INTEGRATED SEISMIC EVENT DETECTION AND LOCATION BY ADVANCED ARRAY PROCESSING

T. Kvaerna[1], S. J. Gibbons[1], F. Ringdal[1], and D. B. Harris[2]

NORSAR[1] and Lawrence Livermore National Laboratory[2]

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ABSTRACT

We have developed a prototype system for the automatic monitoring of seismic events from sources of interest using regional seismic arrays. The aim of such a system is to provide significantly improved location estimates for low-magnitude events compared with current automatic approaches, combined with a low false alarm rate.
The system is a generalization of an algorithm developed under a pilot project to monitor events from the Kovdor mine in NW Russia using only the ARCES regional array at a distance of 300 km, applying carefully calibrated processing parameters based upon previous observations of confirmed events at the site of interest. The new automatic system is therefore suited, but not restricted, to the single array case. We have applied the process to the Fennoscandian arrays and the arrays in Kazakhstan.

As an initial step, every detection at each of the stations employed is reprocessed in two stages: firstly, the onset time is re-estimated using an autoregressive method and, secondly, the slowness is estimated using broadband f-k analysis in several predetermined fixed frequency bands. The slowness observed can vary considerably from one frequency band to another and the frequency band providing the most stable estimates for repeated observations from a given source varies greatly from site to site. For the local and regional events considered, frequencies below 2 Hz rarely provide useful slowness estimates for the Fennoscandian arrays due to the strong background noise. Frequencies above 4 Hz were not used in the reprocessing of the Kazakhstan data due to signal incoherence over the arrays.

The automatic monitoring system is based upon two types of templates: a site template that lists which phases are anticipated at which stations at which times, and a template for each phase specifying a permissible range of slowness and azimuth observations. In order to calibrate the templates required to identify phase arrivals from events at a given site, a dataset of confirmed events is required. For the mining regions on the Kola Peninsula of NW Russia, lists of confirmed industrial blasts were obtained for many different mines, allowing an extensive study of variability of slowness estimates in various frequency bands for each anticipated phase. Such ground truth information was not available for the Swedish mining regions or industrial explosions in Kazakhstan. However, given a small number of events known to have occurred at different sites, lists of events guaranteed to have occurred in the near vicinity of these master events have been generated by performing waveform correlation on signals from likely candidate events.

Conventional f-k analysis and beamforming assume a plane wavefront which is coherent across the array; this assumption breaks down due to refraction and scattering, leading to energy loss in beamforming and bias in slowness estimates. In matched field processing, the plane-wave steering vectors are replaced with empirical steering vectors estimated from observations of phases from events in the region to be monitored. An efficient suite of calibration software has been developed in this project to filter suites of waveforms from training event sets into a large number of narrow bands and to estimate matched field steering vectors for each band. We present an example whereby a set of steering vectors was calibrated for the Pn-phase at ARCES from compact underground explosions at the Kirovsk mine. In the 7.8-12.5 Hz frequency band, the matched field beam captures a factor of 2 more energy than the conventional beam and, when filtered above 10 Hz, the factor is closer to 3.

OBJECTIVE

This two year collaboration between NORSAR and Lawrence Livermore National Laboratory (LLNL) has explored improvements to the automatic detection and location of seismic events using regional arrays. At the heart of the study has been the calibration of processing parameters for the detection and location of events from a specific region using observations of previous ground truth events at the sites of interest. The goal is to attribute, with a high degree of confidence, automatically located events to active mines or areas with known recurring seismicity. The study has examined sites in Fennoscandia and Kazakhstan using the seismic arrays in these regions.

The signals at a given array station, resulting from a set of events from a site with recurring seismicity, are likely to display common characteristics which may be exploited in order to identify subsequent events from the same region. A template describing the measurements which can be anticipated at a given station at a given time can be used to judge whether or not a detected signal is the likely result of an event from the site of interest. Such templates must be calibrated by investigating the variability of measurements made from events confirmed to have taken place at the sites; such calibrations have been the main focus of this investigation. We have, in addition, explored the potential of applying advanced new “matched field” array processing methods in order to compensate for array processing loss due to refraction and scattering, thus enhancing array gain at high frequencies.

RESEARCH ACCOMPLISHED

Introduction

The ARCES regional array in northern Norway is a primary International Monitoring Station (IMS) seismic station within a few hundred kilometers of many active mining regions, both in north-west Russia and northern Sweden (Figure 1). Signals from routine industrial explosions at these sites in fact dominate the ARCES detection lists and their identification and location require considerable analyst time. Fully automatic event locations at NORSAR are currently provided using the Generalized Beamforming (GBF: Kværna and Ringdal, 1989) system which associates detected phases from the entire network of regional arrays. The collection of ground truth data from mining explosions on the Kola Peninsula (under the DOE funded contract “Ground-Truth Collection for Mining Explosions in Northern Fennoscandia and Russia”; Harris et al., 2003) has provided an excellent opportunity to assess the current state of the automatic event detection and location procedures and to examine approaches for improving it.

