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6.1 Processing of low-magnitude seismic events near Novaya Zemlya

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Introduction

The regional processing system at the NORSAR Data Center, as described in detail by Ringdal and Kværna (2004), comprises the following steps:

- Automatic single array processing, using a suite of bandpass filters in parallel and a beam deployment that covers both P and S type phases for the region of interest.
- An STA/LTA detector applied independently to each beam, with broadband f-k analysis for each detected phase in order to estimate azimuth and phase velocity.
- Single-array phase association for initial location of seismic events, and also for the purpose of chaining together phases belonging to the same event, so as to prepare for the subsequent multiarray processing.
- Multi-array event detection, using the Generalized Beamforming (GBF) approach (Ringdal and Kværna, 1989; Kværna et. al., 1999) to associate phases from all stations in the regional network and thereby provide automatic network locations for events in all of northern Europe. The resulting automatic event list is made available on the Internet (www.norsar.no).
- Interactive analysis of selected events, resulting in a reviewed regional seismic bulletin, which includes hypocentral information, magnitudes and selected waveform plots. This reviewed bulletin is also available on the Internet.

Experience over the past several years has demonstrated that the automated event list generated by the GBF procedure is nearly “complete”, in the sense that it provides an exhaustive search of all possible detected phase combinations that could correspond to real events. The reviewed bulletin is more selective, since our current resources do not allow a complete analysis of all real seismic events that are associated through the automatic algorithms. An important topic of current research is to develop methods to enable the analyst to easily select events from areas of particular interest, and focus on these events in the interactive analysis.

A major enhancement to the monitoring network has been the recent upgrade of the Spitsbergen seismic array, which has included installation of five new three-component seismometers as well as an upgrading of the sampling rate from 40 to 80 Hz. In another contribution in this isssue, Schweitzer and Kværna (2006) describe some recent processing improvements in the Spitsbergen on-line detection system that have been made to take advantage of these enhancements.

Detection of small seismic events near Novaya Zemlya

Over the years, the regional processing system at NORSAR has detected a number of small seismic events on or near Novaya Zemlya. As estimated by Ringdal (1997), the threshold of the array network to confidently detect and locate seismic events in this region is about magnitude

2.5. The two regional arrays Spitsbergen and ARCES are by far the most sensitive monitoring stations, but occasionally other stations will contribute to improved location accuracy for detected events.

Table 6.1.1 lists small seismic events in the Novaya Zemlya region, located outside the nuclear test site and detected over the years by the NORSAR regional processing system. During March 2006, three such events occurred, as listed in the table. These events, which we denote as 2006-064, 2006-073 and 2006-089 were all very small, with magnitudes of 2.7, 2.2 and 2.3 respectively. Figure 6.1.1 shows the location and associated error ellipse of each of these three events. In this paper, we discuss the detection performance and signal characteristics of these three events in some detail.

We first comment briefly upon the performance of the automatic Generalized Beamforming (GBF) system in operation at NORSAR. At the time these events occurred, all three events were well defined by the automatic process (Table 6.1.2), and could thus easily be reviewed by the analyst, with appropriate editing and correction of phase readings. This performance is quite impressive, taking into account the low magnitudes of these events and the considerable epicentral distance (about 1000 km or more to the nearest array). Nevertheless, there are some features that point to the need for further enhancement. In particular, we note that event 2006-073 has no Sn phase detection at the Spitsbergen array but, even so, the event location is quite good. Event 2006-089 has an ARCES Lg phase which is clearly erroneous. Lg phases are never detected at ARCES (or Spitsbergen) for Novaya Zemlya events, because of the blockage effect caused by the thick sedimentary layers in the Barents Sea.

As discussed by Schweitzer and Kværna (2006), the main improvement to the on-line processing systems in operation at NORSAR that has been made possible with the upgraded Spitsbergen array is the ability to improve the detection of Sn-phases. The difficulties in detecting Sn phases at Spitsbergen has been noted in previous Semiannual Reports, and is one of the main reasons behind the inclusion of additional three-component sensors in the current upgrade. We will return to a discussion of possible ways to make optimal use of the horizontal components for Sn-phase detection later in this paper.

We also comment briefly upon the locations shown in Figure 6.1.1. The locations have been made using the two arrays Spitsbergen and ARCES only. The Spitsbergen channel SPB5_BHZ was not used in direction estimates for the 2006-073 event since the time-stamp is demonstrably incorrect at this time. The estimated epicenters are all offshore, but the error ellipses indicate that coastal or inland locations cannot be entirely excluded, even for the event on 30 March. The point here is that accurate location error ellipses are extremely difficult to calculate, since they require knowledge of both the earth model error and the reading errors for the arrival time picks. While we believe that the Barents model is quite reliable, the time picks are subject to a considerable uncertainty, especially in view of the emergent nature of many of the signals. For small seismic events, with low signal-to-noise ratios, the uncertainty in time picks is very difficult to quantify.

