

## REGIONAL SEISMIC THRESHOLD MONITORING

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### **ABSTRACT**

Beginning in September 2000, a large number of small seismic events has been detected in the area near the accident of the submarine Kursk. According to an official Russian announcement, these were underwater explosions carried out by the Russian Navy. This explosion sequence, with numerous explosions ranging in magnitude from very small (about 1.0 on the Richter scale) to fairly large (about magnitude 2.5), provides a unique opportunity to investigate the performance of the threshold monitoring technique. We have thus implemented an experimental site-specific threshold monitoring procedure to monitor the Kursk accident area in the Barents Sea, which has proved to be an efficient tool for revealing small events in this region.

As an integral part of our work to develop an optimized, automatic capability to monitor the seismicity of Novaya Zemlya and adjacent waters of the Kara and Barents Seas, a database of records from seismic events in the area has been compiled, based on information contained in bulletins published by various agencies. The database comprises records from 43 events, carefully selected so as to cover the area with ray paths in the best possible way. Since the major part of the area under study is basically aseismic, the majority of the events in this database is confined to Svalbard, the western Barents Sea, northern Norway, the Kola Peninsula and Novaya Zemlya. The events are earthquakes, mining blasts, other chemical and nuclear explosions, and some are of unknown nature. Magnitudes range from 2 to 4.5, except for two nuclear explosions with magnitudes exceeding 5. Records have been compiled from the ARCES, FINES, NORES, Apatity and Spitsbergen arrays and from the Amderma 3-component station, and have been supplemented by waveforms for KBS, KEV and LVZ requested from Incorporated Research Institutions for Seismology (IRIS). All events have been reanalyzed, and revised event origins as well as consolidated phase identifications have been obtained. The database is being used to determine travel times and frequency-dependent attenuation relations for the various regional phases. This effort will also provide information on the efficiency of Sn and Lg propagation in this area and its correlation with regional geological structures. The information derived from this study will be quantified in terms of parameters that will be needed in the regional seismic threshold monitoring of Novaya Zemlya and adjacent areas.

An important input parameter to regional seismic threshold monitoring is the uncertainty associated with the regional phase attenuation models. From pair-wise comparisons of P-amplitudes from the explosions detonated in the area near the Kursk accident, we find for the arrays on mainland Fennoscandia (ARCES, Apatity, FINES, NORES, and HFS) an inherent single-array magnitude scatter (standard deviation) of about 0.10-0.13 magnitude units. The locations of these explosions show a distribution over a 30-50 km wide area, which is significantly smaller than the resolution of a regional threshold monitoring scheme for Novaya Zemlya and adjacent waters of the Kara and Barents Seas. This suggests that we would be unable to operate any regional threshold monitoring application with an uncertainty better than 0.1 magnitude units for P-phases. Preliminary data analysis indicates that an existing regional P-based attenuation model for Fennoscandia and adjacent areas exhibits a scatter of about 0.25 magnitude units when considering events in the entire Barents Sea region.

**KEY WORDS:** seismic regionalization, threshold monitoring, Barents Sea, data processing and analysis

## **OBJECTIVE**

The main objective of this research is to develop and test a new, advanced method for applying regional seismic array technology to the field of nuclear test ban monitoring. To that end, we address the development and testing of a method for optimized seismic monitoring of an extended geographical region, using a sparse network of regional arrays and three-component stations. Our earlier work on optimized site-specific threshold monitoring serves as a basis for the development of this new method. Emphasis of the research is on algorithms that can be efficiently applied in a real-time monitoring environment, which are using primarily automated processing, and which can be readily implemented in an operational CTBT monitoring system.

## **RESEARCH ACCOMPLISHED**

One of the main research tasks to be addressed in this contract is the development of an optimized, automatic capability to monitor the seismicity of Novaya Zemlya and adjacent waters of the Kara and Barents Seas. In order to accomplish this, we need to derive the data processing parameters applicable to this region. These include a mapping of the occurrence of the different regional phases, travel-time and amplitude-distance curves for the different seismic phases, and the uncertainties associated with the regional attenuation models.

However, we will first report on an experimental implementation of a site-specific threshold monitoring procedure for the submarine Kursk accident area in the Barents Sea, which has proved to be an efficient tool for revealing small events in this region.