The ground truth information for the mining regions on the Kola Peninsula provides the origin times of shots from 13 mines from the four distinct Russian mine clusters color-coded in the upper panel of Figure 1. The corresponding colored symbols in the lower panel of Figure 1 indicate the fully automatic locations from the GBF system for the confirmed events from these mines between October 1, 2001, and September 30, 2002. It is immediately apparent that the distances between the automatic location estimates and the true locations vary enormously. In particular, given a single one of these automatic locations for a recently detected event, it is impossible to ascribe the signal to any of the sources shown without performing a full time-consuming manual analysis upon the signal. The most significant reasons for the large variance of location estimates from the GBF system are the following:

- Azimuth and slowness estimates are performed on data filtered in a frequency band which varies from detection to detection. The frequency band is set in order to optimize the signal-to-noise ratio (SNR) and it is demonstrated in Kværna et al. (2004), the extent to which the slowness estimates for the same set of events become more stable when estimated in fixed frequency bands.
- Many of the events have complicated firing sequences which can lead to an incorrect association of phases. For instance, if two similar blasts follow within seconds of each other, it is possible that an S-phase from the second shot may be associated with the P-phase from the first shot leading to a location estimate at too great a distance. Other combinations of incorrect coda phase associations can lead to similar spurious location estimates.
- The GBF system follows somewhat empirically determined rules which help to determine which of several candidate sources (hypocenter and origin time) is the most likely to have produced a given set of phases. A single trial hypocenter which corresponds to a large number of phases may score more highly than, for example, two hypotheses for different events which would give a more accurate description of the cause of the detected phases.

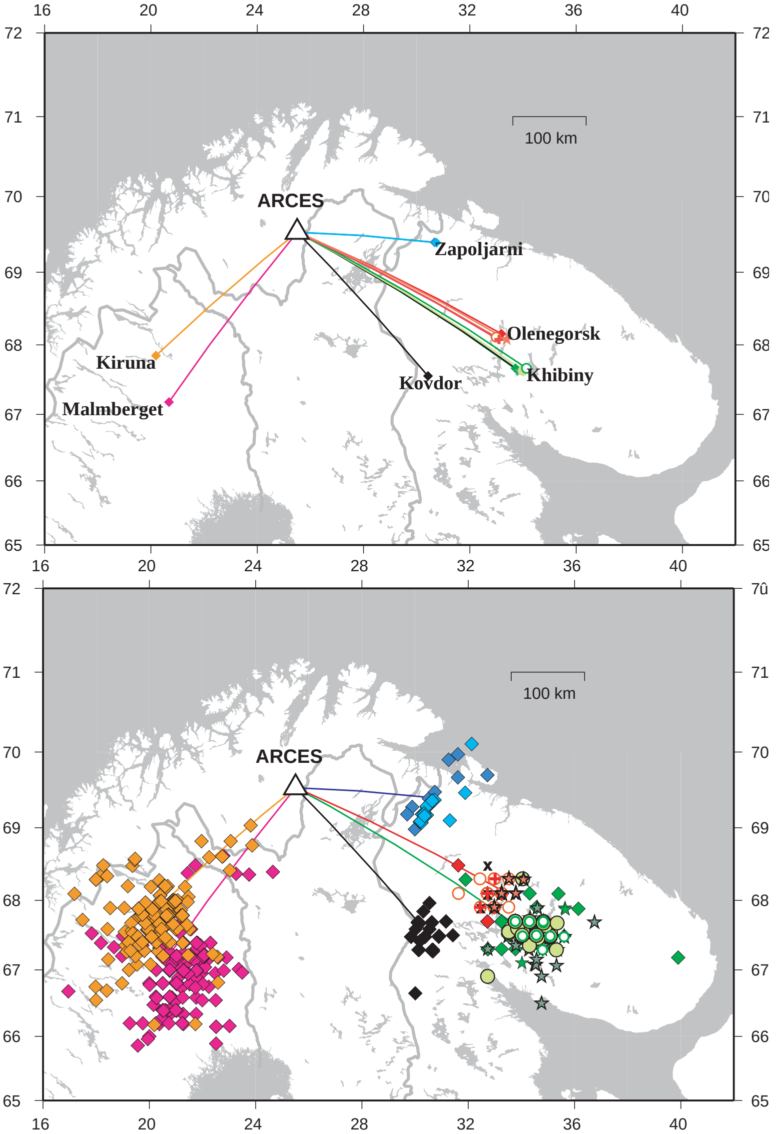

Figure 1. Location of the ARCES regional array in relation to mining regions in northern Sweden and on the Kola Peninsula, Russia (top panel) and automatic event locations using the NORSAR GBF system for events known to have occurred at the sites indicated (lower panel).