High frequency spectral characteristics

The increase in sampling rate from 40 to 80 Hz at the Spitsbergen array enables us for the first time to study high frequency characteristics of the signals recorded at this site. Many studies have emphasized the outstanding quality of high-frequency seismic recordings at this array, e.g. several contributions in previous Semiannual Reports, as well as a publication by Bowers et. al. (2001). We are now in a position to verify some of these projections.

Figure 6.1.2 shows Spitsbergen spectrograms for the 2006-064 event. We have chosen the three-component instrument at array site B1 for this display, and the vertical component is shown along with the rotated longitudinal and transverse components. The most noticeable feature is the high SNR of the P-phase for this small (m_b=2.7) event. In fact, the SNR on the array beam is above 100, indicating that even an event at this site more than an order of magnitude smaller could have been detected. This should not, however, be extrapolated to a general statement about detection thresholds for the Spitsbergen array, since the SNR to a large extent depends upon path-specific focussing effects. Nevertheless, the amount of high-frequency energy is remarkable, taking into account that the epicentral distance is as large as 1100 km. We note that the vertical and radial components have significant P-wave energy even above 20 Hz. The transverse component shows (not unexpectedly) a small P-wave and a much larger S-wave, indicating that the use of transverse components could be useful in detecting S-phases.

This type of spectrogram is also quite useful in studying the data quality as recorded by individual seismometers. As an example, Figure 6.1.3 shows Spitsbergen spectrograms for six individual seismometers (vertical components) for the 2006-089 event. We have chosen the center seismometer and the five seismometers in the B-ring. We note that three seismometers (A0, B2 and B5) have significant and nearly constant noise in the frequency interval 25-30 Hz. The source of this noise, which occurs periodically over extended time intervals, is not known. Furthermore, the seismometer B4 has strong noise at 10 Hz and below. The reaons for these abnormal noise conditions and possibilities for their mitigation are being investigated.

The 2006-089 event shown in Figure 6.1.3 had a magnitude of 2.3 and is thus considerably smaller than the 2006-064 event which was shown in Figure 6.1.2. In addition, the distance to the Spitsbergen array is somewhat greater in this case (1300 km versus 1100 km for the 2006-064 event). Consequently, the signal-to-noise ratio is not quite as large as for the earlier event. Nevertheless, we see that for the best sites signal frequencies well above 20 Hz are recorded. At two of the sites (B4 and B5) the signal is masked by noise. For the site B5, a 20 Hz low-pass filter would give a satisfactory signal-to-noise ratio. The site B4 has too strong noise to be useful for detection purposes, and this site is currently masked out in the on-line detection process. Nevertheless, B4 can be useful for slowness estimation of larger signals.

We would like at this point to give some additional comments about the advantage of high-frequency recordings. Figure 6.1.4 and 6.1.5 show Spitsbergen seismometer B1 filtered in various passbands for events 2006-064 and 2006-089. The event 2006-064 is the largest one, and consequently has stronger signals than 2006-089. Nevertheless, the signal-to-noise ratios are high for all of the filter bands for both of the events. The best filter band for detection appears to be either 5-10 Hz or 10-20 Hz. However, the most remarkable feature is the strong SNR even at the highest frequencies (20-36 Hz). While such a frequency band would not be used for detection purposes, the high frequency data could be very important for signal characterization, as discussed by Bowers et. al. (2001).

Sn-phase detection at the Spitsbergen array

As mentioned earlier, the inclusion of 6 three-component seismometers in the upgraded Spitsbergen array has made possible improved processing of Sn-phases. Figures 6.1.6-6.1.8 show, for each of the three events, Sn beams steered towards the epicenter using the rotated (transverse) components, as well as more conventional Pn and Sn beams from the vertical components.

In each figure, the top trace is a beam steered to the epicenter with a P-wave velocity, and using a typical detection filter (3-16 Hz). The middle trace is an "optimum" beam designed to detect the S-wave. It represents the beams of the transverse components of the six three-component seismometers in the array, filtered in the band 2-4 Hz and steered to the epicenter with an S-phase velocity. The bottom trace shows, for comparison, an Sn-beam of vertical sensors using the same (2-4 Hz) filter.

Although there are some differences in signal-to-noise ratios of the three events, the general interpretation of the three figures is similar: The two beams based upon vertical components (the top and bottom trace of each figure) show clear Pn and Sn phases, but the Sn phase could be difficult to detect by a power detector due to the strong preceding coda from the Pn-phase. In contrast, the middle trace, which uses only the horizontal components, rotated in the transverse direction, shows almost no sign of the Pn phase, whereas the Sn phase is quite strong. Clearly, the detection of Sn-phases could be greatly improved by augmenting the beam deployment with several steered beams, rotated so as to provide transverse components, toward the grid points in the beam deployment system.

