

# 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

## INTEGRATED SEISMIC EVENT DETECTION AND LOCATION BY ADVANCED ARRAY PROCESSING

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### ABSTRACT

The principal objective of this two-year study is to develop and test a new advanced, automatic approach to seismic detection and location using array processing. Our aim is to obtain significantly improved precision in the location of low-magnitude events compared with current automatic approaches, combined with a low false alarm rate. We plan to develop and evaluate a prototype automatic system which uses as a basis regional array processing with fixed, carefully calibrated, site-specific parameters in conjunction with improved automatic phase onset time estimation.

In the first part of this project, we have focussed upon regional events in Fennoscandia and NW Russia using the regional arrays operated by NORSAR and the Kola Regional Seismological Centre (KRSC) in Apatity, Russia. Through a collaboration with KRSC, we have acquired Ground Truth (GT) data for routine industrial mining blasts from four mining regions on the Kola Peninsula at distances between 200 and 410 km from the ARCES regional seismic array. From September 2001 to March 2004, 1977 explosions had been included in this database. The characteristics of signals resulting from events at each of the mines have been investigated in detail. Recordings of the blasts from the open-pit mines are often very complex and the signals from subsequent blasts at the same pit display great differences, indicating significant variation in the nature of the source and ripple-firing techniques.

We have focussed particularly upon the single array scenario since, in the context of explosion monitoring, many low-magnitude events of interest may only be recorded by a single array station. For a test period from October 1st 2001 to September 30th 2002, every detection at the ARCES array was subject to a two-stage reprocessing. Firstly, a careful re-estimation of onset time was performed using an autoregressive method and, secondly, the slowness and azimuth of each phase was estimated using broadband frequency-wavenumber analysis in each of ten fixed frequency bands with corresponding time-windows and array configurations. For GT events from each of the mines being studied, the statistics of the slowness estimates were investigated for each frequency band.

Almost all of the fixed frequency bands provided more stable slowness and azimuth estimates than those determined in a variable frequency band as used by the standard on-line detector (i.e. a frequency band maximizing the signal to noise ratio), although the variance of slowness estimates from known sources differed significantly between the different fixed frequency bands. As an example, slowness estimates for the initial P-phases from events at the Zapoljarni mines at a distance of approximately 200 km from ARCES displayed the most stable slowness estimates in the 2.0 - 4.0 Hz frequency band whereas initial P-phases for events from the more distant Olenegorsk and Khibiny mining regions displayed a far smaller variance in the 4.0 - 8.0 Hz band. In most fixed frequency bands, the slowness estimates from the four main mining regions fall into distinct clusters, which is not the case for the variable frequency bands.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### OBJECTIVE

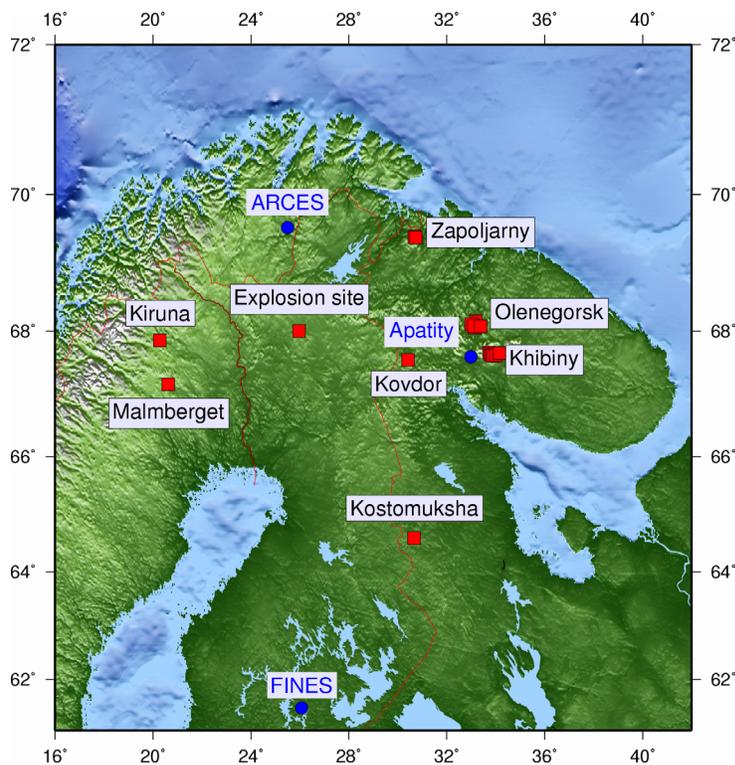
This two-year project is a collaboration between NORSAR (as the lead organization) and Lawrence Livermore National Laboratory (LLNL). The main objective of this study is to investigate new approaches and processing methods for the automatic detection and location of seismic events using arrays. A particular feature of this study will be the utilization of information from previous ground-truth events in the method implementation and parametrization of the processing sequences. A goal for this work will be to attribute, with a high degree of confidence, the automatically detected and located events to active mines or areas with known recurring seismicity.