Under a pilot project, a fully automatic system for the identification and location of events occurring at, and in the close vicinity of, the Kovdor mine in north west Russia, using only the ARCES regional array, was developed. The details of this procedure are provided by Gibbons, Kværna, and Ringdal (2005). Fundamental to this system is the consistency provided by slowness measurements in a fixed frequency band of a given phase from a given site. If, for a given detection, a slowness estimated from broadband f-k analysis in a fixed frequency band falls within the narrow confines of a template calibrated from the observations of previous events, we can immediately form a hypothesis that an event at our monitored site occurred at the indicated time. We subsequently test this hypothesis by examining whether or not slowness measurements in time-windows fixed relative to the hypothetical origin time are consistent with the existing body of observations from that site. Gibbons, Kværna and Ringdal (2005) demonstrate that the single array automatic location estimates are a significant improvement on the existing automatic solutions and are comparable to multi-array analyst locations. The greatest difficulty encountered in this study was the problem in the identification of secondary phases (usually the result of complicated source time histories) which led to many events which could not be located in this manner; these events had to be filed for analyst review.

The goal of the current project has been to construct an integrated framework in which the philosophy behind the single array monitoring system of Gibbons, Kværna and Ringdal (2005) could be generalized to a range of different source regions and seismic arrays. The ground truth collection project had also acquired information on a very large number of events from the Zapoljarni, Olenegorsk, and Khibiny mining regions (Figure 1). These mining clusters present an additional complication in that several mines operate within short distances of each other; the inter-mine separation is not generally large enough for a single array at a distance of several hundred kilometers to be able to differentiate between two sites from a slowness measurement alone, but it is sufficiently large for the fixed time-window scheme of the Kovdor monitoring process to be compromised.

For other sites, such as the Kiruna and Malmberget mining regions in northern Sweden, there exists the problem that we do not possess ground truth data on routine explosions which are necessary in order to calibrate the templates. The approximate times of the daily routine detonations were however known for both sites which made it possible to identify very likely events and perform a careful analyst location for each of these. With a few master events for each mine, large numbers of events were subsequently identified using a correlation detection algorithm as being almost certain to have originated within a few hundred meters of the master events. The detected events which corresponded to reasonably high correlation coefficients and which displayed a satisfactory signal-to-noise ratio were selected to build up the databases of events assumed to originate from these source regions. All the orange and magenta symbols in the lower panel of Figure 1 were identified in this way.

Calibrating the event and phase templates

Given a sufficiently large set of events from the sites for calibration, it is necessary to identify properties of the resulting wavefields which provide the most stable characteristics for the subsequent identification of new events. The most stable property is almost always the slowness estimate for the initial P-arrival from each event; this is demonstrated clearly in Figure 8 of Kværna et al. (2004). It also emerges that the frequency band which provides the most stable slowness estimates for a given event population varies greatly (c.f. Figure 6 of Kværna et al., 2004). For the Zapoljarni mines, for example, the 2-4 Hz frequency band gave a far smaller spread of slowness estimates than other frequency bands whereas, for the Khibiny mines, the 4-8 Hz frequency band gave the most consistent estimates.

This raises the question of how a “likely candidate phase” should best be identified and, given the results from the processing of the Kola ground truth mining events, it was deemed that the best procedure would be to perform broadband f-k analysis in a wide range of fixed frequency bands for every detection made by the arrays. In this way, a detection list could simply be scanned by a number of “trigger templates” each examining the frequency band (or set of frequency bands) which provided the best slowness estimates for the target phase. It would be sensible to construct a trigger template for an initial P-arrival from a Zapoljarni event that would be activated when a slowness estimate in the 2-4 Hz band fell within the permitted bounds (obtained from the set of training events) and a trigger template for a P-phase from a Khibiny event which would test the slowness in a higher frequency band. Experience has however shown that it is advisable to provide a few alternative trigger combinations since the optimal frequency band may give a spurious slowness estimate as a result of, for example, an interfering signal. It was found to be helpful to generate panels displaying the slowness estimates and corresponding beams for each of the fixed frequency bands to allow an “at-a-glance” assessment of the quality of each detection. An example of such a panel is displayed in Figure 5 for a regional phase arrival at one of the arrays in Kazakhstan.