Discussion

This analysis has reconfirmed our previous estimates of the detection capability of the regional array network in northern Europe, indicating that the network is capable of detecting seismic events at Novaya Zemlya down to about magnitude 2.5 (Ringdal, 1997). The automatic detection and location of the three seismic events in March 2006 near Novaya Zemlya have shown that the GBF process in operation at NORSAR works well. Nevertheless, some possibilities for improvements have been noted, in particular the potential for improved Sn-phase detection by the Spitsbergen array, using the recently installed three-component seismometers. An enhanced detection processing system for the Spitsbergen array is discussed in another contribution in this issue (Schweitzer and Kværna, 2006).

The new Spitsbergen array configuration has shown excellent recordings of high-frequency data from Novaya Zemlya events. For the first time, we have been able to verify that significant signal energy at frequencies above 20 Hz can be recorded for events near Novaya Zemlya, at an epicentral distance exceeding 1000 km. This is a quite remarkable observation, and supports the projections made by Bowers et. al. (2001) in their paper discussing the level of deterrence to possible CTBT violations in the Novaya Zemlya region provided by data from the Spitsbergen array.

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Table 6.1.1: List of seismic events in or near Novaya Zemlya (1980-2006) located outside the test site

Date/time	Location	m_b	Comment
01.08.1986/ 13.56.38	72.945 N, 56.549 E	4.3	Located by Marshall et.al. (1989)
31.12.1992/ 09.29.24	73.600 N 55.200 E	2.7	Located by NORSAR
23.02.1995/ 21.50.00	71.856 N, 55.685 E	2.5	Located by NORSAR
13.06.1995/ 19.22.38	75.170 N, 56.740 E	3.5	Located by NORSAR
13.01.1996/ 17.17.23	75.240 N, 56.660 E	2.4	Approximately co-located with preceding event
16.08.1997/ 02.11.00	72.510 N, 57.550 E	3.5	Located by NORSAR
16.08.1997/ 06.19.10	72.510 N, 57.550 E	2.6	Co-located with preceding event
23.02.2002/ 01.21.14	74.047 N, 57.671 E	3.0	Located by NORSAR
27.07.2002 18.20.45	73.720N 56.870E	2.0	Located by NORSAR
10.11.2002 11.04.47	70.880N 47.401E	2.0	Located by NORSAR
08.10.2003/ 23.07.10	75.645N, 63.345E	2.5	Located by NORSAR
05.03.2006/ 23.17.36	76.800N, 66.040E	2.7	Located by NORSAR
14.03.2006/ 20.57.02	75.070N, 53.050E	2.2	Located by NORSAR
30.03.2006/ 10.46.03	70.790N, 51.500E	2.3	Located by NORSAR

Table 6.1.2. Automatic on-line GBF results for three Novaya Zemlya events during March 2006.

NOVAYA ZEMLYA, RUSSIA

Origin time	Lat	Lon	Azres	Timres	Wres	Nphase	Ntot	Nsta	Netmag
2006-064:23.17.35.0	76.80	66.04	8.04	0.56	2.57	3	11	2	2.65

Sta	Dist	Az	Ph	Time	Tres	Azim	Ares	Vel	Snr	Amp	Freq	Fkq	Arid	Mag
SPI	1176.3	72.5	p	23.20.02.4		77.4	4.9	8.4	119.9	1823.9	11.90	2	482426	
SPI	1176.3	72.5	p	23.20.04.6		73.9	1.4	7.8	14.8	368.4	5.73	1	482427	
SPI	1176.3	72.5	p	23.20.08.6		78.4	5.9	8.0	9.9	1944.8	9.82	3	482428	
SPI	1176.3	72.5	p	23.20.13.8		83.5	11.0	8.2	5.9	507.9	5.36	1	482429	
SPI	1176.3	72.5	Sn	23.21.56.4	0.0	66.5	-6.0	4.8	27.2	279.8	4.58	2	482431	2.49
SPI	1176.3	72.5	s	23.21.59.9		69.9	-2.6	4.2	9.8	671.4	5.06	3	482438	2.78
SPI	1176.3	72.5	s	23.22.02.5		74.5	2.0	5.0	6.9	1388.2	8.90	3	482440	
ARC	1497.3	39.9	Pn	23.20.43.4	-1.5	57.5	17.6	9.6	4.8	38.0	6.25	2	482275	
ARC	1497.3	39.9	p	23.20.47.5		47.0	7.1	10.4	6.5	44.4	7.00	1	482276	
ARC	1497.3	39.9	Sn	23.23.03.8	-0.1	39.4	-0.5	3.5	9.0	44.9	3.46	3	482289	2.42
ARC	1497.3	39.9	s	23.23.09.3		59.0	19.1	5.0	7.2	62.0	3.72	3	482292	2.53

NOVAYA ZEMLYA, RUSSIA

Origin time	Lat	Lon	Azres	Timres	Wres	Nphase	Ntot	Nsta	Netmag
2006-073:20.56.46.0	74.72	57.94	9.10	0.50	2.77	3	7	2	2.23