We will evaluate the results from applying this approach for selected sites with recurring mining explosions in Fennoscandia and Kazakhstan, with emphasis on the one-array monitoring scenario. In addition, we plan to develop and test an initial framework for multi-array processing. In this study we will also investigate the potential of applying advanced new array-processing methods to obtain even further improvements. Specifically, we plan to develop and test a so-called “matched field processing” technique that aims at compensating for array processing loss due to refraction and scattering, and thus enhances array gain at high frequencies.

### RESEARCH ACCOMPLISHED

#### Introduction

During the first year of this study we have focused on the development of algorithms for processing of mining events from the northern Fennoscandian region, using the ARCYES array. As shown in Figure 1, there are several active mines in this region, which are used as targets for this study. Since September 2001, an extensive collection of ground truth (GT) information on mining explosions in the Kola Peninsula has been conducted on the DoE funded contract entitled “Ground-Truth Collection for Mining Explosions in Northern Fennoscandia and Russia” (Harris et al., 2003). Our plan has been to use the ground truth events for the one-year time period October 2001 - September 2002 for development and tuning of the algorithms, and to use events after September 2002 for evaluation.

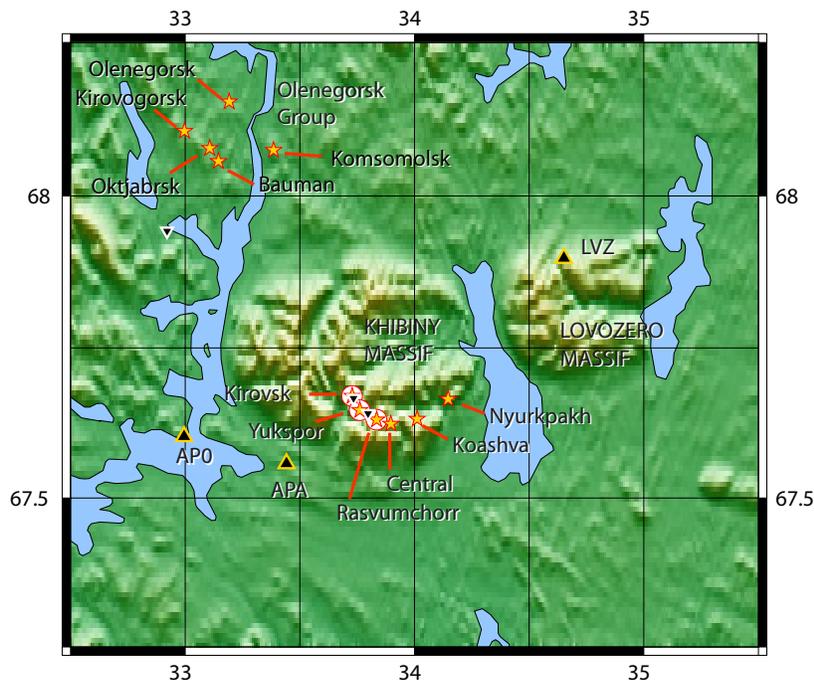


**Figure 1.** Locations of the main mining regions in NW Russia and Sweden, together with the location in Finland of a site regularly used by the Finnish military for destruction of ammunition. Also shown are the locations of the seismic arrays in the region (ARCYES, Apatity and FINES).

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### Regional observations of underground and open-pit mine blasts

We have investigated in detail events from the Khibiny and the Olenegorsk mines (see Figure 2). Ground truth information (Harris et al., 2003) and earlier studies of mining events from this region (Gibbons and Kväerna, 2002; Ringdal et al., 2003) have revealed that a wide range of source types are present at these mines. The blasts in the open-pit mines are usually large ripple-fired explosions, often detonated in several groups with some seconds delay. The regular blasts in the Khibiny Massif underground mines usually have yields between 120 and 240 tons with many delays of 20-35 milliseconds. So-called compact shots are also detonated in these underground mines. The compact shots have yields between 1 and up to a few tons, having only a few delays, and provide the simplest source type available in these mines. The main purpose of the compact shots is to remove smaller parts of rocks remaining after the regular underground blasts.



