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7.4 Study of low-magnitude seismic events near the Novaya Zemlya nuclear test site

Introduction

The seismic component of the envisaged CTBT International Monitoring System (IMS) has for some years been nearly complete in Fennoscandia and adjacent regions. This means that the projected capabilities of the monitoring system in these areas can be assessed with basis in actually observed performance of the regional array network in Northern Europe. In particular, the capabilities of this network are representative when it comes to monitoring low magnitude seismic events, since such events would not usually be detectable at teleseismic distances. Thus, even though additional high-quality teleseismic stations in other regions are planned to be included in the IMS network at a later date, the capabilities of the global network to detect and locate small events in the region surrounding Fennoscandia will remain largely unchanged.

Of particular interest is to evaluate the performance of the regional network for seismic events in Novaya Zemlya. These islands comprised one of the two main USSR nuclear test sites for many decades, and became, after the breakup of the USSR, the only designated nuclear testing grounds in the Russian Federation.

This paper provides a brief overview of the history of underground nuclear testing at Novaya Zemlya, with a discussion of the seismic recordings both by the global network and the regional array network in Fennoscandia. This is followed by a discussion in some detail of seismic events at Novaya Zemlya other than the announced nuclear explosions. We focus in particular on some recent, low-magnitude events, for which an excellent coverage of regional arrays has been available.

This paper makes mainly use of seismic stations actually envisaged for the IMS. However, we also use supplementary data from other stations when appropriate, and also make an assessment of the potential contributions of such supplementary data in a CTBT monitoring context.

Station network

The network of regional arrays used in this study is shown in Fig. 7.4.1 and has been described in previous NORSAR Semiannual Technical Summaries. It comprises in general small-aperture arrays, supplemented by the large NORSAR array which has been in operation since 1970. For events occurring before 1985, the NORSAR data have been the main source of information on small events at Novaya Zemlya, whereas for later years, the regional network has provided a significant improvement in monitoring capability for this region.

The first regional array, NORESS, was established in southern Norway in 1984, and has formed the standard for later development of such arrays worldwide, both with regard to array geometry, instrumentation and processing techniques. While NORESS and ARCESS (in northern Norway) were configured with as many as 25 SP sensor sites deployed over an area of 3 km in diameter, most of the arrays constructed later have been somewhat smaller. Thus, the FINESS array has 16 sites and about half the aperture of NORESS, whereas there are 9 sites within an area 1 km in diameter for the arrays at Spitsbergen and Apatity. The recently installed Amderma array is an example of a microarray (Kværna and Ringdal, 1992), comprising 4 SP sites, with a 3-component seismometer in the center, and an aperture of only about 100 m.

All of the arrays in the regional network, with the exception of Amderma, have telemetry to the NORSAR data center at Kjeller. This enables continuous automatic detection processing to be made, supplemented by interactive analysis of the detected signals. The resulting regional bulletins complement the bulletins produced at the GSETT-3 IDC, and provide a useful reference for evaluation and calibration purposes. NORSAR has produced such regional bulletins since 1989.

The regional processing algorithms in use at the NORSAR Data Center comprise 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 approach (Ringdal and Kværna, 1989) to associate phases from all stations in the regional network, and thereby provide automatic network locations for events in all of northern Europe.

The processing steps described above result in an automated bulletin that is made available on-line via the Internet. Experience over the past several years has demonstrated that the procedure described above is extremely efficient, and is furthermore "complete" in the sense that it provides an exhaustive search of all possible phase combinations that could correspond to real events. The processing steps described above have now been adopted, with appropriate modifications, at the IDC for global processing, and are also gaining use for other networks.

Seismic events at Novaya Zemlya

Confirmed underground nuclear explosions

A comprehensive list of nuclear explosions in the former USSR has recently been published by Russian authorities (Mikhailov et al, 1996). Table 7.4.1 lists the 42 announced underground explosions that have taken place from 1964 through 1990 at these testing grounds. The table contains comments on the detection of these explosions by the global network of seismograph stations. As can be seen, all of the larger explosions have been well recorded teleseismically, and have been listed in the bulletins of the International Seismological Centre (ISC) and the US National Earthquake Information Service (NEIS). In those cases where two explosions have been carried out simultaneously, only one entry is listed in the global bulletins.

One of the explosions, on 27 July 1972, has not been detected by the global network. We have reviewed the automatic NORSAR detection list for this particular day, and found no detection that could correspond to a Novaya Zemlya explosion. This indicates that the explosion must have been very small, probably below m_b 3.0, which is the approximate detection threshold of the automatic processing at NORSAR. Since the raw data for this day has not been retained, we have not been able to go back and use optimized processing techniques to try to detect this event by more specialized methods than those applied routinely, and we are therefore not in a position to provide a more precise upper limit on the magnitude of this event. Nevertheless, the large scaled depth of this explosion (>400m/(kt)$^{1/3}$ according to Russian sources) suggests that it went off at a yield significantly below the planned yield.

The magnitudes listed in Table 7.4.1 are station-corrected m_b, most of them from Lilwall and Marshall (1986). For events not listed in their paper, we have calculated m_b in a way consistent with their estimates, using either world-wide data or NORSAR recordings.

Other detected seismic events

Very few Novaya Zemlya seismic events apart from the nuclear explosions listed in Table 7.4.1 have been detected by the available station network over the past 25 years. A list of such events, detected either by the global network, by NORSAR or by the regional array network described above, is given in Table 7.4.2. Below, we comment briefly on some of these events, while others will be discussed in more detail in the subsequent sections.

The events in 1973-74, which were all near the southern Novaya Zemlya test site, are thought to be aftershocks of the very large underground nuclear explosions (several megatons yield) at that time. A detailed description of the aftershocks for the first 4 hours following the explosion on 27 October 1973 has been published by Israelson, Slunga and Dahlman (1974).

The event on 1 August 1986 has been analyzed by Marshall, Stewart and Lilwall (1989), who found that this event could be confidently classified as an earthquake at a depth of 24 km. This is the only confirmed, teleseismically recorded, earthquake that is known from this region. In fact, Marshall et al (1989) in their analysis of the 1 August 1986 Novaya Zemlya earthquake, noted that all previous teleseismically detected signals from this region appear to have been resulting from nuclear tests or post-test tectonic activity such as cavity collapses and aftershocks.

It is interesting to note that all of the events in Tables 7.4.1 and 7.4.2 with magnitude 4.0 and higher have been reported in the ISC bulletin, while almost none below this threshold have been listed. This performance is generally consistent with the expected teleseismic detection capability of the global network, which, according to the estimates by Ringdal (1986) would be approximately m_b=4.0 at the 90 per cent level for the Novaya Zemlya region.

NORSAR P-wave recordings of selected events

The large-aperture NORSAR array is situated about 20 degrees from Novaya Zemlya, and has an excellent detection capability for events from this area. The recorded waveforms are usually complex and very high-frequent due to the short epicentral distance and triplication effects caused by heterogeneities in the upper mantle. The signal amplitude variation across the array is quite large, which is a feature attributed to upper mantle focusing effects that is generally typical for signals recorded at this array, at regional as well as teleseismic distances (Ringdal and Husebye, 1982).

A study of such focusing effects for Novaya Zemlya events has been carried out by Ringdal (1990). Fig. 7.4.2 shows the typical amplitude pattern at NORSAR for events from the northern test site. The amplitudes vary by an amount corresponding to more than one magnitude unit, with the strongest signals recorded at subarrays 02C and 03C. In particular, the site at 03C01 has very high amplitudes, even compared to other sites in the same subarray. The amplitude pattern across 02C is much more consistent. Fig. 7.4.3 illustrates the variability in signal shapes and amplitude levels for one of the events in the data base.

In practice, detectability is determined by the signal-to-noise ratio in the "best" frequency band. For NORSAR recordings of Novaya Zemlya events, the filter band of 2.5-4.5 Hz is close to optimum, and because of the amplitude variations described above, the "best" single sensor or subarray has a SNR comparable to or higher than the full array beam. Thus, the focusing effects can be exploited to obtain improved detectability.

Figs. 7.4.4 and 7.4.5 give comparisons of NORSAR P-wave recordings of 3 small events in the data base, one of which is a nuclear explosion. A comparison of the waveforms reveals no significant differences in signal shapes, except for such differences that could be attributed to local (near-source) geology and seismic noise interference, and thus indicates that all of these events are likely to be of a similar source nature. Presumably, the two unknown events are chemical explosions conducted at the test site.

The examples given previously show that seismometers located at sites with favorable receiver effects can be exploited to provide improved detectability, and indicate that signals well below magnitude 3.0 could be detected, using an appropriate high-frequency filter, at a single NORSAR sensor or subarray. Nevertheless, the traditional detection algorithms employed at NORSAR require detection on an array beam in order to provide a location estimate, and high-frequency filters have not been routinely applied in the past. In practice, the actual detection capability of NORSAR, as represented by events listed in the NORSAR bulletin, is estimated to approximately $m_b = 3.0$ for the Novaya Zemlya region. For the years 1970-1990, the list of detected events provided in Tables 7.4.1 and 7.4.2 can therefore be expected to be nearly complete at m_b 3.0 and above.

Recent events recorded by the regional network

As earlier mentioned, the capabilities for monitoring Novaya Zemlya have significantly improved in recent years, with the installation of a high-quality regional array network in Fennoscandia and adjacent regions.

On 31 December, 1992, the regional array system detected and located a small seismic event (m_b=2.7) near the northern Novaya Zemlya test site. This event has been extensively analyzed by the nuclear monitoring community (see e.g. Ryall, 1993). The general consensus in these analyses was that the event could not be confidently classified as either an earthquake or explosion, based on the available data.