It was also demonstrated by Kværna et al. (2004) that autoregressive onset time estimates frequently provided far better estimates than amplitude-only-based methods and so a two-stage reprocessing system was activated for each array in which we first obtain the best possible arrival time estimate and then obtain the slowness estimates in each of the specified frequency bands. This reprocessing procedure can be performed for an arbitrarily specified time and can consequently be applied to any form of detection. It is currently applied for every conventional detection from each of the regional arrays which supply data to NORSAR. However, it could conceivably also be applied to correlation detections, detections from matched-field processing, or simply at times for which there is reason to suspect that an arrival of interest may have occurred.

On each occasion that a trigger template is activated, an event hypothesis is formed for the site region for which the activated template is calibrated. Each such calibrated site has a corresponding “site template” listing the phases which ought to be observed whenever an event at that site occurs. Each of these phases corresponds to a “phase template” stating at which time the phase should be observed, which range of slowness values are consistent with the phase in a specified set of frequency bands, how large an SNR should be observed to support the assumption that the phase has indeed arrived at the stated time, and which range of autoregressive arrival time estimates are acceptable under the considered event hypothesis. The following section considers an automatic event detection algorithm using the very simplest form available for site templates: a single P-phase and a single S-phase recorded at a single array.

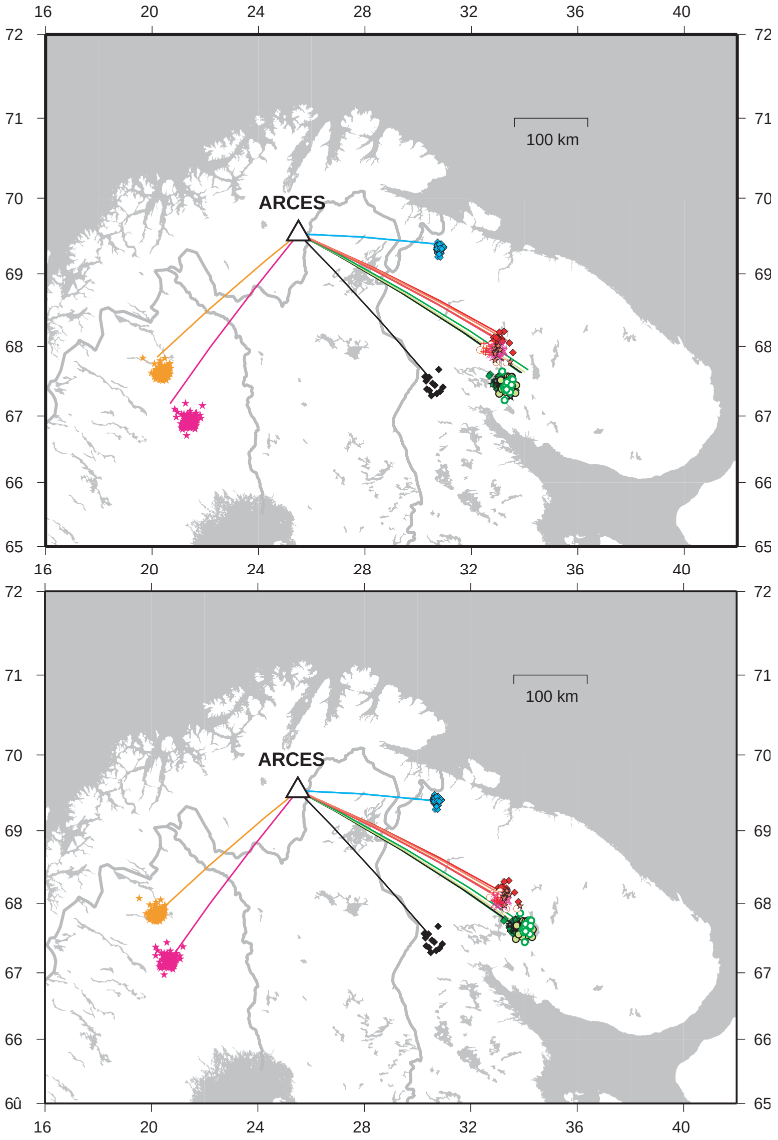

Figure 2. Locations of the events in the lower panel of Figure 1 based upon the site-specific location algorithms with slowness and azimuth estimated in fixed frequency bands selected for each site, and phase onset times estimated by autoregressive methods. The upper panel features the locations made without systematic slowness and travel-time corrections in the location procedure and the lower panel features locations made applying corrections. Note that not all of the events shown in Figure 1 are included in these figures since events which fail to match required components of the templates are excluded prior to the location procedure. Each event which is located showed sufficient evidence of belonging to the geographical region represented by the template; this essentially eliminates the possibility of events being located at large distances from the target sites. Locations are made using the HYPOSAT algorithm (Schweitzer, 2001) using only the Pn and Sn phase arrivals at the ARCES array (Pg and Sg for the Zapoljarni mines).

