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6.3 Site-specific GBF monitoring of the Novaya Zemlya test site

Introduction

In the two preceding NORSAR Semiannual Technical Summaries we have reported on our developments concerned with monitoring the Lop Nor test site in China (Lindholm et. al., 2002; Kværna et. al., 2002a). Using data from the global arrays and single stations having the best detection capability for the area, we have developed and tested both an optimized site-specific threshold monitoring (SSTM) and a site-specific Generalized Beamforming (SSGBF) system for the Lop Nor test site.

For the former test site on Novaya Zemlya (NZ), a continuous seismic threshold monitoring scheme has been operational at NORSAR for several years. A comprehensive description and discussion of this processing if given by Kværna et. al., 2002b. In order to improve the experimental monitoring capability, we have now also developed a site-specific Generalized Beamforming (SSGBF) for the NZ test site.

Development of site-specific GBF

The Generalized Beamforming (GBF) technique, originally developed by Ringdal and Kværna (1989), is now widely accepted as the most efficient method for associating seismic phases from a global or regional network. In a typical implementation, a large number of generalized "beams" are steered to the points in a global or regional grid. An automatic detector is applied to each station or array in the network, and a set of "box-car" or "triangular" functions is generated for each station, such that the non-zero parts of these functions correspond to a time interval around a detection. By summing these functions with appropriate weights and with time delays corresponding to the particular phase-station-grid point combination, one obtains a "beam" that may then be subjected to a detector algorithm.

A common feature of such implementations is the need to group the large number of individual beam "detections" in order to eliminate side-lobes and associate the detection group with an event at the correct hypocenter. This grouping, which can become quite complex, is clearly unavoidable when a large geographical region is to be monitored. However, if one is monitoring a particular site, such as a suspected nuclear test site, it is possible to simplify this procedure considerably, and at the same time optimize the parameter settings to ensure the best possible detection probability for the target site. This idea was first tested by Ringdal and Kværna (1993) to monitor the aftershocks of a large earthquake sequence occurring in Western Caucasus during the GSETT-2 experiment. They concluded that the approach showed a superior performance compared with the association procedures being employed at the four experimental international data centers operating during GSETT-2. In the present paper we elaborate further on this site-specific GBF (SSGBF) approach to monitoring the Novaya Zemlya test site.

Array network and analysis procedure

The 4-array network displayed in Fig. 6.3.1 has been shown to provide a monitoring capability for the NZ test site down to m_b 2.0 for most time intervals (Kværna et. al., 2002b). Similarly, we have in the implementation of the SSGBF processing used the same 4-array network, and the processing parameters have been derived from the same events in the Novaya Zemlya region as have been used for the tuning of the SSTM process (Kværna et. al., 2002b). Table 6.3.1 summarizes the station and phase information and also lists the range of the azimuth and slowness parameters used for forming the beam towards the test site. The limits on arrival time tolerances are not defined in Table 6.3.1, since these tolerances are to a large extent dependent on the desired sharpness of the generalized beam. We have used the formula:

$$dT = S \cdot R$$

where dT is the time tolerance in seconds, R is the desired beam radius in km and S is the P-phase slowness (in s/km) corresponding to the distance from the target site to the station being processed. We have chosen to use fairly large tolerances, to ensure that there is only a small probability of missing real detections corresponding to an event at the site. Specifically, for NZ we used a radius of 100 km. The expected Pn-wave phase velocity at ARCES and SPITS is about 8 km/s, so the assumed range of the time tolerance is approximately +/- 12 seconds.

The beamforming procedure follows the GBF standard, except that only one generalized beam is formed in the site-specific case. The main steps are:

- Applying an automatic detector at each of the stations/arrays in the network
- Summing “boxcar” or “triangular” weight functions representing the detector outputs with the appropriate restrictions on travel time, azimuth and slowness
- Applying a thresholding procedure on the resulting generalized beam

We have used “triangular” functions centered at the expected arrival time for the beamforming in our NZ analysis. Experiments have shown that the effect of sidelobes is reduced compared with when using “boxcar” functions, while still retaining high sensitivity for detecting events in the target area.

Example 1: 23 February 2002

Our first example, shown in the left part of Fig. 6.3.2, is the day 23 February 2002. At 01:21:12.1 GMT on that day there was an event with a magnitude of about 3.2, located about 100 km north-east of the former nuclear test site. The SSGBF traces for each phase considered are shown, together with the network trace on top. The peaks of the panels for each phase represent detections that fall within the NZ azimuth and slowness ranges given in Table 6.3.1. To align the detections we have subtracted the phase travel-time from NZ to the respective arrays. The network trace on top is calculated by adding “triangular” functions surrounding each detection, using the six phases given in Table 6.3.1.

Alerts (red diamonds) are declared when the network trace (the full network) has a value of at least 2. To obtain a value of 2 using “triangular” weight functions, we would need at least two matching phases with perfect time fit. However, but more realistically, three matching detections would be required. From the SSGBF traces of Fig. 6.3.2 we find that during 23 February 2002 there is only one event trigger. By summing the “triangular” weight functions of the six detected phases, we obtained a network SSGBF value of about 4.7 for the NZ event.