Sta	Dist	Az	Ph	Time	Tres	Azim	Ares	Vel	Snr	Amp	Freq	Fkq	Arid	Mag
SPI	1126.7	88.5	Pn	20.59.10.6	-0.3	96.1	7.6	8.4	18.5	435.7	9.54	3	519913	
SPI	1126.7	88.5	p	20.59.12.9		101.3	12.8	8.0	8.6	492.4	10.38	3	519915	
SPI	1126.7	88.5	p	20.59.15.4		98.0	9.5	9.1	7.7	450.3	9.73	3	519916	
SPI	1126.7	88.5	p	20.59.18.3		97.4	8.9	8.4	5.9	337.2	9.57	3	519919	
ARC	1232.8	47.7	Pn	20.59.24.4	0.6	57.5	9.8	10.6	5.4	47.1	5.65	2	519914	
ARC	1232.8	47.7	Sn	21.01.20.0	0.6	57.5	9.8	4.7	4.4	57.2	6.19	3	519921	2.07
ARC	1232.8	47.7	s	21.01.22.3		55.8	8.1	5.4	5.5	58.5	4.36	2	519923	2.23

BARENTS SEA

Origin time	Lat	Lon	Azres	Timres	Wres	Nphase	Ntot	Nsta	Netmag
2006-089:10.46.43.0	70.61	42.57	8.59	0.80	2.95	4	13	2	2.30

Sta	Dist	Az	Ph	Time	Tres	Azim	Ares	Vel	Snr	Amp	Freq	Fkq	Arid	Mag
ARC	659.1	71.6	Pn	10.48.11.0	-0.1	75.7	4.1	8.6	18.3	70.1	5.08	1	35736	
ARC	659.1	71.6	p	10.48.16.5		72.2	0.6	9.1	5.7	64.5	6.63	2	35737	
ARC	659.1	71.6	p	10.48.21.7		72.9	1.3	8.8	5.3	71.8	3.35	1	35738	
ARC	659.1	71.6	p	10.48.27.0		76.0	4.4	8.4	3.8	51.5	4.73	1	35742	
ARC	659.1	71.6	Sn	10.49.17.0	1.3	47.4	-24.2	4.7	3.8	375.4	1.00	1	35752	1.65
ARC	659.1	71.6	Lg	10.49.50.2	-1.0	73.8	2.2	5.3	12.4	305.6	3.91	1	35753	2.00
ARC	659.1	71.6	s	10.49.53.6		83.3	11.7	3.2	10.8	407.1	3.07	1	35754	2.23
ARC	659.1	71.6	s	10.49.57.1		78.3	6.7	3.1	4.8	163.6	3.71	3	35755	
ARC	659.1	71.6	s	10.50.06.0		75.9	4.3	3.9	4.0	249.0	2.50	1	35756	
SPI	1136.4	123.8	p	10.48.54.5		104.4	-19.4	8.3	6.7	167.9	4.78	2	35882	
SPI	1136.4	123.8	Sn	10.50.55.2	-0.8	120.0	-3.8	5.5	4.8	126.2	5.46	3	35886	1.99
SPI	1136.4	123.8	s	10.50.58.5		113.2	-10.6	5.0	7.1	229.6	5.95	2	35887	
SPI	1136.4	123.8	s	10.51.02.6		102.7	-21.1	5.4	5.4	193.4	4.39	1	35888	2.36