A template-based event location procedure

For each of the mining regions displayed in Figure 1, a site template was formulated listing two anticipated phases: the initial P-arrival at ARCES (which would be used to trigger an event hypothesis) and the first S-arrival (only used to confirm an event hypothesis). The first S-arrival at ARCES is Sn for all of the sites shown except for the Zapoljarni mines for which the Sg-phase is the first secondary phase to arrive. The slowness bounds for each of the phase templates were set according to the variability observed for the sets of training events (see Kværna et al., 2004). Since an initial P-arrival at ARCES from one of the Khibiny mines would not permit the system to exclude the possibility that the phase originated from one of the other Khibiny mines, it was decided that a site-template would be set up for each one of the mines, and all would trigger for an initial P-phase from any one of the Khibiny sites. Each of the site templates would differ in the initial setting of the time-window for the examination of the secondary phases but, unlike the Kovdor monitoring process (Gibbons, Kværna and Ringdal, 2005) in which slowness estimates were only performed in time-windows fixed relative to the initial P-arrival, we allow here a small deviation through a limited number of iterations. In practice, this means that we measure the slowness in a time-window fixed relative to the initial P-arrival, then form a beam steered by these parameters, measure a new autoregressive onset time, then confirm that the new time falls within a permissible time-window and that the slowness measured at the new time falls within the accepted range. The new slowness is subsequently used to form a new beam and the procedure is repeated. If, at any stage, a test is failed then the event hypothesis is rejected (or at least filed for analyst review); this will limit how far from the specified site template the solution can deviate but should permit a location to be found even if the event is a short distance away from the exact site for which the site-template was tuned.

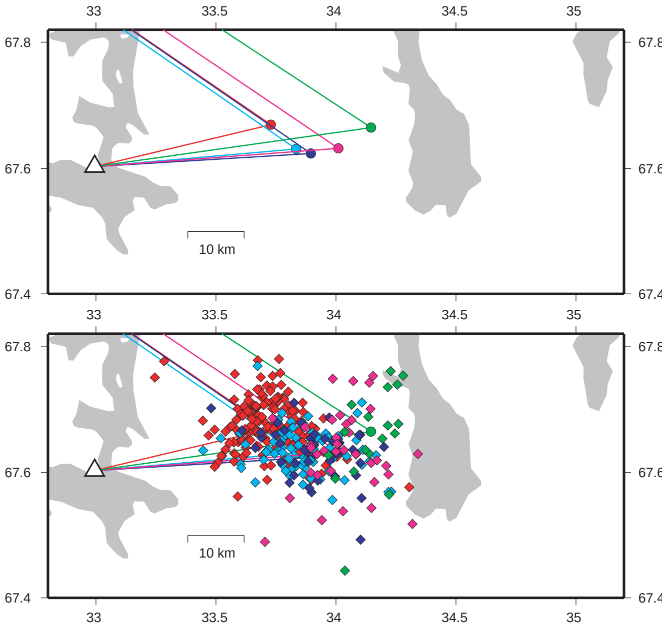

Figure 3. Zoom-in view of the locations of the mines of the Khibiny Massif near the town of Apatity in NW Russia (upper panel) together with automatic, single-array locations of confirmed events from these mines between October 2001 and September 2002 (lower panel). All locations are made using HYPOSAT using only the Pn and Sn phases only from the ARCES array at a distance of approximately 410 km to the North West. The triangle indicates the location of the Apatity array (not used in these locations) and the colored lines indicate the shortest routes from the mines to the seismic arrays.

Figure 2 shows the automatic event locations obtained for the events shown in the lower panel of Figure 1 using the slowness and azimuth estimates obtained from the frequency bands specified in each of the phase templates and phase arrival times measured by the autoregressive onset estimates. This figure indicates the vast improvement to the location estimates afforded by this controlled process and also the importance of applying slowness and travel-time corrections to the solution prior to calling a location algorithm. If the azimuth measured in the most stable frequency band is interpreted directly as being the geographical backazimuth, large systematic biases (of up to 50 km) can be introduced. In fact, the Kovdor mine is unique among these mining regions in that the systematic azimuthal bias for this site can essentially be ignored; the systematic azimuth bias for the other sites is often of the order of 5 degrees.

