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# Study of Regional Surface Waves and Frequency-dependent $M_s$:$m_b$ Discrimination in the European Arctic

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*Abstract*—Accurate discrimination of seismic events with a regional network requires detailed knowledge of the propagation characteristics of seismic waves in the region. At present, such propagation characteristics are reasonably well known for *P* and *S* waves in the European Arctic, however much work remains to be done regarding surface wave propagation and magnitude estimation.

Regional long-period or broadband seismic data in digital form has been available in the European Arctic for only a few years. In order to assess regional surface wave propagation, and in particular to evaluate the $M_s$:$m_b$ discriminant at regional distances, it is therefore necessary to take advantage of the historic analog recordings. The station APA in Apatity forms a unique source of such data, with high-quality long-period seismic recordings of regional earthquakes and nuclear explosions dating back about 30 years.

This paper presents initial results from a project to digitize APA surface waves of selected regional events. The recordings for recent years have been compared to a colocated broadband Guralp three-component seismometer in order to verify the response characteristics and the quality of the digitization process. It turns out that the quality of the digitized records is excellent, and can be used over a spectral band ranging from 5 seconds to at least 30 seconds period.

We demonstrate the capabilities of the APA surface wave recordings to provide a promising separation of earthquakes and explosions in the European Arctic over a range of frequencies using the $M_s$:$m_b$ discriminant, although we note that additional work is required in regionalization of the propagation paths to take into account the major tectonic features in the region. We also note that the body-wave magnitudes provided by international agencies are not always reliable for events in this region, and must be reassessed in order to make full use of the earthquake-explosion discrimination potential.

**Key words:** Surface waves, earthquake-explosion discrimination, regional phases.

## *Introduction*

As part of a project aimed at improving seismic monitoring capabilities for the Barents/Kara Sea region, NORSAR and Kola Regional Seismological Centre (KRSC) are conducting a comprehensive study of seismicity, seismic wave propagation and seismic event characterization in the European Arctic. This work is particularly relevant to the development of event screening criteria, which is one of

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the main tasks of the expert work conducted by Working Group B of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

The purpose of event screening is to "screen out" events that are thought to be consistent with natural causes (such as earthquakes), so that a detailed analysis can be focused on those events that are truly of interest for monitoring purposes. The current seismic screening procedure employed at the International Data Centre (IDC) focuses on two criteria: event focal depth and $M_s$:$m_b$. These are considered to be the most robust criteria currently available, but have the disadvantage that they are difficult to apply to small events or events recorded only by a few stations. Other criteria, such as the high-frequency $P/S$ ratio, hold the promise of being applicable at considerably lower event magnitudes, and this is currently an area of active research (see e.g., RINGDAL *et al.*, 2002).

By focusing on regional recordings of surface waves, it might be possible to apply the $M_s$:$m_b$ discriminant to low magnitude events, perhaps approaching $m_b = 3.0$–$3.5$. This is the motivation for the present study. As is well known, accurate discrimination of seismic events with a regional network requires detailed knowledge of the propagation characteristics of seismic waves in the region. At present, these propagation characteristics are reasonably well known for short-period $P$ and $S$ waves in the European Arctic, (see e.g., SERENO *et al.*, 1988), but substantial work remains to be done regarding surface-wave propagation and magnitude estimation. In the following we describe certain initial results obtained for this region.

## *Database*

The regional seismic network operated by the Kola Regional Seismological Center currently comprises a combination of digital and analog stations. Several stations of the analog type have been in operation for many years (see Fig. 1), whereas the digital stations in this network have only a few years of available recordings (ASMING *et al.*, 1998).

In order to assess surface wave propagation, and in particular to evaluate the $M_s$:$m_b$ discriminant, it is necessary to take advantage of the historic analog recordings. The station APA in Apatity forms a unique source of such data. This station has had high-quality LP recordings since 1969, and thus a database is available of regional earthquakes and nuclear explosions dating back about 30 years. The LP seismometer is a three-component system, with analog recording at a constant amplification of 1000 relative to ground displacement in the band 5–25 seconds. It is supplemented by a low-gain vertical channel (amplification 100), which is used for the largest seismic events.