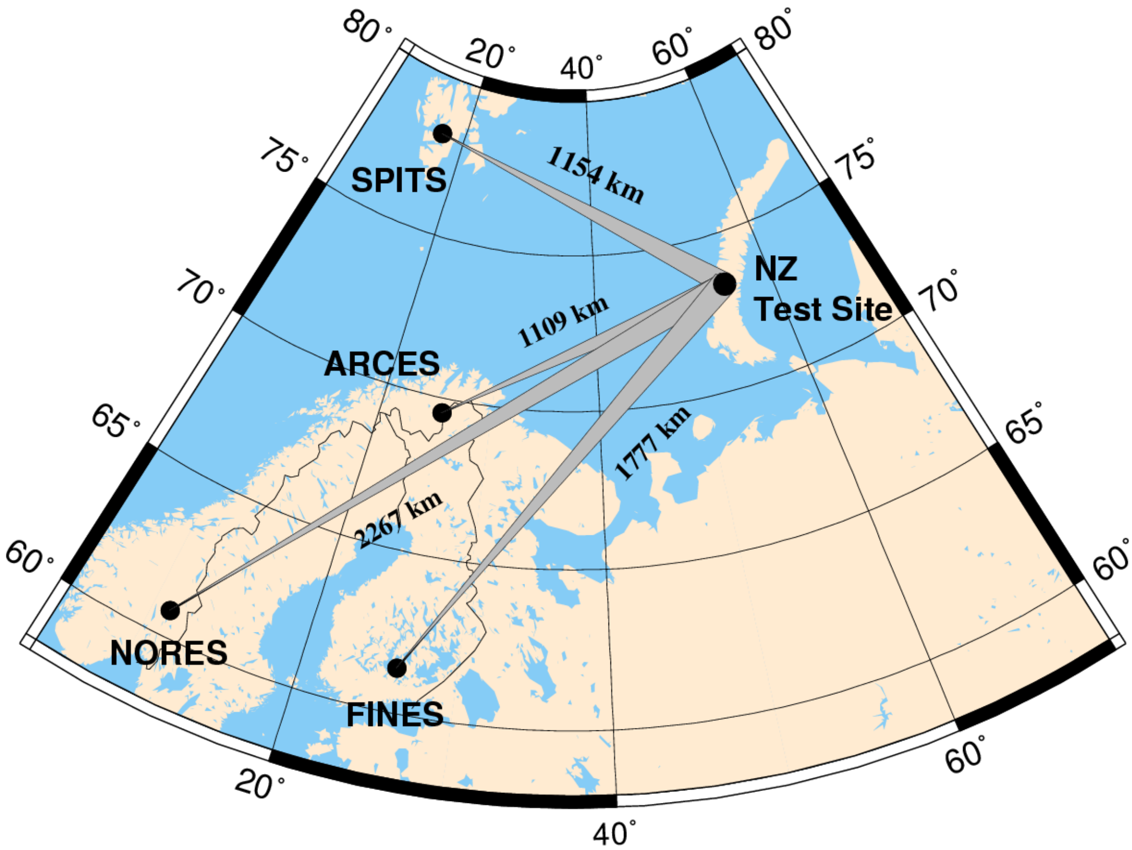

Fig. 6.3.1. Map showing the arrays used for both site-specific Threshold Monitoring and site-specific Generalized Beamforming of the former Novaya Zemlya test site.

Table 6.3.1. The stations used for Site-Specific Generalized Beamforming processing of the former Novaya Zemlya test site. In order for a signal detection to be used as a candidate for an event at the NZ test site, its azimuth and slowness estimates have to be within the ranges given in the table.

Station	Type	Phase	Distance (km)	Travel time (s)	Azimuth Range (deg)	Slowness Range (sec/deg)
ARCES	Array	Pn	1108.6	147.5	47.2-77.2	10.6-17.1
ARCES	Array	Sn	1108.6	254.2	49.3-79.3	19.8-31.8
SPITS	Array	Pn	1154.2	152.6	77.6-227.6	10.6-17.1
SPITS	Array	Sn	1154.2	263.0	77.6-227.6	19.9-34.8
FINES	Array	P	1776.9	224.2	11.6-47.6	10.6-14.8
NORES	Array	P	2267.3	281.4	18.6-48.6	9.3-14.3

For comparison, the corresponding SSTM traces are shown in the right part of Fig. 6.3.2. From the SSTM traces we see that the magnitude threshold is below mb 2.0 for most of the day except for a few time intervals, including the NZ event at 01:21:12.1 GMT.

SSGBF and SSTM traces for a one-hour interval surrounding the NZ event is shown in Fig. 6.3.3.