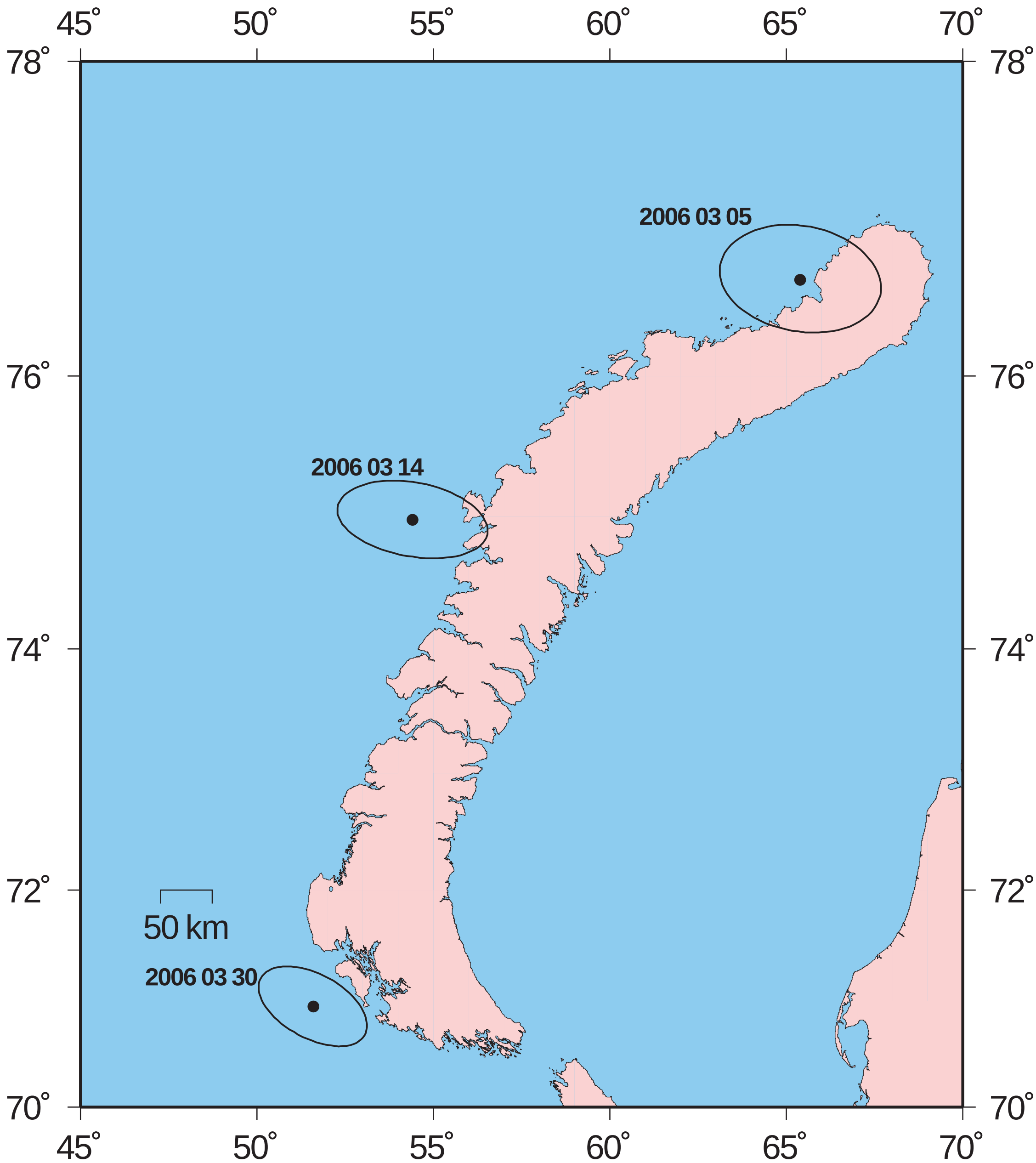

Fig. 6.1.1. Map of Novaya Zemlya showing the location of three seismic events during March 2006 as discussed in the text, together with their 90% confidence ellipses.