We have initiated a project to digitize surface waves of selected regional events in the APA database of LP recordings. The digitization method is based on a semi-automated algorithm. The original seismograms are amplified by photocopying and

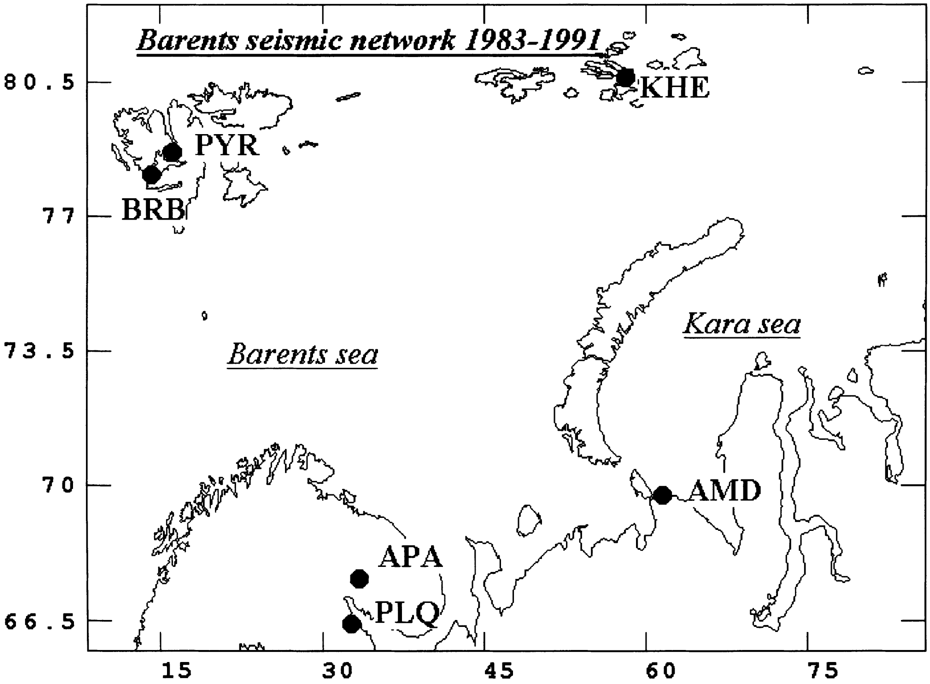


Figure 1
Stations in the Barents seismic network operated by KRSC. The station APA, which has both three-component SP and LP seismometers, is the longest in operation, from 1969 until present. APA has in addition a Guralp CMG-3T broad-band digital seismometer, which has been operational since 1991.

scanned into an image on a PC. An automatic algorithm calculates the midpoint of each trace for a given time interval, and thus creates an initial digital record. The analyst can interactively verify the output and make corrections as necessary (for example when lines on the seismogram cross each other). Finally, the record is resampled to a uniform sampling rate.

We have checked the performance of this method by comparing digitized analog LP recordings to the digital recordings of a colocated broadband station in order to verify the response characteristics and the quality of the digitization process. This comparison can only be done for the most recent years, during which a colocated broadband Guralp three-component seismometer has been in operation in Apatity. An illustration of such a comparison for an earthquake in 1998 near Spitsbergen is shown in Figures 2 and 3. As seen from these illustrations, the quality of the digitized records is excellent, and can be used over a spectral band ranging from 5 seconds to about 30 seconds period. In fact, the recordings in the various filter bands are nearly identical, except that for the lowest filter band (0.03–0.04 Hz or 25–33 seconds) the broadband recordings have slightly more ringing of the signal than the digitized LP recordings. The relative amplitudes in the different frequency bands likewise show