Not every event from the mining regions was able to be located using this single-array, two phase site template algorithm. Many events were excluded for having failed a test (a slowness estimate which was not consistent with a phase template or an arrival time estimate which did not fall within the permissible range or which displayed too low an SNR). In particular, many events from the Kovdor mine failed this two-phase algorithm due to the failure of the Sn phase to record an acceptable slowness value in the pertinent time-window; this is often caused by a low amplitude, emergent Sn phase compounded by complicated firing sequence. Gibbons, Kværna, and Ringdal (2005) improve the number of events located by also considering the far stronger Lg phase. An alternative strategy would be to attempt to detect phase arrivals at a different station, which would reduce the importance of detecting a secondary phase.

Figure 3 shows a zoom-in of the calibrated single-array locations for the mines on the Khibiny massif. While the events from the Kirovsk mine (red symbols) cluster to the West and events from the Norpakh mine (green symbols) cluster to the east, as would be hoped from the source locations, we see that this single array process is unable to resolve these populations. This limit of location resolution is consistent with that experienced by Gibbons, Kværna, and Ringdal (2005) for the Kovdor mine. However, even without use of the nearby Apatity array, this location algorithm is probably sufficiently good to provide a preliminary clustering of events which can then undergo a full waveform source identification procedure.

Application of calibrated array processing to data from Kazakhstan

Like Fennoscandia, Kazakhstan is a region containing several seismic arrays and large numbers of routine industrial explosions. Figure 4 shows the locations of the arrays together with reviewed bulletin locations of events over a one month period for which at least one regional phase was recorded at the Akbylak array. It is clear from this distribution that a large number of events cluster around small regions which coincide with the locations of mines.

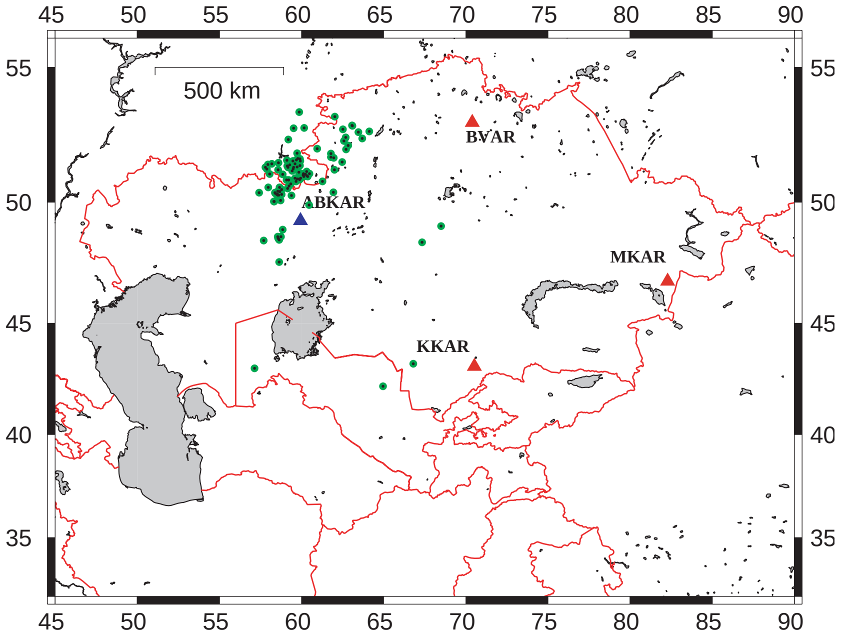

Figure 4. Locations of the four 9-element arrays in Kazakhstan together with locations from the Kazakhstan NDC reviewed event bulletin of all events during May 2004 for which regional phases were recorded at the Akbylak array (ABKAR). Also shown are the arrays at Borovoye (BVAR), Makanchi (MKAR), and Karatau (KKAR).

While ground truth information for the mining sites is not yet available, it appears that the waveform-correlation bootstrapping approach applied to the Swedish mining regions may also be applied here. Many of the analyst-located events in the Kazakhstan bulletin occur within a small geographical region at times at which the mines are known to conduct routine explosions. When the waveforms are filtered in a sufficiently low-frequency band, many events are observed to show a high degree of waveform semblance indicating a small separation between the source regions.