### ***Monitoring of the submarine Kursk accident area***

On 12 August 2000, signals from two presumed underwater events in the Barents Sea were recorded by Norwegian seismic stations. The first of these events, at 07.28.27 GMT, was relatively small, measuring 1.5 on the Richter scale. The second event, 2 minutes and 15 seconds later, was much more powerful, with a Richter magnitude of 3.5. These events were associated with the accident of the 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.

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 in the following some of the results from this investigation.

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 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. These stations were thus included in the monitoring scheme.

Figure 1 shows the summary plot with threshold traces for 20 November 2000, where the upper panel shows the network threshold trace and the subsequent panels show the 5 individual station thresholds (P-phases). Following the calculation of the magnitude thresholds the automated analysis contains the following steps:

- Detection of significant threshold peaks on the network trace, using the long-term median as the basis. The detection limits are shown by the line (blue) plotted above each threshold trace. Note that several peaks are identified on the network threshold trace which have to be investigated in more detail.

- Associating seismic phases detected at each station to the time intervals with high network magnitude thresholds.
- Comparing the azimuth and slowness of the associated phases to the expected values for phases originating at or near the Kursk accident area. The number of stations and phases having a close match are used to form a metric indicating the likelihood of the event occurring in the target region. This metric is shown above the upper network threshold trace, where numbers 2 or higher indicate a high likelihood that the event occurred at or near the Kursk accident area.

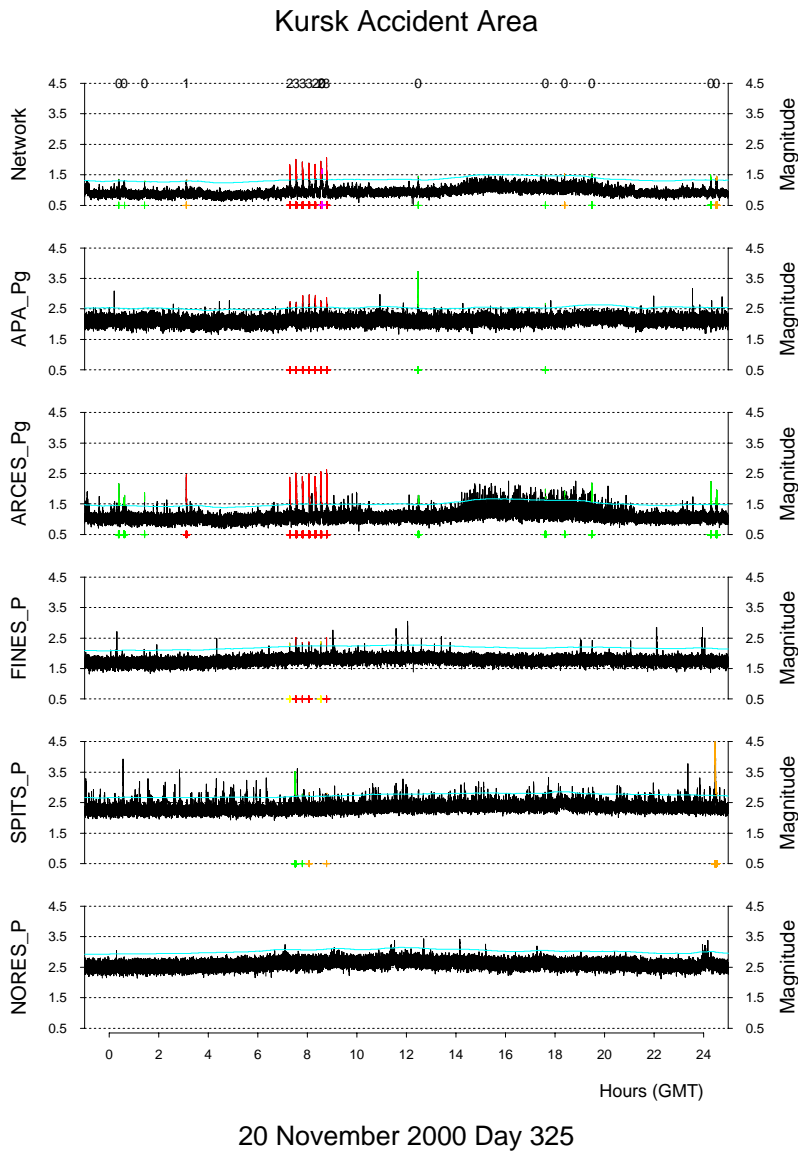


Figure 1. Site-specific threshold monitoring of the Kursk accident area for 20 November 2000 (day 325). The plot shows the 5 individual station thresholds (P-phases), with the combined threshold trace on top. Peaks which are likely to be caused by events in or near the Kursk accident area are indicated by the numbers 2 or 3 (red peaks) on top of the figure, above the network threshold trace.