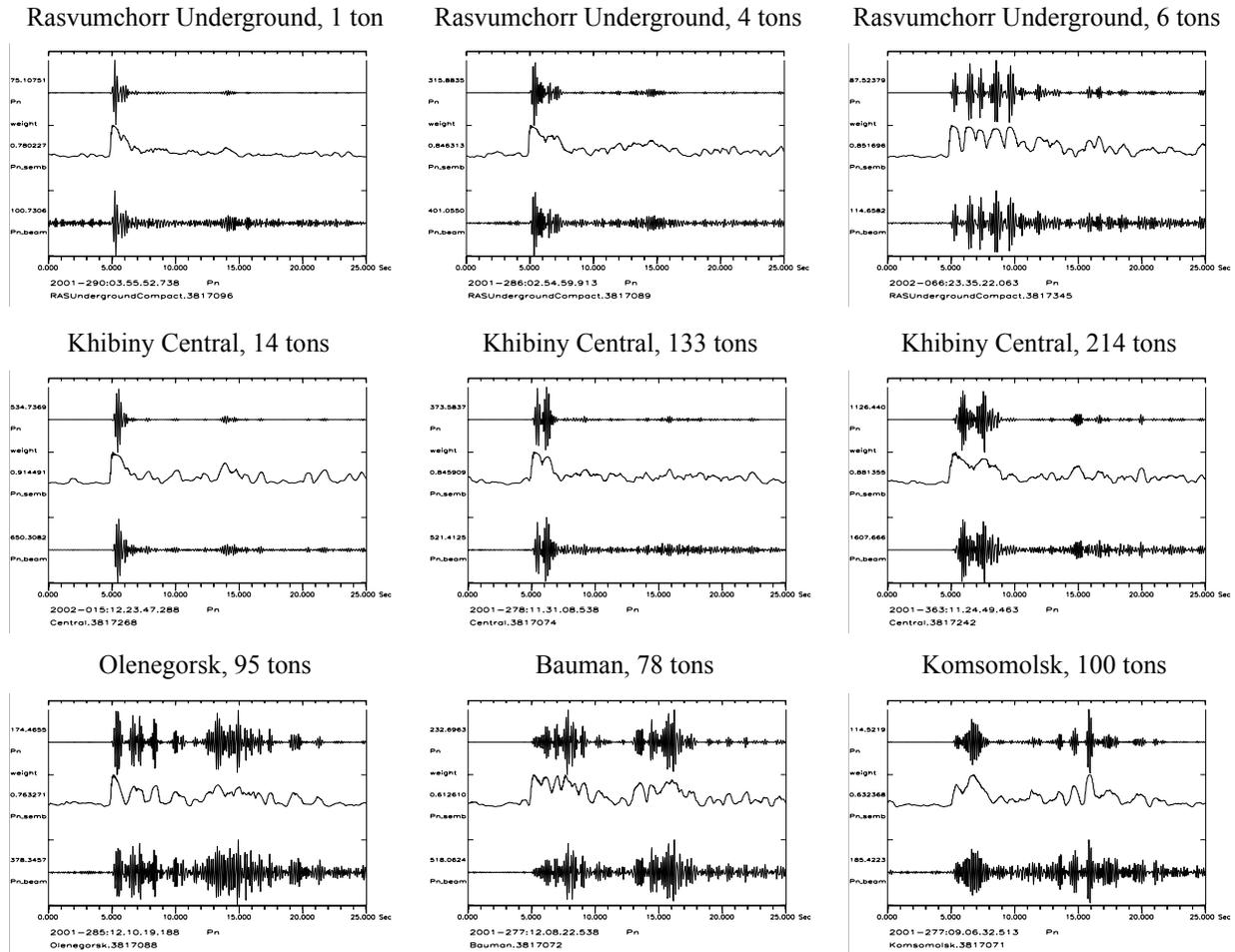
**Figure 2.** Locations of the mines (stars; circles indicate mines with both underground and surface facilities), permanent stations (triangles) and temporary stations (inverted triangles) in the vicinity of the Khibiny Massif. The five mines in the Olenegorsk group are all open-pit mines.

In order to get an overview of typical seismograms observed at the ARCES array from explosions in the Khibiny and Olenegorsk mines, we have taken a closer look at the compact shots from the underground Rasvumchorr mine in the Khibiny Massif. The distance from ARCES to the Rasvumchorr mine is approximately 400 km. For each of the 99 events in the ground truth database (October 2001 - September 2002), we have calculated the Pn beam and the corresponding semblance coefficient. In order to enhance the coherent parts of the wavetrain, we also calculated the Pn beam weighted with the semblance coefficient. The frequency band used for this analysis was 4 - 8 Hz. The Pn beam was formed using the ARCES center instrument (A0), the C- and D-ring instruments steered with an apparent velocity of 7.5 km/s and a back-azimuth of 121.0 degrees. The semblance coefficients were calculated for 0.5 second window lengths with a 40 Hz sampling rate.

