RESEARCH IN REGIONAL SEISMIC MONITORING

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Sponsored by Defense Threat Reduction Agency

Contract No. F08650-01-C-0055

ABSTRACT

This project represents a continuing effort aiming at three main topics: (a) to carry out research in regional monitoring of the European Arctic, (b) to apply experimental methods such as site-specific threshold monitoring to target areas of interest and assess the results and (c) to contribute to the global location calibration effort currently being undertaken by the Preparatory Commission (PrepCom) of the Comprehensive Nuclear Test-Ban-Treaty Organization's Working Group B in Vienna, Austria.

We have used data from the regional networks operated by NORSAR and the Kola Regional Seismological Centre (KRSC) to assess the seismicity and characteristics of regional phases of the European Arctic. An especially interesting recent seismic event, which has been analyzed in detail, occurred on Novaya Zemlya on 23 February 2002. This small event (magnitude about 3.0) is the first seismic event detected in or near Novaya Zemlya since the two Kara Sea events of 16 August 1997. The event was recorded with particularly high signal-to-noise ratio (SNR) by the International Monitoring System (IMS) arrays Spitsbergen and ARCES, and by the Amderma station (operated by KRSC) south of Novaya Zemlya. We have located the event at the eastern coast of Novaya Zemlya, approximately 100 km NE of the former nuclear test site. Our attempts to estimate the depth of this event proved inconclusive, and a depth of 0 could not be ruled out. We present comparisons of the recordings of this event to recordings of previous small events in the Novaya Zemlya region.

We have begun an effort to develop an optimized site-specific threshold monitoring system for the Lop Nor test site in China. Our aim is to calibrate all available high-quality seismic stations within regional distances and the best IMS arrays at teleseismic distances. As a calibration database, we have used several past nuclear explosions at the test site, combined with nearby, well-recorded earthquakes. Even though most events were recorded by only a few stations, this data set was sufficient to obtain a reasonable amplitude calibration for the purposes of this study.

Initial results show that, among the available stations, the IMS Makanchi array in Kazakhstan (at an epicentral distance of 6 degrees) is the most sensitive station for detecting events at Lop Nor, followed by some of the best teleseismic arrays, for example the NORES array in Norway. Combining the data by using the threshold monitoring technique, we have found that the Lop Nor site can be monitored down to a threshold close to m_b 3.2. This threshold is about 0.8 magnitude unit higher than the corresponding capability for the Novaya Zemlya test site, for which the highly sensitive arrays ARCES and Spitsbergen are both at a distance of only 10 degrees. We note that no stations inside China were selected for the Lop Nor study.

A workshop was held in Oslo, Norway, during 22-26 April 2002 in support of the global seismic event location calibration effort currently being undertaken by PrepCom's Working Group B in Vienna. The workshop, which was chaired by Dr. Frode Ringdal, was attended by 66 scientists from 12 countries and the Provisional Technical Secretariat of the CTBTO. The workshop was held jointly by the International Data Centre (IDC) Experts Groups on location calibration and event screening, and the results and recommendations were reported to Working Group B.

OBJECTIVE

This work represents a continued effort in seismic monitoring, with emphasis on studying earthquakes and explosions in the Barents/Kara Sea region, which includes the Russian nuclear test site at Novaya Zemlya. The overall objective is to characterize the seismicity of this region, to investigate the detection and location capability of regional seismic networks, and to study various methods for screening and identifying seismic events in order to improve monitoring of the Comprehensive Nuclear-Test-Ban Treaty. Another objective is to apply advanced site-specific seismic monitoring methods to other sites of special interest, in particular known nuclear test sites. A third objective is to support the international effort to provide regional location calibration of the International Monitoring System (IMS).

RESEARCH ACCOMPLISHED

Introduction

NORSAR and Kola Regional Seismological Centre (KRSC) of the Russian Academy of Sciences have for many years cooperated in the continuous monitoring of seismic events in northwest Russia and adjacent sea areas. The research has been based on data from a network of sensitive regional arrays that has been installed in northern Europe during the last decade in preparation for the CTBT International Monitoring System. This regional network, which comprises stations in Fennoscandia, Spitsbergen and NW Russia, provides a detection capability for the Barents/Kara Sea region that is close to m_b = 2.5 (Ringdal, 1997).