The plot in Figure 1 shows seven consecutive (red) peaks on the top network trace which are indicated by metric number 2 or 3. 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 site-specific threshold monitoring of the Kursk accident area has been implemented and tested for several months in NORSAR's experimental pipeline. The associated automatic explanation facility has provided us with a very convenient tool for detecting events in this region and for purposes of continuous monitoring.

### ***Pn station magnitudes***

Access to applicable amplitude attenuation curves for the different regional phases is key to this project. The study by Jenkins et al. (1998) provides useful results on this subject for regional phases in Fennoscandia as well as in other stable tectonic regions. In order to utilize their results, we have to validate our time-domain measurements used for threshold monitoring, and we would also like to evaluate the applicability of their attenuation models for distances below 200 km and for events located in the Novaya Zemlya and Barents Sea regions. Using the phase readings of NORSAR's analyst reviewed regional seismic bulletin as a starting point, we have carried out time-domain measurements of the regional phases and compared these to the predictions of the regional phase attenuation models of Jenkins et al. (1998).

The NORSAR analyst produces a bulletin of regional seismic events. Using data from the regional arrays NORES, ARCES, HFS, FINES, Apatity, and SPITS, an average of about 90 events are analyzed every month. However, due to numerous explosions in the Kursk accident area, a total number of 167 events were analyzed during November 2000. 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 than 1.5, but also other events of interest in the European Arctic are included in the reviewed bulletin.

For the time period 10 November 2000 to 28 February 2001 NORSAR's regional bulletin contains a total of 376 events. Since 10 November 2000 all incoming waveform data from all arrays have been stored permanently on disk and can thereby be directly accessed by any analysis program. This has facilitated our development of an application which analyzes the phase amplitudes reported in the regional bulletin. So far we have focused our attention on the Pn phase, but we also plan to include analysis of the other regional phases (Pg, Sn, Lg).

The Pn amplitude was measured on a beam steered with the azimuth and apparent velocity estimated from f-k analysis. The amplitude was measured in four different frequency bands using the short-term average (STA) within a 5 second window starting at the onset of the arriving phase. The frequency bands used were 2-4 Hz, 3-6 Hz, 4-8 Hz, and 8-16 Hz.

The time-domain STA amplitudes of each filter band were made comparable with the spectral amplitudes used by Jenkins et al. (1998), using the relation

$$\bar{A} \approx \frac{STA \cdot resp_{f_c}}{f_c},$$

where  $f_c$  is the center frequency of the passband and  $resp_{f_c}$  is the displacement response at this center frequency. The amplitudes were then corrected for frequency dependent attenuation using the distance dependent term

$$acorr = \left(\frac{\Delta}{200}\right)^{-(af_c + b)}$$

where  $\Delta$  is the distance in km,  $f_c$  is the center frequency and  $a$  and  $b$  are the Pn attenuation coefficients derived by Jenkins et al (1998) for stable continental regions ( $a = 0.08$ ,  $b = 1.44$ ).

Station magnitudes were then calculated using the relation

$$stamag = \log_{10}(\bar{A} \cdot acorr)$$

Note that the absolute scale of these station magnitudes is arbitrary and that these magnitudes are internally consistent for measurements within each separate frequency band. The problem of addressing the absolute scale of the station magnitudes will be discussed at a later stage.

### ***Scatter of Pn station magnitudes***

For each of the four frequency bands both the Pn amplitude of the beam and the corresponding signal-to-noise ratio (SNR) were measured. The frequency band 3 to 6 Hz provides the overall best SNR for the Pn phases analyzed in this study, and we will in the following present statistics on the station magnitudes for this frequency band for phases with SNR > 3.

Out of the total number of 376 events, 75 were associated with explosions detonated in the vicinity of the site of the submarine Kursk accident. Figure 2 shows pair-wise comparisons of Pn station magnitudes, using ARCES as the reference station. We have split the events into two groups.