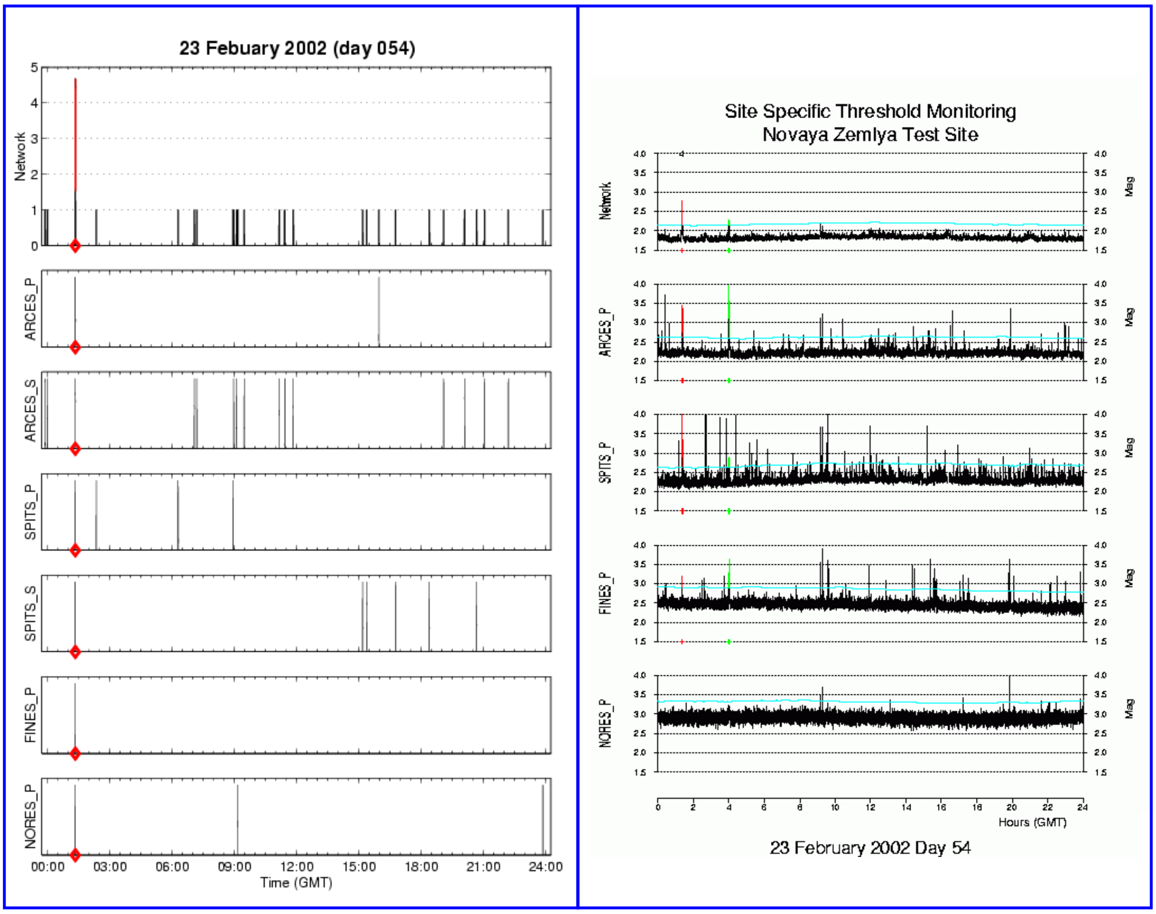

Fig. 6.3.2. SSGBF traces for 23 February 2002 are shown in the left part of the figure. The peaks of the panels for each phase represent detections that fall within the NZ azimuth and slowness ranges given in Table 6.3.1. To align the detections we have subtracted the phase travel-time from NZ to the respective arrays. The network trace on top is calculated by adding "triangular" functions surrounding each detection, using the six phases given in Table 6.3.1. Alerts (red diamonds) are declared when the network trace (the full network) has a value of at least two.
The corresponding SSTM traces are shown in the right part of the figure. For detailed information on SSTM we refer to Kværna et. al., 2002b.