The research carried out during this effort is documented in detail in several contributions contained in the NORSAR Semiannual Technical Summaries. In the present paper we will limit the discussions to some recent results of interest in the general context of regional monitoring of seismic events in the European Arctic, a presentation of an initial threshold monitoring study for the Lop Nor test site in China and a brief review the location calibration effort currently underway for the IMS.

Low-magnitude seismic events in or near Novaya Zemlya

We have updated our previous studies of low-magnitude events in the Novaya Zemlya region recorded by the NORSAR regional seismic network. Table 1 and Figure 1 summarize the information on such events detected since 1980. In spite of the low threshold for detection, only eight seismic events with estimated location outside the test site have been recorded during these more than 20 years. Furthermore, we have since 1992 applied the site-specific threshold monitoring network to the test site, and have thereby been able to confirm that no other seismic event of magnitude 2.5 or greater has occurred in this region since then.

An especially interesting recent seismic event, which has been analyzed in detail, occurred on Novaya Zemlya on 23 February 2002. This small event (magnitude about 3.0) is the first seismic event detected in or near Novaya Zemlya since the two Kara Sea events of 16 August 1997. The event was recorded with particularly high SNR by the IMS arrays Spitsbergen (SPITS) and ARCES, and by the Amderma station (AMD), operated by KRSC, south of Novaya Zemlya. We have located the event at the eastern coast of Novaya Zemlya, approximately 100 km northeast of the former nuclear test site.

For this recent event, as well as other events recorded by the regional network, we have frequently noted uncertainties in onset measurements amounting to 1-2 seconds. This is, in fact, a general problem, and is due partly to the low SNR for some phases, partly to the emergent nature of some signal recordings. We have conducted a study to assess the effects of such uncertainty on location and depth estimates, using a number of seismic events in the European Arctic (Novaya Zemlya, Kara Sea, northern Norway, Kola Peninsula). For each event, and each detected phase, we selected up to three onset time picks, spanning the estimated uncertainty (typically +/- 1-2 seconds). We then relocated each event using all possible combinations of such time picks, and compiled all solutions except those which showed clear inconsistencies. In this way, we obtained a large number of locations and depths for each event, and made plots to indicate the distribution of both the epicenters and the estimated depths.

The results for the 23 February 2002 event near Novaya Zemlya are illustrated in Figure 2. We note that the epicentral error area is similar to the 90% confidence ellipse in Figure 1. The depth distribution is inconclusive, although most solutions have an estimated depth near 0. From the general study, we note that for all the analyzed events, except for one known earthquake in northern Norway, a depth of zero cannot be ruled out. We consider that this should serve as a caution against using estimated depth as a screening criterion in this region. In particular, we note that depth estimation using regional velocity models depend very strongly on the assumed Vp/Vs ratio.

Waveforms for the 23 February 2002 event from a number of seismic stations at regional distances from Novaya Zemlya are shown in Figure 3. The high SNRs indicate that this event is well above the detection threshold, especially for the Amderma, SPITS and ARCES stations. Note that by array beam forming, the SNR at ARCES and SPITS could be improved by more than 0.5 magnitude units. This again reconfirms the capability of this regional network to monitor seismic events at Novaya Zemlya down to a magnitude level of 2.0-2.5, depending on the actual background noise levels.

In the context of event screening, which is an important topic for the IDC, it is clear from these results that no screening should take place for a region with seismic activity as low as Novaya Zemlya. In fact, any seismic event in this region is of potential monitoring interest, and with a frequency of occurrence of magnitude 2.5 or larger at less than one event per year, the actual analysis work would be quite modest. Similarly, as noted by Ringdal *et. al*. (2000), the much larger geographical area of western Russia and the Barents Sea is also characterized by modest natural seismic activity, and could be exempted from event screening, at least at the current magnitude threshold of 3.5 for screening purposes.