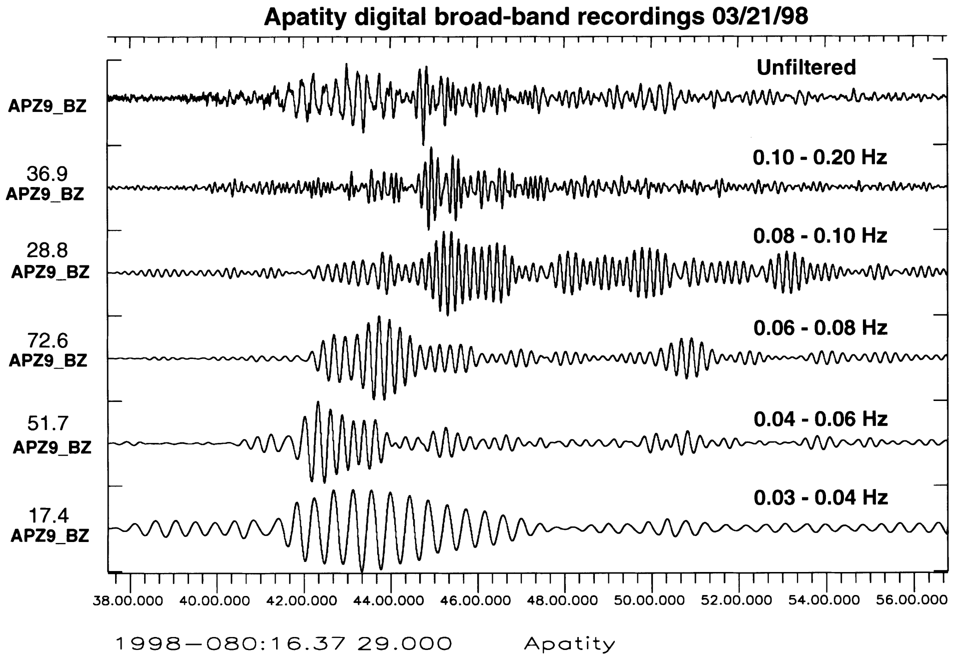


Figure 2
Digital recording by the broadband Guralp vertical seismometer in Apatity for an earthquake near Spitsbergen on 21 March, 1998. The unfiltered data are shown in the top trace, with the other traces showing a suite of narrow-band filters applied to the recording. Numbers in front of each filtered trace represent ground motion (maximum amplitude) in microns.

good agreement, again with a reservation for the lowest frequency band. We attribute the differences noted above to uncertainties in the nominal response characteristics of the seismometers and recording systems at the lowest frequencies.

## *Data Analysis*

We have initially applied this digitization process to 28 seismic events at regional distances and various azimuths from the APA station (see Table 1). Eleven are nuclear explosions, as listed by MIKHAILOV *et al.* (1996), mostly from the Novaya Zemlya test site. The remainder are intermediate and low magnitude earthquakes (typical magnitude range 4.0–5.0). All of the earthquakes have continental propagation paths. While the earthquakes (by necessity) are at azimuths different from the majority of the explosions, we consider that the variations in azimuths and propagation paths are sufficient to provide a representative sample of the characteristics of the seismic source and propagation effects in the region being considered.

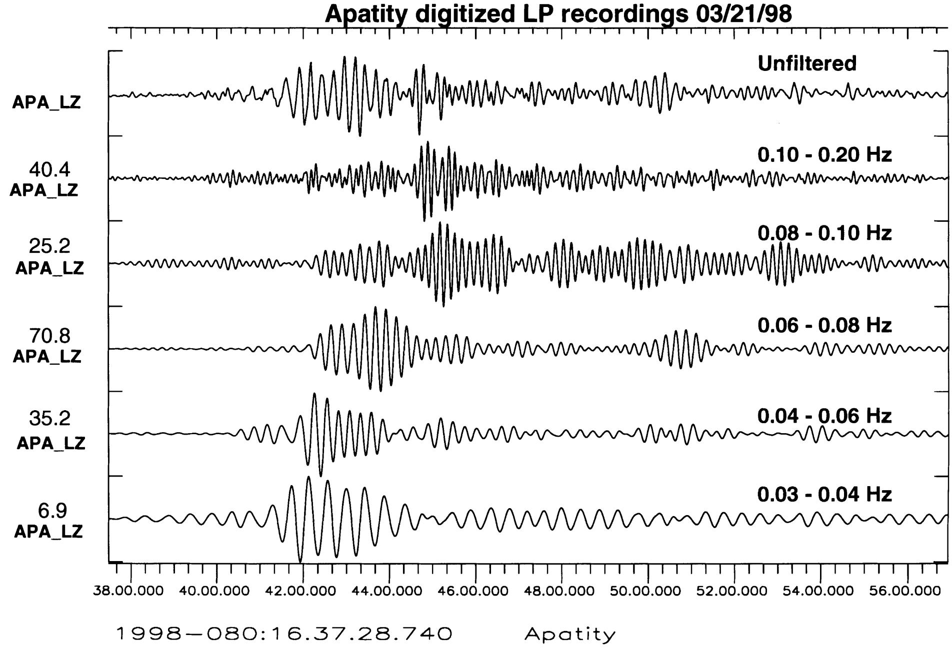


Figure 3
Digitized recordings based on the APA LP vertical component colocated with the Guralp broadband seismometer for the same event shown in Figure 2. Numbers in front of each filtered trace represent ground motion (maximum amplitude) in microns. Note the close correspondence of the traces shown in the two figures.

The lack of reliable $m_b$ estimates by international agencies for events in this region has been a source of concern. As an example, the ISC $m_b$ can on occasion be biased high by one full magnitude unit, e.g., when only one or two high-amplitude teleseismic stations have detected a given event. While most of the Novaya Zemlya nuclear explosions have a reasonably accurate magnitude estimate (RINGDAL, 1997), corresponding reliable estimates are not generally available for the earthquakes in our database. For this reason we have chosen to recompute $m_b$ values for all the processed events, using the maximum-likelihood method of RINGDAL (1986). These values are listed in Table 1 as $m_b$ (MLE).

