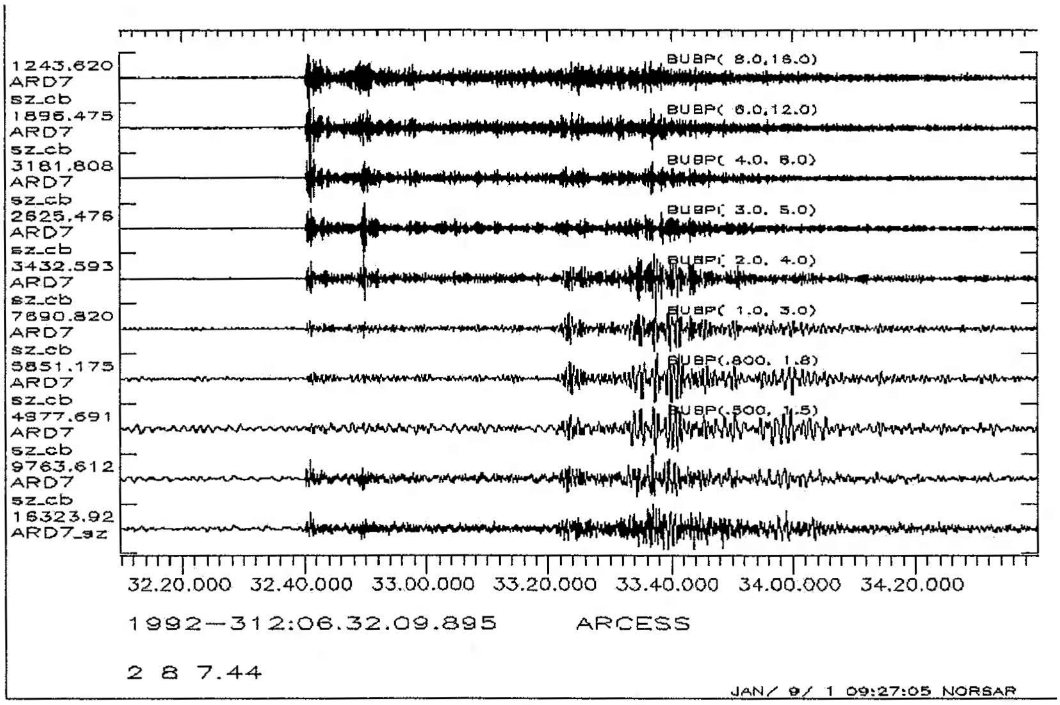


Fig. 6.4.4: The figure shows recordings at the ARCES array. The bottom trace is the unfiltered seismogram for the site ARD7_sz; the one above is the unfiltered P-beam from all the z-components in the array, and the remaining traces show the beam filtered with the same frequency bandpass filters as in the two preceding figures.

Table 6.4.2. GBF locations of the 36 mining events from the Khibiny Massif, with location errors (red) in kilometers.

Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6
Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)
67.75,34.44,31.4	67.60,34.26,21.8	67.35,34.67,47.5	67.45,34.70,39.4	67.45,34.70,35.7	67.75,33.91,13.8
67.75,34.70,42.1	67.75,34.70,41.4	67.60,34.26,18.4	67.45,33.92,19.4	67.75,34.44,22.4	67.45,34.97,42.5
67.75,34.44,31.4	67.75,34.70,41.4	67.45,34.70,42.0	67.45,34.70,39.4	67.45,34.70,35.7	67.75,34.70,25.3
67.45,34.70,39.0	67.45,34.70,45.6	67.45,35.75,84.1	67.75,34.70,36.9	67.60,34.26,11.2	67.75,34.70,25.3
67.60,33.47,13.7		67.75,34.70,39.0	67.45,34.44,30.2		67.45,34.70,33.7
67.75,33.91,11.8			67.45,33.92,19,4		67.75,34.44,15.6
67.75,34.70,41.6			67.55,35.52,69.6		
67.75,34.16,20.0			67.45,34.70,39.4		
67.75,34.70,41.6					

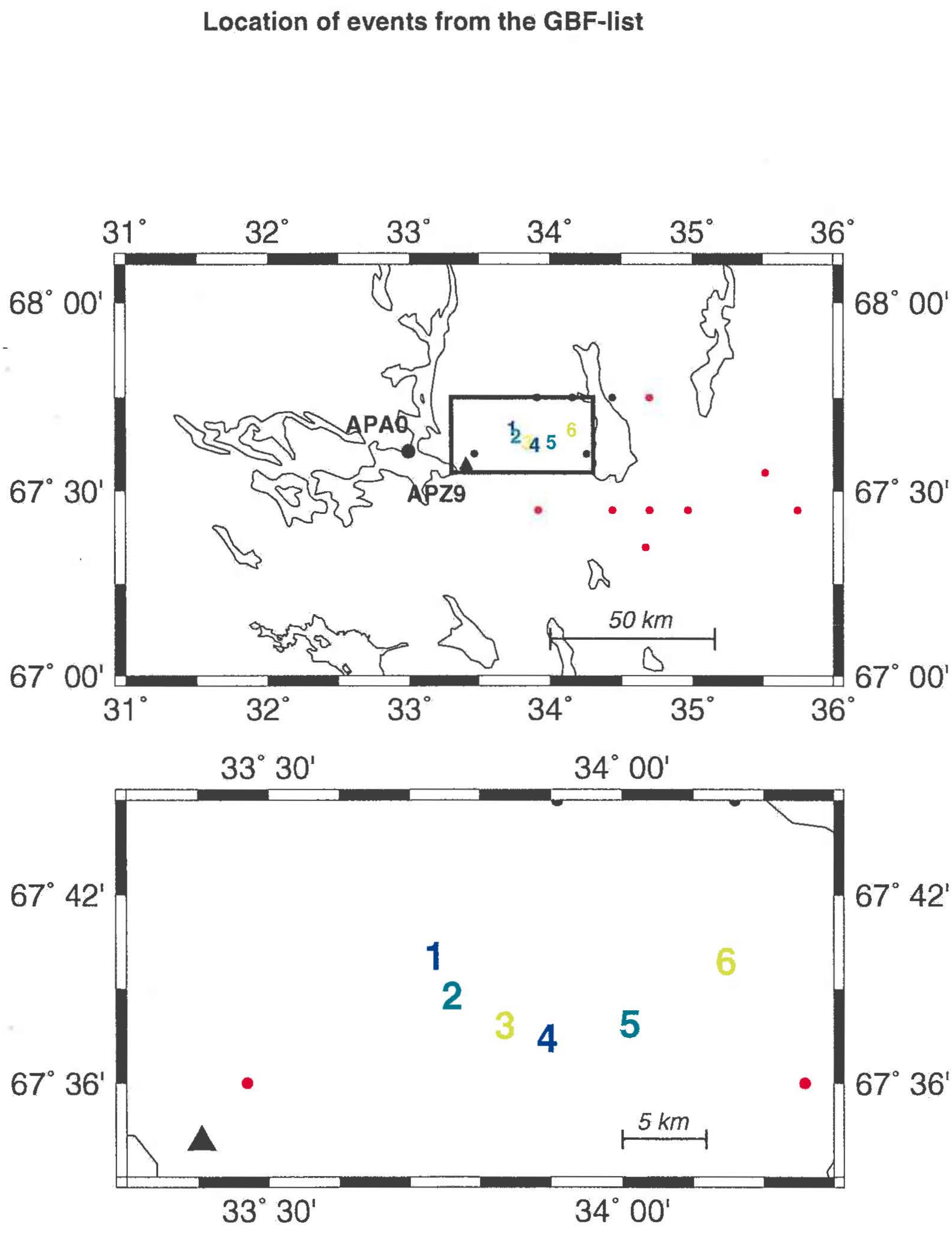


Fig. 6.4.5. Map showing the locations of the 36 events as given in the GBF list. The bottom part is an expanded view showing the locations closest to the 6 mines (numbered 1 to 6).

Determination of the onset time when GBF data are missing

As mentioned earlier in this contribution, the GBF system does not use data from the Apatity three-component station (APZ9) in the processing. Thus we have no initial onset, azimuth and slowness for the Pg and Lg phase from this station.

Since we need the initial data for the Apatity three-component station (APZ9) in the processing, we will have to establish a model for finding estimates for the data. First we have calculated the azimuth from the center point of the mining area to the three-component station. Then we have subtracted this azimuth from the backazimuth for the Apatity array (APA0) found earlier in the processing. This difference is called "azimuth_difference" in the following equations. The distance between the Apatity three-component station and the Apatity array was calculated, and the velocity for Pg and Lg phases in the Apatity area was derived from a local traveltime model. Thus we could find the approximate time difference for signals reaching the three-component station and the array, both for Pg and Lg phases. The time difference for a Pg phase is thus given by:

time_difference_Pg = distance_between_stations*cos(azimuth_difference)/velocity_Pg

and the time difference for a Lg phase is given by:

time_difference_Lg = distance_between_stations*sin(azimuth_difference)/velocity_Lg

To find the initial Pg onset time, we now subtracted time_difference_Pg from the new Pg onset time found from the Apatity array (APA0) processing. The initial Lg onset time was found in the same way. In this way we had established initial onset times to be used later in the processing, for the relevant phases at the Apatity three-component station (APZ9).

Determination of origin time for the reference events

Since we did not know the origin times of the reference events, we had to establish a model to find them. For each of the 36 events, we used the new Pg onset time for the Apatity three-component station, APZ9. This is the station closest to the mining area, thus the seismic waves will have the shortest path to travel. We assume that the influence of an erroneous traveltime model is less for this station and this phase than for other phases and stations. From this onset time and the distance from the station to each mine, the origin time for each event could be found using a local traveltime model. This origin time was later used to find local corrections for traveltimes, azimuth and velocity.

6.4.5 Processing details for the different stations

We have derived a set of parameters for each station we use in our processing (the Apatity array (APA0), the Apatity three-component station (APZ9), and the ARCES array). As outlined earlier in this text, these parameters are derived from initial testing and viewing of the data.

In the next (sub)paragraphs we will outline the parameters for each station and phase. The following descriptions is a general outline of the use of each parameter:

- The trace(s) used in the processing: For the Apatity array and the ARCES array, the traces used are the P- or the S-beam of the z-component channels in the arrays. For the Apatity three-component station, when processing the P phase, we use the z-component, and when processing the S phase, we use the rotated, transverse component.
- The initial azimuth and slowness is read from the GBF-list, predicted from a local traveltime model, or is derived from a FK-analysis of other (earlier) phases.
- The initial onset time is read from the GBF list, or predicted from local traveltime models based on the GBF locations.
- The time window to search for the maximum SNR is defined around the initial onset from the GBF-list or derived from local traveltime models.
- A (Butterworth) bandpass filter is applied to filter the seismic traces prior to running the AR-AIC method. The bandpass filter is usually fixed for all events.
- The parameters for the AR-model are: time window for calculations of the AR-coefficients, the time length to look back from initial time point, and the total length of the AR-window.
- The parameters for the FK-analysis are: time window around the initial onset, maximum slowness, and the chosen frequency range.

Processing details for the Apatity array, Pg phase

- SNR time window: +/- 3.0 seconds around the initial onset.
- Bandpass filter: 4 - 8 Hz.
- AR-coefficients' time window: 4.0 seconds. The time length to look back: 7.0 seconds. Total length of the AR-window: 10.0 seconds.
- FK time window: 0.3 seconds before, and 2.0 seconds after the new Pg onset. Maximum slowness: 0.4.

Processing details for the Apatity array, Lg phase

- SNR time window: From + 2.0 seconds after the new Pg onset to + 5.0 seconds from the initial Lg onset time.
- Bandpass filter: 2 - 8 Hz.
- AR-coefficients' time window: 3.0 seconds. The time length to look back: the time difference between the initial Lg onset, and the new Pg onset, minus 0.5 seconds. Total length of the AR-window: the time difference between the initial Lg onset, and the new Pg onset, plus 3.0 seconds

- FK time window: 0.4 seconds before, and 3.0 seconds after the new Lg onset. Maximum slowness: 0.4.

Processing details for the Apatity array, Rg phase

- The peak of the Rg phase was identified from the STA envelope created from z-component data. Bandpass filter: 0.8 - 2.0 Hz.
- The start of the STA envelope was set 1.0 second after the new Pg onset time, and the length was set to 19.0 seconds.
- FK time window: 1.5 seconds before, and 1.5 seconds after the peak of the Rg phase. Maximum slowness: 0.6.