Table 1: List of seismic events in or near Novaya Zemlya (1980-2002) located outside the test site

Date/time	Location	m_b	Comment
01.08.86/ 13.56.38	72.945 N, 56.549 E	4.3	Located by Marshall *et.al*. (1989)
31.12.92/ 09.29.24	73.600 N 55.200 E	2.7	Located by NORSAR
23.02.95/ 21.50.00	71.856 N, 55.685 E	2.5	Located by NORSAR
13.06.95/ 19.22.38	75.170 N, 56.740 E	3.5	Located by NORSAR
13.01.96/ 17.17.23	75.240 N, 56.660 E	2.4	Approximately co-located with preceding event
16.08.97/ 02.11.00	72.510 N, 57.550 E	3.5	Located by NORSAR
16.08.97/ 06.19.10	72.510 N, 57.550 E	2.6	Co-located with preceding event
23.02.02/ 01.21.14	74.047 N, 57.671 E	3.0	Located by NORSAR

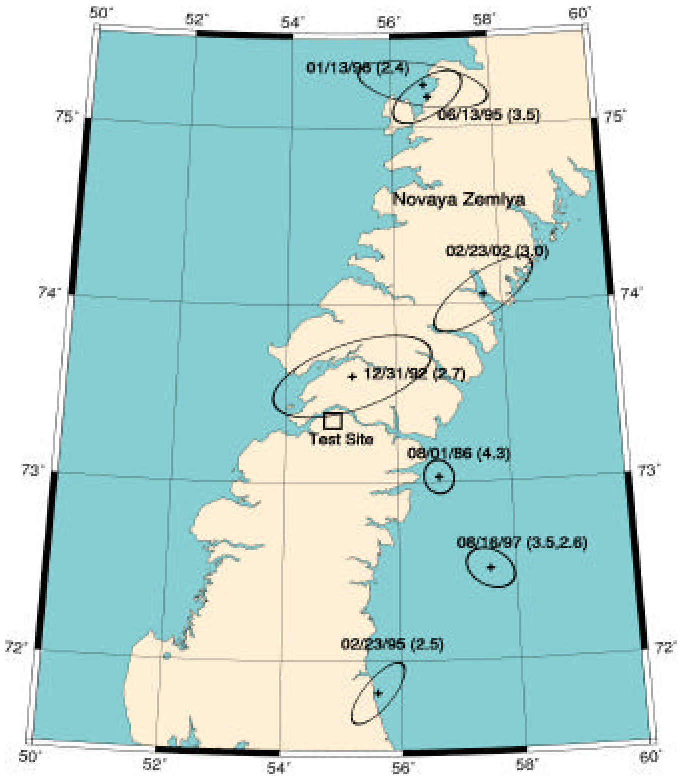

Figure 1. Seismic events detected by the NORSAR regional array system in or near Novaya Zemlya during 1980-2002. Only events with estimated location outside the former nuclear test site are included. Estimated 90% error ellipses are indicated for each event.