An example of digitized data for one of the nuclear explosions is shown in Figure 4. We note that the LP signals are very clear in all the frequency bands considered. In particular, it is interesting to note the strong signals even at the highest frequency band in the figure (0.1–0.2 Hz or 5–10 seconds period).

Figure 5 shows a map of the propagation paths (top) and a comparison of the normalized surface-wave spectra (bottom). These normalized spectra have been computed by adjusting for distance as well as body-wave magnitude. The distance adjustment makes use of the standard formula for $M_s$ computation (VANEK *et al.*, 1962):

Table 1

*List of seismic events used in this study*

| No. | DATE | Time | Lat. (N) | Lon. (E) | $m_b$ (MLE) | Reference |
|---|---|---|---|---|---|---|
| Confirmed nuclear explosions | | | | | | |
| 1 | 1973/09/30 | 05.00.00 | 51.7 | 54.6 | 5.1 | SULTANOV *et al.* (1999) |
| 2 | 1974/08/29 | 10.00.00 | 73.4 | 55.1 | 6.5 | RINGDAL (1997) |
| 3 | 1974/08/29 | 15.00.00 | 67.1 | 62.6 | 4.9 | SULTANOV *et al.* (1999) |
| 4 | 1975/10/21 | 12.00.00 | 73.4 | 55.1 | 6.6 | RINGDAL (1997) |
| 5 | 1976/09/29 | 03.00.00 | 73.4 | 54.8 | 5.8 | RINGDAL (1997) |
| 6 | 1976/10/20 | 08.00.00 | 73.4 | 54.6 | 4.9 | RINGDAL (1997) |
| 7 | 1978/08/10 | 08.00.00 | 73.3 | 54.8 | 6.0 | RINGDAL (1997) |
| 8 | 1984/08/11 | 19.00.00 | 65.1 | 55.1 | 5.3 | SULTANOV *et al.* (1999) |
| 9 | 1985/07/18 | 21.15.00 | 66.0 | 41.0 | 5.1 | SULTANOV *et al.* (1999) |
| 10 | 1988/12/04 | 05.20.00 | 73.4 | 55.0 | 5.8 | RINGDAL (1997) |
| 11 | 1990/10/24 | 14.58.00 | 73.4 | 54.7 | 5.6 | RINGDAL (1997) |
| Presumed earthquakes | | | | | | |
| 12 | 1971/12/16 | 18.35.45 | 77.8 | 18.1 | 4.9 | ISC |
| 13 | 1972/01/16 | 06.31.04 | 77.6 | 18.0 | 3.9 | ISC |
| 14 | 1975/01/20 | 10.47.29 | 71.7 | 14.2 | 5.0 | ISC |
| 15 | 1976/01/18 | 04.46.21 | 77.8 | 18.3 | 5.5 | ISC |
| 16 | 1976/09/09 | 09.27.45 | 77.8 | 7.9 | 5.2 | ISC |
| 17 | 1976/10/25 | 08.39.45 | 59.2 | 23.6 | 4.3 | ISC |
| 18 | 1977/07/17 | 09.22.24 | 77.8 | 18.6 | 4.6 | ISC |
| 19 | 1981/09/03 | 18.39.42 | 69.3 | 14.2 | 4.8 | ISC |
| 20 | 1986/08/01 | 13.56.38 | 73.0 | 56.7 | 4.3 | MARSHALL *et al.* (1989) |
| 21 | 1986/10/26 | 11.34.38 | 61.7 | 3.3 | 4.4 | ISC |
| 22 | 1987/05/26 | 02.44.48 | 76.6 | 25.7 | 3.6 | ISC |
| 23 | 1988/08/08 | 19.59.32 | 63.6 | 2.3 | 5.6 | ISC |
| 24 | 1990/05/28 | 00.35.48 | 55.2 | 58.6 | 4.3 | LOMAKIN and YUNUSOV (1993) |
| 25 | 1990/05/28 | 02.41.28 | 55.2 | 58.7 | 4.4 | LOMAKIN and YUNUSOV (1993) |
| 26 | 1993/09/13 | 05.25.10 | 66.3 | 5.8 | 3.9 | ISC |
| 27 | 1997/12/20 | 21.40.48 | 67.6 | 10.9 | 3.6 | ISC |
| 28 | 1998/03/21 | 16.33.11 | 79.9 | 1.9 | 5.9 | NEIC |

$$M_s = \log \frac{A}{T} + 1.66 \log \Delta + 3.3$$

where $\Delta$ is the epicentral distance in degrees, $A$ is zero-to-peak amplitude in microns and $T$ is the corresponding signal period. This formula is currently used by the International Seismological Centre (ISC), and as noted by VANEK *et al.* (1962), the formula is considered valid in the 10–60 second range and for distances from 5–160 degrees (depth less than 60 km). There are several other proposed formulas for