Processing details for the Apatity array 3-component reference site (APA0), Lg phase

- SNR time window: + 2.0 seconds after the new Pg onset, to + 5.0 seconds from the initial Lg onset time.
- Bandpass filter: 2 - 8 Hz.
- APA0_hn and APA0_he were rotated with the azimuth found from the FK-analysis of Pg from the Apatity array.
- AR-coefficients' time window: 3.0 seconds. The time length to look back: the time difference between the initial Lg onset, and the new Pg onset, minus 0.5 seconds. Total length of the AR-window: the time difference between the initial Lg onset, and the new Pg onset, plus 4.0 seconds
- FK time window: 0.5 seconds before, and 3.0 seconds after the new Lg onset. Maximum slowness: 0.2, and alpha was set to 6.0, beta was set to 3.46.

The Lg data from the processing of the Apatity array 3-component central station, APA0, were not used in the relocalization. It is included here because it might be interesting to see if onset, azimuth and slowness from this station are more consistent than the results from Lg-phase processing using the full Apatity array.

Processing details for the Apatity 3-component station APZ9, Pg phase

- SNR time window: +/- 3.0 seconds around the initial onset.
- Bandpass filter: 4 - 8 Hz.
- For the processing we used the APZ9_bz component, no rotation of the trace.
- AR-coefficients' time window: 1.5 seconds. The time length to look back: 7.0 seconds. Total length of the AR-window: 10.0 seconds.
- FK time window: 0.5 seconds before, and 2.0 seconds after the new Pg onset. Maximum slowness: 0.2, and alpha was set to 6.0, beta was set to 3.46.

Processing details for the Apatity 3-component station APZ9, Lg phase

- SNR time window: + 2.0 seconds after the new Pg onset, to + 5.0 seconds from the initial Lg onset time.

- Bandpass filter: 2 - 8 Hz.
- APZ9_bn and APZ9_be were rotated with the azimuth found from the FK-analysis of Pg from APZ9_bz.
- AR-coefficients' time window: 1.5 seconds. The time length to look back: the time difference between the initial Lg onset, and the new Pg onset. Total length of the AR-window: the time difference between the initial Lg onset, and the new Pg onset, plus 5.0 seconds
- FK time window: 0.5 seconds before, and 3.0 seconds after the new Lg onset. Maximum slowness: 0.2, and alpha was set to 6.0, beta was set to 3.46.

Processing details for the ARCES array, Pn phase

- SNR time window: +/- 3.0 seconds from the initial onset.
- Bandpass filter: 4 - 8 Hz.
- AR-coefficients' time window: 4.0 seconds. The time length to look back: 7.0 seconds. Total length of the AR-window: 10.0 seconds.
- FK time window: 0.3 seconds before, and 2.0 seconds after the new Pn onset. Maximum slowness: 0.4.

Processing details for the ARCES array, Sn phase

- SNR time window: + 2.0 seconds after the new Pn onset, to + 5.0 seconds from the initial Sn onset time.
- Bandpass filter: 3 - 5 Hz.
- AR-coefficients' time window: 4.0 seconds. The time length to look back: 6.0 seconds. Total length of the AR-window: 12.0 seconds.
- FK time window: 0.4 seconds before, and 3.0 seconds after the new Sn onset. Maximum slowness: 0.4.

Processing details for the ARCES array, Lg phase

- SNR time window: + 2.0 seconds after the new Sn onset, to + 5.0 seconds from the initial Lg onset time.
- Bandpass filter: 2 - 4 Hz.
- AR-coefficients' time window: 5.0 seconds. The time length to look back: the time difference between the initial Lg onset, and the new Sn onset, minus 3.0 seconds. Total length of the AR-window: 20.0 seconds.
- FK time window: 0.4 seconds before, and 3.0 seconds after the new Lg onset. Maximum slowness: 0.4.

6.4.6 Processing results

Corrections for azimuth and traveltimes

Since we know the locations of the mining events, we could calculate the correct azimuth from the events to the different stations. The mean value and standard deviation of the azimuth residuals were found from taking the mean residual for each mine, and then taking the mean value of all the mines. The mean value and standard deviation of the slowness/velocity were found in a similar way. As the "correct" slowness, we used the value from a local slowness model for the different phases.

The exact origin time for each event was unknown, thus we had to find a way to estimate the origin time. We used the new Pg onset from the Apatity three-component station, APZ9, as an initial value. Then the origin time was derived from a local traveltime model for Pg phases. Since APZ9 is the closest station to the mining events from the Khibiny Massif, we would expect least deviations from the correct Pg onset time for this station. This origin time was then used to derive the mean value and standard deviation of the traveltimes for the phases at the different stations. The mean value and standard deviation for Pg traveltimes for APZ9, were set to the values for the Apatity array, APA0.

The derived corrections for azimuth, slowness and traveltime are given in Tables 6.4.3 to 6.4.5..

Table 6.4.3. Mean value and standard deviation of azimuth residuals.

	Mean (^{0})	std (^{0})
Pg - Apatity array	10.16	3.35
Lg - Apatity array	7.38	4.09
Rg - Apatity array	-1.55	2.34
Pn - ARCES array	4.89	0.52
Sn - ARCES array	3.20	4.43
Lg - ARCES array	-2.9	5.67
Pg - APZ9	6.91	15.09

Table 6.4.4. Mean value and standard deviation of velocity residuals.

	mean (km/s)	std (km/s)
Pg - Apatity array	1.02	0.12
Lg - Apatity array	0.36	0.43
Pn - ARCES array	-0.61	0.06
Sn - ARCES array	-0.47	0.33
Lg - ARCES array	-0.06	0.16
Pg - APZ9	3.75	2.86

Table 6.4.5. Traveltime corrections, mean value and standard deviation.

	mean (s)	std (s)
Pg - Apatity array	-0.13	0.15 (fixed)
Lg - Apatity array	-0.18	1.0 (fixed)
Pn - ARCES array	0.14	0.1 (fixed)
Sn - ARCES array	0.83	0.5 (fixed)
Lg - ARCES array	-2.11	1.0 (fixed)
Pg - APZ9	0.0 (fixed)	0.15 (fixed)
Lg - APZ9	0.22	0.4 (fixed)

Onset time results

From Figs. 6.4.6 to 6.4.8 we can see the results of the automatic processing for the Apatity array, the Apatity three-component station and the ARCES array. In all figures (except Fig. 6.4.6, the line from trace 8: which is the maximum of the STA-envelope) the vertical lines give the minimum of the AR-AIC curve, and thus the new onset time.

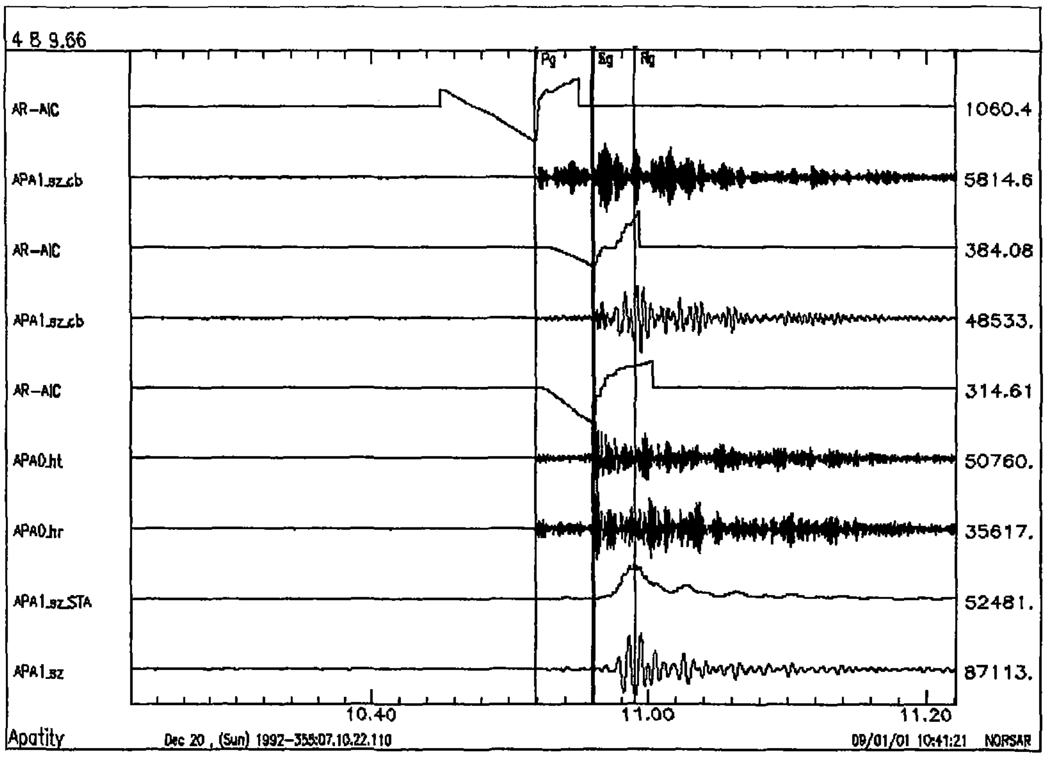


Fig. 6.4.6: Signals from APA0. The 2nd trace from the top is the P-beam filtered in the 4-8 Hz band, with the AR-AIC curve above. The 4th trace is the S-beam filtered in the band 2-8 Hz. The 6th and 7th traces are the rotated, transverse and radial traces from the APA0 three-component seismometer. The 9th trace is the Rg-beam filtered in the band 0.8-2 Hz, with the STA-envelope above it.

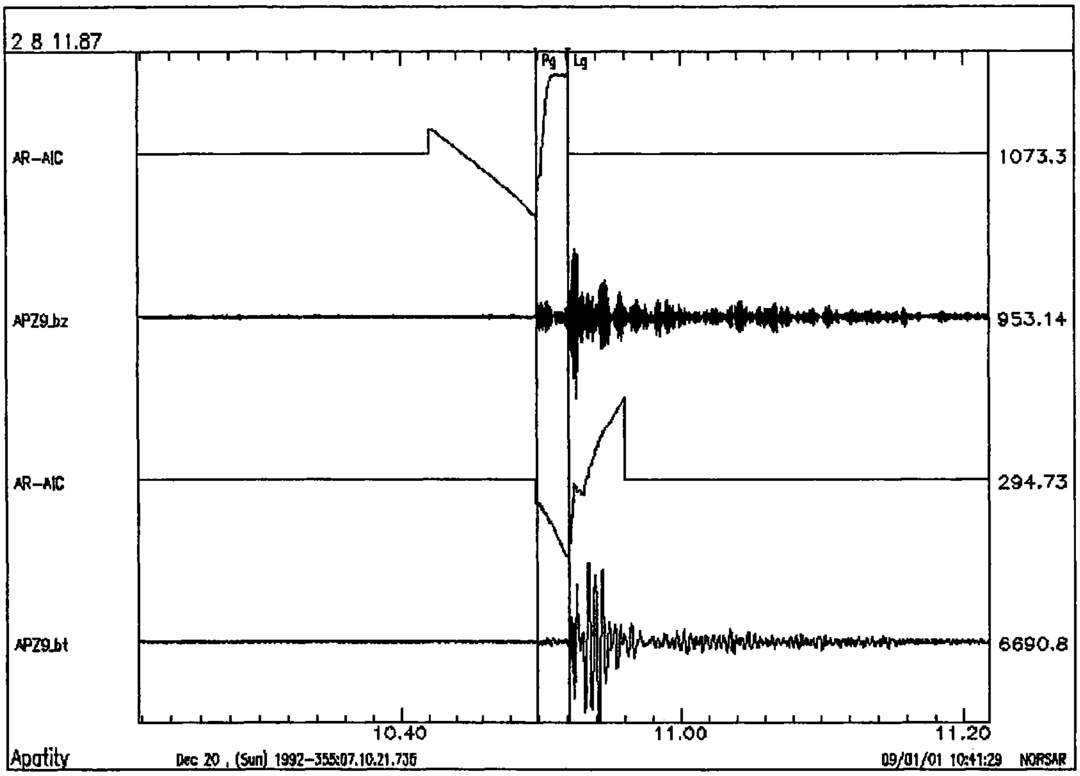


Fig. 6.4.7: Signals from APZ9. The 2nd trace from the top is the vertical trace filtered in the band 4 -8 Hz, with the AR-AIC curve above it. The 4th trace is the rotated, transverse trace filtered in the band 2-8 Hz, with the AR-AIC curve above.