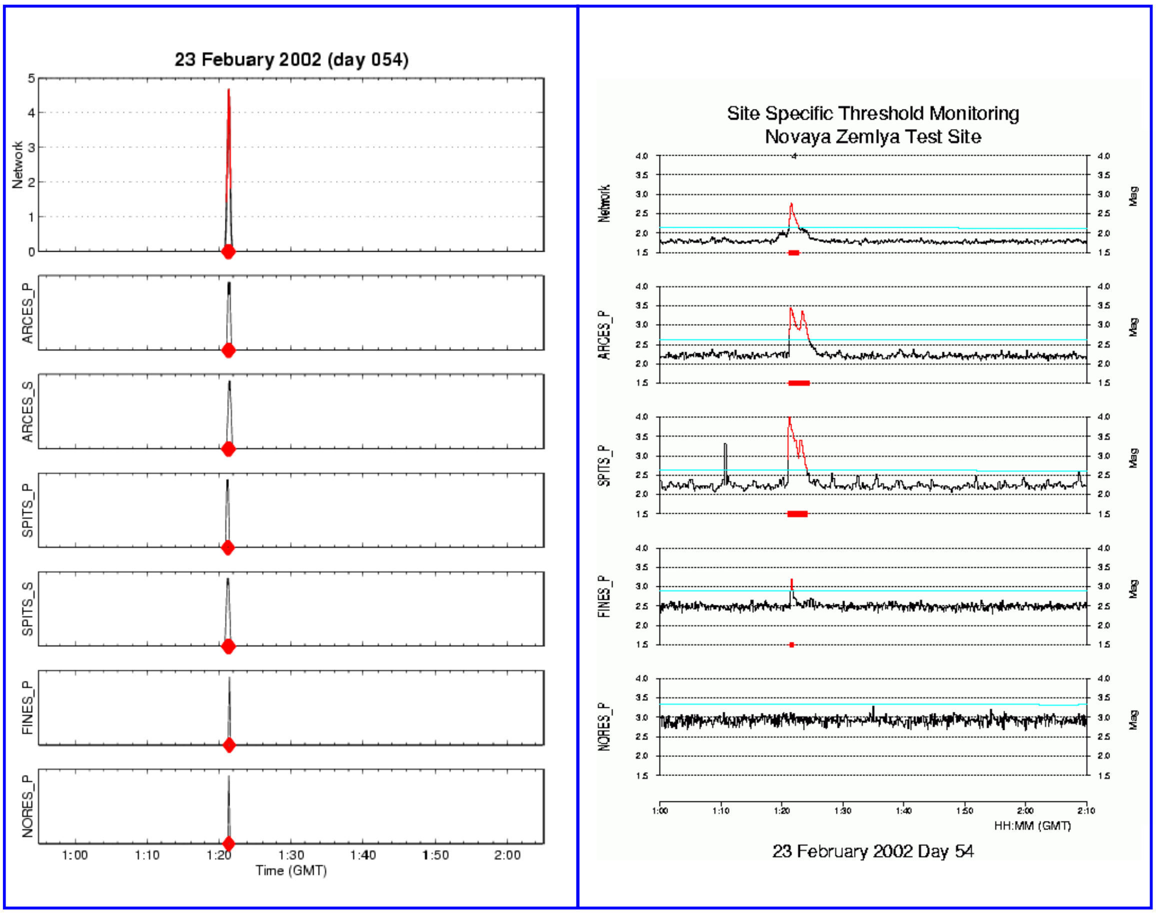

Fig. 6.3.3. SSGBF and SSTM for 23 February 2002, 01:00 - 02:00 GMT. See Fig. 6.3.2 for details. Notice the triangular shape of the SSGBF weight functions.

Example 2: 11 January 2002

For most days the SSGBF plots have no triggers, like for 11 January 2002, shown in Fig. 6.3.4. For the two-moth time period January-February 2002, there were only two additional instances where alerts were declared, i.e., when the network trace (the full network) has a value of at least 2. Both these alerts were false alarms that could be ruled out as being NZ events by analyzing the corresponding array data. We have also experimented with lower alert thresholds, which of course provided higher false alarm rates. For example an alert threshold of 1.7 provided 10 false alarms during January and February 2002

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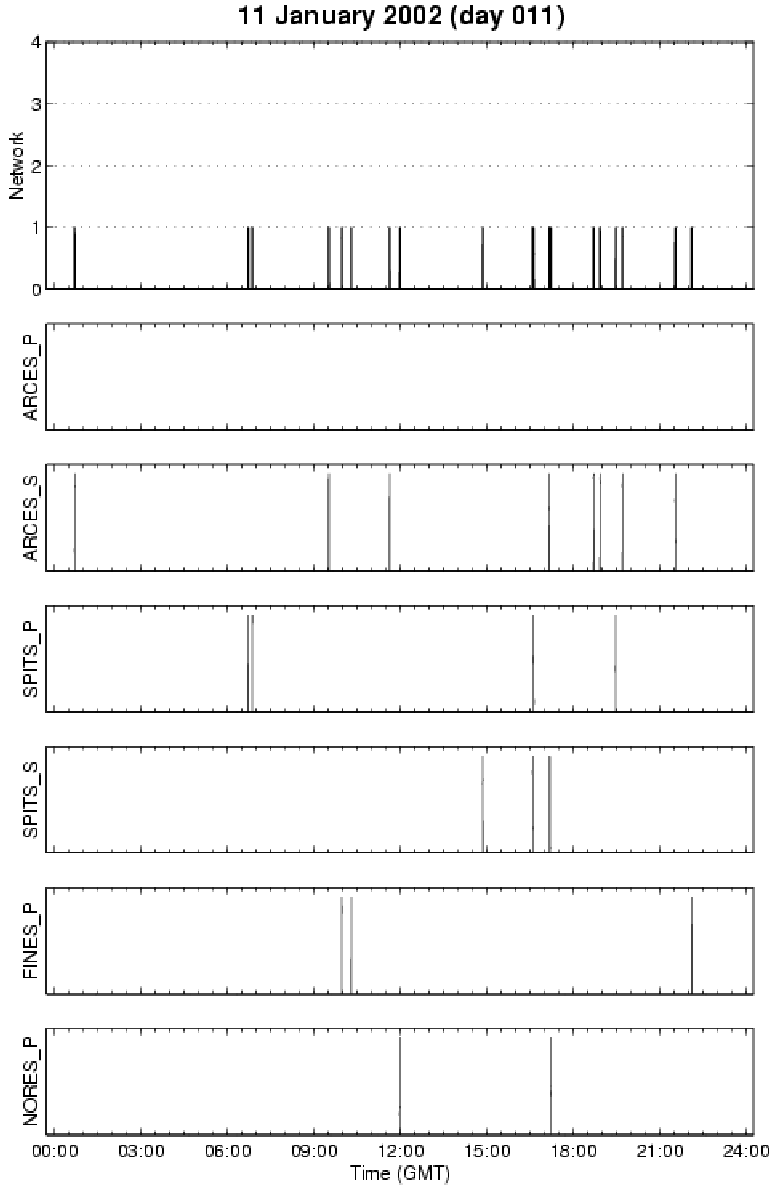