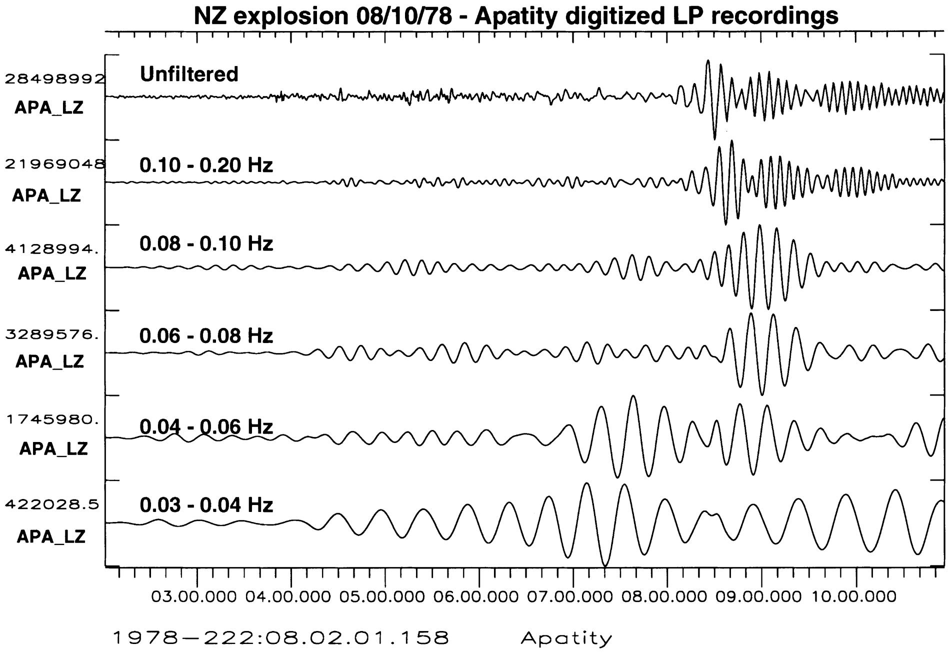


Figure 4

Digitized recordings based on the APA LP vertical component seismometer for the nuclear explosion at Novaya Zemlya on 10 August, 1978. Numbers in front of each trace are maximum amplitudes (not converted to ground motion). Note the high SNR in all the filter bands.

surface-wave magnitudes (notably MARSHALL and BASHAM, 1972), and in many such formulas the distance coefficient is significantly less than 1.66 as used above. Since most events discussed in this study are at a similar distance from the APA station (typically about 10 degrees), the distance coefficient is not critical, and we have therefore chosen to use the standard $M_s$ formula in this analysis.

The adjustment for body-wave magnitude makes use of the current event screening criterion for $M_s$:$m_b$ employed at the prototype International Data Centre (MURPHY *et al.*, 1998), which is of the form:

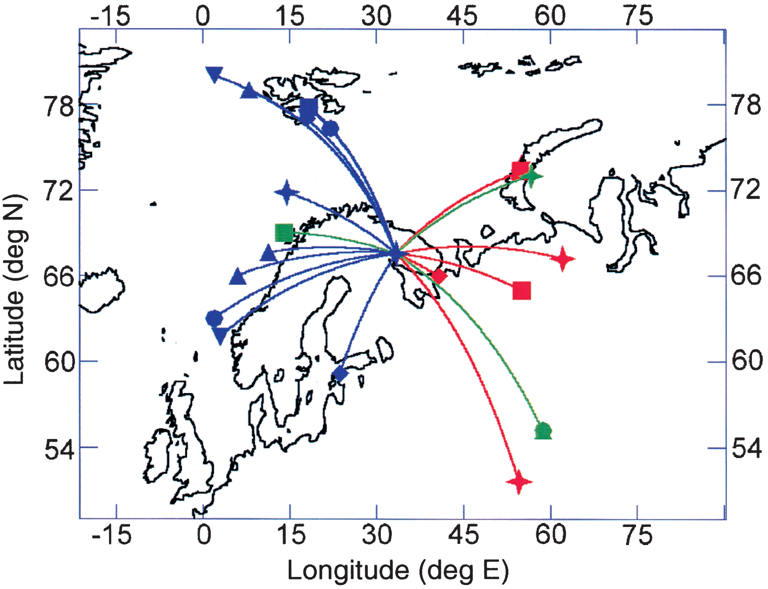
$$M_s = 1.25m_b - 2.20 \quad .$$

The important term in our context is the slope (1.25) of this relationship. We use the two above formulas to normalize the distance-corrected spectral log amplitude values by calculating, at each frequency, the quantity:

$$\log \frac{A}{T} + 1.66 \log \Delta - 1.25m_b \quad .$$

In this way we obtain measurements of log A/T, shown in the figure, that have been corrected for distance and body-wave magnitude. In all cases, the signal-to-

a) Paths from events to Apatity LP station



b) Corrected surface wave spectra

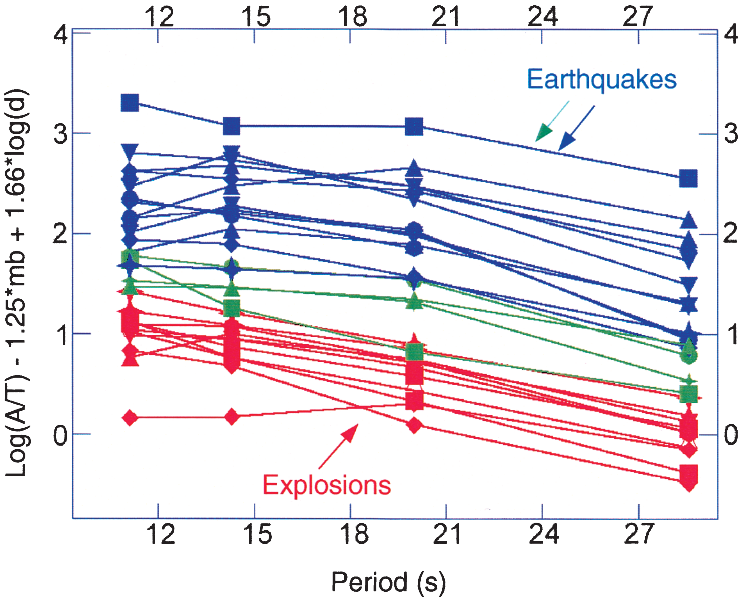


Figure 5

Spectral plot for a database of earthquakes and nuclear explosions with continental travel paths to the APA LP station. The top part shows the events and the travel paths to APA, whereas the bottom part shows surface-wave spectral levels ranging from 10 to 30 second periods. The spectral levels have been corrected for distance and body-wave magnitude (see text for details). The four "borderline" events marked in green are discussed separately in the text.

noise ratios of the recordings are sufficient to ensure that the amplitudes are true measurements of the signal, and not of the microseismic noise. Although somewhat simplified, the diagram can be seen as a frequency-dependent $M_s$:$m_b$ plot, and the separation between the earthquakes and explosions is similar over the entire frequency range. Four "borderline" cases (marked in green color on the plot) are discussed briefly below.

The first borderline case is an earthquake off the coast of Norway, very close to the oceanic/continental margin (event no. 19 in Table 1). The table shows that the location of this earthquake is on the oceanic side, and this could account for the anomalously small surface waves (the event is in fact inseparable from the explosion population). To study this topic further we digitized surface-wave recordings from several additional earthquakes in the oceanic part of the Norwegian Sea close to the oceanic/continental margin. These earthquakes were consistently close to the explosion population (they are not shown in the plot). It is well known that for earthquakes on an oceanic path the Airy phase is shifted to higher frequencies and thus these earthquakes exhibit lower amplitudes in the 5–20 seconds range (see e.g., MARSHALL and BASHAM, 1972). However, in the cases studied here, most of the propagation paths are continental, and this suggests that the low surface-wave amplitudes could, at least in part, be due to attenuation when crossing the oceanic/continental margin.

The next borderline cases are two colocated seismic events in the Ural Mountains (event nos. 24 and 25 in Table 1). According to LOMAKIN and YUNOSOV (1993) these events were rockbursts in the "Kurgazakskaya" bauxite mine. We have searched the ISC bulletins for other events in the central and northern Ural Mountains to be used in this study, however those events which we have found have all been identified as mine rockbursts or collapses. We have therefore been unable to include any tectonic earthquakes from this region in our study.