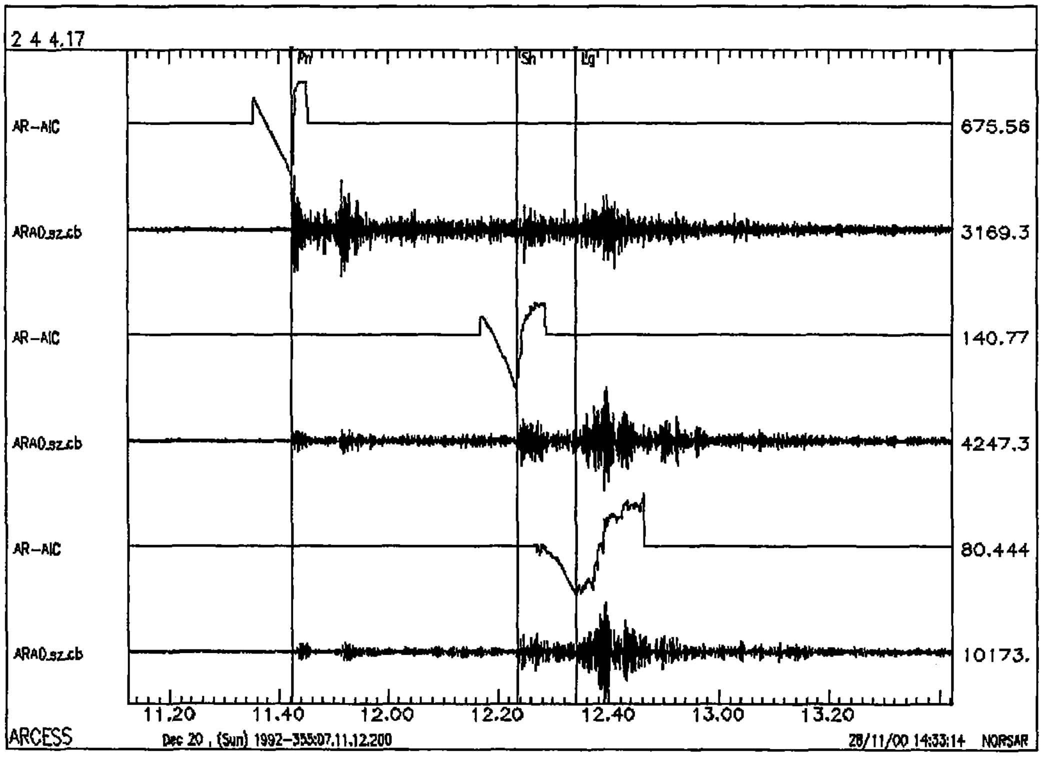


Fig. 6.4.8: Signals from ARCES. The 2nd trace from the top is the P-beam filtered in the band 4-8 Hz, with the AR-AIC curve above it. The 4th trace is the S-beam filtered in the band 3-5 Hz, with the AR-AIC curve above. The 6th trace is S(Lg)-beam filtered in the band 2-4 Hz, with the AR-AIC curve above.

Relocation results of mining events in the Khibiny Massif

After processing of the 36 events from the Khibiny Massif mining area, we have new and improved locations. The new locations are given in Table 6.4.6, and are also seen in Fig. 6.4.9. Compared to Fig. 6.4.5 and Table 6.4.2, the improvement is obvious.

6.4.7 Conclusions

The work so far has been focused on recreating the processing environment used for the original post-processing studies, and adapting this environment to a semi-automatic processing scheme to be applied on a routine basis. As shown in this paper, this has been successfully achieved.

The next step will be to apply the method to other nearby mines, e.g. Kovdor, Zapolyarnyi and Olenegorsk, which are also on the Kola Peninsula, and where our contacts at the Kola Regional Seismological Centre will be in a position to provide us with appropriate ground truth data.

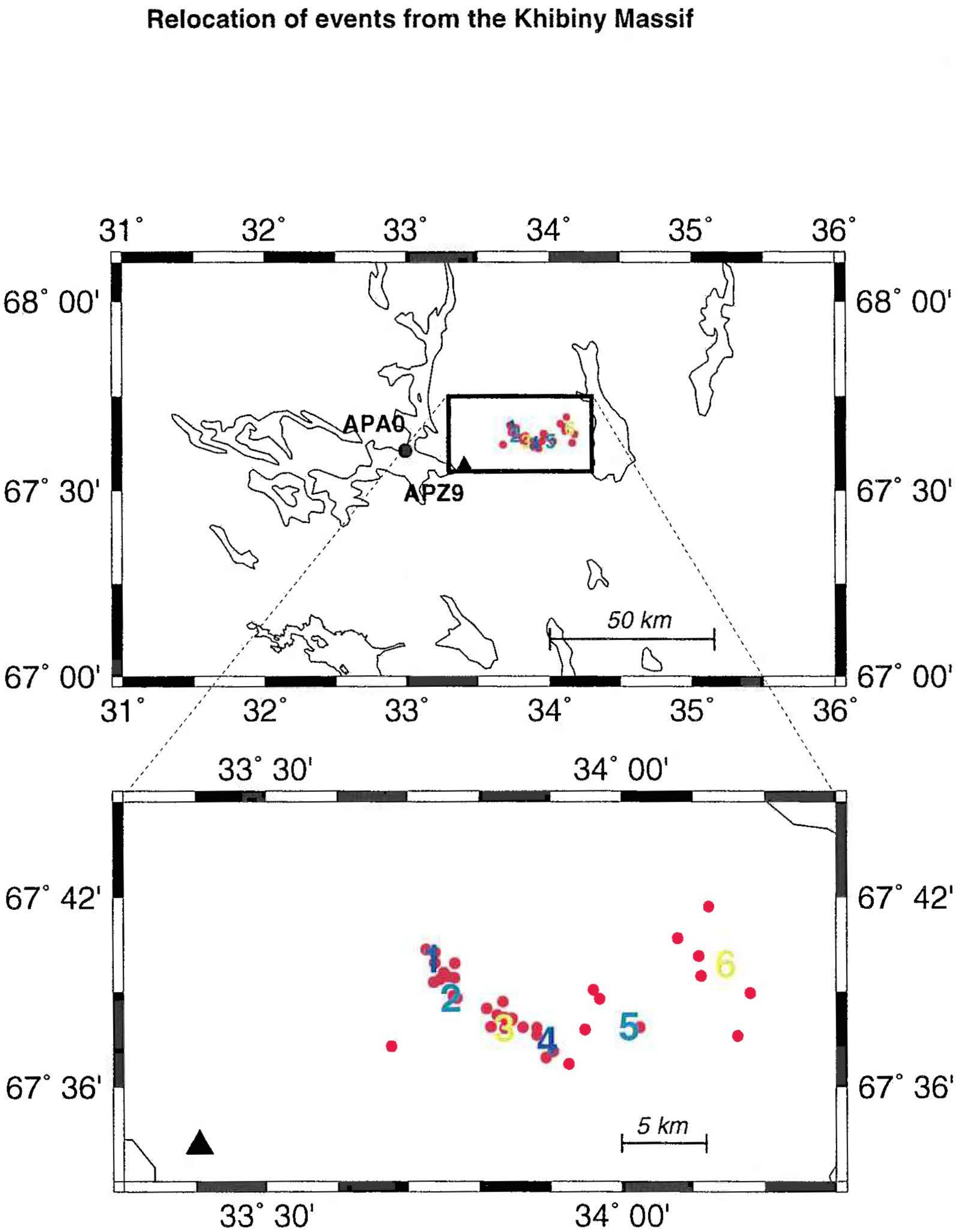


Fig. 6.4.9. The map shows the location of the 36 events after reprocessing the observations as described in the text. The bottom part is an expanded view showing the locations relative to the 6 mines (numbered 1 to 6).

Table 6.4.6. Relocation of the 36 mining events from the Khibiny Massif, with location errors in kilometers (red).

Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6
Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)	Lat Lon Err (km)
67.6652,33.7387,0.7	67.6445,33.8334,3.1	67.6307,33.8359,0.1	67.6306,33.8809,1.0	67.6510,33.9608,3.0	67.6688,34.1085,1.6
67.6722,33.7264,0.2	67.6551,33.7370,1.4	67.6311,33.8616,1.1	67.6152,33.8941,1.0	67.6462,33.9692,2.4	67.6267,34.1633,4.3
67.6708,33.7386,0.4	67.6476,33.7649,0.2	67.6363,33.8350,0.6	67.6184,33.9038,0.7	67.6311,34.0262,0.7	67.6582,34.1118,1.6
67.6581,33.7560,0.9	67.6313,33.8167,2.9	67.6558,33.8463,2.8	67.6410,33.8109,4.1	67.6300,33.9485,2.7	67.6780,34.0792,3.2
67.6648,33.7668,1.7		67.6374,33.8253,0.8	67.6350,33.8449,2.5		67.6493,34.1804,2.3
67.6600,33.7512,0.6			67.6272,33.8809,0.7		67.6948,34.1225,3.5
67.6466,33.7692,2.3			67.6213,33.6774,9.3		
67.6566,33.7457,0.9			67.6118,33.9258,1.9		
67.6573,33.7658,1.3					

Later, we will expand the processing to other mining areas in Fennoscandia and NW Russia. Eventually, such a two-step reprocessing should be available for the entire European Arctic region covered by the Fennoscandian array network. To apply a similar algorithm on an even broader basis is a natural goal in the long term, but there are many aspects that must be investigated and evaluated before this can be achieved.

We should note that one important reason for the very high location precision obtained for the Khibiny Massif, and documented in this paper, is the geometry of the surrounding array network, in particular the availability of local stations (in Apatity). This situation will of course not be the same for other regions to be processed, and therefore one cannot expect location accuracies as high as 1-2 km on a general basis. Nevertheless, it ought to be possible to improve significantly on the current GBF location precision, which is typically about 20-30 km for "good" solutions and significantly worse in some other cases.

Finally, an interesting project is to evaluate the effect of using "subnetworks" of the available Fennoscandian station network. As is well known, the combination of close-in stations with more remote stations could in some cases make the location less accurate rather than more accurate. We will also study the performance of single-array location relative to network location. This could be useful to develop optimized processing methods for small events, which might be expected to be seen at only one IMS station.

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6.5 Online databases for the European Arctic — New developments of the NORSAR web site

6.5.1 Introduction

In September 1998 a new version of the software used for analyzing regional seismic events was installed at NORSAR. From 10 November 2000 all waveform data from the available arrays (NOA, NORES, ARCES, SPITS, HFS, FINES, and Apatity) have been stored on disk for subsequent rapid access. Together with this we have also upgraded NORSAR's Web site to include both epicenter maps, event information with phase readings, and standard waveform plots of the Reviewed Regional Seismic Bulletin. For the time period preceding 10 November 2000 the waveform plots are not included. The main motivation for this work has been to facilitate the combined use of the reviewed bulletin information and online data for research purposes. The information available on the Internet is updated as events are analyzed, typically several times a month.

Fig. 6.5.1 shows the starting calendar view found on NORSAR's Web site (*http://www.norsar.no/)*. By clicking on the selected month, a map and list of the events within this period is displayed, as shown in Fig. 6.5.2.

6.5.2 NORSAR's Analyst Reviewed Regional Seismic Bulletin

The starting point for the analyst review are the locations and magnitudes provided by NORSAR's fully automatic bulletin generated by the Generalized Beamforming method (Kværna et al., 1999). The analyst is focusing on regional events with magnitude greater that 1.5, but also other events of interest in the European Arctic are included in the reviewed bulletin.

Fig. 6.5.2 shows an example from March 2001 of the monthly analyst reviewed results, with a map and list of the locations, magnitude, region and some information on residuals and number of stations and phases. Using data from the regional arrays NORES, ARCES, HFS, FINES, Apatity, and SPITS, an average of about 90 events are analyzed every month. Pages covering four sub-regions are available by clicking on the map, Fig. 6.5.3. shows the Northern Norway/ Kola Peninsula page for March 2001. Detailed data about single events are available by clicking on the Origin ID (Orid) in the lists, as shown in Fig. 6.5.4. This consists of a detailed location map with error ellipse, more detailed hypocenter location information and also phase arrival data used in the location. Waveform data plots from the stations used in the location are available, and are shown in a pop-up window. Waveform data examples are shown in Fig. 6.5.5.