Fig. 6.3.4. SSGBF traces for 11 January 2002. See Fig.6.3.2 for details

Regional GBF processing for the Barents Sea region

In order to investigate the sensitivity of the SSGBF approach for monitoring, we have developed a regional implementation of the method covering the Barents Sea region. The grid system, having a spacing of about 28 km, is shown in Fig. 6.3.5**.** The 'barey' travel-time model of Schweitzer and Kennett (2002) was used for predicting the P- and S-phase arrival times and slownesses at the four arrays ARCES, SPITS, FINES and NORES. For FINES and NORES only P-type phases are considered, whereas for ARCES and SPITS we use Pn and Sn. Azimuth tolerances of ±30 degrees and a slowness tolerance of ±4 sec/degree around the predicted slowness are applied. The time tolerances, calculated from the grid spacing, were about ±3 seconds for Pn and about ±5 seconds for Sn.

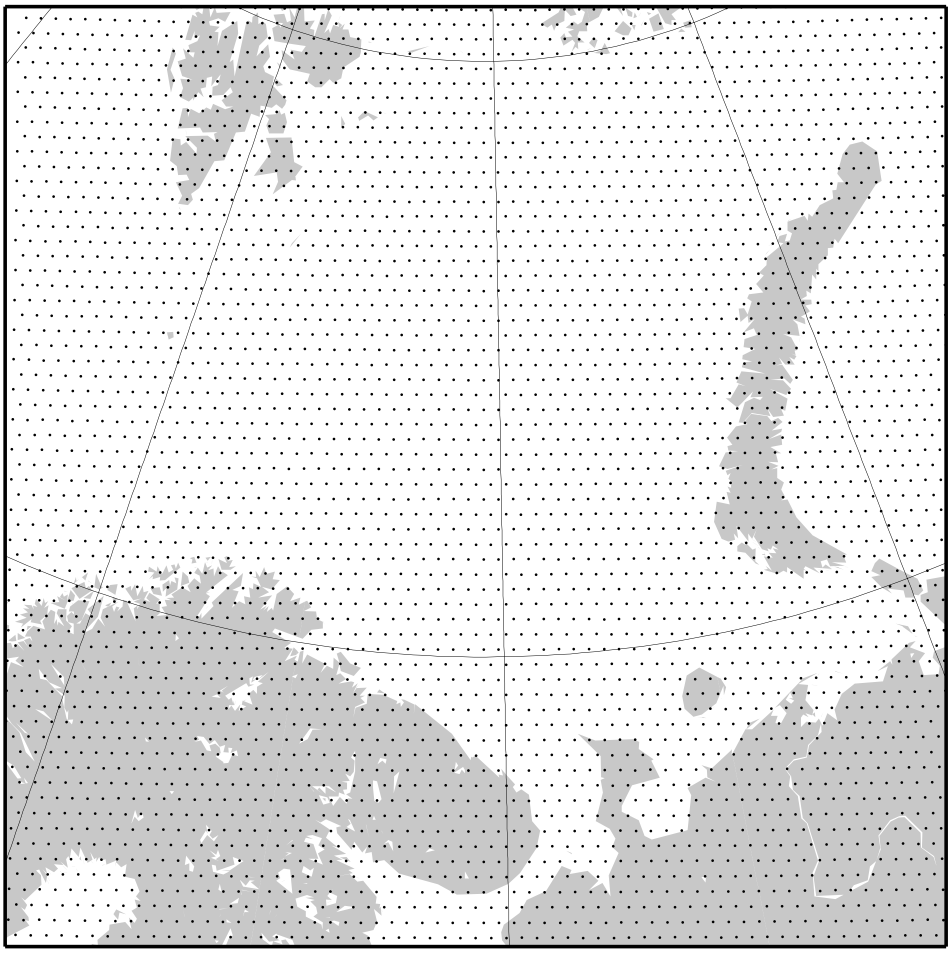

Fig. 6.3.5. Regional GBF grid system covering the Barents Sea Region, having a grid spacing of about 28 km.

An illustration of the regional GBF results for 23 February 2002 is given in Fig. 6.3.6. The upper trace shows the time-wise maxima of the network GBF traces for all targets of the grid system. Notice that there are several instances where the network GBF values exceed the alert threshold of 2 used for the SSGBF of the NZ test site. The color coding of the map below represents the point-wise maxima of the network GBF traces during the 24 hour time interval. Notice the high values on Novaya Zemlya, on the Kola Peninsula and in Northern Sweden, all corresponding to seismic events in these regions. See Fig. 6.3.2 for a comparison with SSGBF and SSTM.