The fourth and final borderline case in Figure 5 is the 1 August 1986 event near Novaya Zemlya (event no. 20 in Table 1). This event is generally presumed to have been an earthquake, based upon the depth estimate (19 km) and focal mechanism provided by MARSHALL *et al.* (1989). We note that the event is separated from the explosion population, nevertheless it is rather close. In any case, we agree with MARSHALL *et al.* (1989) that caution should be exercised in interpreting $M_s$:$m_b$ data unless a network of stations at a variety of azimuths is available, and Figure 5 should not be interpreted as an attempt to identify this event on the basis of the $M_s$:$m_b$ criterion.

## *Interfering Surface Waves*

We have shown that the measurement of surface wave magnitudes at regional distances holds significant promise to lower the limit for applying the $M_s$:$m_b$

criterion, and would be of particular importance for the event screening currently being implemented at the IDC. Furthermore, regional surface waves have a significant energy at shorter periods (down to 5–10 seconds), and this could be exploited in extending the magnitude range for useful $M_s$ measurements.

In particular, measurement of such shorter period surface waves at regional distances could contribute to reducing the influence of coda from surface waves of large teleseismic earthquakes, which often mask ordinary surface waves from small events for hours. This is brought about because these strong surface waves generally have a dominant period of 20 or more seconds, with far less energy in the shorter period bands.

An example of this is given in Figures 6 and 7, which make use of data recorded by the large-aperture NORSAR array (BUNGUM *et al.*, 1971). The figures show steered array beams (phase velocity 3.5 km/s and azimuth 40 degrees) based on 7 LPZ seismometers distributed over an area 60 km in diameter. Figure 6 is recordings of a large nuclear explosion ($m_b = 5.8$) at Novaya Zemlya on 25 October, 1984. An unfiltered array beam is displayed together with the beam filtered in the "standard" 17–25 seconds band and a "high-frequency" 8–10 seconds band. Note the high SNR of this regional recording (distance = 20 degrees) even at the higher frequencies. Figure 7 shows a similar plot of NORSAR LPZ array beam recordings of a small

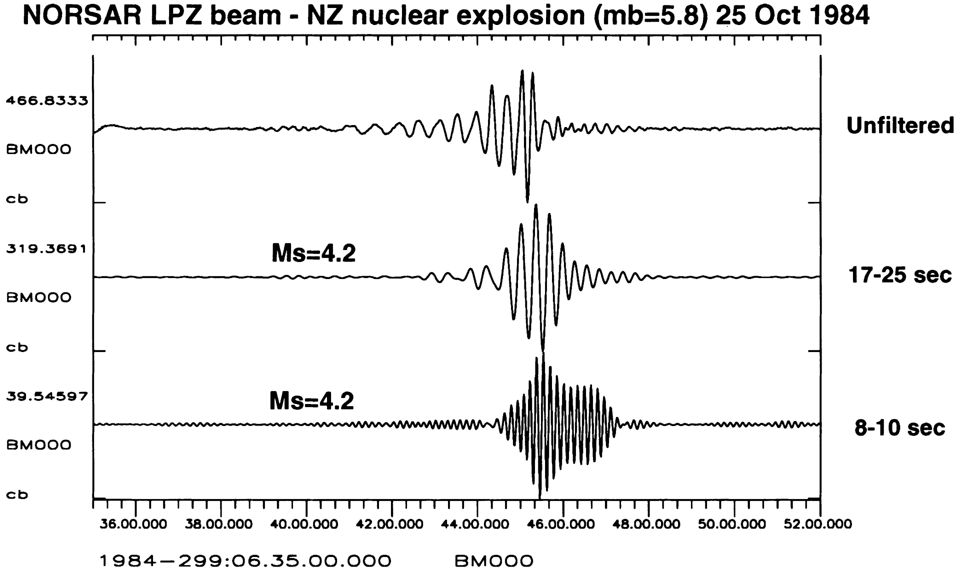


Figure 6
NORSAR LPZ steered array beam recordings of a large nuclear explosion ($m_b = 5.8$) at Novaya Zemlya on 25 October, 1984. An unfiltered beam is shown together with the beam filtered in the "standard" 17–25 seconds band and a "high-frequency" 8–10 seconds band. Note the high SNR of this regional recording (distance = 20 degrees) even at the higher frequencies.