6.5.3 Near-real-time data plots

A method for quickly viewing seismic data has been developed for NORSAR's web site. Each plot contains one full day of data from the vertical component of the central instrument within each array, filtered to enhance regional and local arrivals. These "virtual helicorder plots" are updated every fifteen minutes, and older plots are archived for later retrieval, as shown in Fig. 6.5.6. Data going back to 24 January 2001 are currently available. Sample plots for 31 March 2001 from NORES and 31 May from ARCES are shown in Fig. 6.5.7.

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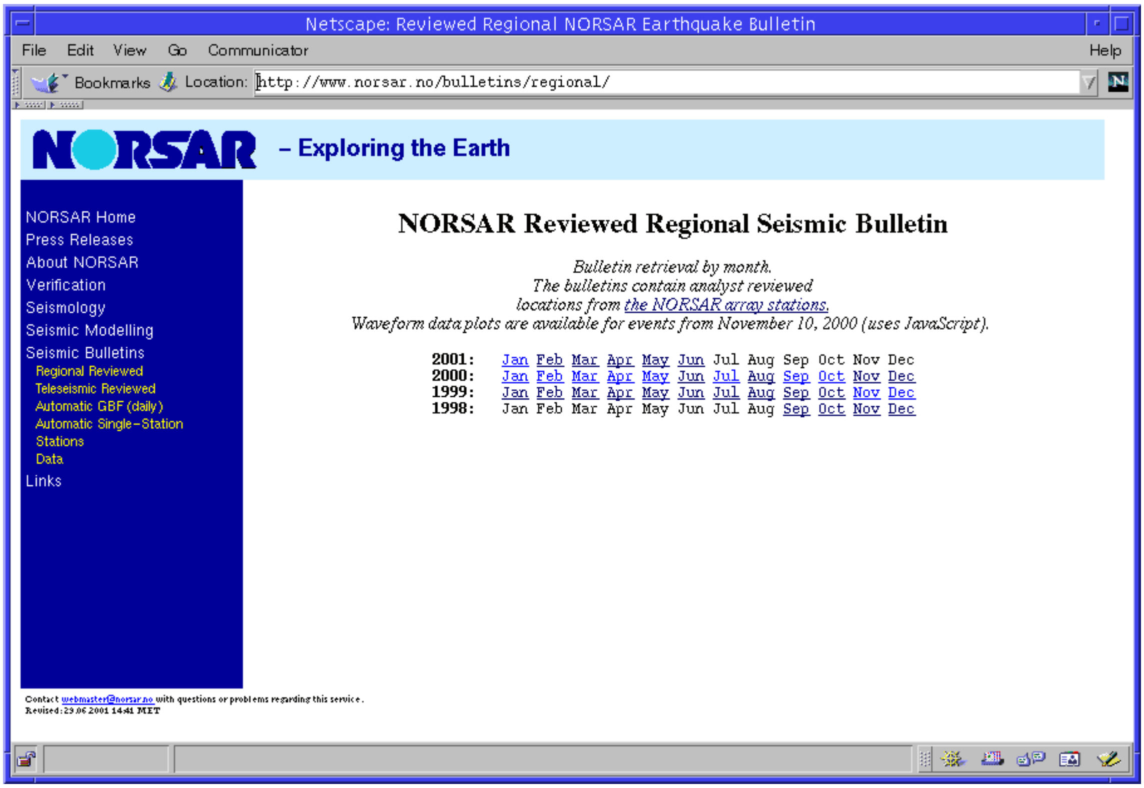

Fig. 6.5.1. Start page calendar for NORSAR's online Reviewed Regional Seismic Bulletin.

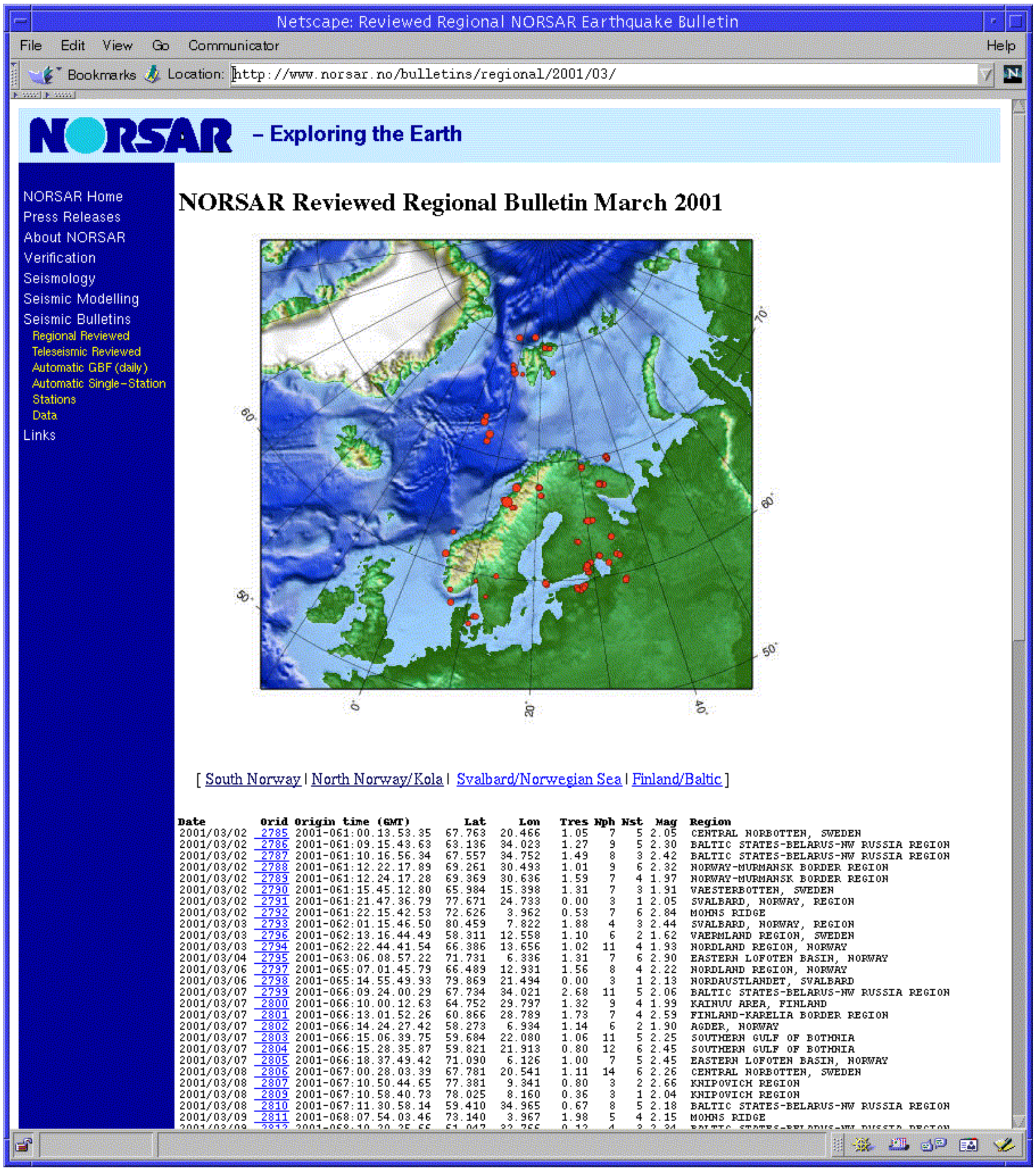

Fig. 6.5.2. Locations of events in NORSAR's Analyst Reviewed Regional Seismic Bulletin for March 2001. Using data from the regional arrays NORES, ARCES, HFS, FINES, Apatity, and SPITS, an average of about 90 events are analyzed every month. Below the map with events follows a summary list with the basic event information (Origin Time, Origin ID, Location, No. of phases/stations, Magnitude and Region). The following figures further illustrate the structure of this Web application (Figs. 6.5.3-6.5.5).

Netscape: Reviewed Regional NORSAR Earthquake Bulletin

File Edit View Go Communicator Help

Bookmarks Location: http://www.norsar.no/bulletins/regional/2001/03/nn.html

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Data
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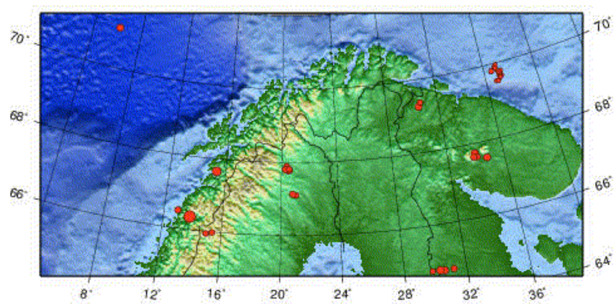
NORSAR Reviewed Regional Bulletin March 2001



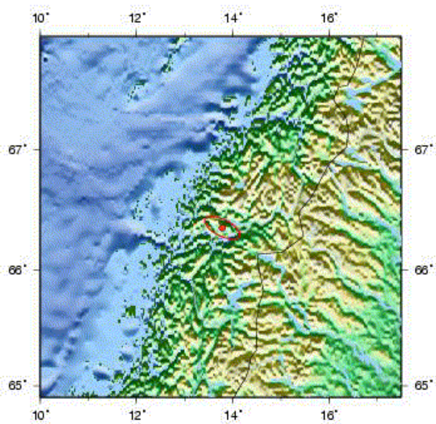
Date	Orid	Origin time (GMT)	Lat	Lon	Tres	Nph	Nst	Mag	Region
2001/03/02	2785	2001-061:00.13.53.35	67.763	20.466	1.05	7	5	2.05	CENTRAL NORBOTTEN, SWEDEN
2001/03/02	2787	2001-061:10.16.56.34	67.557	34.752	1.49	8	3	2.42	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/02	2788	2001-061:12.22.17.89	69.261	30.493	1.01	9	6	2.32	NORWAY-MURMANSK BORDER REGION
2001/03/02	2789	2001-061:12.24.17.28	69.369	30.636	1.59	7	4	1.97	NORWAY-MURMANSK BORDER REGION
2001/03/02	2790	2001-061:15.45.12.80	65.984	15.398	1.31	7	3	1.91	VAESTERBOTTEN, SWEDEN
2001/03/03	2794	2001-062:22.44.41.54	66.386	13.656	1.02	11	4	1.93	NORDLAND REGION, NORWAY
2001/03/04	2795	2001-063:06.08.57.22	71.731	6.336	1.31	7	6	2.90	EASTERN LOFOTEN BASIN, NORWAY
2001/03/06	2797	2001-065:07.01.45.79	66.489	12.931	1.56	8	4	2.22	NORDLAND REGION, NORWAY
2001/03/07	2799	2001-066:09.24.00.29	67.734	34.021	2.68	11	5	2.06	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/07	2800	2001-066:10.00.12.63	64.752	29.797	1.32	9	4	1.99	KAINUU AREA, FINLAND
2001/03/07	2805	2001-066:18.37.49.42	71.090	6.126	1.00	7	5	2.45	EASTERN LOFOTEN BASIN, NORWAY
2001/03/08	2806	2001-067:00.28.03.39	67.781	20.541	1.11	14	6	2.26	CENTRAL NORBOTTEN, SWEDEN
2001/03/09	2814	2001-068:17.35.25.88	67.094	21.024	0.80	9	5	1.98	CENTRAL NORBOTTEN, SWEDEN
2001/03/12	2817	2001-071:17.32.12.53	65.945	14.982	1.29	6	2	2.02	VAESTERBOTTEN, SWEDEN
2001/03/14	2822	2001-073:16.49.22.66	67.128	20.791	0.84	8	5	2.26	CENTRAL NORBOTTEN, SWEDEN
2001/03/15	2825	2001-074:00.22.14.68	67.888	20.350	1.68	4	2	2.00	CENTRAL NORBOTTEN, SWEDEN
2001/03/16	2826	2001-075:10.41.05.54	67.693	34.007	0.74	9	3	2.14	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/16	2830	2001-075:12.32.46.88	67.742	33.973	1.40	8	4	2.41	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/19	2843	2001-078:00.19.39.31	67.799	20.264	1.26	9	4	2.21	CENTRAL NORBOTTEN, SWEDEN
2001/03/22	2836	2001-081:15.30.11.70	69.520	36.779	0.75	7	3	1.43	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/23	2852	2001-082:09.59.41.48	64.737	30.570	1.34	9	5	2.35	FINLAND-KARELIA BORDER REGION
2001/03/23	2837	2001-082:11.08.14.62	69.906	36.918	0.56	6	3	1.52	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/23	2838	2001-082:11.14.28.80	69.792	36.547	0.86	7	3	1.39	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/23	2839	2001-082:11.24.37.62	69.815	36.590	1.08	6	3	1.82	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/23	2858	2001-082:12.54.20.59	67.628	34.071	1.80	8	3	2.21	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/24	2859	2001-083:10.54.15.97	69.585	37.102	1.10	7	3	1.29	BARENTS SEA
2001/03/24	2840	2001-083:15.34.54.67	69.519	36.952	1.14	7	3	1.52	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/25	2860	2001-084:03.41.18.69	67.633	33.837	1.70	11	5	2.26	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/25	2841	2001-084:14.20.03.10	69.621	37.153	0.98	7	4	1.64	BARENTS SEA
2001/03/26	2863	2001-085:05.33.42.16	69.754	37.081	0.87	6	2	-	BARENTS SEA
2001/03/26	2864	2001-085:16.21.31.48	69.621	37.136	0.65	7	4	1.50	BARENTS SEA
2001/03/27	2865	2001-086:04.30.42.12	69.963	37.026	0.22	5	2	1.25	BARENTS SEA
2001/03/28	2868	2001-087:05.59.36.39	69.767	37.319	0.80	6	3	1.38	BARENTS SEA
2001/03/28	2869	2001-087:10.14.09.13	64.760	30.298	1.41	12	4	2.53	FINLAND-KARELIA BORDER REGION
2001/03/30	2877	2001-089:09.46.42.40	64.749	31.158	2.47	7	4	2.14	BALTIC STATES-BELARUS-NW RUSSIA REGION
2001/03/30	2889	2001-089:14.52.50.88	67.658	15.344	1.10	17	7	2.92	NORDLAND REGION, NORWAY
2001/03/30	2881	2001-089:15.55.10.85	69.632	37.296	0.44	7	4	1.67	BARENTS SEA
2001/03/30	2882	2001-089:15.56.28.69	69.691	37.164	0.68	8	4	1.79	BARENTS SEA
2001/03/30	2884	2001-089:15.59.50.80	69.611	37.118	0.13	5	3	1.33	BARENTS SEA
2001/03/30	2886	2001-089:16.00.44.99	69.636	37.180	1.03	8	5	1.66	BARENTS SEA
2001/03/30	2887	2001-089:16.04.51.93	69.613	37.142	0.87	7	4	-	BARENTS SEA
2001/03/30	2885	2001-089:16.07.08.52	69.597	37.196	0.91	8	5	1.46	BARENTS SEA
2001/03/30	2888	2001-089:23.17.17.59	67.811	20.529	1.92	8	4	2.02	CENTRAL NORBOTTEN, SWEDEN
2001/03/31	2890	2001-090:11.30.54.29	66.354	13.783	1.01	20	8	4.00	NORDLAND REGION, NORWAY
2001/03/31	2891	2001-090:13.13.37.19	69.861	36.950	0.27	7	4	1.62	BALTIC STATES-BELARUS-NW RUSSIA REGION