- Events not in the Kursk accident area
- Events in the Kursk accident area, believed to have a location scatter of a few tens of kilometers

#### ***ARCES - Apatity array***

The two upper panels of Figure 2 show the magnitude comparison between ARCES and the Apatity array. The 36 events not in the Kursk accident area are quite randomly distributed on mainland Fennoscandia and in the western part of the Barents Sea. The Pn magnitudes at the Apatity array have a negative bias of -0.135 as compared to ARCES, and the magnitude difference has a scatter of 0.263.

For the 57 events in the Kursk accident area satisfying the SNR criterion, the Apatity array has a comparable negative bias (-0.137) seen in relation to ARCES, and the magnitude difference has a slightly smaller scatter of 0.198.

#### ***ARCES - SPITS***

The two middle panels of Figure 2 show the magnitude comparison between ARCES and SPITS. The 50 events not in the Kursk accident area are almost all located in the western part of the Barents Sea and on the mid-Atlantic ridge. The Pn magnitudes at SPITS have a consistent positive bias of 0.228 as compared to ARCES, and the magnitude difference has a scatter of 0.328.

For the 23 events in the Kursk accident area the positive bias is only 0.09 with a scatter of 0.143.

Six events in the Khibiny Massif area on the Kola Peninsula are the only events from mainland Fennoscandia providing Pn observations at SPITS. For these six events SPITS has a negative bias of 0.333 as compared to ARCES, and the magnitude difference has a scatter of 0.122.

#### ***ARCES - FINES***

The two lower panels of Figure 2 show the magnitude comparison between ARCES and FINES. The 121 events not in the Kursk accident area are quite randomly distributed on mainland Fennoscandia and a few events are located on the mid-Atlantic ridge. The Pn magnitudes at FINES have a negative bias of -0.119 as compared to ARCES, and the magnitude difference has a scatter of 0.264.

For the 48 events in the Kursk accident area, FINES has a very large positive bias as compared to ARCES (0.473), and the scatter is only 0.168. For the five common events located in the Khibiny Massif, the pattern is quite reversed. FINES has a negative bias of -0.638 as compared to ARCES, and the scatter is 0.132.