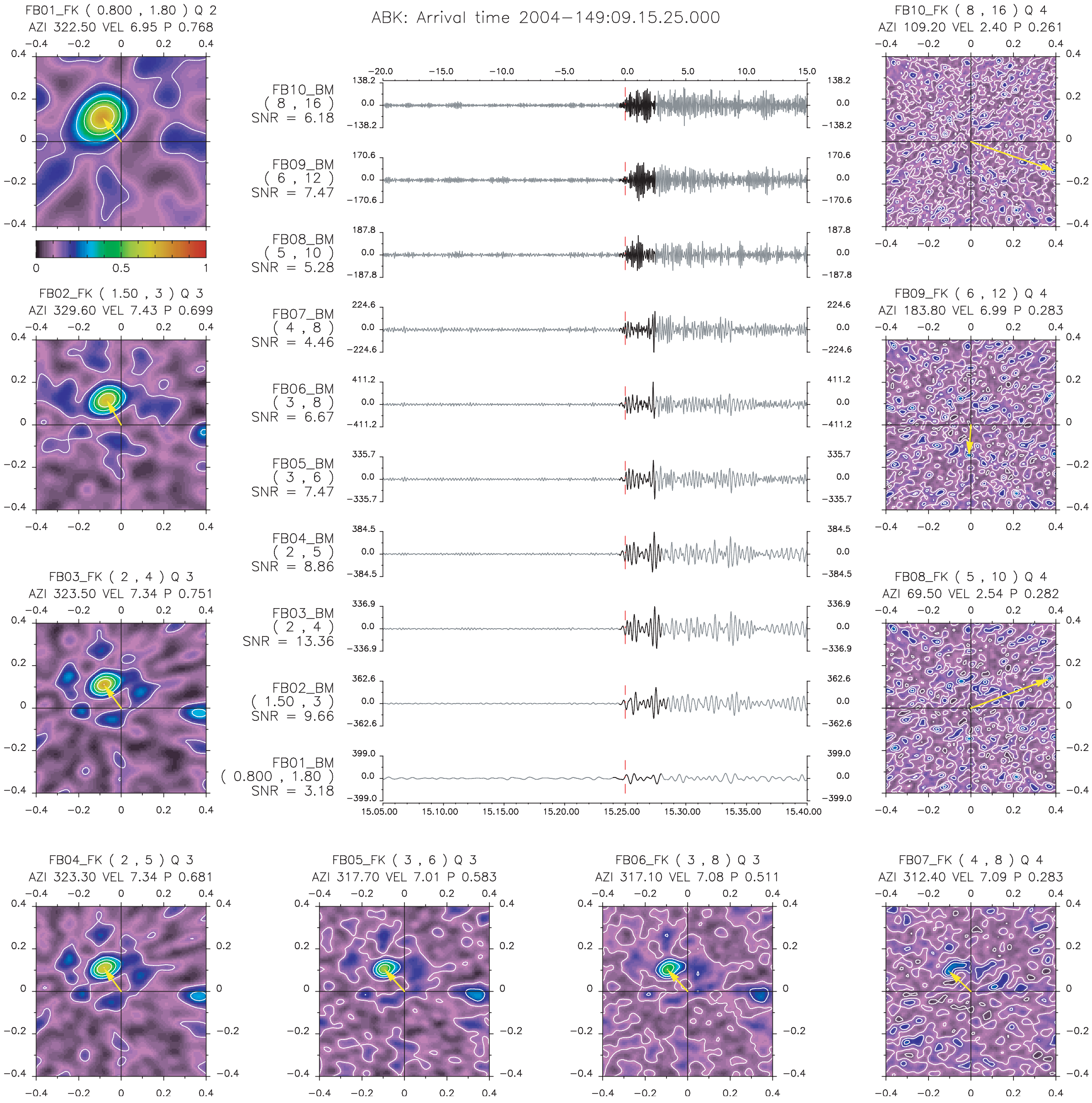

Figure 5. Slowness and azimuth estimates in a predetermined set of fixed frequency bands for a first P-arrival from regional event at a distance of approximately 150 km from the Akbylak array in Kazakhstan.

It appears that the events in the clusters identified so far exhibit a similar “slowness and azimuth as a function of frequency band” to that observed at ARCES (see Figure 5). However, the frequency bands in which regional signals are best observed are very different at the arrays in Kazakhstan from those in Fennoscandia. For ARCES and the other Fennoscandian arrays, frequencies below 2 Hz are essentially unusable for regional signals because of the high-microseismic noise. The SNR for most of the mining explosions simply improves as the frequency increases and the optimal analysis frequency band is a trade-off between SNR and coherence. In Kazakhstan, the low frequencies do allow good observations of regional phases and the frequency bands above 4 Hz for these arrays do not give good slowness estimates due to signal incoherence. The set of fixed frequency bands for the reprocessing is therefore chosen accordingly.

Compensation for array loss using matched-field processing

Classical beamforming transforms the incident waveforms using steering vectors which are set according to the assumption of a plane-wavefront. Array loss occurs when the coherence of the waveforms is diminished or the plane-wavefront assumption is otherwise violated due to diffraction or scattering. It has already been noted that many of the signals of interest exhibit the best (single channel) SNR at high frequencies for which beamforming is ineffective due to low waveform semblance. A method of compensating for such array loss by replacing the theoretical steering vectors with empirical steering vectors calibrated from measurements of the wavefield structure, the so-called "matched-field processing" method, has already been employed successfully in the field of underwater acoustics (Baggeroer et al., 1993). The steering vectors are calculated as the eigenfunctions of sample covariance matrices obtained from narrow-band filtered waveforms from populations of events known to have come the same source location.