On 13 June 1995, the GSETT-3 IDC reported a small seismic event (m_b=3.4) near Novaya Zemlya, Russia. The estimated epicenter in the REB was 75.32°N, 54.85°E, placing the event approximately 100 km west of the islands, but the location error ellipse was rather large and an onshore location could not be excluded. The event was re-analyzed by Ringdal (1996), who located the event near the shore of the northern Novaya Zemlya island, but still at a significant distance from the test site.

On 13 January 1996, the ARCESS and Spitsbergen arrays detected a small seismic event (m_b=2.4) close to the epicenter of the 13 June 1995 event. Although both stations were participating in the GSETT-3 experiment at the time, the IDC did not report the event, presumably because it did not satisfy the criteria imposed to form an event.

It might be of interest to comment briefly on the performance of the automatic detector algorithms employed at the NORSAR data center for such small events. As an example, Table 7.4.3 shows the automatic detection log for the Spitsbergen array during the time periods of the 13 June 1995 and 13 January 1996 events. It can be seen that several phases with consistent azimuths are detected in each case, and that the estimated velocities can be readily used to assign phase type (P or S) to each detection. Note in particular the interfering phase for the 13 January event — this is discussed later in the text.

These three seismic events recorded since 1990 are of special interest in a seismic monitoring context, since they can serve to illustrate the capabilities and limitations of the envisaged International Monitoring System. In the following we present an analysis of these events in some detail, with comparisons to previously recorded underground nuclear explosions at Novaya Zemlya.

Location of the three events since 1992

Fig. 7.4.6 shows our epicentral locations, with error ellipses, of the events of 31 December 1992, 13 June 1995 and 13 January 1996. The figure also shows the approximate geographical extent of the Novaya Zemlya nuclear testing grounds.

As is well known, the 31 December 1992 event was quite close to the test site, and our error ellipse does not exclude a possible on-site location. We note that analysis of this event by other authors has given a smaller error ellipse in some cases (with no overlap with the test site). However, as appropriately noted by both Ryall (1993) and Israelson (1993), there are many unknown factors in the regional calibration for this area, and arrival times are difficult to compare between large and small events, due to the emergent onset of regional phases. It should also be noted that a key station like Spitsbergen has no recordings for known nuclear explosions that could be used for calibration purposes.

The analysis of the 13 June 1995 event has been based on recordings obtained at the three regional arrays Spitsbergen, ARCESS, and Amderma in the distance range 7-10 degrees, whereas we have used only ARCESS and Spitsbergen for locating the 13 January 1996 event. Figs. 7.4.7 and 7.4.8 show filtered Spitsbergen records (4-8 Hz) of a P-beam, an S-beam and one vertical sensor from each of these two events, and it is seen that both the Pn and Sn phases can be clearly identified.We have not been able to observe any Lg phase for these event at Spitsbergen or ARCESS, probably due to the Lg blockage associated with thick sedimentary layers below the Barents Sea as noted in numerous earlier studies. At Amderma, a low frequency Lg phase could be observed for the 13 June 1995 event (Ringdal, 1996), but we have not made use of it in this study.

The events of 13 June 1995 and 13 January 1996 appear to have occurred at approximately the same place, and can with high confidence be located near the coast of the northern Novaya Zemlya islands. Without question, these two events were located at a considerable distance from the northern testing grounds.

Waveform comparisons

It is interesting to compare the waveform characteristics of the small events discussed above to previous nuclear explosions at Novaya Zemlya. In particular it would be of interest to see whether or not it might be possible to "screen out" such events in an automatic screening procedure as envisaged in the CTBT protocol. While we have not at this stage attempted to develop specific screening criteria, there are some obvious comparisons that could be applied to get an indication of how such a procedure might work. We will briefly address this issue in the following.

We have made waveform comparisons of the 5 most recent events at Novaya Zemlya using the ARCESS array. The reason for selecting ARCESS is that this is the only station for which we have high SNR recordings of both the three recent small events and of previous known nuclear explosions. Fig. 7.4.9 shows, as a representative example, ARCESS data from the D4 sensor filtered in a 4-8 Hz band for five events: 13 January 1996, 13 June 1995, 31 December 1992, 24 October 1990 and 4 December 1988 (the latter two being confirmed nuclear explosions).

From Fig. 7.4.9 we note first of all the large differences in SNR as indicated by the amplitude scaling in front of each trace. This is of course due to the differences in event size — the two confirmed nuclear explosions being 2-3 magnitude units larger than the other events. The P-to-S ratios are of particular interest. The S phase is relatively much stronger for the three smaller events, although there is some difference also between the two nuclear explosions.

In Fig. 7.4.10, which shows the same sensor filtered in a high-frequency band (8-16 Hz), the difference in P/S ratio between the two nuclear and the three unknown events is even more pronounced. However, it is premature to draw any firm conclusions about the source type from these observations. First of all, the inherent variability in P/S ratio for the same source type is unknown, and the significance of the observed differences in these ratios is therefore not possible to assess. Moreover, source scaling may be a factor in explaining this difference.

We also note from these two figures that the P/S ratios of the 13 January 1996, 13 June 1995 and the 31 December 1992 events are quite similar in both frequency bands. (The P-S time difference is slightly larger for the former two events because of a greater station-to-event distance.) Again, however, we cannot confidently state that these three events are of the same source type, but the short period data shown are certainly consistent with such a hypothesis.

Magnitudes

In view of the different P/S ratios shown earlier for the five events, their relative magnitudes, as estimated from ARCESS data, would show a different pattern if we use P-phases or S-phases (or S coda phases) for magnitude estimation purposes. We have chosen to use the P-phase in this study and Fig. 7.4.11 shows the P-beam in the 2-4 Hz filter band at ARCESS for the 5 events discussed above. The resulting magnitude (m_b) values are listed in Table 7.4.4.

Our reason for selecting the 2-4 Hz band is that this band is close to the frequencies used at teleseismic distances for m_b computation. In fact, small-aperture arrays in shield areas (such as NORESS and ARCESS) usually have their best teleseismic SNR in this filter band or a band close to it. We note, however, that for events at regional distances, it might sometimes be necessary to choose a higher filter passband, especially for small events with little or no "low frequency" signal energy. This would, because of source-scaling effects, cause a shift towards relatively higher magnitudes for smaller events, when comparing them to larger events with the same filter.

To illustrate this point, we can consider the two filters previously shown (Figs. 7.4.9 and 7.4.10) for ARCESS, and assess the relative sizes of the P-waves in these filter bands. We have found it reasonable to use the single sensor (D4) displayed in these figures, rather than the array beam, in order to avoid beamforming loss at these high frequencies. We use the peak amplitudes of P in each filter band as representative of the relative mb values. The relative magnitude increase for the smaller events at high frequencies is up to 0.5 m_b units, as is reflected in the m_b values listed in Table 7.4.4. This confirms that calculation of magnitudes at regional distances can easily result in ambiguous values. The frequency range of the recorded signal must be given special consideration, and must probably be compensated for by some empirical formula.

Finally, we have looked at the surface waves for the events recorded by the regional network. Once more, the ARCESS array is the most useful reference system. Not unexpectedly, it has been impossible for us to detect surface waves from the two smallest events (31 Dec 92 and 13 Jan 96), but the event of 13 June 95 is large enough to be of interest in this connection. Ringdal (1996) showed narrow-band filtered long period recordings (0.04-0.06 Hz or 17-25 seconds) for the ARCESS center sensor for the two events 24 October 1990 and 13 June 1995. The surface waves for the first event were clearly seen, and the M_s is estimated to 3.5 using Marshall and Basham's (1972) formula. The surface waves of the 13 June 1995 event were marginal, but appeared to just exceed the background noise. The corresponding M_s for this event would be 2.4, using the same formula.

While the M_s:m_b is an effective discriminant at teleseismic distances, its performance in the regional range is not generally proven (recall that the distance from ARCESS to the two events is 10-11 degrees). The values for 13 June 1995 (m_b=3.5, M_s=2.4) would seem to place this event in an intermediate category between the "expected" earthquake population and explosion population, but an appropriate reference data base is not available for this region. It should also be noted that these single-station magnitudes (in particular the M_s value) have a fair amount of uncertainty. Thus, the M_s:m_b data cannot conclusively be used to identify the 13 June 1995 event, but a reasonable screening criterion based on M_s:m_b would probably point out this event as a candidate for more extensive analysis. For the two smallest events (m_b below 3.0), surface waves are not possible to extract with the available station data, and M_s:m_b is therefore not applicable.

Some comments on the location of the 13 January 1996 event

The location of the Novaya Zemlya event of 13 January 1996 has been the subject of considerable debate among seismologists, as discussed in the paper by van der Vink and Wallace (1996). To our knowledge, location estimates for this event range from several tens of kilometers west of our location to as much as 100 kilometers away. We will briefly discuss some of the uncertainties that in our opinion have led to these widely diverging estimates.

We first note that this event has been particularly difficult to locate precisely. In fact, the event serves well to illustrate that very careful analysis is required in order to avoid large location errors when using a sparse network. The problems in this case are twofold:

1. With only two arrays available and poor azimuthal resolution, the application of properly calibrated travel-time curves becomes essential.
2. At one of the arrays (Spitsbergen) there is an interfering local signal immediately preceding the S phase of the Novaya Zemlya event, thus causing problems in reading the S onset.

In the following, we comment briefly on these two points.