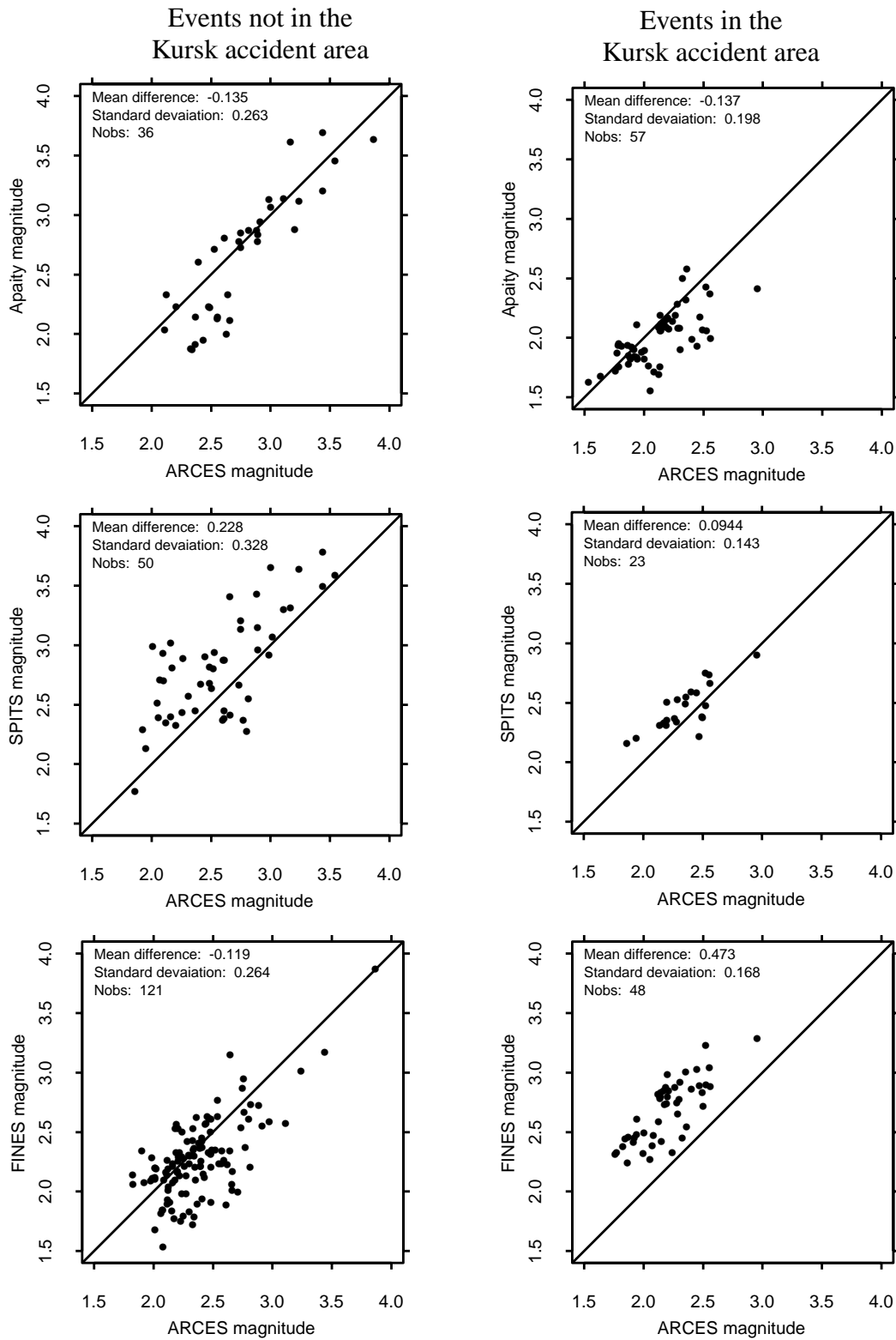


Figure 2: Pair-wise comparisons of STA-based Pn station magnitudes in the frequency band 3.0-6.0 Hz. Notice that the absolute level of the magnitude scale is arbitrary, such that the plots only give information on the internal consistency.

Pair-wise comparisons of ARCES-NORES and ARCES-HFS Pn station magnitudes showed a scatter of the same order as was found for ARCES-FINES (see Figure 2). However, there appeared to be a systematic bias in the station magnitudes between NORES and HFS. For 98 events outside the Kursk accident area HFS has a consistent positive bias of 0.221, with a standard deviation of 0.211 as compared to NORES. This is in accordance with our experience that HFS consistently provides larger ML estimates than NORES, based on Lg amplitudes. With these observations at hand we would like to further investigate this, e.g., by comparing the background noise levels and by independent measurements of the system response at HFS. The NORES system response has been verified through several independent measurements.

### ***An event database for Novaya Zemlya and adjacent waters of the Kara and Barents Seas***

As an integral part of our work to develop an optimized, automatic capability to monitor the seismicity of Novaya Zemlya and adjacent waters of the Kara and Barents Seas, a database of records from seismic events in the area has been compiled, based on information contained in bulletins published by various agencies.

The database comprises currently records from 43 events (see Figure 3), selected so as to cover the area with ray paths in the best possible way. Since the major and in particular the central part of the area under study is basically aseismic, the majority of the events in this database is confined to the mid-Atlantic ridge system, Svalbard, the western Barents Sea, northern Norway, the Kola Peninsula and Novaya Zemlya. The events are earthquakes, mining blasts, other chemical and nuclear explosions, and some are of unknown nature. Magnitudes range from 2 to 4.5, except for two nuclear explosions with magnitudes exceeding 5. Records have been compiled from the ARCES, FINES, NORES, Apatity and Spitsbergen arrays and from the Amderma 3-component station, and have been supplemented by waveforms for KBS, KEV and LVZ requested from Incorporated Research Institutions for Seismology (IRIS). Figures 4 and 5 show the ray-paths to the stations ARCES and SPITS.