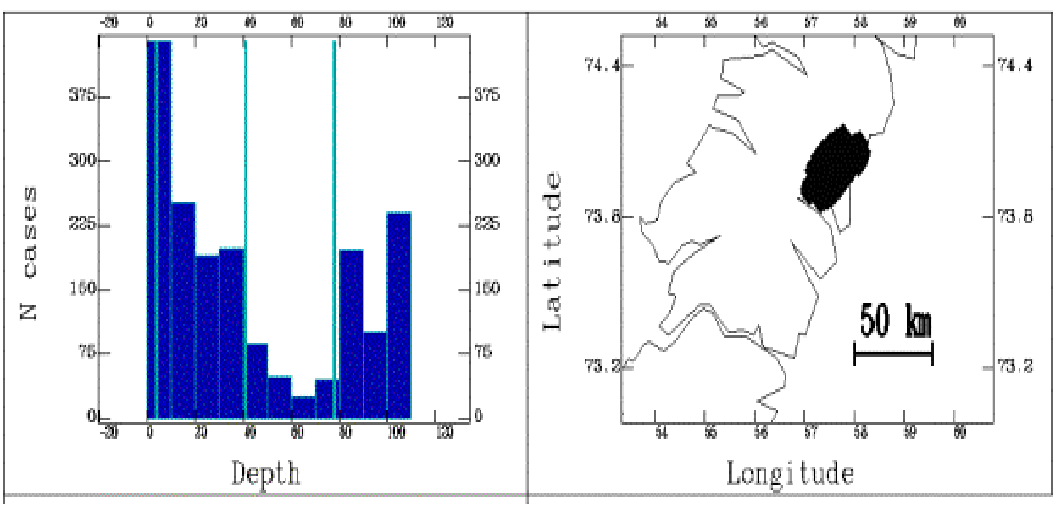

Figure 2. Estimates of the location of the 23.02.2002 seismic event, as explained in the text. Note that the epicenters correspond well with the estimated uncertainty ellipse of Figure 1, and that the depth of the event cannot be conclusively determined.

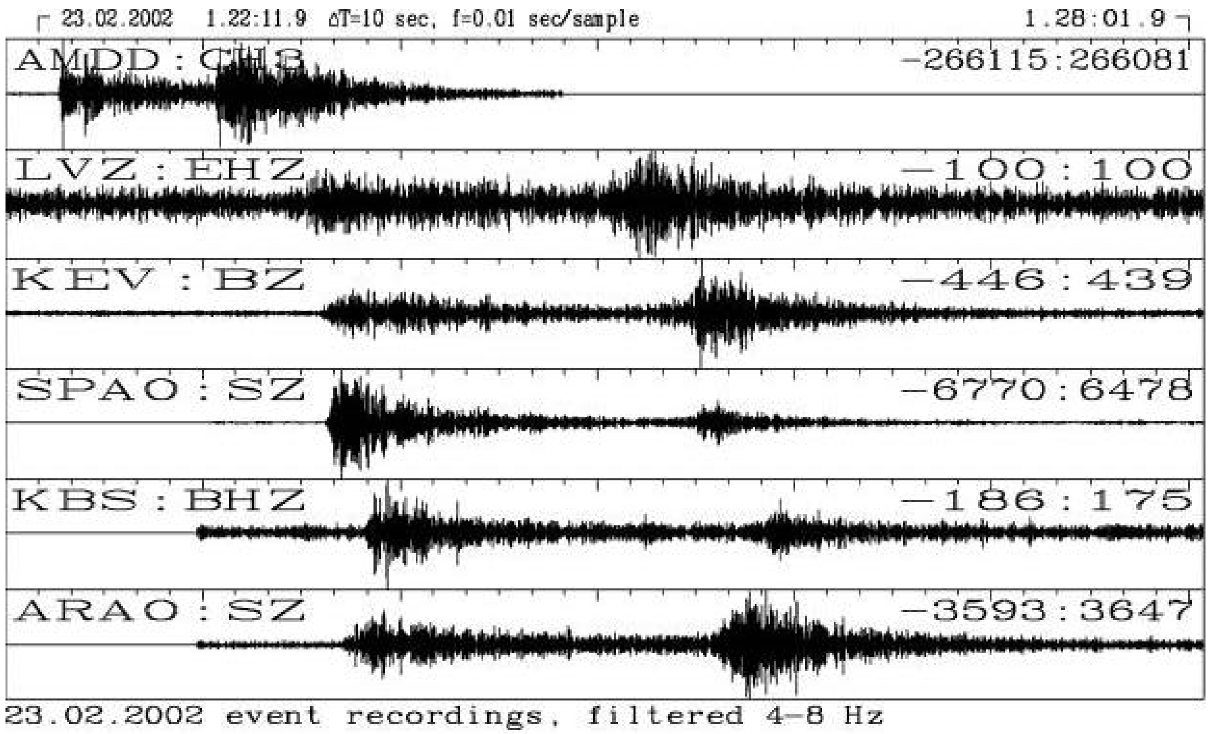

Figure 3. Recorded SPZ waveforms for the 23.02.2002 seismic event. The data are filtered in the 4- to 8-Hz band. Note the high P-phase SNR in particular at the Spitsbergen array (sensor SPA0) and the Amderma station (AMDD). Note also the relatively weak S-phase for the two stations at Spitsbergen (SPA0 and KBS).