Effects of uncalibrated travel-time curves

There are several regional travel-time curves available for the Fennoscandian-Barents region, and Figure 7.4.12a) compares the model used at NORSAR to the IASPEI 1991 model. The figure shows Sn-Pn times as a function of epicentral distance (zero depth), and illustrate the typical systematic bias that could be introduced at a distance of 9-10 degrees if uncalibrated travel-time curves are used. It is seen that this bias alone can cause an error in the distance estimate from a given station of about 60 km. It might be noted that for the 13 January 1996 event, the distance relative to Novaya Zemlya is largely governed by the S-P time of the Spitsbergen array. Thus the application of an uncorrected model to locate this event would result in a location estimate close to 60 km offshore, even if the correct phase readings are made.

Effects of the interfering phase at Spitsbergen

It appears that the S-phase at the Spitsbergen array is preceded by an interfering high-frequency local P-phase, probably originating from an earthquake on the North Atlantic Ridge near 80N, 9E. This is illustrated in Fig. 7.4.13, which shows one sensor trace (B2) filtered in different frequency bands, together with array f-k analysis results. The first arriving phase has a P-type apparent velocity and an azimuth toward the northwest, and the spectral characteristics of this phase are very different from the real S-phase that has an onset about 5 seconds later. As can be seen, the f-k results from this second phase show an S-velocity and an azimuth toward east, in the direction of Novaya Zemlya.

Moreover, we have analyzed recordings from the IRIS station at Kings Bay (KBS), which is situated about 130 km northwest of the Spitsbergen array, and which thus should be closer to the interfering event. This analysis has in fact indicated the presence of both a P and an S phase consistent with such a local event.

It is of course quite a coincidence that this local phase appears just before the S phase of the 13 January 1996 event, but extensive analysis seems to confirm unambiguously that this is in fact the case. It might be noted that local signals are very common at the Spitsbergen array, occurring at a rate of typically several hundred per day, from various azimuths.

With this interpretation, combined with our regional velocity model, the resulting location is at the NZ coast, quite close to the 13 June 1995 event, as previously shown in this paper.

Figure 7.4.12b) illustrates the combined effects of using an uncalibrated velocity model and picking an early arrival (due to the local phase) at the Spitsbergen array. The resulting mislocation would be about 100 km, and this explains the reasons for the very diverging location estimates obtained by different seismologists for the 13 January 1996 event.

An important point resulting from this case study is that locating small events using a sparse network can easily cause ambiguous and sometimes very diverging results, even when the data are analyzed by experts. Awareness of such possible differences in interpretation will be important in a future CTBT monitoring regime.

Conclusions

The Novaya Zemlya region is a low-seismicity area, with only one earthquake clearly identified over the past 30 years. This is in spite of the fact that this area is well covered with regard to seismic stations at both teleseismic and regional distances. Thus, the detection capability of the global network has been estimated at close to m_b 4.0 for Novaya Zemlya. Since 1970, the NORSAR array has provided a detection capability near m_b 3.0. Currently, the detection capability for this area is near m_b 2.5, due to the excellent regional array network that has been developed for CTBT monitoring.

Examples have shown that events of magnitude well below 3.0 can be not only detected, but also located with good accuracy (estimated uncertainty 20-30 km) using the present regional network. However, this capability is by no means matched by the capability to identify detected events as either earthquakes or underground explosions. Even identifying the earthquake of 1 August 1986 (m_b=4.3) was not easy, and required extensive work before a positive identification could be made (Marshall et. al., 1989).

This study has shown that the calculation of body-wave magnitudes at regional distances needs to take into account the bias effects caused when using high-frequency filters. In fact, a positive bias of up to 0.5 magnitude units is introduced in the examples shown here, when comparing a 4-8 or 8-16 Hz filter band to a "teleseismic" 2-4 Hz band.

The 13 June 1995 event provides a particularly interesting case study for the Novaya Zemlya region. It highlights the fact that even for this well-calibrated region, where numerous well-recorded underground nuclear explosions have been conducted, it is a difficult process to reliably classify a seismic event of approximate m_b 3 1/2. It is also shown that supplementary data from a national network can provide useful constraints on event location, especially if the azimuthal coverage of the monitoring network is inadequate. It is clear from this study that more research is needed on regional travel-time calibration, regional signal characteristics and application of M_s:m_b at regional distances. In applying the latter criterion, it would be particularly useful to estimate an upper confidence limit on M_s for events with marginal or non-detected surface waves.

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References

Israelson, H. (1993): Estimates of the epicenter uncertainty for a small Novaya Zemlya event Dec 31 1992, Sci. Rep. No. 1, Center for Seismic Studies.

Israelson, H., R. Slunga and O. Dahlman (1974): Aftershocks caused by the Novaya Zemlya explosion on October 27, 1973, *Nature*, Vol 247 No 5441, 450-452.

Kværna, T. and F. Ringdal (1992): Integrated array and three-component processing using a seismic microarray. *Bull. Seism. Soc. Am.*, 82, 870-882.

Lilwall, R.C. and P.D. Marshall (1986): Body wave magnitudes and locations of Soviet underground explosions at the Novaya Zemlya test site, AWRE Report No. O 17/86, HMSO, London.

Marshall, P.D. and P.W. Basham (1972): Discrimination between earthquakes and underground explosions employing an improved M_s scale. *Geophys. J.R. astr. Soc.*, 28, 431-458.

Marshall, P.D., R.C. Stewart and R.C. Lilwall (1989): The seismic disturbance on 1986 August 1 near Novaya Zemlya: a source of concern? *Geophys. J.*, 98, 565-573.

Mikhailov, V.N. et. al. (1996): USSR Nuclear Weapons Tests and Peaceful Nuclear Explosions, 1949 through 1990, RFNC - VNIIEF, Sarov, 1996, 63 pp.

Ringdal, F. (1986): Study of magnitudes, seismicity and earthquake detectability using a global network, *Bull. Seism. Soc. Am.* 76, 1641-1659.

Ringdal, F. (1990): P-wave focusing effects at NORSAR for Novaya Zemlya explosions, in Report GL-TR-90-0330, Hanscom AFB, Massachusetts.

Ringdal, F. (1996): The seismic event at Novaya Zemlya 13 June 1995. Semiannual Technical Summary, 1 October 1995-31 March 1996, NORSAR Sci. Rep. No. 2 1995/96, Kjeller, Norway.

Ringdal, F. and E.S. Husebye (1982): Application of arrays in the detection, location and identification of seismic events, *Bull. Seism. Soc. Am.* 72, S201-S224.

Ringdal, F. and T. Kværna (1989), A multi-channel processing approach to real time network detection, phase association and threshold monitoring, *Bull. Seism. Soc. Am.* 79, 1927-1940.

Ryall, A. (1993): The Novaya Zemlya event of 31 December 1992 and seismic identification issues. ARPA Rep., 15th Seismic Research Symposium, 8-10 Sep 1993, Vail, Colorado.

van der Vink, G.E. and T. Wallace (1996): The political sensitivity of earthquake locations. In: *IRIS Newsletter*, Vol XV, No 3, 20-23.

Table 7.4.1: List of the 42 underground nuclear explosions conducted at Novaya Zemlya during 1964-1990, as published by Mikhailov et al (1996). Seismic information is taken mostly from ISC or NEIS bulletins, supplemented by m_b values from Lilwall and Marshall (1986).

No	Date	Time (GMT)	Lat	Lon	Depth	mb	Comment
1	64-09-18	7:59:57.8	73.3	55.4	0	4.20	
2	64-10-25	7:59:58.8	73.5	53.7	0	4.82	
3-4	66-10-27	5:57:57.7	73.4	54.9	0	6.47	Double
5-6	67-10-21	4:59:58.4	73.4	54.4	0	5.99	Double
7	68-11-07	10:02:05.3	73.4	54.9	0	6.11	
8-9	69-10-14	7:00:06.2	73.4	54.8	0	6.18	Double
10	70-10-14	5:59:57.1	73.3	55.1	0	6.77	
11	71-09-27	5:59:55.2	73.4	55.1	0	6.63	
12	72-07-27		71.0	54.0			No detection
13	72-08-28	5:59:56.5	73.3	55.1	0	6.46	
14	73-09-12	6:59:54.3	73.3	55.2	0	6.96	
15	73-09-27	6:59:58.0	70.8	53.9	0	5.83	
16	73-10-27	6:59:57.4	70.8	54.2	0	6.90	
17	74-08-29	9:59:55.5	73.4	55.1	0	6.54	
18	74-11-02	4:59:58.0	70.8	53.8	0	6.75	
19	75-08-23	8:59:57.9	73.4	54.6	0	6.55	
20-21	75-10-18	8:59:56.3	70.8	53.7	0	6.70	Double
22	75-10-21	11:59:57.3	73.4	55.1	0	6.59	
23	76-09-29	2:59:57.4	73.4	54.8	0	5.77	
24	76-10-20	7:59:57.7	73.4	54.6	0	4.89	
25	77-09-01	2:59:57.5	73.4	54.6	0	5.71	
26	77-10-09	11:00:00.3	73.6	53.2	0	4.51	
27	78-08-10	7:59:57.7	73.3	54.8	0	6.04	
28	78-09-27	2:04:58.2	73.4	54.7	0	5.68	
29	79-09-24	3:29:58.3	73.4	54.7	0	5.80	
30	79-10-18	7:09:58.3	73.3	54.8	0	5.85	
31-32	80-10-11	7:09:57.0	73.4	55.0	0	5.80	Double
33	81-10-01	12:14:56.8	73.3	54.8	0	5.91	
34	82-10-11	7:14:58.2	73.4	54.6	0	5.52	
35	83-08-18	16:09:58.6	73.4	54.9	0	5.84	
36	83-09-25	13:09:57.7	73.3	54.5	0	5.71	
37	84-08-26	3:30:00.0	74.1	53.8	0	3.80	NORSAR only
38	84-10-25	6:29:57.7	73.4	55.0	0	5.77	

No	Date	Time (GMT)	Lat	Lon	Depth	mb	Comment
39	87-08-02	1:59:59.8	73.3	54.6	0	5.71	
40	88-05-07	22:49:58.1	73.4	54.4	0	5.52	
41	88-12-04	5:19:53.0	73.4	55.0	0	5.79	
42	90-10-24	14:57:58.1	73.4	54.7	0	5.60	

Table 7.4.2: List of additional seismic events at Novaya Zemlya from ISC bulletins, supplemented by NORSAR and regional array data.