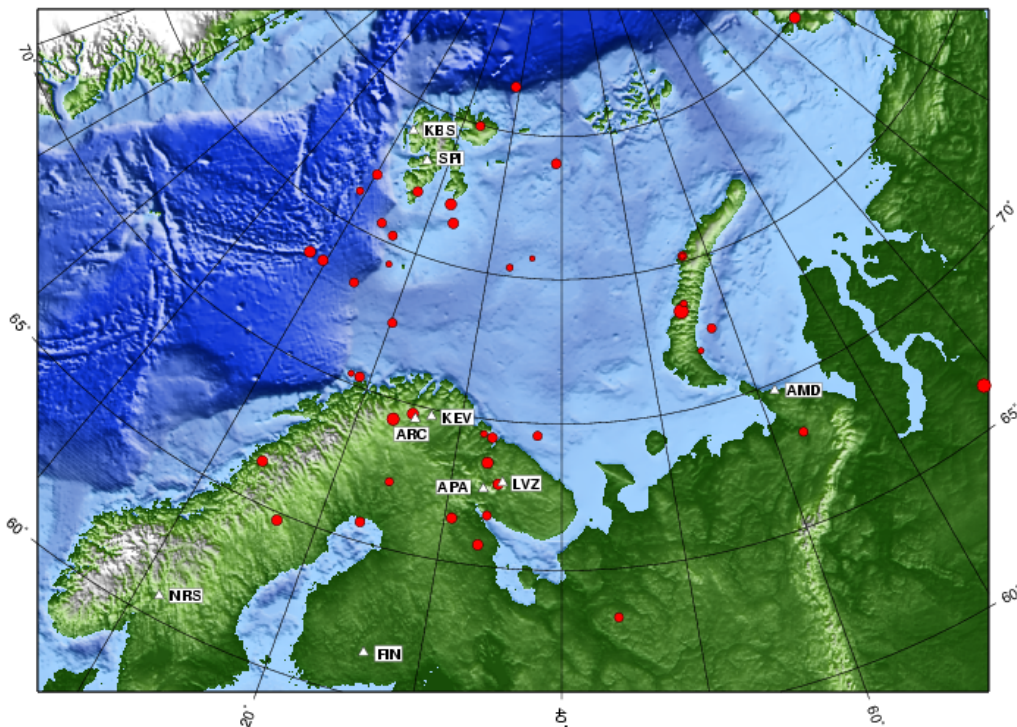


Figure 3. Map with events and stations used for deriving wave propagation characteristics of the Barents Sea and adjacent areas. The event symbol sizes are proportional to the event magnitudes.

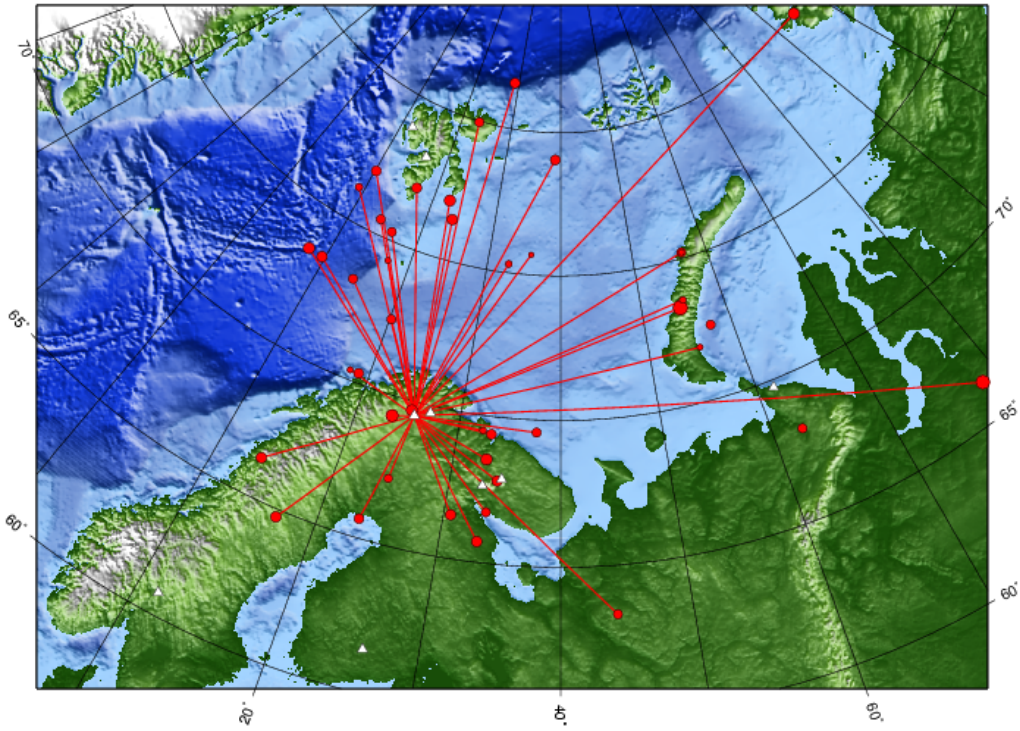


Figure 4. Map showing the ray-paths of the database events recorded at the ARCYES array.