Regional GBF results for the one-hour time interval 01:00 - 02:00 on 23 February 2002 are shown in Fig. 6.3.7. During this time interval there was only one event, located in the vicinity of Novaya Zemlya, such that the areal extent of the topmost part of the GBF peak reflects the sensitivity of the SSGBF method with respect to events in the NZ region.

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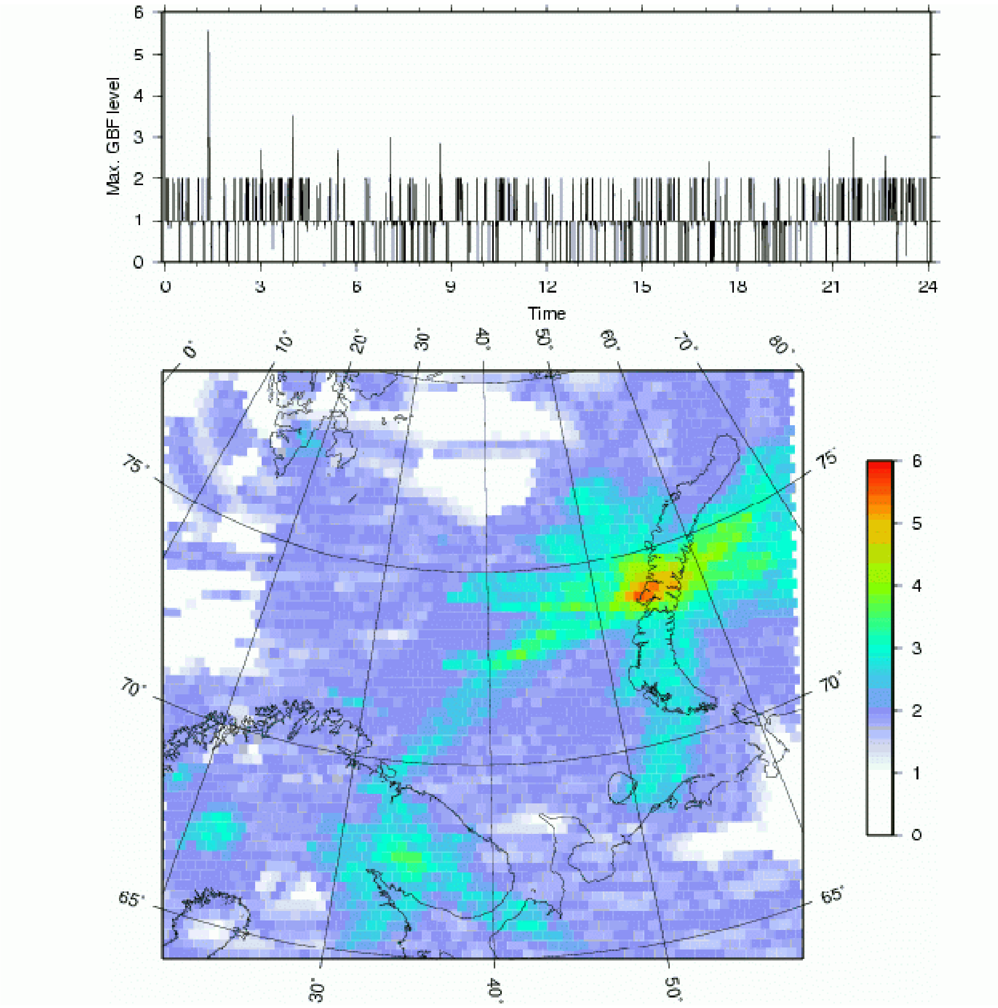

Fig. 6.3.6. Regional GBF results for 23 February 2002. The upper trace shows time-wise maximum of the network GBF traces for all targets of the grid system. The map below represents the point-wise maxima of the network GBF traces during the 24 hour time period. Triangular weight functions are used.