No	Date	Time (GMT)	Lat	Lon	Depth	mb	Source
1	73-10-27	7:52:25.8	71.0	52.6	0	4.5	ISC
2	73-10-27	8:03:58.2	71.0	52.7	0	4.5	ISC
3	73-10-27	8:09:36.0	70.7	53.4	0		ISC
4	73-10-27	8:21:21.8	71.0	52.6	0	4.6	ISC
5	73-10-27	8:56:04.0	71.7	50.7	0	4.0	ISC
6	73-10-27	9:13:51.3	71.2	51.8	0	4.6	ISC
7	74-07-07	16:11:02.0	70.9	52.7	0		ISC
8	74-07-22	1:32:21.5	70.7	53.5	0		ISC
9	74-11-02	5:22:38.0	70.8	53.8	0		ISC
10	78-11-15	8:30:00.0	73.4	55.0	0	3.6	NORSAR
11	86-08-01	13:56:37.8	73.0	56.7	24	4.3	Marshall et al
12	87-08-25	14:00:00.0	74.1	54.6	0	3.2	NORSAR
13	92-12-31	9:29:24.0	73.6	55.2	0	2.7	Reg. arrays
14	95-06-13	19.22.37.9	75.2	56.7	0	3.5	Reg. arrays
15	96-01-13	17:17:23.0	75.2	56.7	0	2.4	Reg. arrays

Table 7.4.3: Excerpts of Spitsbergen array automatic detection log corresponding to the times of two events discussed in the text (13 June 95 and 13 January 96). Note the interfering phase on 13 January, marked as *).

	Station	DPX	Arrival_time	Beam	SNR	Vel	Azi	Phase
13 Jun 1995	SPI	911511	164:19.24.54.3	S083	363.10	7.40	98.70	Pn
	SPI	911513	164:19.24.57.8	S021	5.40	6.10	95.80	Px
	SPI	911514	164:19.25.02.1	S077	9.30	7.30	94.00	Px
	SPI	911515	164:19.25.04.7	SI05	5.60	7.60	100.10	Px
	SPI	911518	164:19.25.06.7	SI04	3.20	7.60	94.80	Px
	SPI	911523	164:19.26.38.1	SI05	8.70	3.20	87.10	Sn
	SPI	911525	164:19.26.41.9	S076	8.10	3.80	89.80	Sx
	SPI	911526	164:19.26.42.4	S097	7.80	4.20	95.40	Sx
13 Jan 1996	SPI	620810	013:17.19.38.6	S073	25.20	7.80	98.90	Pn
	SPI	620813	013:17.19.42.3	S084	9.60	7.10	97.20	Px
	SPI	620816	013:17.19.43.0	S058	5.80	7.20	94.40	Px
	SPI	620818	013:17.19.47.9	S074	6.70	7.00	97.30	Px
	SPI	620820	013:17.21.17.3	S066	4.60	12.00	306.90	*)
	SPI	620821	013:17.21.24.3	SI05	6.30	3.70	84.40	Sn
	SPI	620823	013:17.21.26.8	S075	5.50	3.90	83.80	Sx

Table 7.4.4: Magnitudes (m_b and M_s) measured at ARCESS for the five events discussed in the text. The m_b values (2-4 Hz) have been normalized using m_b=5.6 of the 24 October 1990 event as a reference, and the effect of choosing two higher frequency bands is also shown.

	ARCESS m_b	"High-frequency" m_b		ARCESS M_s
	2-4 Hz	4-8 Hz	8-16 Hz	(20 s)
4 Dec 1988	5.67	5.65	5.71	-
24 Oct 1990 (reference)	5.60	5.60	5.60	3.5
31 Dec 1992	2.75	3.16	3.34	-
13 Jun 1995	3.54	3.88	3.85	2.4
13 Jan 1996	2.40	2.62	2.81	-

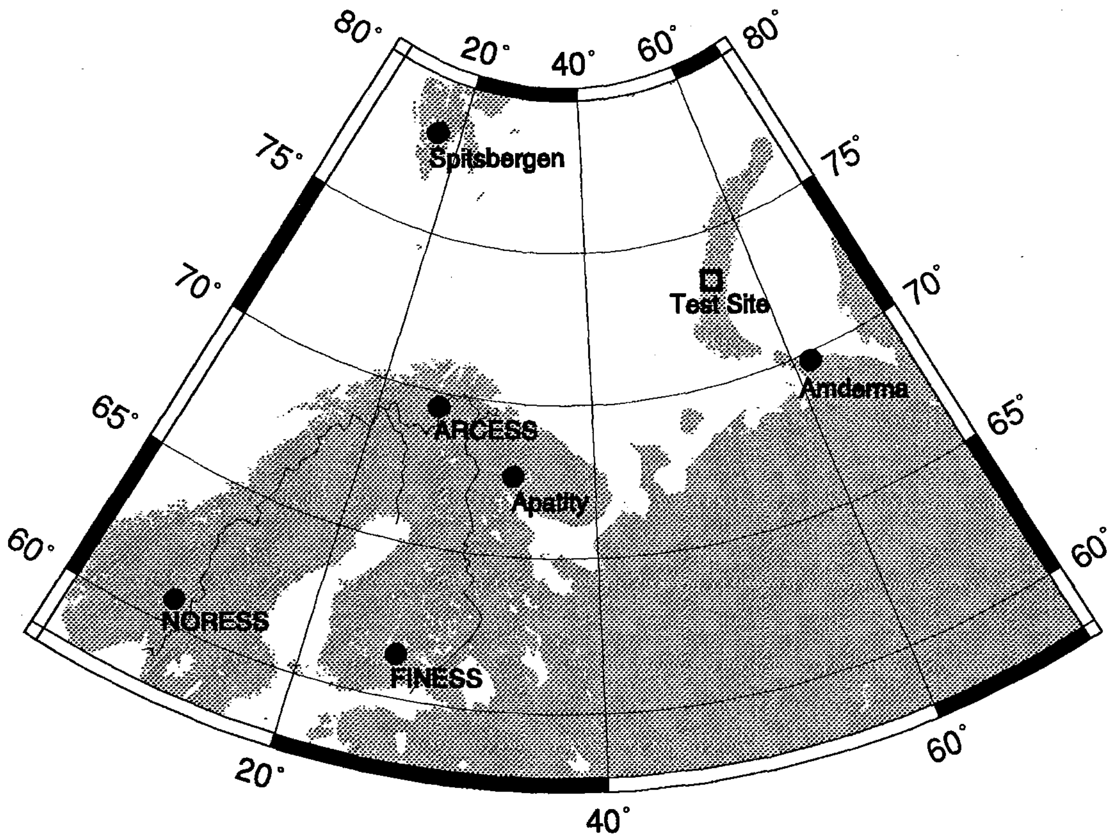


Fig.7.4.1. Map showing the locations of regional arrays in Northern Europe. The location of the northern Novaya Zemlya nuclear test site is also shown.