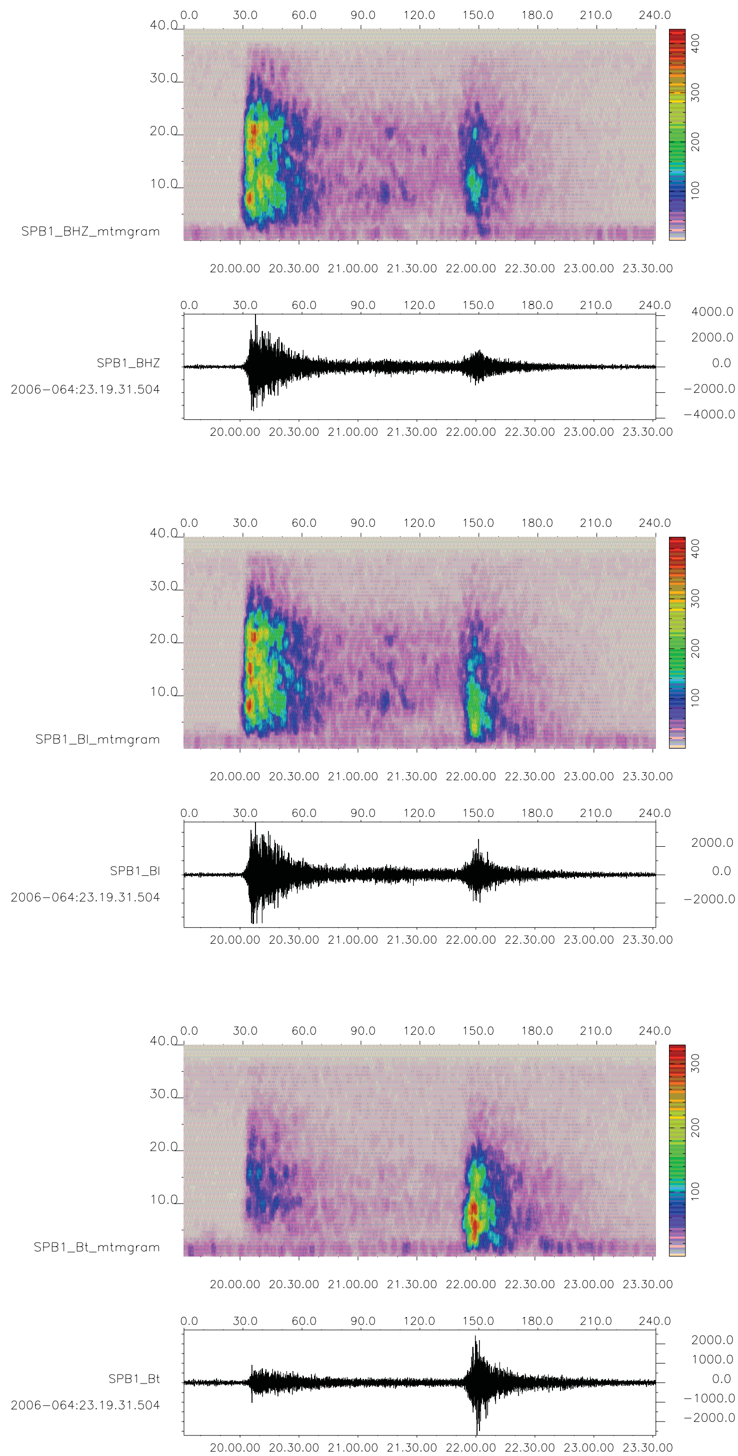

Fig. 6.1.2. Spectrograms for the Spitsbergen B1 seismometer for the Novaya Zemlya event on 5 March 2006. Top: vertical component; middle: longitudinal rotation; bottom: transverse rotation. The waveform traces are filtered with a 2 Hz high-pass filter. See text for details.

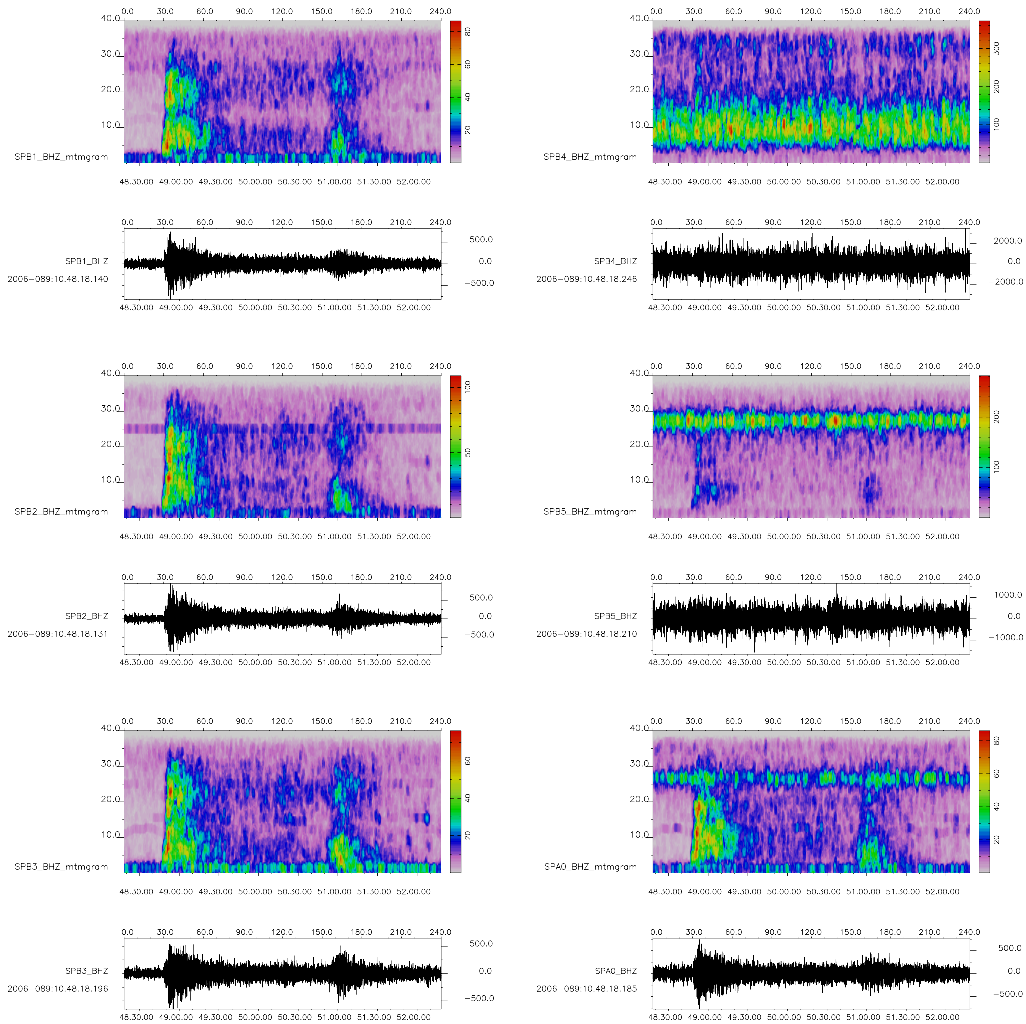

Fig. 6.1.3. Spectrograms for the Spitsbergen A0 and B-ring seismometers (vertical components) for the Novaya Zemlya event on 30 March 2006. The waveform traces are filtered with a 2 Hz high-pass filter. See text for details.