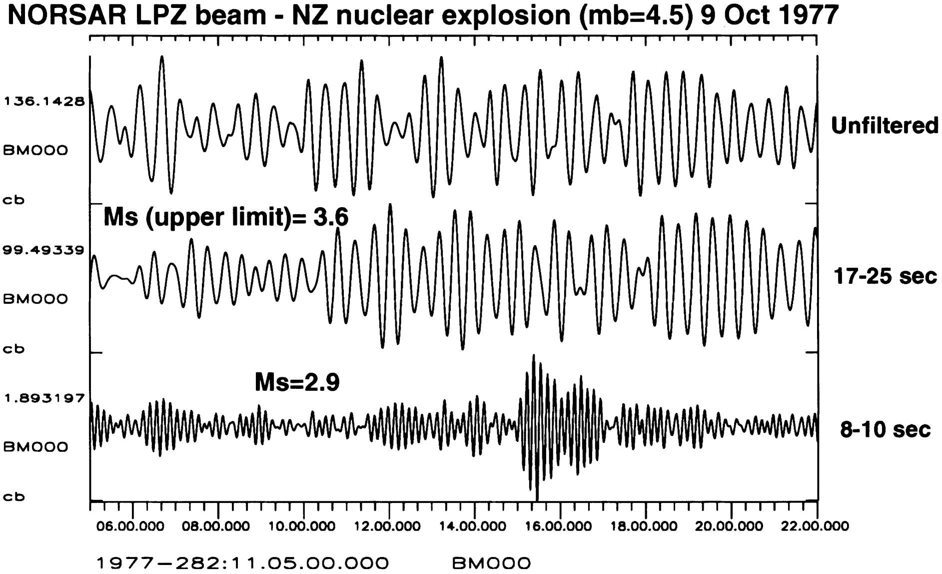


Figure 7
NORSAR LPZ steered array beam recordings of a small nuclear explosion ($m_b = 4.5$) at Novaya Zemlya on 9 October, 1977. The traces correspond to those shown in Figure 6. Note that an interfering earthquake masks the explosion surface waves in the 17–25 seconds band, whereas the explosion signal is clearly seen in the 8–10 seconds band.

nuclear explosion ($m_b = 4.5$) at Novaya Zemlya on 9 October, 1977. A few minutes before this latter explosion, a large earthquake occurred in the Philippine Islands, causing significant interfering surface waves at NORSAR during the expected time of surface wave arrival for the explosion. From Figure 7, we can see how the interfering event masks the explosion surface waves in the 17–25 seconds band, and it is only possible to estimate an upper bound on the $M_s$ in this band. On the other hand, the explosion signal is clearly seen in the 8–10 seconds band, and a surface wave magnitude can be calculated by direct comparison with the explosion in Figure 6.

There are several other techniques, such as matched filtering using a nearby event, that could be applied to enhance the signal-to-noise ratio of surface waves in the presence of an interfering earthquake. The use of narrow band filtering of regional recordings at high frequencies as discussed above has the advantage of being applicable even if no suitable reference event is available, and will become progressively more important for the International Monitoring System as the density of the station deployment increases.

## *Conclusions*

The station APA is situated at a regional distance from the Novaya Zemlya test site, and has a long history of surface wave recordings of nuclear explosions from there, all prior to being converted to digital operation. We have demonstrated the quality of the analog recordings at this station by comparing recordings from a modern broadband seismometer at the same place as signals digitized from the analog equipment.

We further show that the APA surface-wave recordings, normalized for distance and magnitude, provide an encouraging degree of separation between earthquakes and explosions in the European Arctic. We demonstrate that this separation can be achieved in a wide frequency band (at least 10–25 seconds period). We note that this gives promise for applying the $M_s$:$m_b$ discriminant down to lower magnitudes and at lower signal periods than is possible using teleseismic recordings. We also note that the shorter-period energy available in surface waves recorded at regional distances can be exploited in improving the monitoring capabilities during periods with strong interfering surface waves from large distant earthquakes.

In order to further develop the $M_s$:$m_b$ discriminant for event screening purposes, it will be necessary to study extensive historical recordings of nuclear explosions and earthquakes in various tectonic regions. Fortunately, many of the stations in the emerging International Monitoring System (IMS) have retained such recordings, but nevertheless the majority of IMS stations were not established at the time when most of the historic nuclear explosions were conducted. The event screening criteria must therefore be developed based to a large extent on non-IMS data, including available high-quality stations (such as APA) with a long history of analog recording. Additional work is also required in regionalization of the propagation paths to allow for the major tectonic features in calibrating the monitoring network.

Furthermore, since event magnitudes are important in most of the proposed screening criteria, the problem of computing magnitudes of historic seismic events in a way compatible with the current magnitude calculations must be addressed. We plan to develop a more general application of the maximum-likelihood method of RINGDAL (1986), and to compare the derived values to coda-based estimates (MAYEDA, 1993) and to other available magnitude estimators.

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