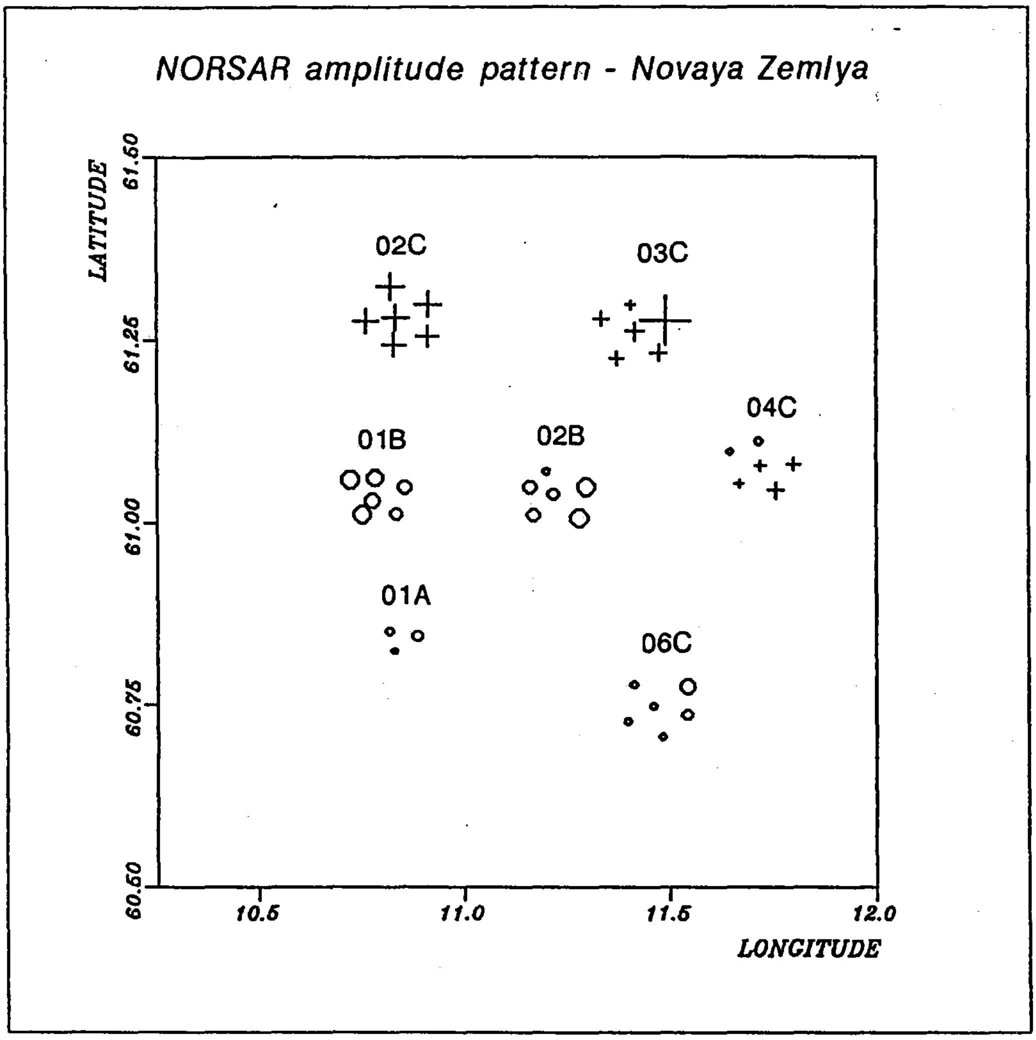


Fig. 7.4.2. Typical P-wave amplitude pattern across the NORSAR array for seismic events from the northern Novaya Zemlya test site. The symbols represent magnitude bias relative to average NORSAR m_b. Plusses indicate positive values), and the symbol size is proportional to the size of the bias. Note the high bias for all sites within subarray 02C, and the especially high bias value at 03C01. The range of the bias values is from +0.9 (03C01) to -0.3 (01B05).

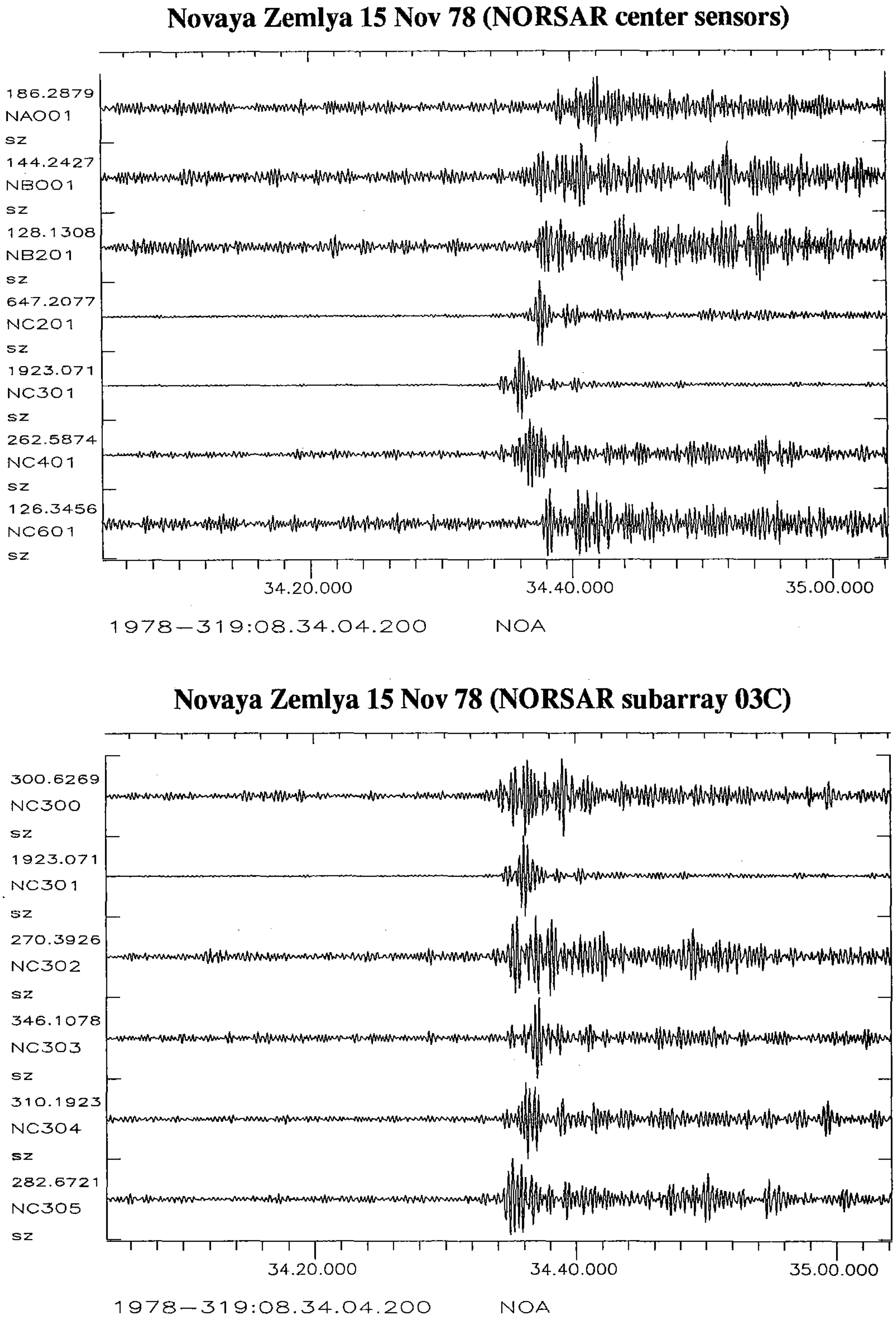
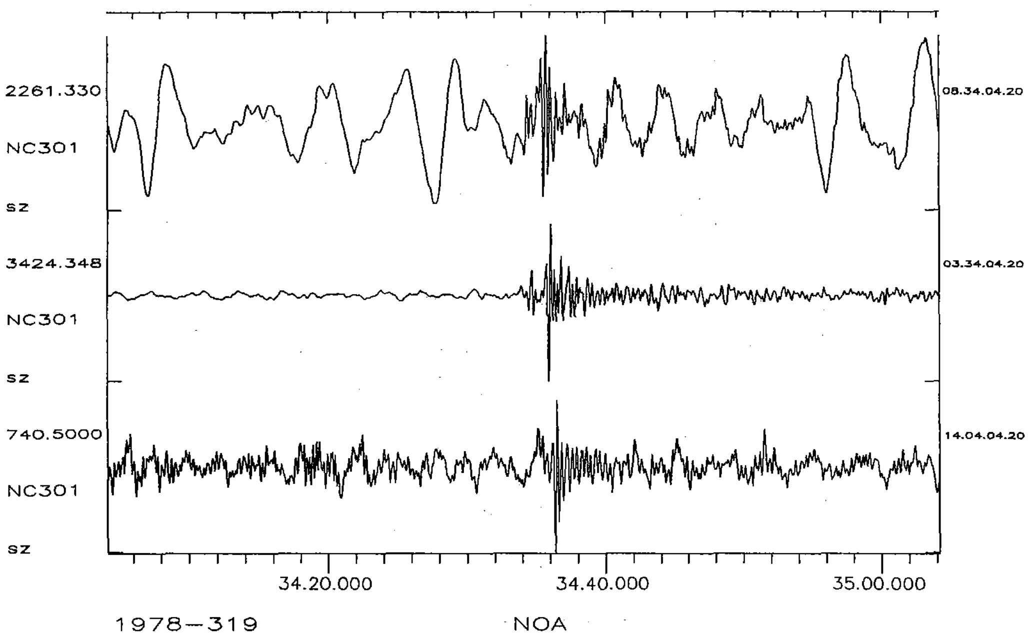


Fig. 7.4.3a and b. Recordings of a Novaya Zemlya event (15 Nov 78) at the center sites of the NORSAR subarrays (top) and at all sites of subarray 03C (bottom). Data have been filtered in the band 2.5-4.5 Hz, and scaling factors are shown to the left of each trace. Note the large variations in amplitudes, signal shapes and signal-to-noise ratios.