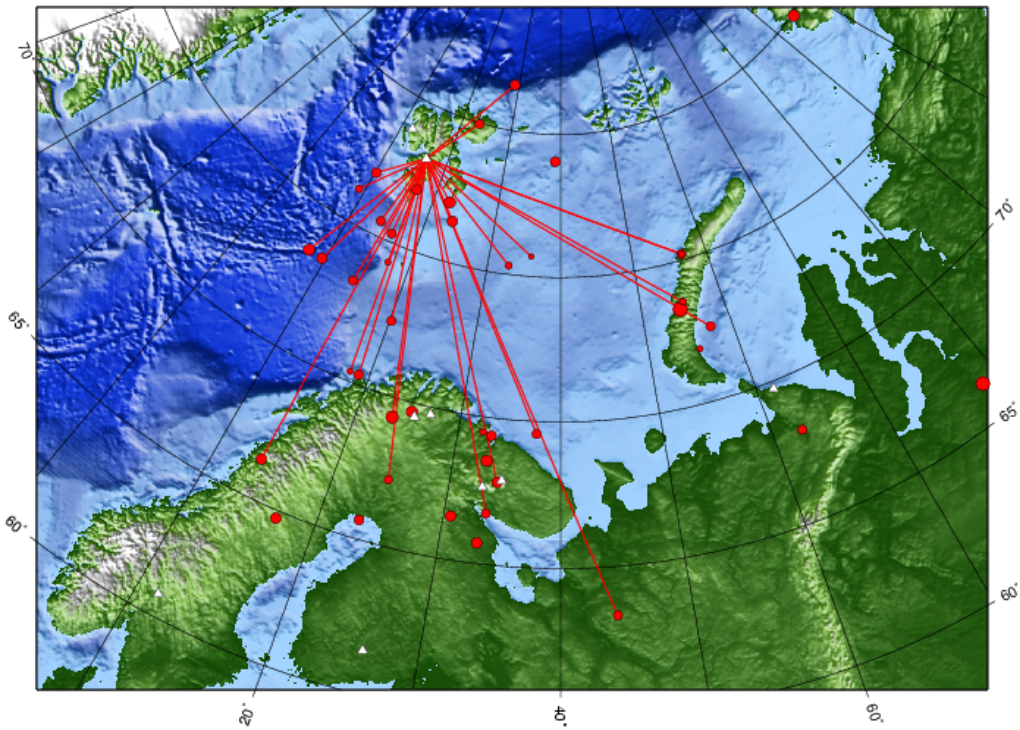


Figure 5. Map showing the ray-paths of the database events recorded at the SPITS array.



All events have been reanalyzed, and revised event origins as well as consolidated phase identifications have been obtained. Figure 6 shows analyzed waveforms and phases identified for one event in the database.