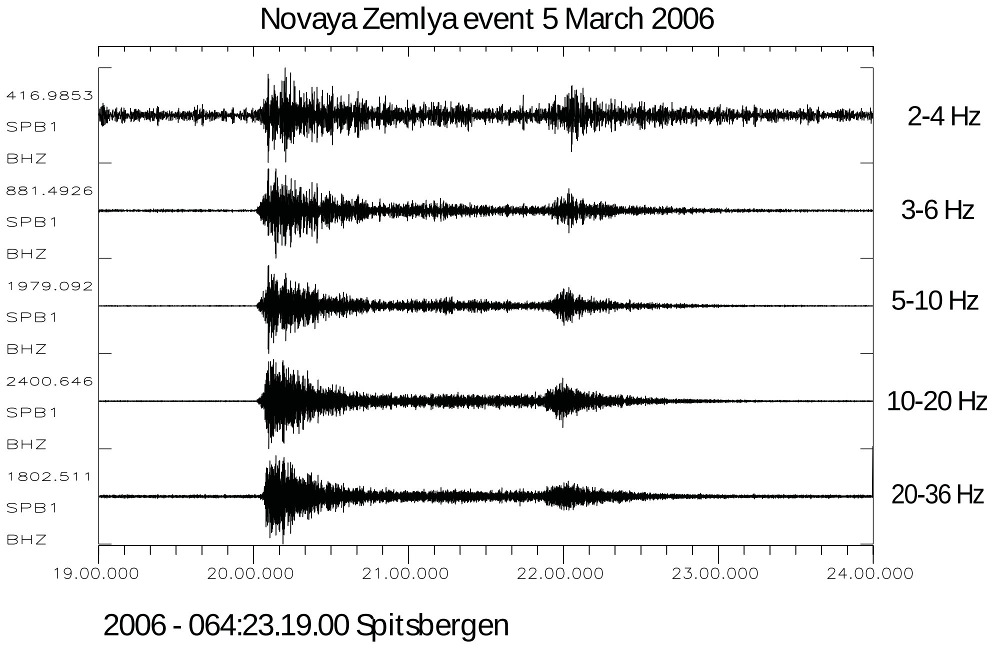

Fig. 6.1.4. ***Spitsbergen seismometer B1 recording for the 5 March 2006 Novaya Zemlya event, filtered in various passbands . Note the strong SNR even at the highest frequencies (20-36 Hz).***

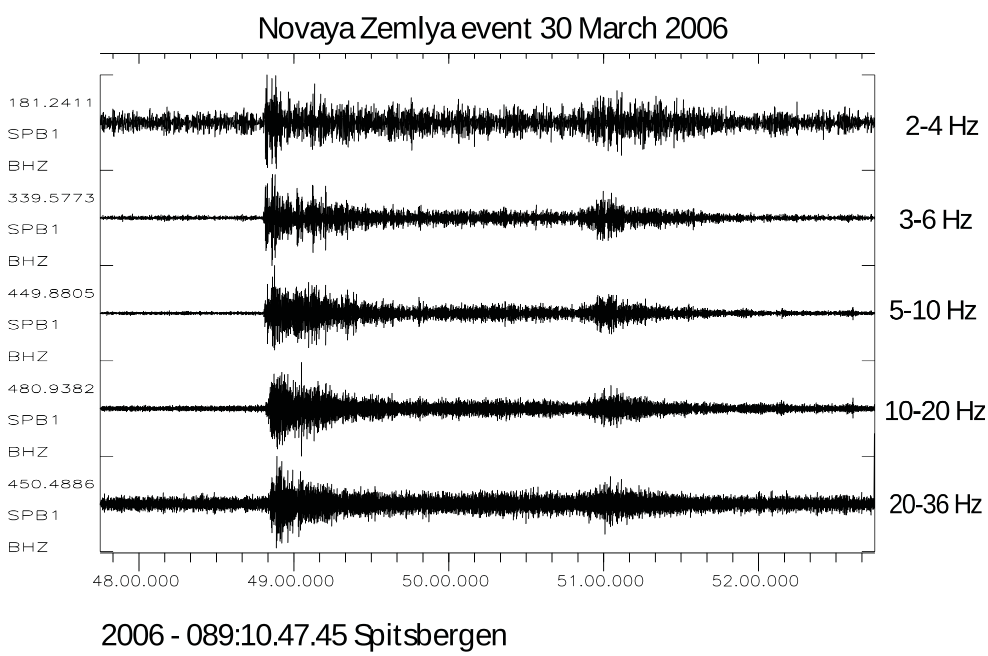

Fig. 6.1.5. ***Spitsbergen seismometer B1 recording for the 5 March 2006 Novaya Zemlya event, filtered in various passbands. Although the SNR is less than for the 5 March event, there is still significant signal energy in all of the frequency bands.***