NORSAR 03C01 data for 3 Novaya Zemlya events (unfiltered)



NORSAR 03C01 data for 3 Novaya Zemlya events (2.5-4.5 Hz)

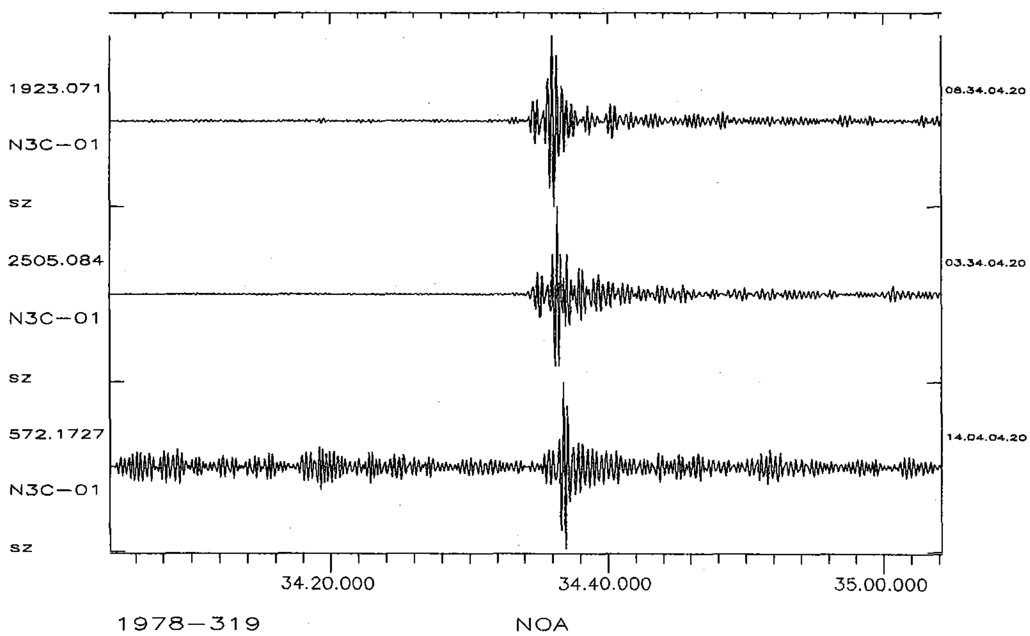


Fig. 7.4.4 a and b. Comparison of recordings at NORSAR site 03C01 for three low-magnitude events near the northern Novaya Zemlya test site (from top to bottom 15 Nov 78, 26 Aug 84 and 25 Aug 87). Data are shown unfiltered (top) and in the 2.5-4.5 Hz passband (bottom). One of these (the middle trace, 26 Aug 84) is a confirmed nuclear explosion. Note the similarity of the three event recordings.

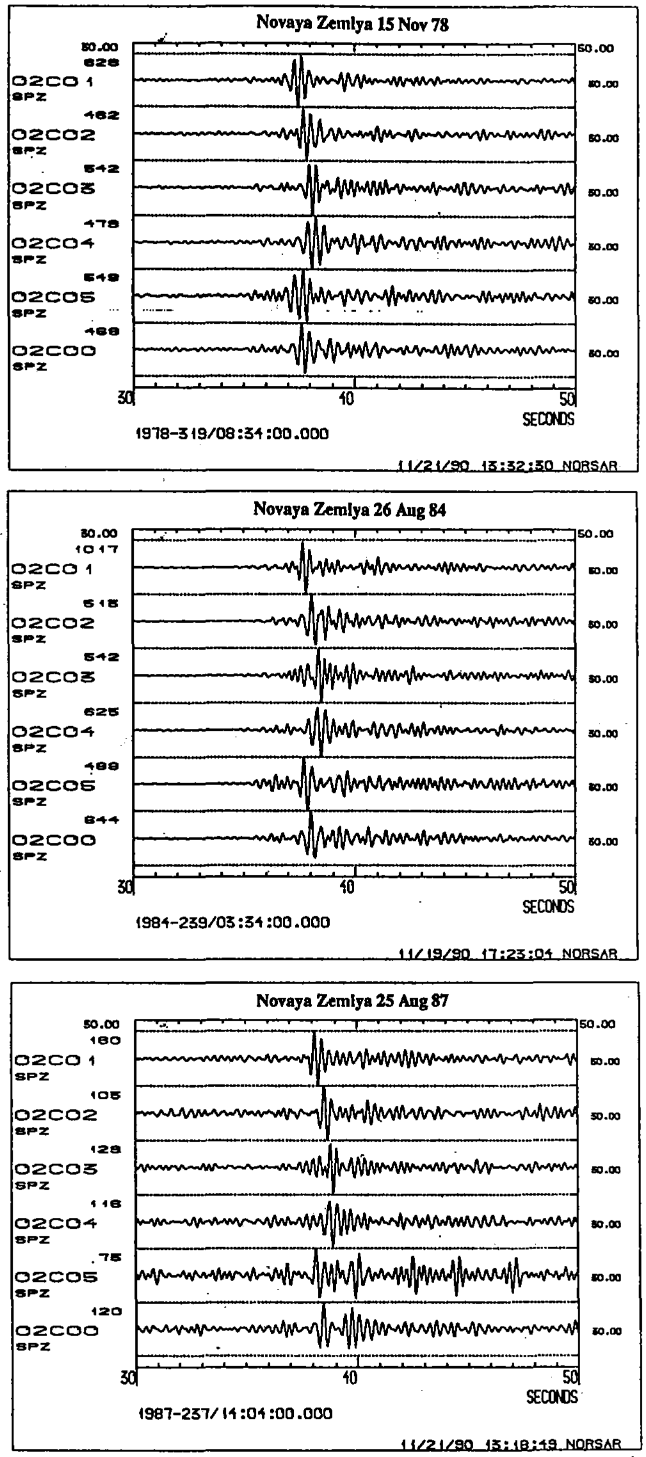


Fig. 7.4.5. Comparison of the same three events as displayed in Fig. 7.4.4, showing the recordings across a NORSAR subarray (02C). The signal patterns are very similar, with slight differences between the events that could be explained by a combination of local (near-source) scattering and interference of background seismic noise.

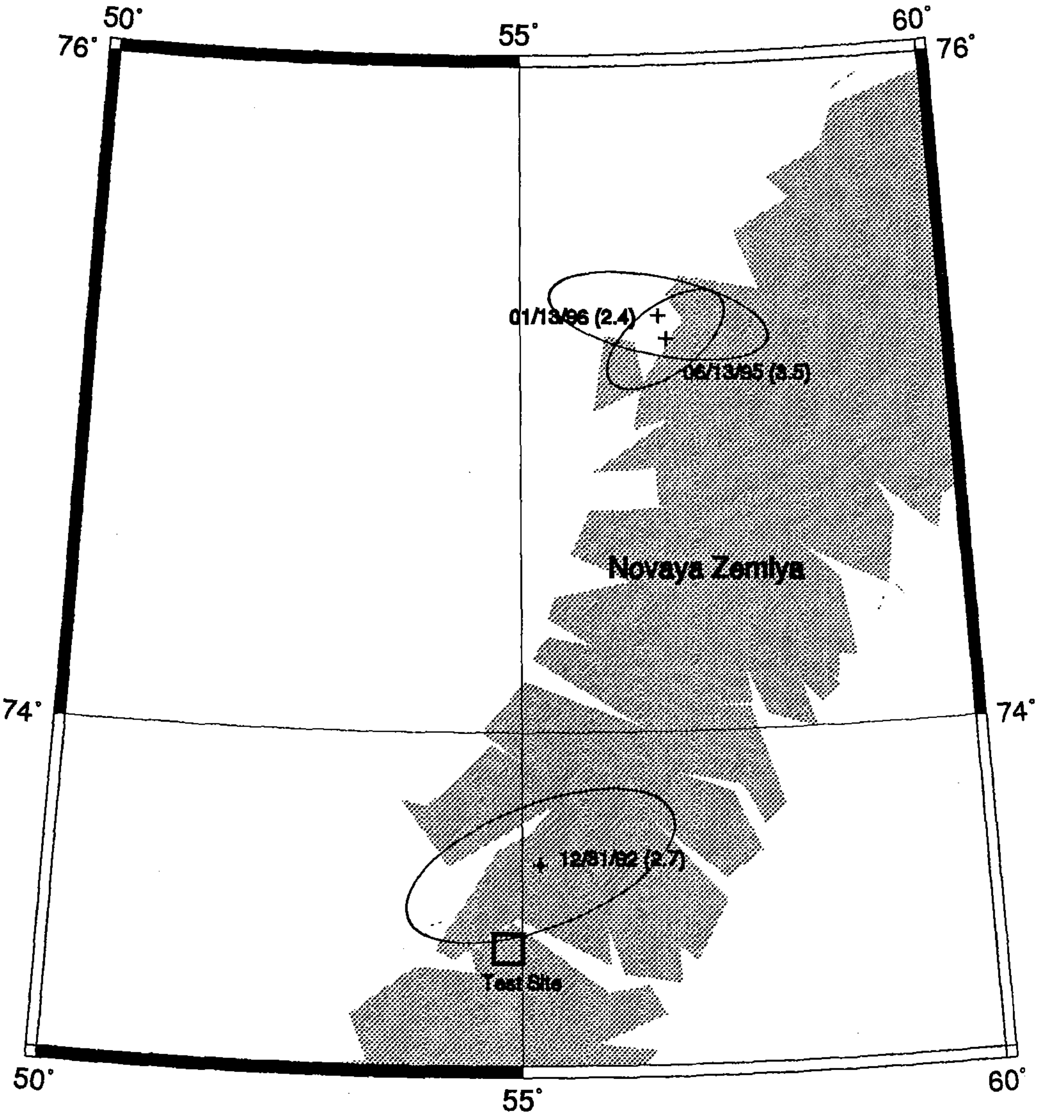


Fig. 7.4.6. NORSAR's location estimates of the three small events at Novaya Zemlya detected since 1992. The error ellipses (90% confidence) are based on assumed prior uncertainties in the regional travel-time tables and onset time readings, and must be taken as only a tentative indication of the actual epicentral accuracy.