Fig. 6.5.3. Zoom of the events in Northern Norway and on the Kola Peninsula. More information on each event can be found by mouse clicking on the Origin Id (Orid). Details concerning the highlighted event (Orid. 2890) are shown in Fig. 6.5.4.

Netscape: Origin ID 2890

File Edit View Go Communicator Help

Bookmarks Location: http://www.norsar.no/bulletins/regional/2001/03/2890.html



- APA data
- ARC data
- FIN data
- HFS data
- NRS data
- SPI data

Origin ID 2890 NORDLAND REGION, NORWAY

Origin time	Lat	Lon	Depth	Trms	Azrms	Nph	Nsta	MLGBF	Majax	Minax	Strike	Area
2001-090:11.30.54.29	66.3539	13.7834	12.73	1.01	8.51	20	8	4.00	17.8	7.7	116.8	433.6

Sta	Dist	Az	Ph	Time	Tres	Azim	Ares	Vel	Slow	Slres	Snr	Amp	Freq	Def	Arid
NC4	597.67	8.92	Pn	11.32.13.58	-0.04	-	-	-	-	-	-	-	-	T--	2440
NC4	597.67	8.92	Sn	11.33.16.10	1.40	-	-	-	-	-	-	-	-	T--	2438
ARC	605.57	239.70	Pn	11.32.13.66	-0.87	232.0	-7.7	8.4	13.2	-0.1	365.7	3.54	7.69	T--	3954695
ARC	605.57	239.70	Sn	11.33.15.46	-0.90	243.5	3.8	5.4	20.8	-3.4	7.7	55.72	1.92	T--	3954715
ARC	605.57	239.70	Lg	11.33.44.29	-1.12	231.7	-8.0	3.9	28.3	-3.1	4.9	157.46	1.54	T--	3954759
NAO	634.48	12.06	Pn	11.32.17.55	-0.45	-	-	-	-	-	-	-	-	T--	2441
NAO	634.48	12.06	Lg	11.33.50.93	-2.63	-	-	-	-	-	-	-	-	T--	2439
NRS	637.04	9.09	Pn	11.32.18.13	-0.17	1.0	-8.1	8.6	12.9	-0.4	927.4	3.55	5.26	T--	3954692
NRS	637.04	9.09	Sn	11.33.23.28	0.11	28.2	19.1	4.3	25.7	1.8	6.8	19.79	4.55	T--	3954716
NRS	637.04	9.09	Lg	11.33.54.66	0.37	16.7	7.6	4.5	24.7	-6.8	6.2	175.28	1.64	T--	3954727
HFS	694.30	0.32	Pn	11.32.24.78	-0.37	354.7	-5.6	7.7	14.5	1.2	440.4	3.86	5.00	T--	3954730
HFS	694.30	0.32	Sn	11.33.36.83	1.38	353.1	-7.2	3.8	29.6	5.8	6.5	51.20	4.55	T--	3954742
HFS	694.30	0.32	Lg	11.34.11.21	0.73	11.8	11.5	3.1	35.6	4.2	7.2	220.14	1.11	T--	3954755
FIN	813.72	317.60	Pn	11.32.40.58	0.84	316.3	-1.3	8.8	12.6	-2.4	285.2	1.97	5.56	T--	3954699
FIN	813.72	317.60	Sn	11.34.01.73	1.25	317.4	-0.2	5.0	22.3	-1.1	3.8	20.77	4.55	T--	3954721
FIN	813.72	317.60	Lg	11.34.45.05	0.84	323.8	6.1	3.5	31.5	0.1	7.9	145.10	1.35	T--	3954723
APA	848.08	269.48	Pn	11.32.43.57	-0.63	277.0	7.5	8.6	12.9	-0.9	12.6	14.46	2.50	T--	3954750
APA	848.08	269.48	Sn	11.34.08.11	-0.18	260.1	-9.3	5.1	22.0	-5.6	14.8	26.56	4.55	T--	3954767
APA	848.08	269.48	Lg	11.34.54.48	0.54	263.9	-5.6	4.7	23.9	-7.6	5.9	72.79	2.13	T--	3954772
SPI	1324.55	185.06	Pn	11.33.41.06	1.39	174.9	-10.2	9.0	12.3	-0.6	40.0	0.21	6.67	T--	3954739

Fig. 6.5.4. Detailed information page for Orid 2890, 31 March 2001. This is an earthquake in the Mo i Rana area in Nordland. Below the high resolution map showing the event location and the associated error ellipse, detailed bulletin information for this event, including the phase readings are listed. For each station used in the event location a station field is displayed to the right of the map. By clicking on a station field, the station waveforms for the given event will be shown in a popup window. Waveform plots from the highlighted ARCES (ARC) and NORES (NRS) stations are shown in Fig. 6.5.5.

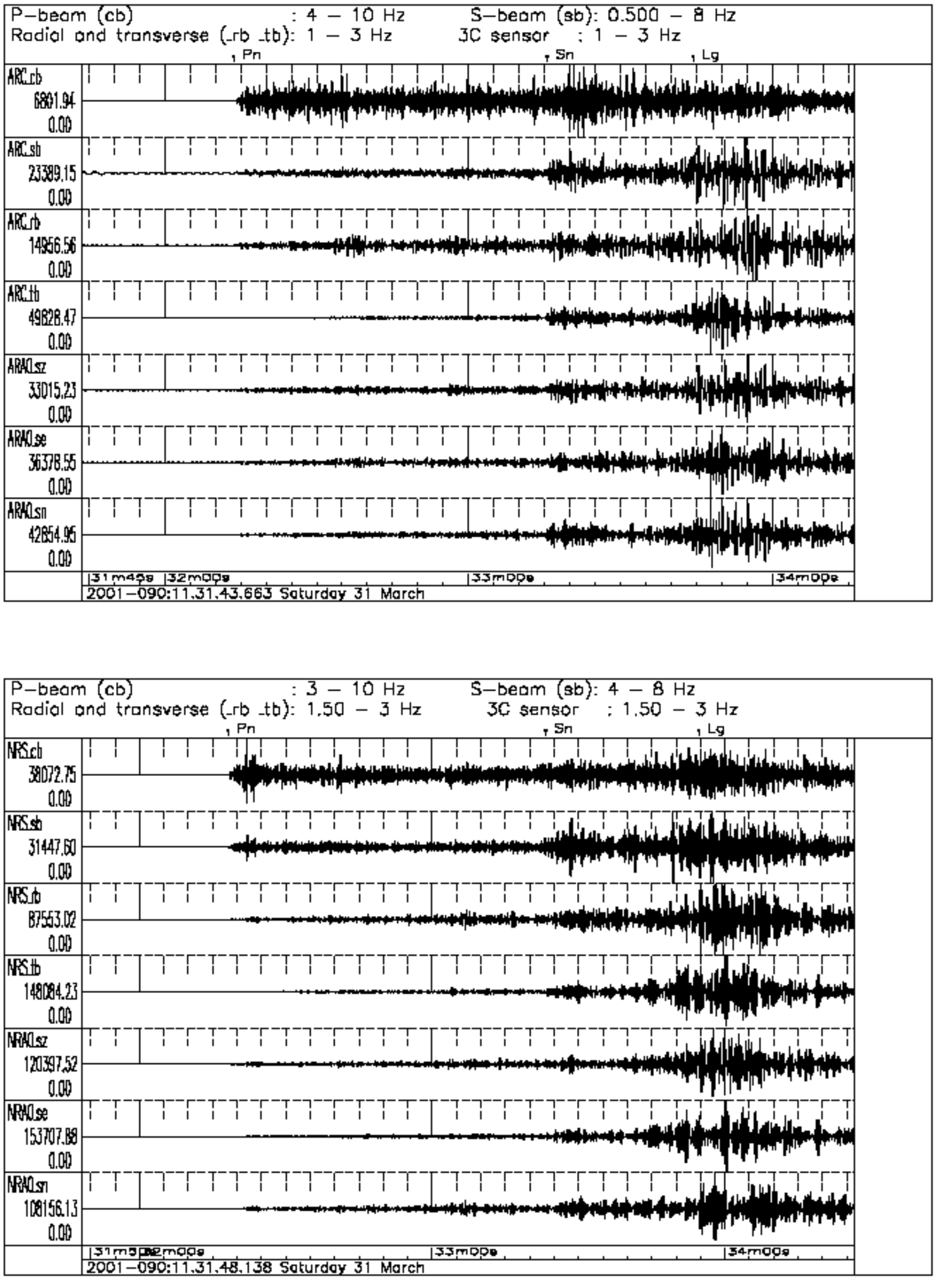
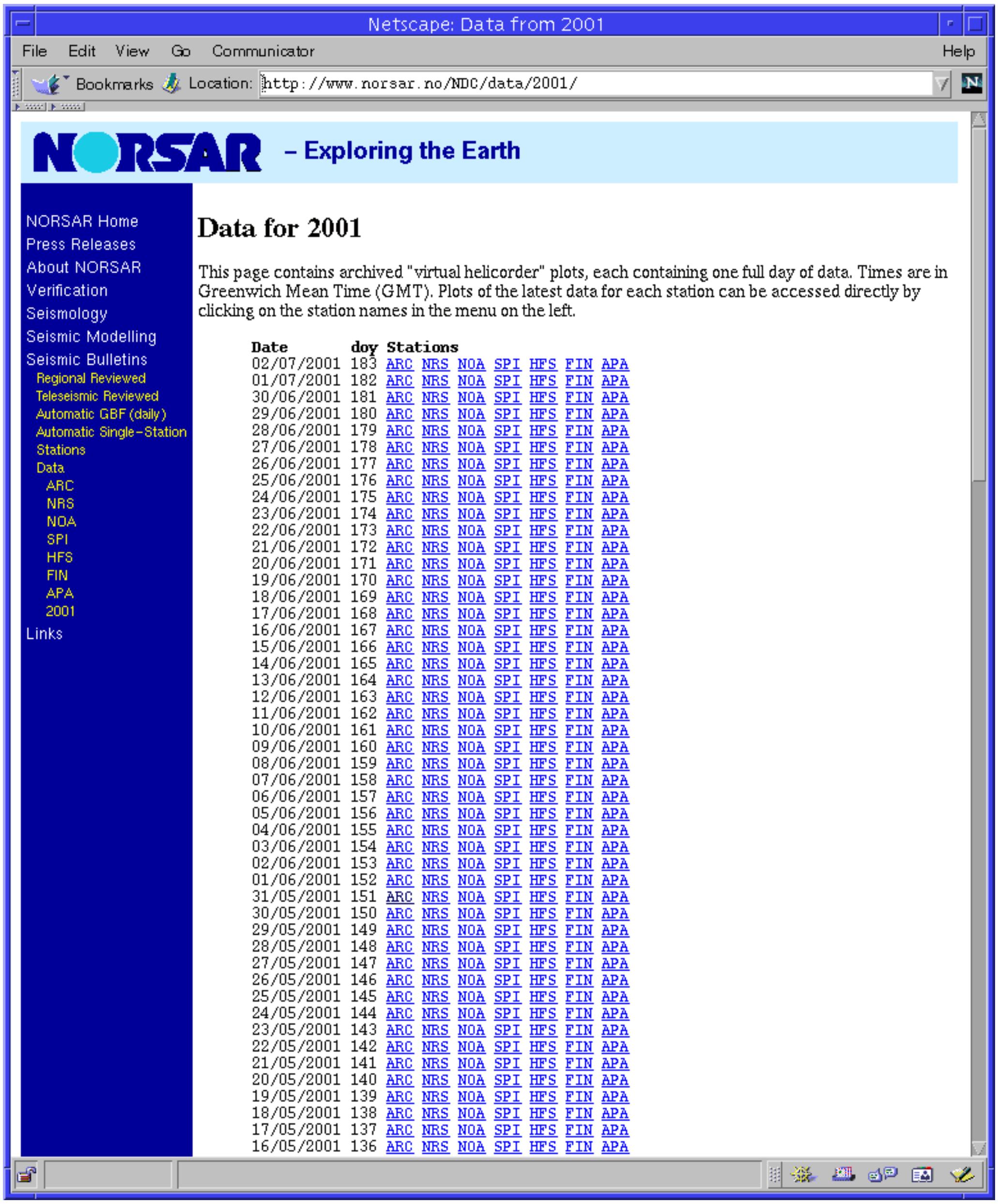