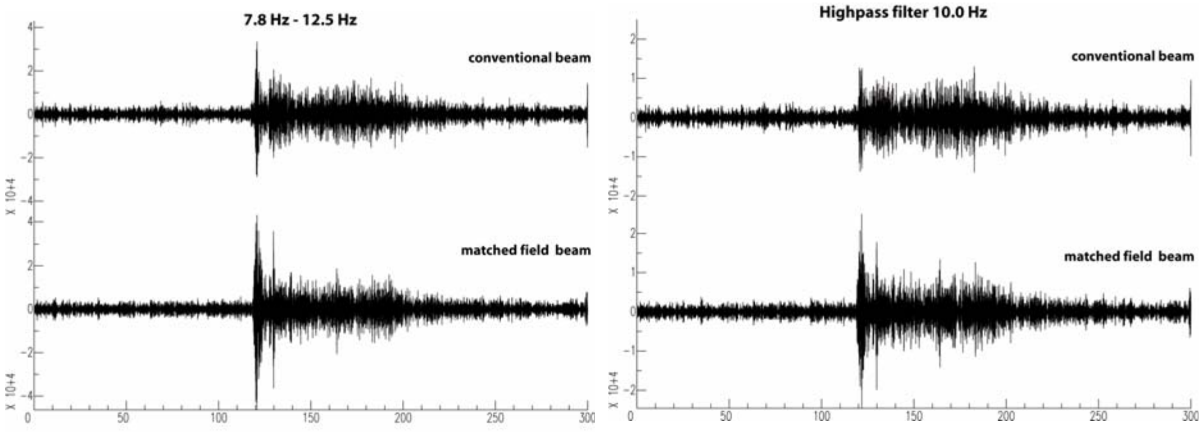

Figure 6. A comparison of conventional and emprical matched field Pn beams using the ARCES array for signals generated by a confirmed compact underground explosion at the Kirovsk mine on the Khibiny massif. A low-frequency array geometry was used here to illustrate the possible gains of matched field processing in situations where signals are only partially coherent. The matched field beam captures between and 3 and 5 dB more Pn energy depending on the frequency band considered.

These calibrations can be applied by performing narrow-band filtering upon an incoming data-stream and beamforming the resulting waveforms using the empirical steering vectors. Figure 6 illustrates the improvement in the SNR on the matched-field beam over a conventional beam for a Pn arrival from a Khibiny massif event. The effect may be even greater for high-frequency regional signals on the arrays in Kazakhstan for which loss of coherence at high frequencies presents a serious problem.

CONCLUSIONS AND RECOMMENDATIONS

We have designed a framework for the automatic monitoring of seismic events from sites of interest using regional seismic arrays. Under the current automatic detection and event location algorithms employed at NORSAR and elsewhere, slowness and azimuth estimates are calculated using broadband f-k analysis in frequency bands which are determined on a detection by detection basis in order to capture the best possible part of the signal. Whereas this generally leads to the best SNR it also leads to a demonstrable variability in automatic event location estimates (Figure 1) which necessitates a costly manual event location procedure for every such signal detection. Under the system proposed here, each detection is reprocessed by performing f-k analysis in each of several fixed frequency bands. This has the advantage that, since the fixed band slowness estimates are typically more stable for events from any given site and that the optimal frequency band varies from site to site, candidate detections can be readily picked out by a process which detects slowness estimates in a specified band (or combination of bands) which fall within a given set of calibrated bounds. Each time such a candidate phase detection causes a trigger, a full process testing a site template can be initiated which tests any appropriate combination of phases at any appropriate combination of stations. For each time of an anticipated arrival, a new fixed-band slowness estimate is initiated together with an arrival time determination procedure. We have demonstrated that, even in the case of a single array with a two-phase site template, the fully automatic location estimates provide a great improvement over the existing solutions. We have also demonstrated the need to correct for systematic bias in direction and travel time measurements in the location procedure.

The most time consuming and difficult part of this procedure is in the calibration of templates for events known to have originated from a given site. This has been facilitated in this study by the provision of ground truth information from operators of the mines in NW Russia and the application of waveform correlation procedures elsewhere. To conclude this project, we will examine the effectiveness of such a procedure for sites of recurring seismicity in Kazakhstan.

ACKNOWLEDGEMENTS

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