Novaya Zemlya 13 Jun 1995 — Spitsbergen

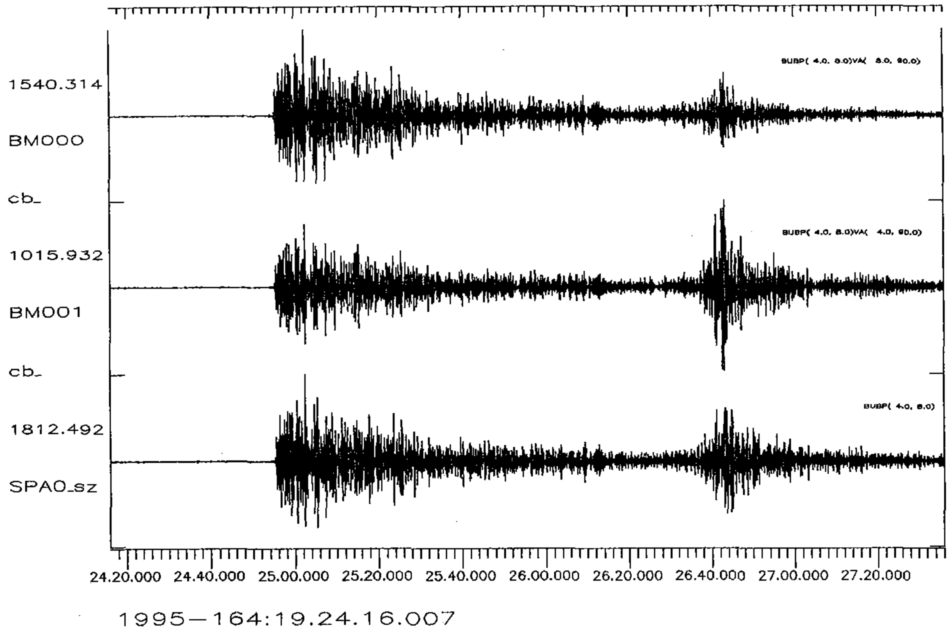


Fig. 7.4.7. Recordings by the Spitsbergen array of the event of 13 Jun 95. The traces represent (from top to bottom) an array beam steered with P-velocity toward the epicenter, an array beam with S-velocity and the array center sensor, each filtered in the band 4-8 Hz.

Novaya Zemlya 13 Jan 1996 — Spitsbergen

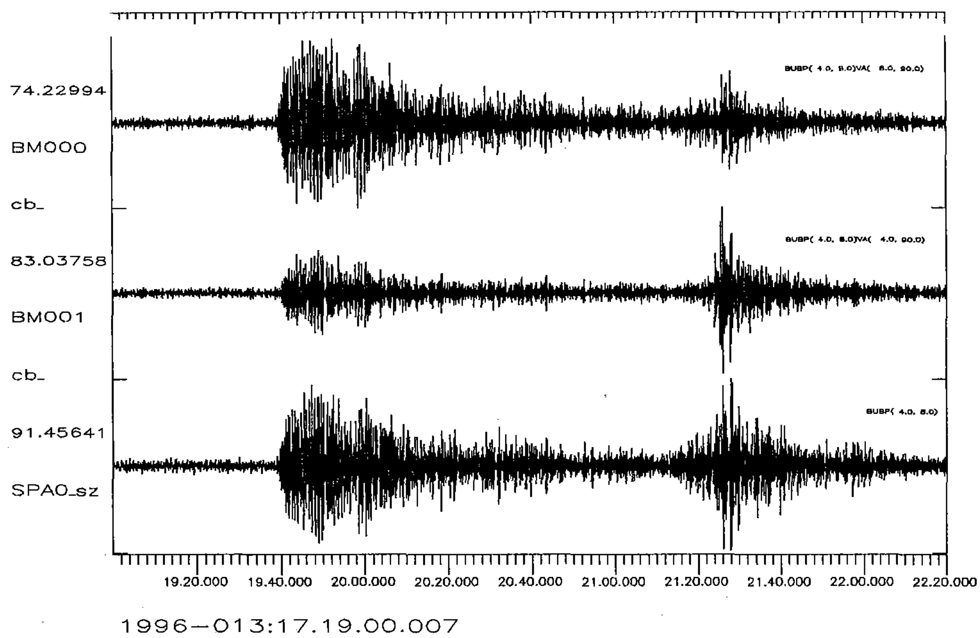


Fig. 7.4.8. Recordings by the Spitsbergen array of the event of 13 Jan 96. The traces represent (from top to bottom) an array beam steered with P-velocity toward the epicenter, an array beam with S-velocity and the array center sensor, each filtered in the band 4-8 Hz. Note the similarity to Fig. 7.4.7.

ARCESS data for 5 Novaya Zemlya events (4-8 Hz)

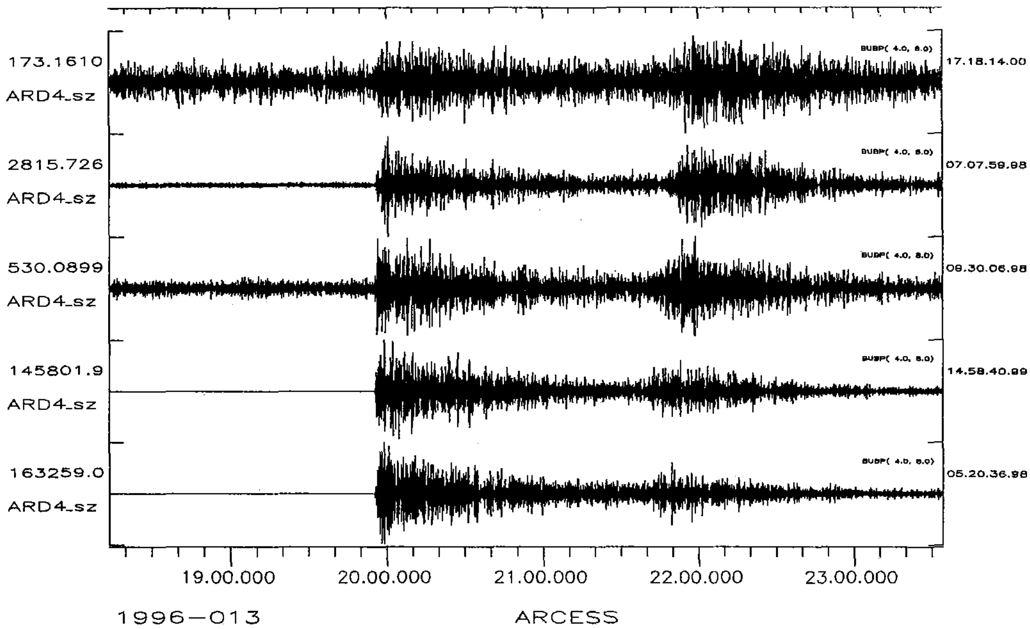


Fig. 7.4.9. Bandpass filtered recordings (4-8 Hz) of the ARCESS D4 sensor for 5 Novaya Zemlya events. From top to bottom: 13 Jan 96, 13 Jun 95, 31 Dec 92, 24 Oct 90 and 4 Dec 88. Note the variations in P/S ratios.

ARCESS data for 5 Novaya Zemlya events (8-16 Hz)

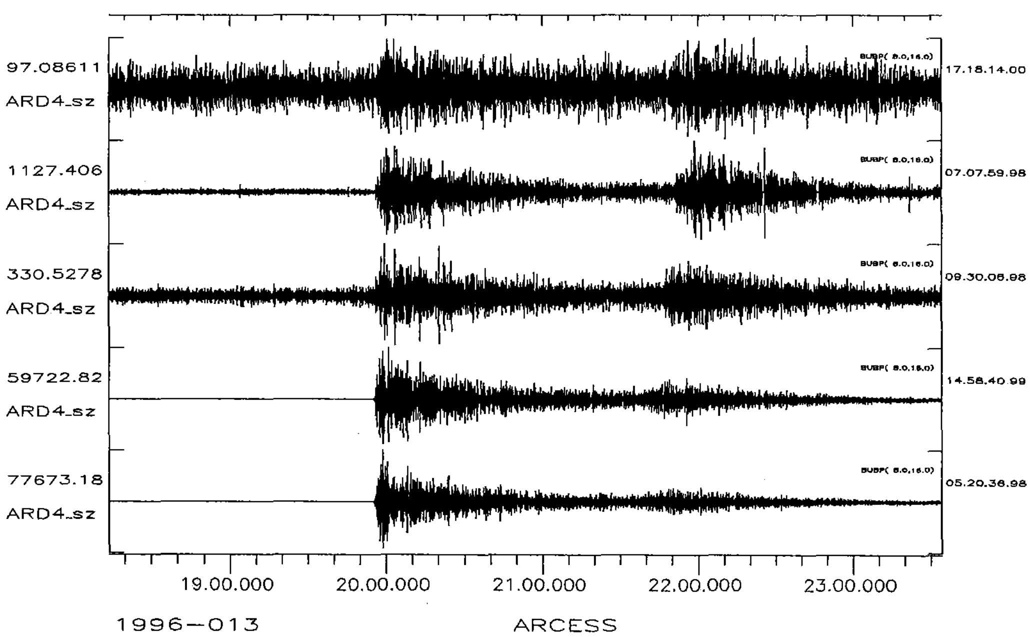


Fig. 7.4.10. Same as Fig. 7.4.9, but for the 8-16 Hz filter band.