Khibiny mines

We have continued our research on rockbursts and mining explosions in the mining areas of NW Russia, in particular the Khibiny Massif. Recently, seismic instrumentation has been installed inside the mines in the Khibiny Massif of the Kola Peninsula in order to provide origin times of the seismic events as well as to contribute to additional validation of the location accuracy. Figure 4 shows an example of recordings for a mining explosion of about magnitude 2.0.

We are also cooperating with Lawrence Livermore National Laboratory in a project funded by the National Nuclear Security Administration to carry out more detailed studies of the characteristics of recordings from mining events in northern Fennoscandia and Western Russia. That project includes the installation of additional seismometers along profiles in Norway, Finland, and the Kola Peninsula, for recording over a period of one year.

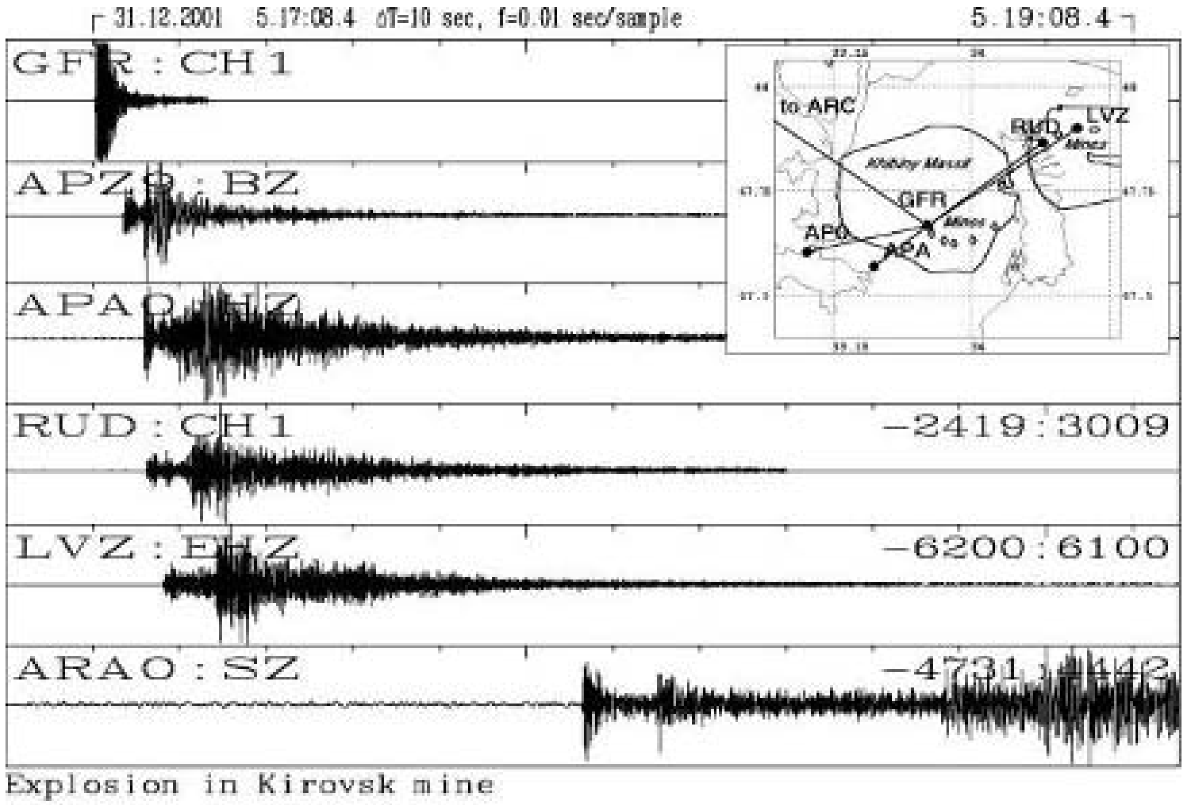

Figure 4. Example of recordings of a mining explosion in the Khibiny Massif, Kola Peninsula, using a network of recently installed local stations as well as stations at regional distances.