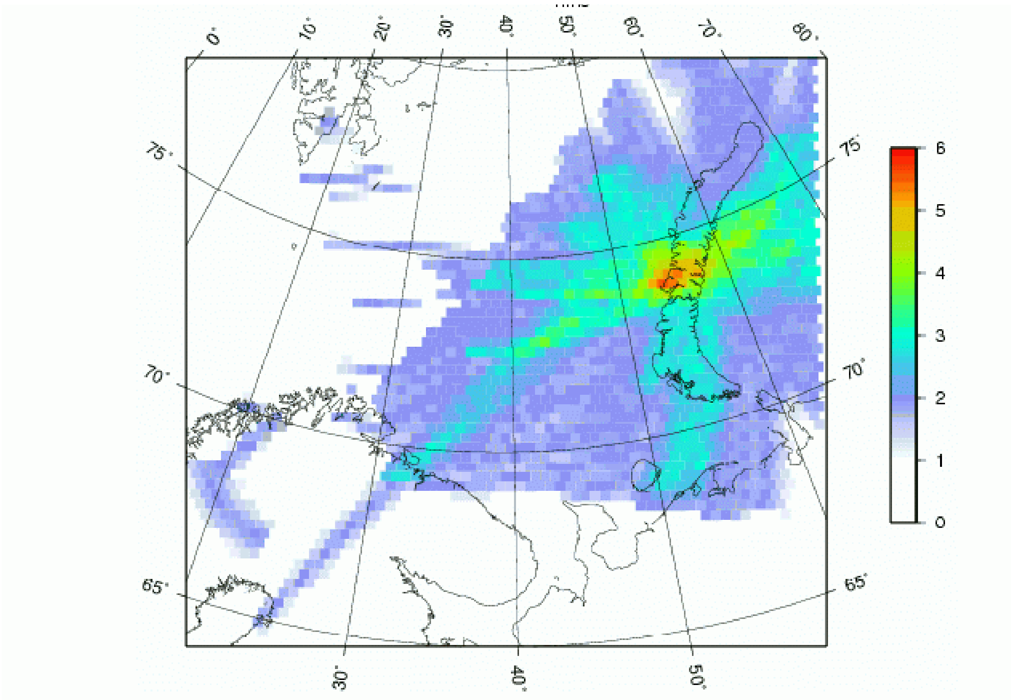

Fig. 6.3.7. Regional GBF results for 23 February 2002, 01:00-02:00 GMT. See Fig. 6.3.3 for comparison with the SSGBF and SSTM results.

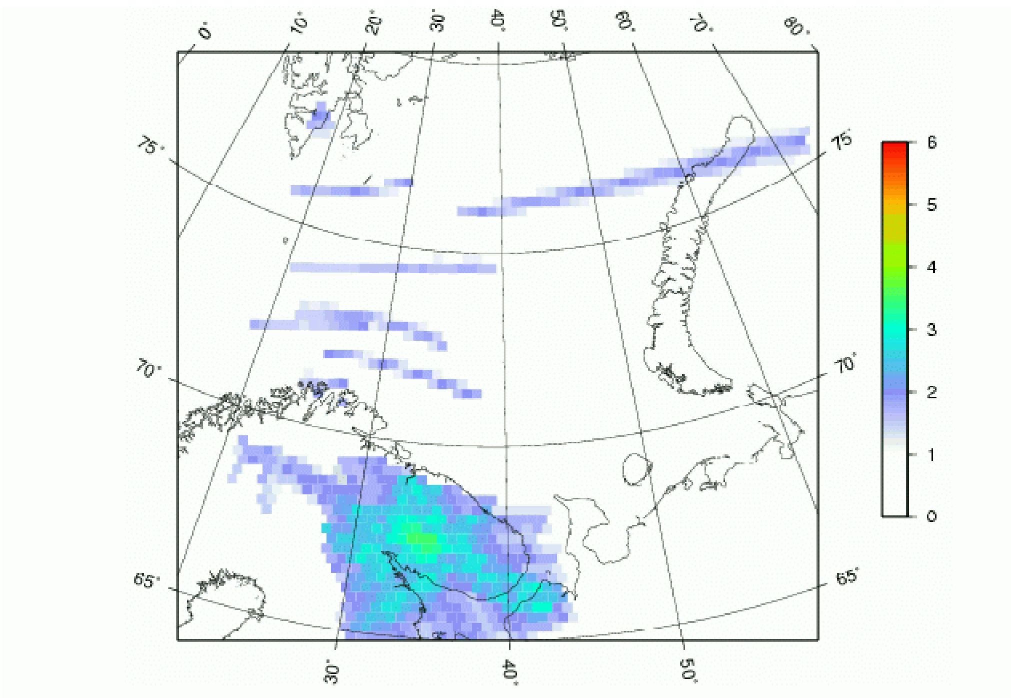

Fig. 6.3.8. Regional GBF results for the one-hour time interval 04:00-05:00 GMT on 23 February 2002. At 04:00:37 there was an 76 ton underground explosion in one of the mines in the Khibiny Massif on Kola.

Regional GBF results for the one-hour time interval 04:00 - 05:00 on 23 February 2002 are shown in Fig. 6.3.8. During this time interval there was one event occurring in the Khibiny Massif on the Kola peninsula. As seen from the figure, there is an area of at least 100x100 km for which the network GBF levels are very close to the peak value.

As a final example we show in Fig. 6.3.9 the regional GBF results for 11 January 2002. As seen from Fig. 6.3.4 there were no SSGBF alerts for the NZ test site during this day. This is also seen on the regional GBF map where there are no indications of increased levels near NZ. The peak are south of Svalbard correspond to signals from a magnitude 3 earthquake at 17:14 GMT.