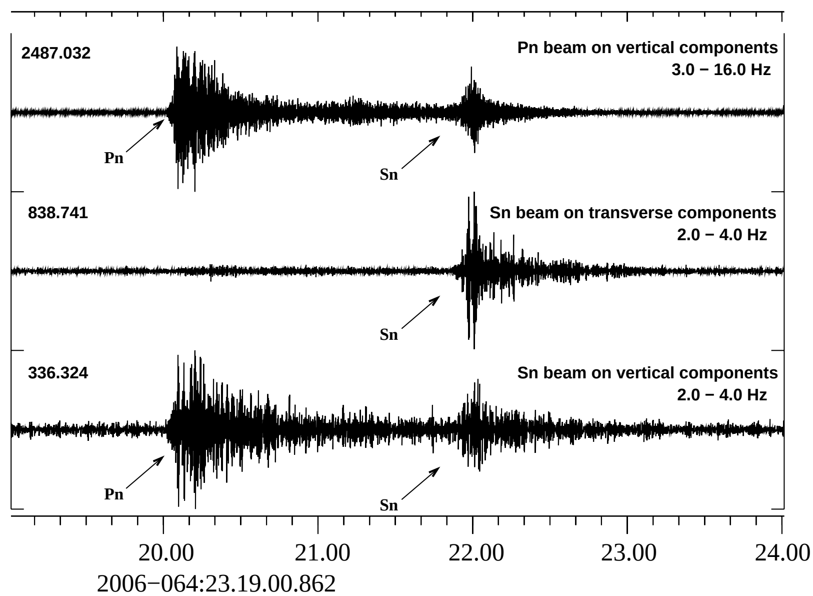

Fig. 6.1.6. ***Spitsbergen array waveforms for the 5 March 2006 Novaya Zemlya event. Note the greatly improved SNR gain for the Sn phase shown in middle trace, which represents the beams of the transverse components of the six three-component seismometers in the array.***

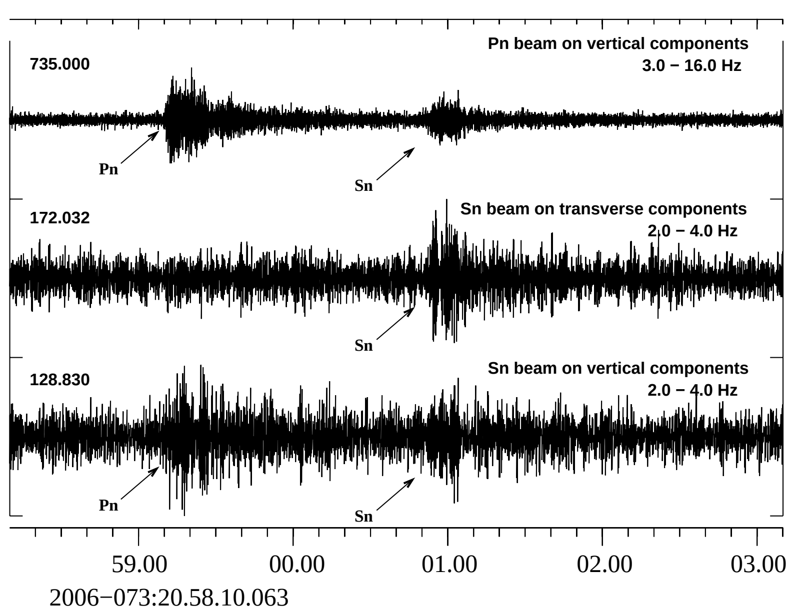

Fig. 6.1.7. ***Spitsbergen array waveforms for the 14 March 2006 Novaya Zemlya event.***

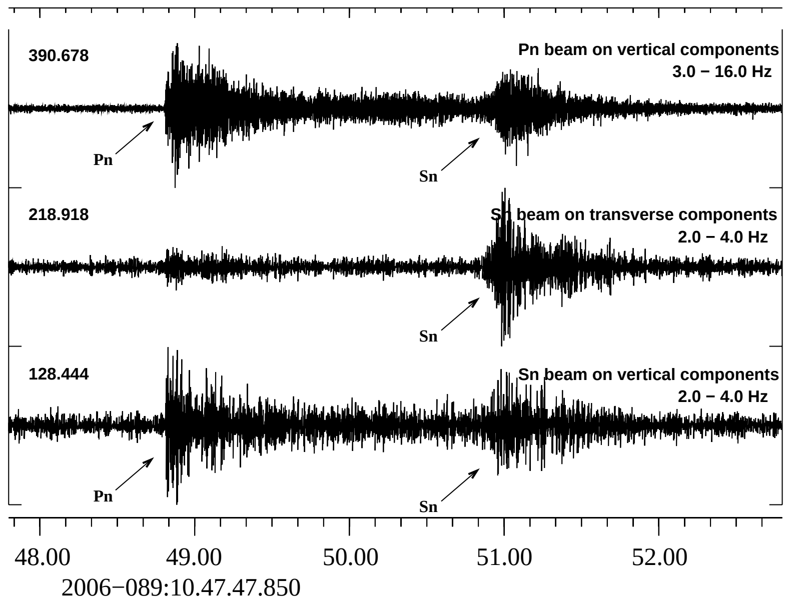

***Fig. 6.1.8.** Spitsbergen array waveforms for the 30 March 2006 Novaya Zemlya event.*