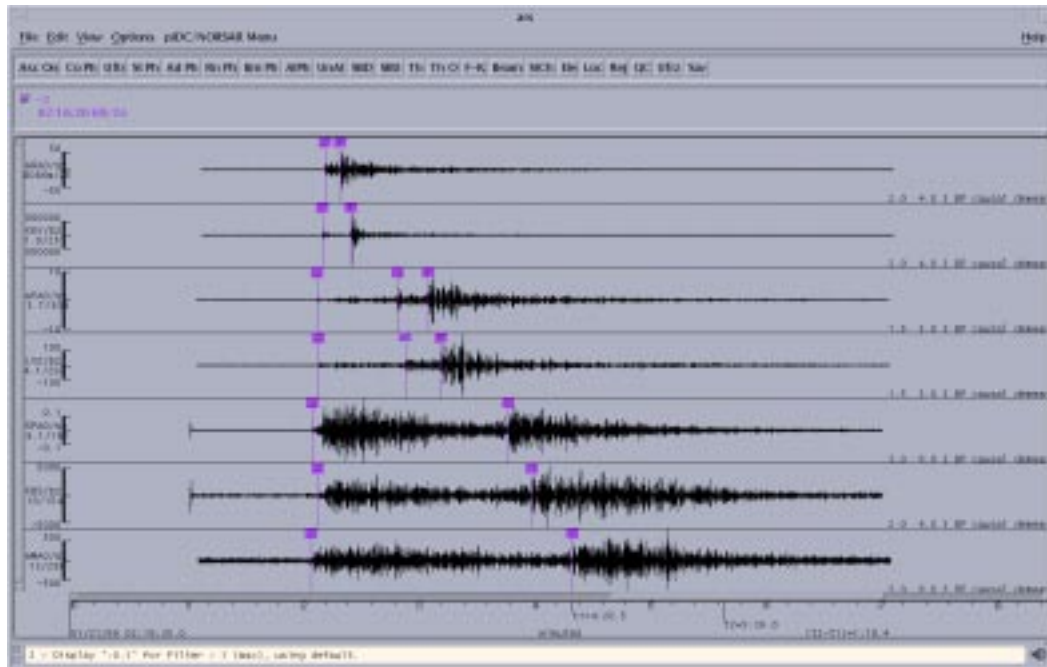


Figure 6. Panels showing the results after analyst review of the 21 January 1996 event located in Finnmark, northern Norway. Note the absence of Lg for paths crossing the Barents Sea. The panels show vertical component recordings at the following seven stations (from top to bottom): ARCES, KEV, Apatity, LVZ, SPITS, KBS, and AMD.

The database is being used to determine travel times and frequency-dependent attenuation relations for the various regional phases. This effort will also provide information on the efficiency of Sn and Lg propagation in this area and its correlation with regional geological structures. The information derived from this study will be quantified in terms of parameters that will be needed in the regional seismic threshold monitoring of Novaya Zemlya and adjacent areas.

### **CONCLUSIONS AND RECOMMENDATIONS**

We have established an experimental application of the site-specific threshold monitoring technique for the submarine Kursk accident area in the eastern Barents Sea, using data from the arrays Apatity, ARCES, SPITS, FINES, NORES and HFS. The daily results are being made available on NORSAR's internal web pages, which has provided us with a practical tool for monitoring the activity in this area. Along with this work, we are now in the process of implementing the software to be used for site-specific threshold monitoring at the Center for Monitoring Research (CMR). This will enable the CMR to run this processing method for any given target area. The only requirements are that each target area must be tuned, preferably based on recordings of previous events in the region, and that access is provided to continuous seismic data, preferably from those stations that are the most sensitive to events in the target area.

Pair-wise comparisons of station magnitudes confirm that the Pn regional phase attenuation model of Jenkins et al. (1998) is a valid approximation for Fennoscandia and adjacent areas. Excluding events in the Kursk accident area, the pair-wise magnitude scatter when comparing with ARCES is almost similar (0.26-0.28) for all arrays on mainland Fennoscandia (Apatity, FINES, NORES, and HFS). If we assign equal variance to the individual array estimates (which would seem to be a reasonable assumption), the inherent single array magnitude scatter would be 0.2 magnitude units (dividing by  $\sqrt{2}$ ).

For SPITS the scatter is somewhat larger (0.328), but the majority of events detected at SPITS are located in the western part of the Barents Sea and on the mid-Atlantic ridge, which have a more tectonic style of Pn attenuation characteristics.

For P-amplitudes from the explosions detonated in the area near the Kursk accident, we find for the arrays on mainland Fennoscandia (ARCES, Apatity, FINES, NORES, and HFS) an inherent single-array magnitude scatter (standard deviation) of about 0.10-0.13 magnitude units. The locations of these explosions show a distribution over a 30-50 km wide area, which is significantly smaller than the resolution of a regional threshold monitoring scheme for Novaya Zemlya and adjacent waters of the Kara and Barents Seas. This suggests that we would be unable to operate any regional threshold monitoring application with a uncertainty better than 0.1 magnitude units for P-phases.

A database of records from 43 seismic events in the Novaya Zemlya area and adjacent waters of the Kara and Barents Seas has been compiled and manually analyzed. The events have been carefully selected so as to cover the area with ray paths in the best possible way. Using the analyst reviewed phase readings as the starting point, we will in our further work investigate various parameters related to seismic wave propagation, i.e., travel-times, phase amplitudes, attenuation relations and the efficiency of Sn and Lg propagation. This information will be applied in the parameterization of a regional threshold monitoring processing scheme for Novaya Zemlya and adjacent waters of the Kara and Barents Seas.

#### **ACKNOWLEDGEMENTS**

We would like to thank Berit Paulsen for reanalyzing the events of the Novaya Zemlya/Barents Sea database in a an accurate and consistent manner.

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