<u>Threshold monitoring of the Lop Nor, China, test site</u>

As part of the US Department of Defense Advanced Concept Demonstration (see Kohl, *et al*, this Proceedings), we have applied the Site-Specific Threshold Monitoring (SSTM) technique to the Lop Nor test site in China (Lindholm *et. al*., 2002). The emphasis has been on detection (and location) of small seismic events with mb < 4.0, and the purpose is to evaluate the SSTM method as a potential monitoring tool for this site. In contrast to most previous case studies, which have been based on recordings by seismic arrays at regional distances, we have in this study applied a combination of three-component stations and arrays, at both regional and teleseismic ranges.

Our efforts so far, as reported in this contribution, comprise mainly a study of available seismic stations, selection of those stations that are most sensitive to seismic events in the Lop Nor general area, and tuning of the signal parameters of these stations so as to prepare processing recipes for the application of the threshold monitoring tool.

Development of processing recipes

For the successful implementation of SSTM, beams filtered in optimal frequency bands must be steered from the individual arrays towards the Lop Nor test site, and amplitude calibration constants developed from older events are applied to facilitate the calculation of continuous magnitude thresholds for the site. For single (or three-component) stations, the vertical component is filtered in the optimal frequency band.

For the purposes of this study, 23 single stations and arrays were initially chosen as shown in Figure 5. For each of the stations, data were collected from known nuclear tests at Lop Nor, and supplemented with data for low-magnitude earthquakes near the test site. We note that for most stations only a few data sets with explosions were available for the calibration.

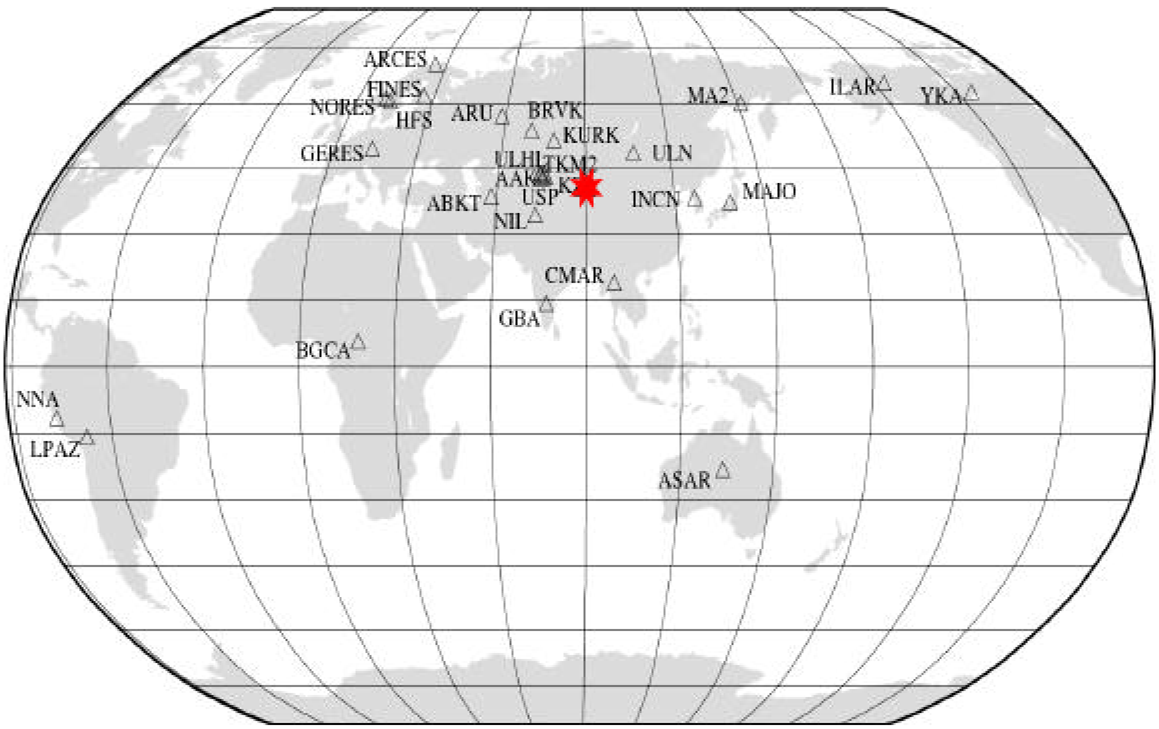

Figure 5. Network selected for threshold monitoring of the Lop Nor, China test site. The test site is marked with a star symbol.