ARCESS P-beams for 5 Novaya Zemlya events (2-4 Hz)

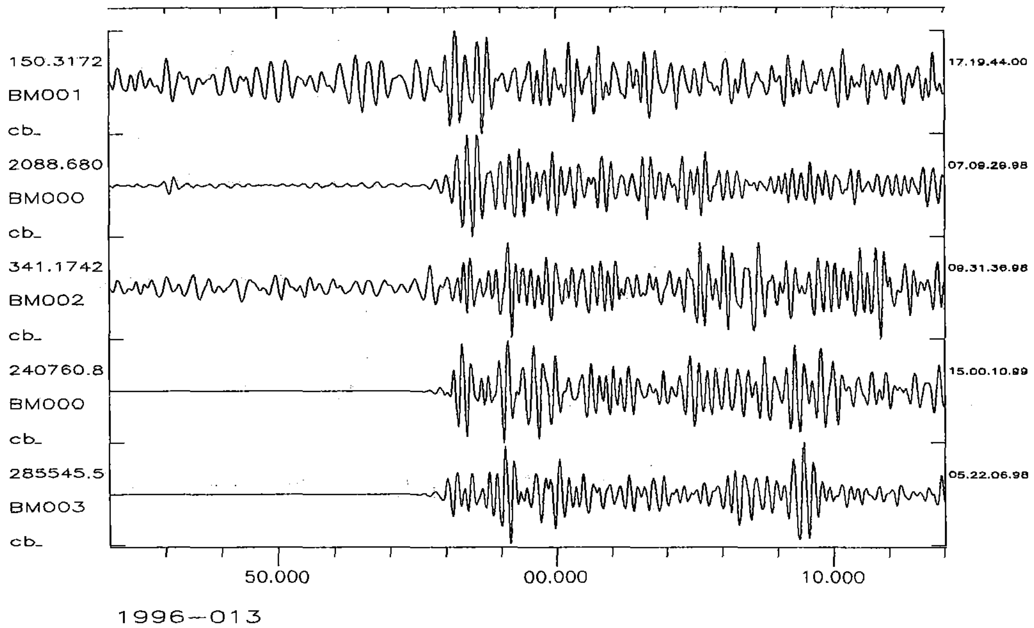
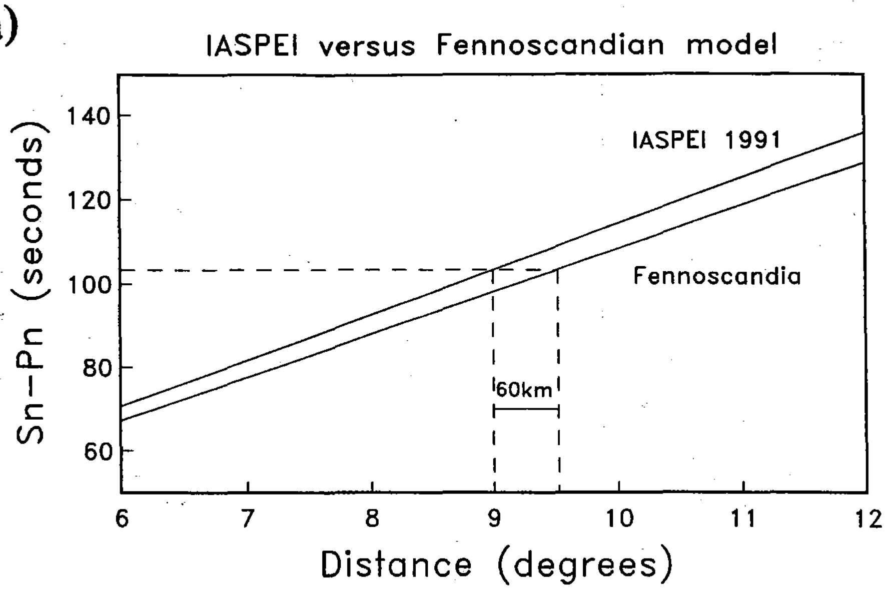


Fig. 7.4.11. P-waves (ARCESS array beam) for five Novaya Zemlya events. From top to bottom: 13 Jan 96, 13 Jun 95, 31 Dec 92, 24 Oct 90 and 4 Dec 88. The data have been filtered in the 2-4 Hz band, which is not the best band for detection, but which provides consistency in magnitude estimates between large and small events. Scaling factors are shown to the left of each trace.

a)



b)

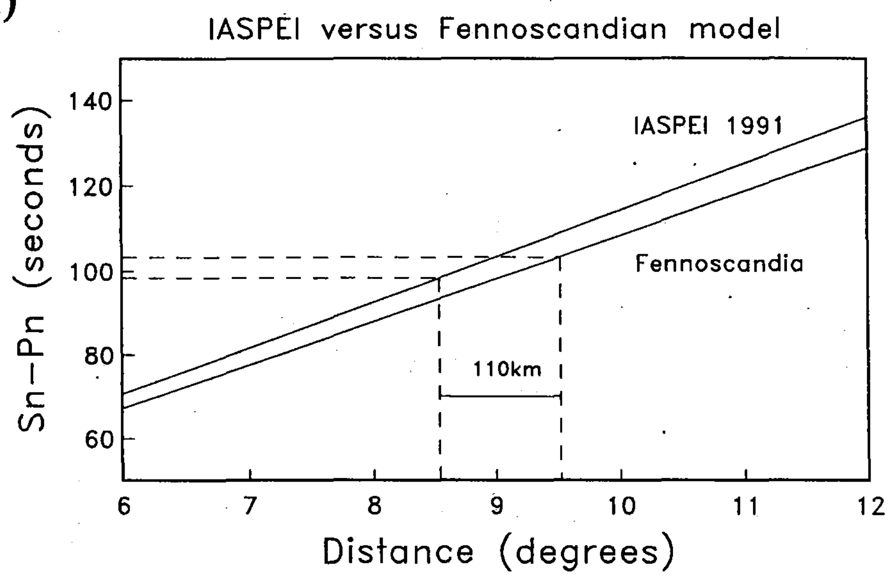


Fig. 7.4.12. Illustration of differences in epicentral distance estimates as discussed in the text:

a) "Error" resulting from applying the IASPEI91 traveltime curves rather than the Fennoscandian model. The difference is about 60 km for the Spitsbergen array.

b) Combined "error" resulting from applying an uncorrected model as well as reading the S-phase at Spitsbergen 5 seconds early. The location "error" in this case amounts to about 110 km.

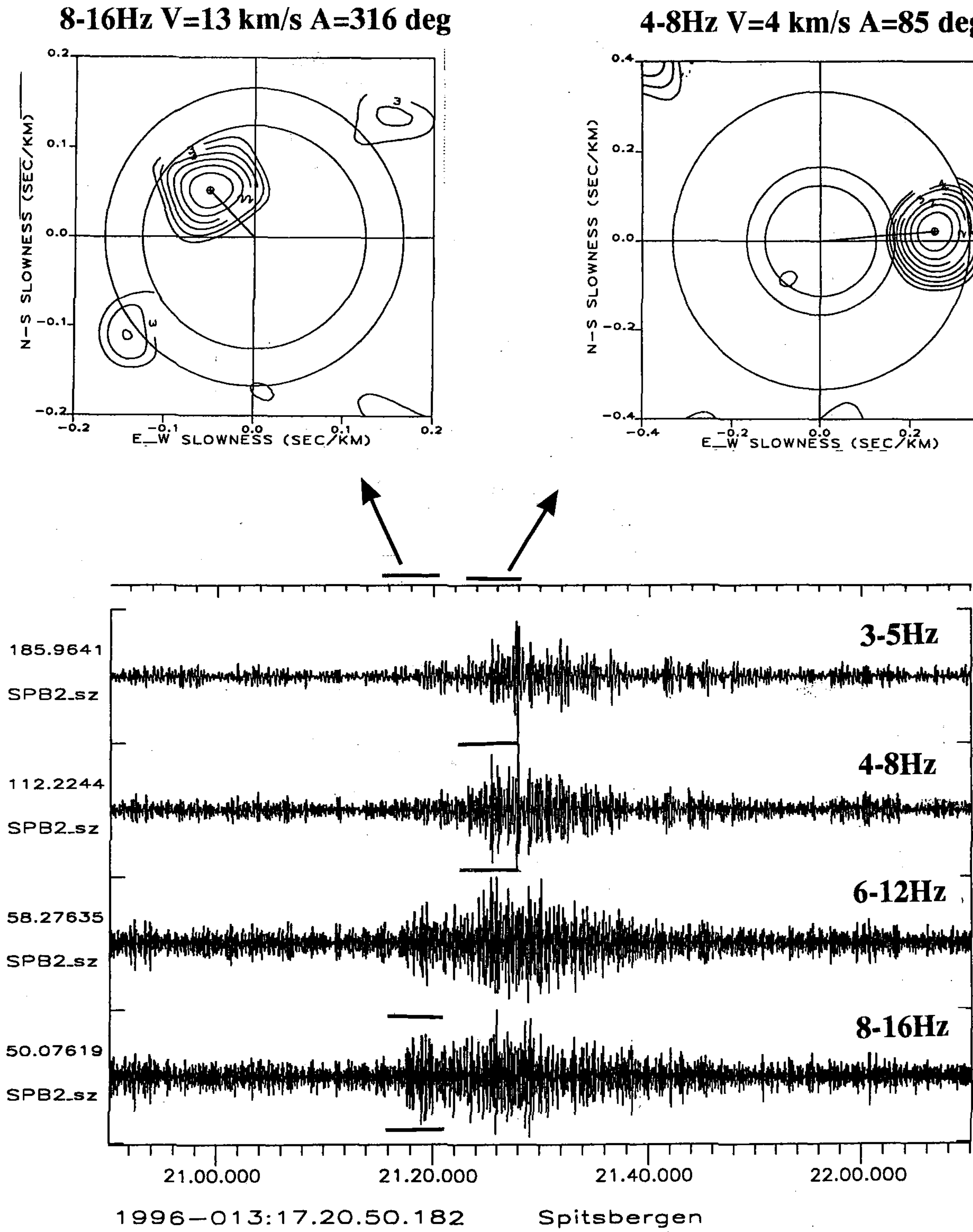


Fig. 7.4.13. Recordings of the January 13, 1996 event at the Spitsbergen B2 seismometer, in four different filter bands. Note the local P-phase preceding the S-phase from the Novaya Zemlya event. This P-phase has both a different f-k solution and different spectral characteristics compared with the S-phase following it.