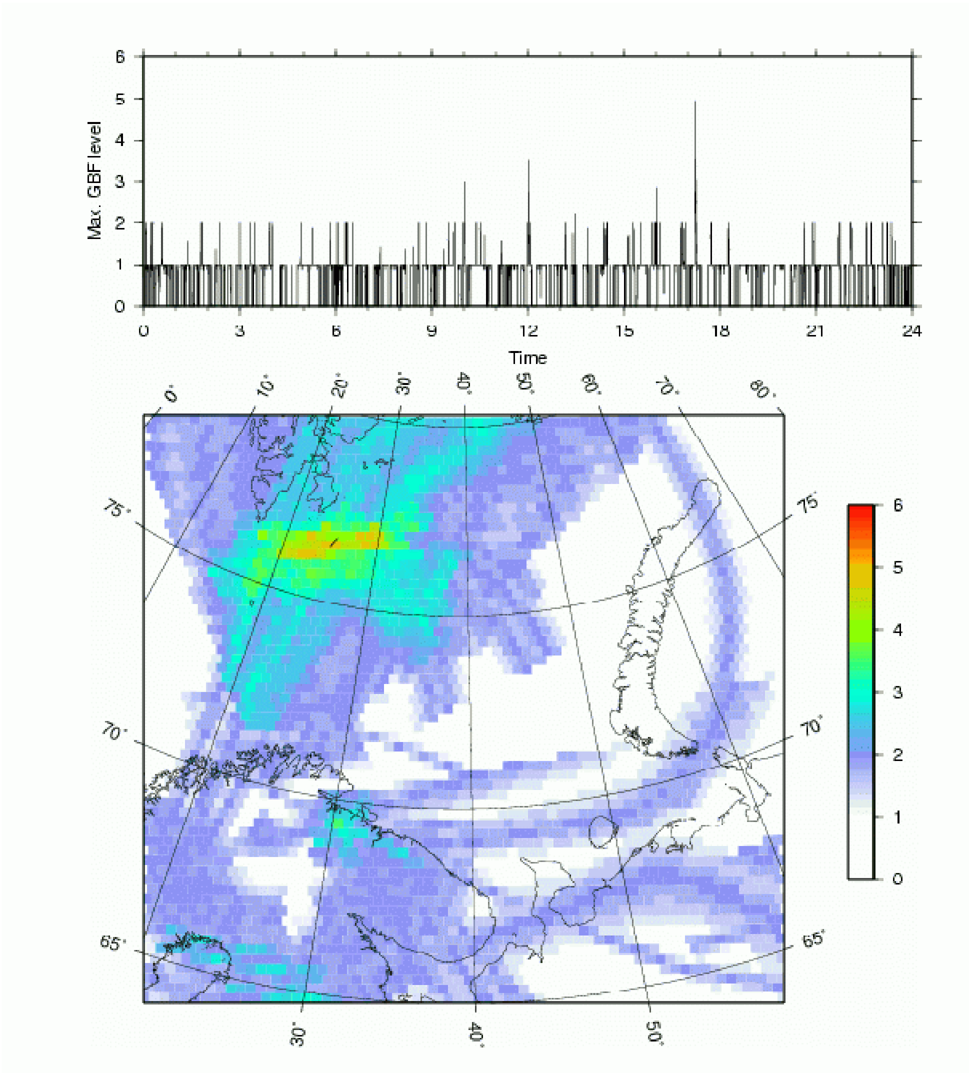

Fig. 6.3.9. Regional GBF results for 11 January 2002. The main peak area is caused by a magnitude 3 earthquake south of Svalbard at 17:14 GMT.

Conclusions

The combination of the SSTM and the SSGBF methods has been shown to provide a very convenient tool for day-to-day monitoring of the Novaya Zemlya test site. The SSTM technique has as its main strength the ability to display the real seismic field, regardless of "station detector performance". On the other hand, the SSGBF technique takes advantage of the individual station detector outputs, and uses this combined information to narrow down the number of possible candidates for events in the target area.

These two monitoring tools have now been running in parallel on a daily basis at NORSAR since the beginning of 2002, and calendars with standard displays are made available via a Web application. Based on the accumulated processing results we plan to investigate the threshold settings for declaring alerts, false alarm rates, and possibly also the introduction of more sensitive detectors aimed at capturing signals from the Novaya Zemlya Region.

A regional GBF implementation has also been made for the Barents Sea Region, and the graphical output from this processing provides a visual overview of major events in the region. The spatial and temporal pattern from the regional GBF provides information on the resolution of a site-specific GBF, e.g., steered towards the Novaya Zemlya test site. We find that using the four-array network ARCES, SPITS, FINES and NORES, all events within 100 km of the test site are efficiently captured by the site-specific approach. If larger areas are to be monitored, site-specific GBF distributed with a spacing of 100 - 150 km would be preferable.

We finally provide some comments on the selection of station networks for optimized site-specific monitoring. In this regard, there is a fundamental difference between the SSGBF and the SSTM procedures. With SSGBF, it is very important to include only those stations with the best monitoring capability for the target site. Including additional, poorer, stations in the network will cause no increase in the monitoring capability, but may well cause a significant increase in the number of false alarms. On the other hand, for SSTM, inclusion of such additional, poorer stations will cause no significant change in the monitoring results.

In this paper, we have used the same four-array network for SSGBF and SSTM of the Novaya Zemlya test site. Since two of the arrays (ARCES and SPITS) have significantly better capability than the other two, it would be interesting to consider only these two "best" arrays in the SSGBF procedure. This might contribute to an even lower false alarm rate than seen for the current process (2 false alarms during two months, given a GBF threshold of 2.0). Admittedly, if one (or both) of these arrays are inoperational, the inclusion of additional arrays would indeed be important, so the picture is not clear-cut. Nevertheless, the idea of reducing the array coverage and assessing the impact on the false alarm rate should be investigated in the future. In such a scenario, the SNR thresholds for the individual array detection processing as well as the GBF threshold could be reduced to increase the sensitivity while maintaining an acceptable false alarm rate.

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