Preliminary Results

Two performance tests were carried out. First, data for one day (September 10, 2001) were collected, and in these data the recordings of four explosions were scaled and embedded at some (but not all of the) stations. The explosions were scaled to magnitude 3.5 and 3.0, so that a total of eight embedded explosions were included. Secondly, a 10-day test period with data from August 2 through 11, 2001, was selected and data were collected for all available stations in our network. Figure 6 shows examples of network results of these two performance tests.

From these tests the following preliminary observations can be stated:

- Out of the eight embedded explosions on day 253, six were detected automatically on the threshold trace, and the remaining two could be clearly seen on the trace, even if the automatic detector did not trigger.
- The quiet day (214) did not have any events flagged.
- On day 217 the SSTM method triggered on two large teleseismic events.
- The network threshold is close to or better than 3.0 (based on both arrays and single stations). The "trigger level" (shown as a continuous, smooth line in Figure 6) is at magnitude 3.2 or lower.
- In a monitoring situation, all peaks exceeding the threshold could be analyzed. The maximum number of such peaks during one day was 10-15 for the days processed. If such peaks were analyzed, all of the scaled events on day 2001-253 would have been found.

The above observations should be evaluated under the perspective that the calibration is a preliminary one, where the majority of the stations could only be calibrated with one or two events/explosions, and where only some of the calibrated stations were included in the performance test. Furthermore, the day with embedded events did not include embedded data for all the stations, and this did reduce the performance of the threshold monitoring.

In the paper by Lindholm *et. al.* (2002), there is also some discussion of the relative performance of individual stations in the network. The SSTM threshold traces for single stations and arrays can in fact be used to assess this performance. We have observed that the arrays generally have thresholds between magnitude 3.2 and 3.8, and that the single stations vary considerably, from about 3.5 for the best (closest) stations to almost 4.5 for some of the lower performing stations. Some stations in the data set feature frequent data problems.

As the IMS is further developed, there is a clear potential for improvement in the performance illustrated above. For example, the sensitive array in Makanchi, Kazakhstan, was not available to us for the test period in August/September 2001. Studies of the performance of this array have indicated that it has a superior capability for detecting events at Lop Nor compared to the other stations in the network, and therefore would contribute to significantly improved thresholds, once included.

We also note that the current study has been done without including any Chinese IMS stations in our experimental network. Including such stations would no doubt contribute to improved thresholds, but there are other considerations that may make it useful to evaluate how the test site can be monitored using only stations outside the country.

Location Calibration

Oslo Workshop on location calibration

A workshop was held in Oslo, Norway, during 22-26 April 2002 in support of the global seismic event location calibration effort currently being undertaken by Working Group B of the CTBTO Preparatory Commission in Vienna, Austria. Dr. Frode Ringdal chaired the meeting, which was attended by 66 experts from 12 countries and the Provisional Technical Secretariat of the CTBTO   The recommendations from this workshop have been provided in the paper CTBT/WGB/TL-2/70, issued by Working Group B of the CTBTO Preparatory Commission.

CONCLUSIONS AND RECOMMENDATIONS

The analysis of the 23 February 2002 Novaya Zemlya seismic event has reconfirmed our previous estimates of the detection and location capability of the regional network in northern Europe. This experimental network operation will continue, and will be used to evaluate and supplement the IMS network in this region. Further research is required in regional event identification criteria, especially depth estimation. In the case of depth estimates, a detailed study of the Vp/Vs ratio, as well as its uncertainty limits, should be undertaken.

Our initial performance tests of Site-Specific Threshold Monitoring for the Lop Nor test site were successful. We recommend that these initial tests be followed by more detailed studies, where, in particular, the calibration parameters should be more firmly established. It is also of interest to include additional sensitive IMS arrays in the monitoring network, and evaluate the ensuing improvement in capability.

The location calibration effort will continue to be an important part of our work. The recommendations provided in the paper CTBT/WGB/TL-2/70 should be followed up by the international community, and the progress of this work will be reviewed in a planned workshop in Oslo during 4-9 May 2003.