Fig. 6.5.5. ARCES (top) and NORES (bottom) waveforms for Orid 2890. The small markers on top of the plots show the analyst reviewed phase readings. The traces correspond to various array beams and single channels, and have been filtered with bandpass filters designed to enhance various phases. The top trace is a P-type beam focusing on the first arrivals. The second trace is an S-type beam, and traces nos. 3 and 4 are the radial and transverse components, both focusing on the S-phases. The three lower traces show the data of the three-component sensor located centrally within the arrays. The individual filter parameters as shown are adapted depending on event size, distance etc. for each type of trace.



Data for 2001

This page contains archived "virtual helicorder" plots, each containing one full day of data. Times are in Greenwich Mean Time (GMT). Plots of the latest data for each station can be accessed directly by clicking on the station names in the menu on the left.

Date	doy	Stations						
02/07/2001	183	ARC	NRS	NOA	SPI	HFS	FIN	APA
01/07/2001	182	ARC	NRS	NOA	SPI	HFS	FIN	APA
30/06/2001	181	ARC	NRS	NOA	SPI	HFS	FIN	APA
29/06/2001	180	ARC	NRS	NOA	SPI	HFS	FIN	APA
28/06/2001	179	ARC	NRS	NOA	SPI	HFS	FIN	APA
27/06/2001	178	ARC	NRS	NOA	SPI	HFS	FIN	APA
26/06/2001	177	ARC	NRS	NOA	SPI	HFS	FIN	APA
25/06/2001	176	ARC	NRS	NOA	SPI	HFS	FIN	APA
24/06/2001	175	ARC	NRS	NOA	SPI	HFS	FIN	APA
23/06/2001	174	ARC	NRS	NOA	SPI	HFS	FIN	APA
22/06/2001	173	ARC	NRS	NOA	SPI	HFS	FIN	APA
21/06/2001	172	ARC	NRS	NOA	SPI	HFS	FIN	APA
20/06/2001	171	ARC	NRS	NOA	SPI	HFS	FIN	APA
19/06/2001	170	ARC	NRS	NOA	SPI	HFS	FIN	APA
18/06/2001	169	ARC	NRS	NOA	SPI	HFS	FIN	APA
17/06/2001	168	ARC	NRS	NOA	SPI	HFS	FIN	APA
16/06/2001	167	ARC	NRS	NOA	SPI	HFS	FIN	APA
15/06/2001	166	ARC	NRS	NOA	SPI	HFS	FIN	APA
14/06/2001	165	ARC	NRS	NOA	SPI	HFS	FIN	APA
13/06/2001	164	ARC	NRS	NOA	SPI	HFS	FIN	APA
12/06/2001	163	ARC	NRS	NOA	SPI	HFS	FIN	APA
11/06/2001	162	ARC	NRS	NOA	SPI	HFS	FIN	APA
10/06/2001	161	ARC	NRS	NOA	SPI	HFS	FIN	APA
09/06/2001	160	ARC	NRS	NOA	SPI	HFS	FIN	APA
08/06/2001	159	ARC	NRS	NOA	SPI	HFS	FIN	APA
07/06/2001	158	ARC	NRS	NOA	SPI	HFS	FIN	APA
06/06/2001	157	ARC	NRS	NOA	SPI	HFS	FIN	APA
05/06/2001	156	ARC	NRS	NOA	SPI	HFS	FIN	APA
04/06/2001	155	ARC	NRS	NOA	SPI	HFS	FIN	APA
03/06/2001	154	ARC	NRS	NOA	SPI	HFS	FIN	APA
02/06/2001	153	ARC	NRS	NOA	SPI	HFS	FIN	APA
01/06/2001	152	ARC	NRS	NOA	SPI	HFS	FIN	APA
31/05/2001	151	ARC	NRS	NOA	SPI	HFS	FIN	APA
30/05/2001	150	ARC	NRS	NOA	SPI	HFS	FIN	APA
29/05/2001	149	ARC	NRS	NOA	SPI	HFS	FIN	APA
28/05/2001	148	ARC	NRS	NOA	SPI	HFS	FIN	APA
27/05/2001	147	ARC	NRS	NOA	SPI	HFS	FIN	APA
26/05/2001	146	ARC	NRS	NOA	SPI	HFS	FIN	APA
25/05/2001	145	ARC	NRS	NOA	SPI	HFS	FIN	APA
24/05/2001	144	ARC	NRS	NOA	SPI	HFS	FIN	APA
23/05/2001	143	ARC	NRS	NOA	SPI	HFS	FIN	APA
22/05/2001	142	ARC	NRS	NOA	SPI	HFS	FIN	APA
21/05/2001	141	ARC	NRS	NOA	SPI	HFS	FIN	APA
20/05/2001	140	ARC	NRS	NOA	SPI	HFS	FIN	APA
19/05/2001	139	ARC	NRS	NOA	SPI	HFS	FIN	APA
18/05/2001	138	ARC	NRS	NOA	SPI	HFS	FIN	APA
17/05/2001	137	ARC	NRS	NOA	SPI	HFS	FIN	APA
16/05/2001	136	ARC	NRS	NOA	SPI	HFS	FIN	APA

Fig. 6.5.6. The calendar file for accessing archived data plots for each station.

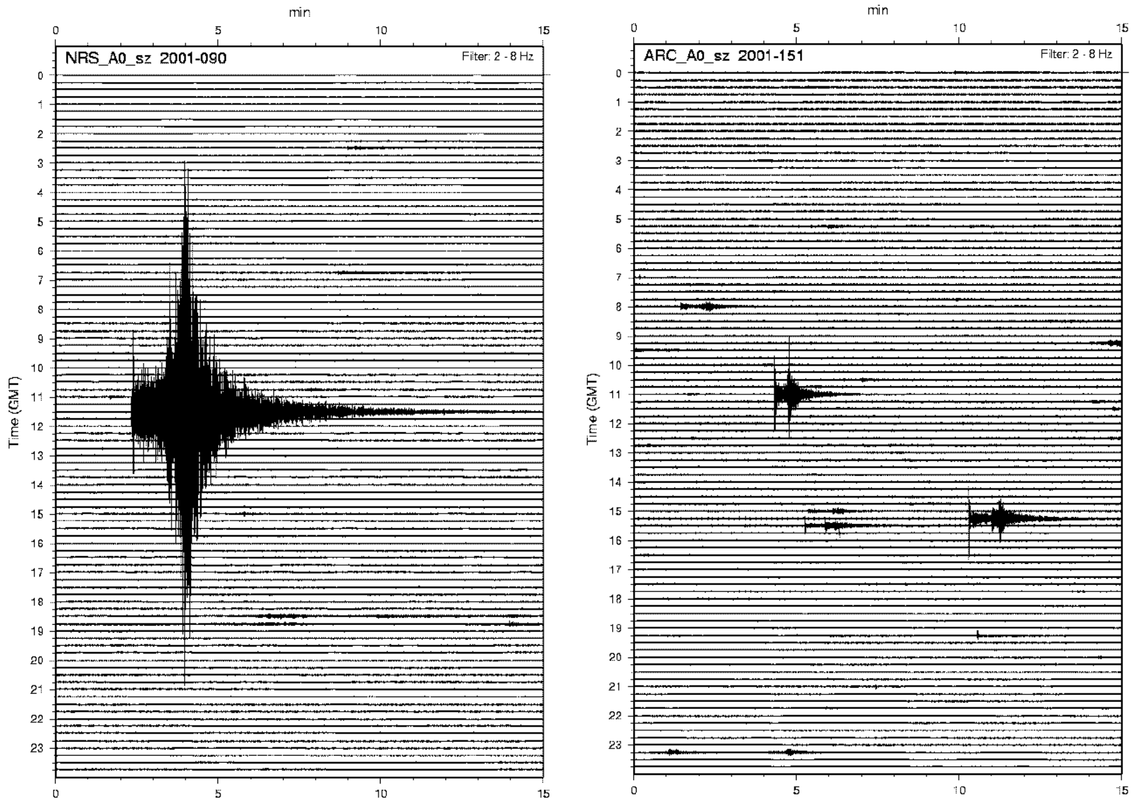


Fig. 6.5.7. Sample "virtual helicorder plots" from NORES for 31 March 2001 (left) showing a relatively large (M_L 4.0) earthquake at a distance of 635km, and from ARCES for 31 May 2001 (right) showing several small local and regional seismic events.

6.6 Study of seismic activity near the Barentsburg mine (Spitsbergen)

6.6.1 Introduction

The work described in this paper is a part of KRSC - NORSAR cooperative activity aimed at a detailed study of seismicity in the Spitsbergen region. Part of the motivation for the study is to improve the quality and availability of well-located reference events ("ground truth data") for location calibration purposes.

Spitsbergen and the adjacent areas are parts of a geologically complex region with moderate to high seismicity. The main seismicity in the area is associated with the North-Atlantic Ridge, and especially the Knipovich Ridge situated at a distance less than 400 km from the archipelago (Sundvor and Eldholm, 1979). In addition, some coal mines are located in the area of Spitsbergen, causing occasional induced seismicity as discussed in this paper.