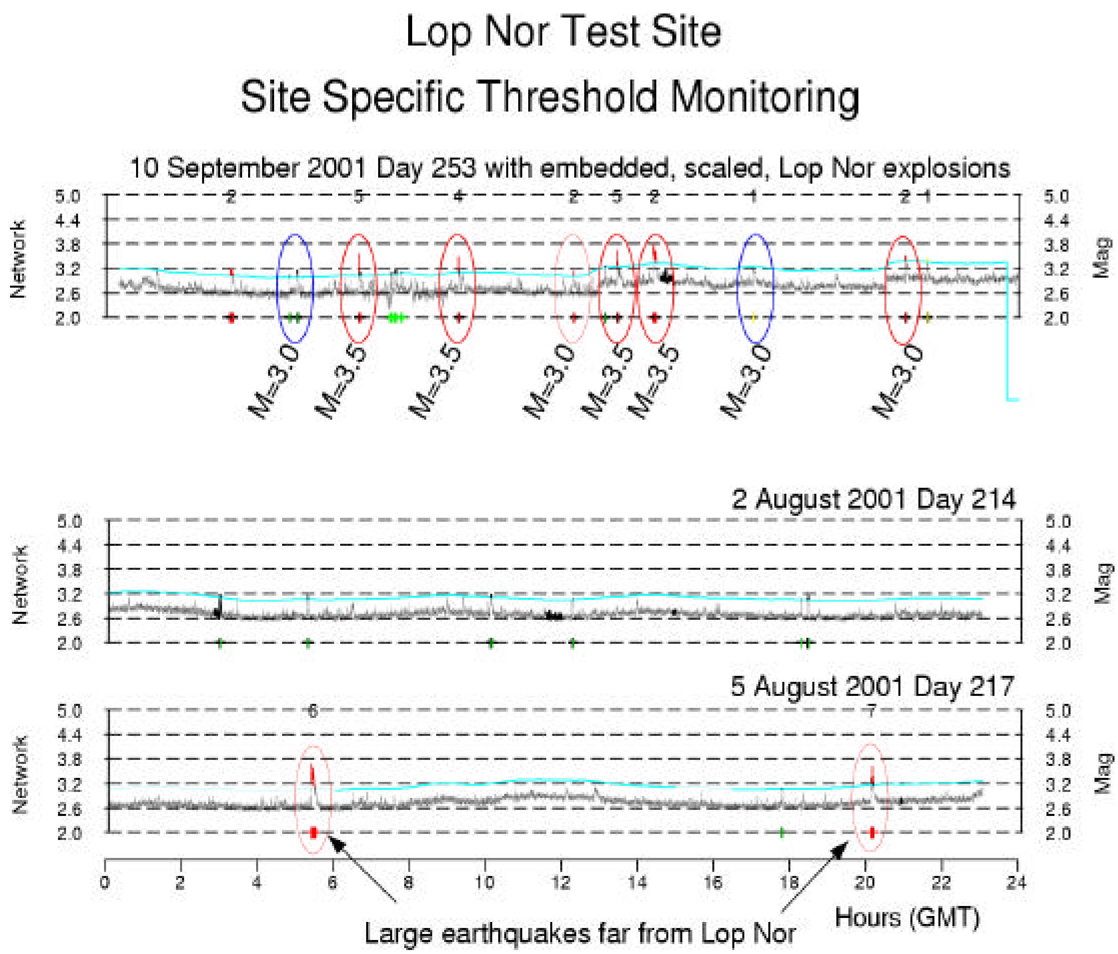

Figure 6. Threshold monitoring network traces from three different days. The upper trace is from day 253 with eight embedded Lop Nor explosion recordings scaled to magnitudes 3.0 and 3.5. The ellipses indicate the times of the embedded explosions. For six of the eight embedded explosions, the SSTM automatic analysis picked the events, while two events (No. 1 and No. 7) were not picked. The lower traces are from days 214 and 217. Day 214 is quiet with no detections, while day 217 shows two detections resulting from "interference" by large earthquakes (located far from Lop Nor). The continuous, smooth line above each threshold trace is an estimated "trigger level" for identifying significant peaks on the threshold trace.

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