6.6.2 Station Installation

During the last years an increased occurrence of rockbursts in the mines near Barentsburg, Spitsbergen has been observed. To obtain more information about these events, KRSC and NORSAR installed a digital 3-component seismic station, BRB, in the town of Barentsburg in December 2000. The station is located at a distance of only about 5 km from the mines.

Since the station was not originally designed for continuous data acquisition we developed our own acquisition software. The software package comprises a set of programs for data acquisition, preliminary processing and analysis.

The main acquisition program GBVMOD can store data on hard disk or external devices such as magneto-optical disks or Exabyte cassettes. If external GPS is connected to computer the program uses the GPS signal for timekeeping by sending synchronization commands to the station.

Optionally the program can make preliminary data processing during the acquisition. As a result detection lists and traces for short-term averaged amplitudes (STA time is 1 sec, frequency band 4-12 Hz) are produced. The traces and detection lists can be downloaded via modem.

The processing program STOREGBV makes copying of data from external devices converting them to a compressed format which is suitable for data analysis program VIEWGBV. During the copying it repeats the same processing as mentioned above, i.e., produces lists of detected phases and STA traces.

The program for data analysis VIEWGBV enables to look through the data (both wave forms and STA traces), convert them to ASCII and CSS formats, make filtering, location, etc.

STA traces appeared to be a convenient tool for quick data survey. Traces for many seismic events have very similar shapes. The typical shape is characterized by abrupt jump of amplitude and its smooth decrease. An example of STA trace (top) and wave forms (bottom) for an event in Spitsbergen is shown in Fig. 6.6.1.

For a quick detection of seismic events near Barentsburg station we have made a program which scans STA traces and for each place estimates a rating function. The function depends on amplitude and steepness of its change. Whenever the function appears greater than some threshold the corresponding piece of wave form is extracted and placed to a CSS file for the next analysis.

6.6.3 Event Location

In order to fine-tune the local velocity model, a small calibration explosion was conducted on 18 March 2001 at 11:03:00. The explosion coordinates were 78.067N, 14.36E; yield was 30 kg; the distance to BRB station was 3.12 km.

To calibrate the local travel times we estimated local velocities taking into account that Vp/Vs is about 1.73 and we obtained Vp = 4.54 km/s and Vs = 2.62 km/s. To develop a model for more distant stations we added a low velocity near-surface layer into the BARENTS model (Kremenetskaya et. al., 2001). We fitted the layer's depth using a well recorded (by SPI, KBS, BRB stations) event occurring on 21 December 2000 at 5.18:56. Initially, we located this event with BRB station only using the P and S velocities estimated above. Then we made the event locations using the three stations for several depths of the low velocity layer. The best result was obtained for depth 1.5 km, and this value was therefore adopted for the model (Table 6.6.1).

Table 6.6.1. Spitsbergen Regional Velocity Model.

Depth(km)	Vp(km/s)	Vs(km/s)
0-1.5	4.54	2.62
1.5-16	6.20	3.58
16-40	6.70	3.87
40-55	8.10	4.60
55-210	8.23	4.68
>210	Same as IASPEI 91	

To locate the recorded events with only the BRB station we applied the polarization analysis technique (Asming et al. 1998) for determination of an event azimuth and P and S phase identification. An example of applying the polarization analysis technique is shown in Figure 6.6.2. For estimating the distance to the event the time difference between the P and S phases was used.

6.6.4 Description of the Recorded Events

A total of 541 seismic events have been detected near Barentsburg from 01/12/2000 to 19/04/2001. The amplitudes of the largest events were close to 30000 GBV station units. The largest events were detected at the IMS station Arces (distance 1000 km) and had a local magnitude (ML) of about 3.0.

The events were mostly rockbursts or earthquakes in the mines documented by mining authorities. One of the largest occurred on 25/03/2001. After this event, work in the mines was discontinued for a full month for safety reasons.

Table 6.6.2. Events between 01.12.2000 and 25.03.2001, with amplitudes greater than 4000.

Date	Time (GMT)	Latitude	Longitude	Amplitude
09/12/00	2:24:18	78.077	14.376	9690
17/12/00	6:07:40	78.074	14.366	6460
28/12/00	4:40:14	78.069	14.399	8680
28/12/00	16:16:03	78.074	14.37	7307
07/01/01	0:24:46	78.074	14.365	8317
18/01/01	6:10:59	78.077	14.376	4288
25/01/01	1:35:14	78.068	14.393	5086
27/01/01	18:34:45	78.074	14.368	4116
27/01/01	20:39:05	78.068	14.384	6435
27/01/01	20:42:51	78.068	14.387	14640
28/01/01	11:01:46	78.078	14.359	25384
05/02/01	22:41:55	78.068	14.387	10025
22/02/01	4:03:03	78.074	14.368	4305
23/02/01	11:17:37	78.068	14.387	30183
28/02/01	19:24:33	78.076	14.382	4235
03/03/01	18:52:31	78.074	14.369	4256
04/03/01	1:56:10	78.069	14.39	8000
05/03/01	14:31:34	78.068	14.39	6419
18/03/01	0:46:39	78.074	14.364	4231
23/03/01	6:30:04	78.068	14.387	4459
23/03/01	13:02:12	78.07	14.401	6223
24/03/01	6:44:06	78.076	14.382	7797
25/03/01	17:41:44	78.069	14.387	22807

After the mines were closed down, the number of seismic events decreased significantly. Thus, only 12 events (maximal amplitude 500) occured there during the period from 26/03/2001 to 19/04/2001 (see Table 6.6.3).

Table 6.6.3. Event occurring from 26.03.2001 to 19.04.2001.

Date	Time	Latitude	Longitude	Amplitude
27/03/01	20:04	78.067	14.356	38
27/03/01	22:57	78.065	14.355	58
30/03/01	18:32	78.068	14.365	234
31/03/01	21:27	78.067	14.362	63
05/04/01	1:17	78.061	14.329	469
06/04/01	12:28	78.076	14.36	127
14/04/01	14:21	78.076	14.372	39
16/04/01	16:38	78.074	14.369	64
18/04/01	21:51	78.075	14.375	502
19/04/01	5:25	78.071	14.369	37
19/04/01	5:38	78.068	14.356	39
19/04/01	8:32	78.076	14.382	103

All of the events have been located manually as described above. The results are shown in Fig.6.6.3 and Fig. 6.6.4. Figure 6.6.3 shows that the locations of events with higher amplitudes are very concentrated, whereas the smaller events are more scattered in their locations. This suggests that the location errors strongly depends on events amplitudes because it is difficult to pick S onsets correctly for weaker events.

The events can be clearly separated into three groups : 1) events occurring in the South mine area, 2) in the North mine area, 3) outside the mines. Statistical parameters of the groups are shown in Table 6.6.4.

Table 6.6.4. Statistical parameters of groups of seismic events near Barentsburg.

Place	Number of events	Min. Amplitude	Max. Amplitude	Average	Standard Deviation
South	271	36	30183	848	2713
North	252	39	25384	782	2037
Outside	18	27	372	176	98

The parameters of events outside the mines are very different from those occurring in either the South or North mines. But the South and North events parameters seem to be quite similar. This leads us to the conclusion that the events outside the mines have natural reasons whereas the events in the mining areas are mostly technogenic. Thus, the Barentsburg area is unusual in the sense that strong technogenic seismicity is mixed with a significant natural seismic 'background'.

We also checked the hypothesis that the occurrences of events in South and North mines are interrelated. We calculated average numbers of events by tens of days for both South and North mines. The resulting curves are shown in Fig.6.6.5. The correlation between the curves (0.72) indicates the existence of statistical relationship.

This confirms the technogenic nature of these events. This could also mean that the occurrences of events in North and South mines are governed by the same factors.

6.6.5 Conclusions

1. A 3-component digital seismic station has been installed in the town of Barentsburg, Spitsbergen, and has proved to be useful in detecting and locating rockbursts and local earthquakes..
2. A local velocity model has been developed by using a calibration explosion in Barentsburg mine, and combining this information with the regional "Barents" model.
3. A large number of seismic events has been registered and located. Most of them are induced earthquakes or rockbursts. The frequency of events decreased significantly during a time period when the mining activity was discontinued.
4. The Barentsburg area appears to be unusual in the sense that strong technogenic seismicity is mixed with a significant natural seismic 'background'.
5. The large amount of the collected data could be useful for future study of induced seismicity. The data could also be useful for developing and verifying travel time correction for location calibration purposes.

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F. Ringdal

References

Asming, V.E., E.O. Kremenetskaya & F. Ringdal (1998): Monitoring seismic events in the Barents/Kara Sea region, *Semiannual Technical Summary, 1 October 1997 - 31 March 1998*, NORSAR Sci. Rep. 2-97/98, Norway.

Kremenetskaya, E., V. E. Asming and F. Ringdal (2001): Seismic location calibration of the European Arctic. *Pure and Applied Geophysics*, 158 No. 1-2, 117-128.

Sundvor E. and O. Eldholm (1979): The western and northern margin off Svalbard. - *Tectonophysics*, 59, 239-250.

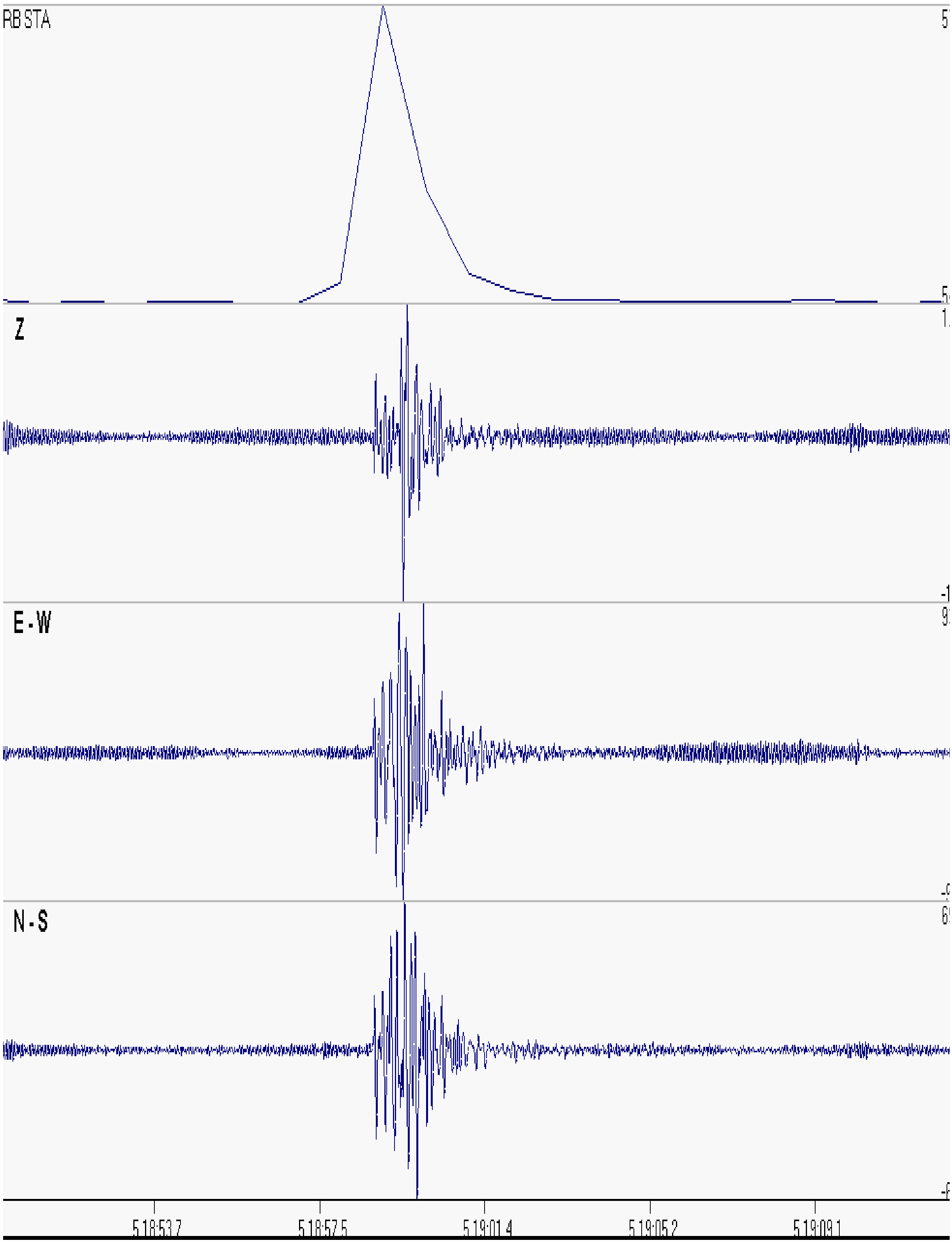

Fig. 6.6.1. An example of STA trace (top) and waveforms (bottom) for the event occurring on 21 December 2000 at 5.18:56 GMT in the Barentsburg mine.

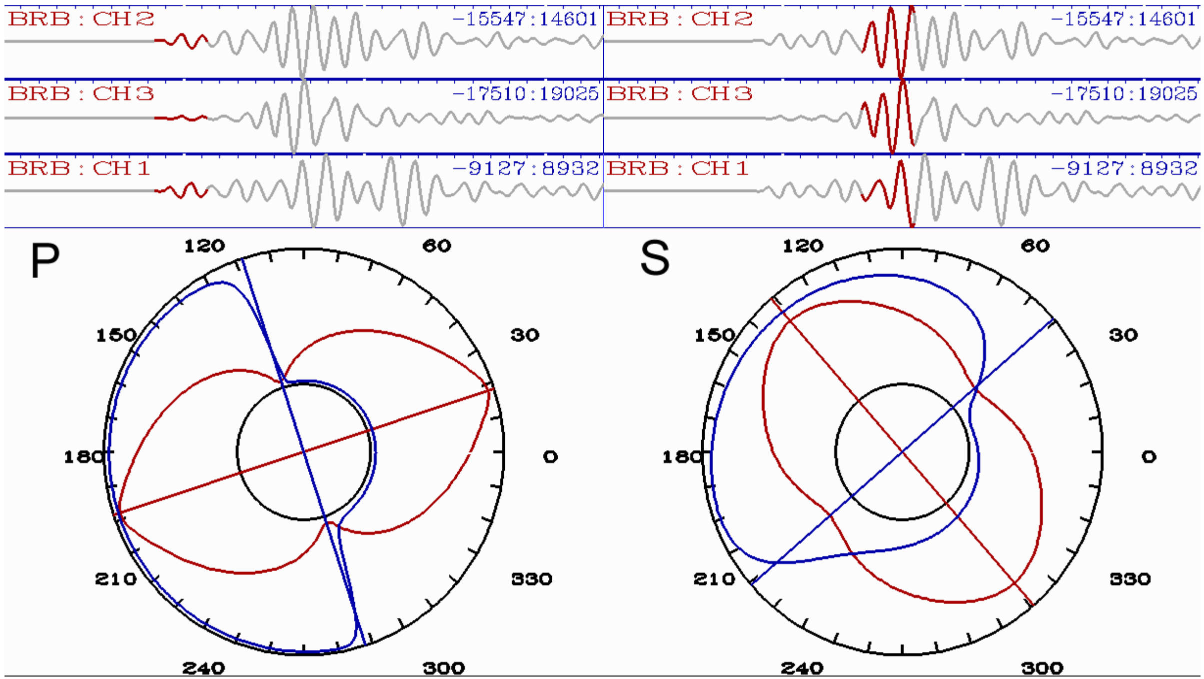

Fig.6.6.2. An example of applying the polarization analysis technique to BRB recordings.

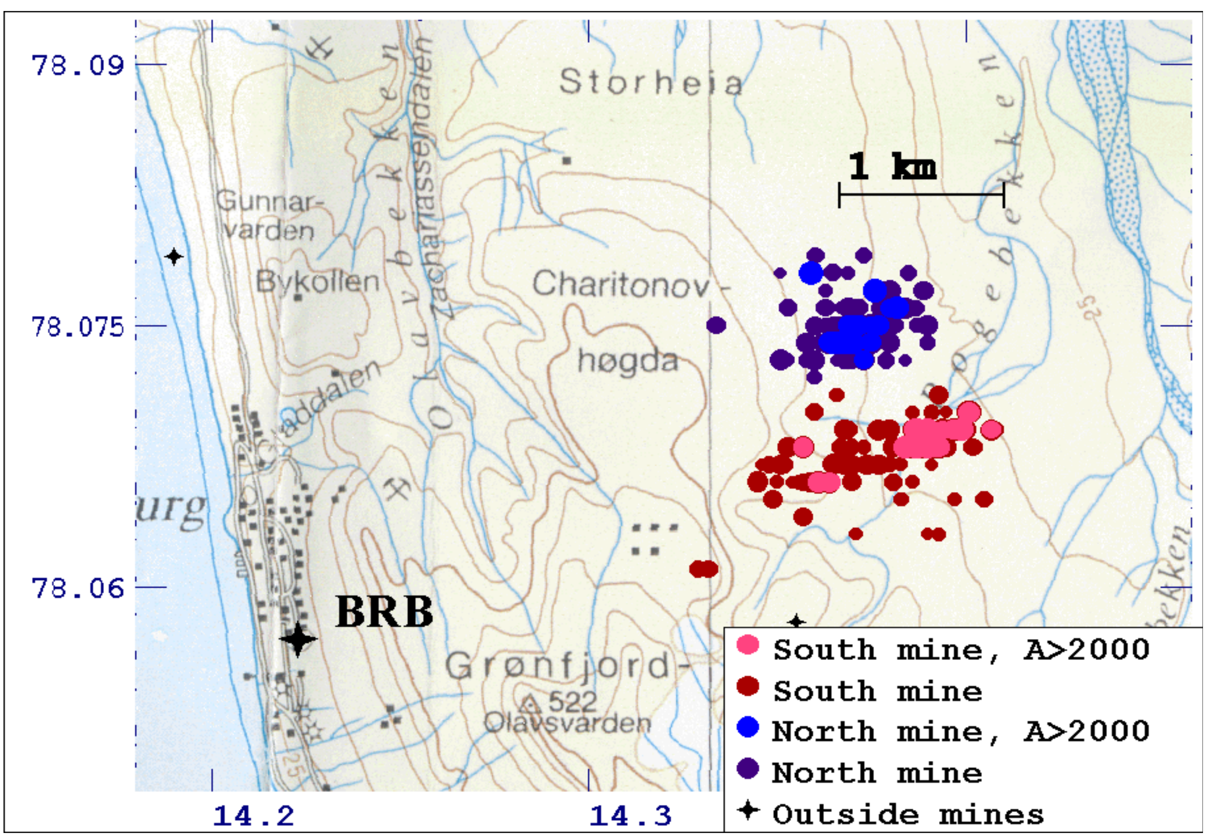

Fig.6.6.3. Seismic events occurring from 01.12.2000 to 26.03.2001.

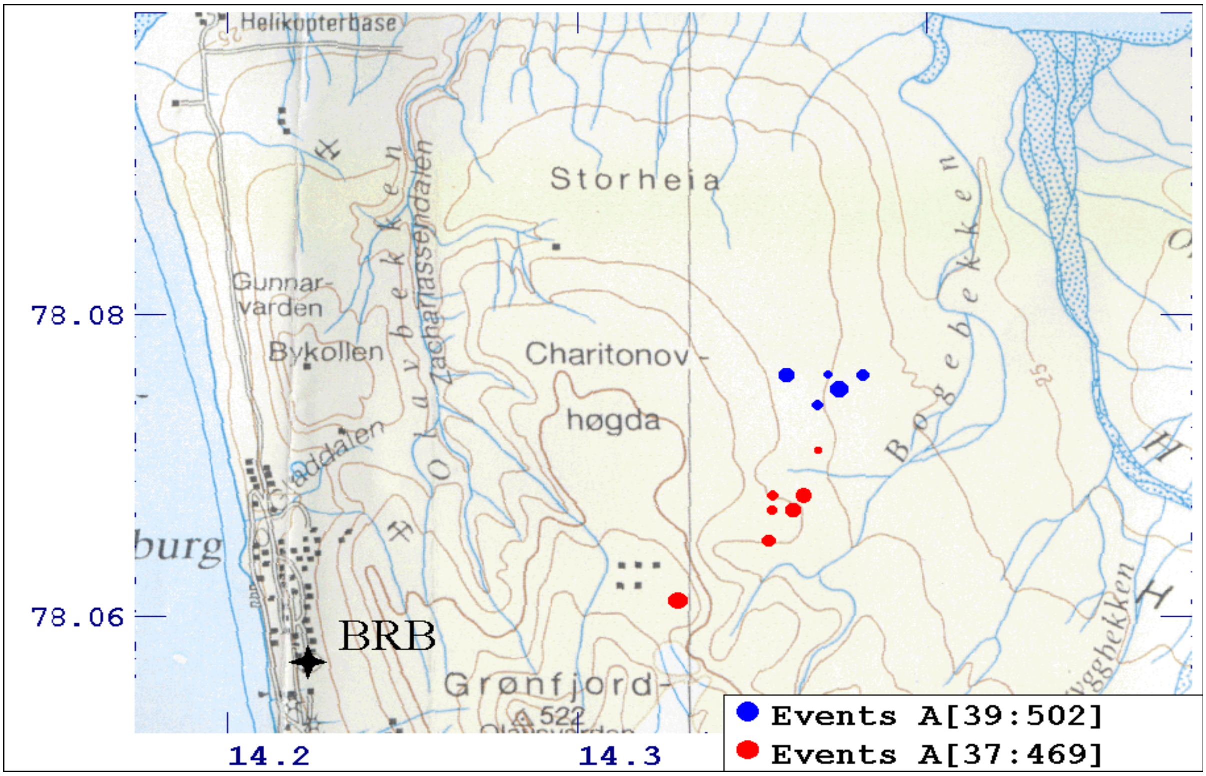

Fig 6.6.4. Seismic events occurring from 26.03.2001 to 19.04.2001.

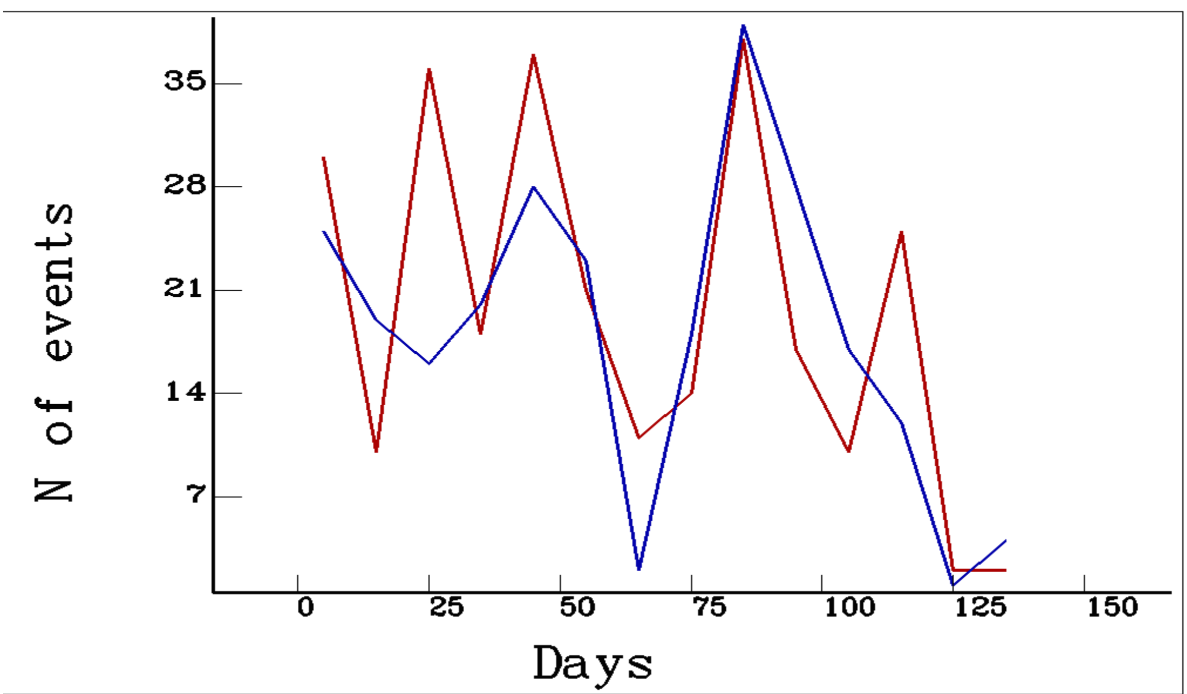

Fig. 6.6.5. Average numbers of events over ten-day windows for the southern (red line) and northern (blue line) mines.