The three upper panels of Figure 3 show the processing results for three selected compact shots in the underground Rasvumchorr mine. For these compact shots we know the total yield, but not the number of individual detonations (holes). However, we have information from the mine operators that the common 1 ton compact shots consist of one or two individual detonations. We can see that the first event has a relatively simple Pn signature, which most likely is the result of a single one-ton compact shot. The second event, with a total yield of 4 tons, has a Pn signature with a slightly longer duration, whereas five separate pulses can clearly be seen for the third event, having a total yield of 6 tons. From the observation of relatively simple Pn signatures at ARCES for the smallest compact shots, it is reasonable to assume that observed complex Pn signatures generally result from more complex source types.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

Processing results for three blasts in the Khibiny Central open-pit mine are shown in the middle panel of Figure 3, whereas the three lower panels show results for three typical events at the open-pit mines in the Olenegorsk group. Detailed information obtained on the blasting technique used for some events (Harris et al., 2003; Ringdal et al., 2003), reveal that events in the open-pit mines can consist of up to 5 separate, ripple-fired explosions detonated in sequence in different parts of the mine with some seconds delay.



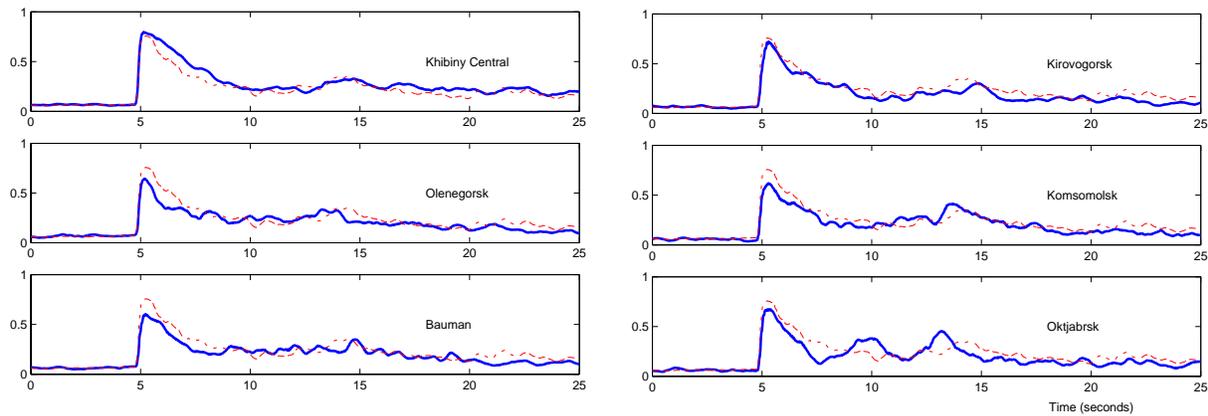
**Figure 3.** The upper three panels show ARCES recordings of 3 compact shots in the underground Rasvumchorr mine in the Khibiny Massif. In each panel we show the 4-8 Hz Pn beam (bottom), the semblance coefficient (middle) and the Pn beam weighted with the semblance coefficient. The total yields reported for each blast or blasting sequence are also given. The three middle panels show similar traces for 3 events in the Khibiny Central open-pit mine, whereas the three lower panels show typical recordings of events at the open-pit mines in Olenegorsk group.

The semblance analysis (illustrated in Figure 3) conducted for 107 GT events in the Olenegorsk group shows that the vast majority of these blasts act as very complex seismic sources, having a duration often exceeding 10-15 seconds. Most of the 48 ground-truth events from the Khibiny Central open-pit mine also show complex Pn signatures at ARCES, but with generally shorter duration than the Olenegorsk events. However, some of the smaller events have a relatively simple Pn signature, indicating simpler sources. Out of the 99 ground-truth events from the underground Rasvumchorr mine, most of the 1 ton compact shots have Pn signatures similar to those shown in the upper left panel of Figure 3. The larger compact shots have generally slightly longer duration, and in some cases separate pulses can be observed.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

To investigate further the source and propagation effects of events from the underground Rasvumchorr mine, we have stacked the ARCES Pn semblance coefficients of the 99 events in the ground truth database. The stacking is aimed at reducing random effects from the source, while retaining consistent propagation and source effects. The stacked semblance trace is shown by the red curve in the panels of Figure 4, and we note the close similarity between the stacked semblance trace and the “simple” waveform semblance trace shown in the upper left panel of Figure 3. The Khibiny Central mine is located within 1-3 km of the underground Rasvumchorr mine, and we find from the upper left panel of Figure 4 that, except for the first few seconds after Pn, the stacked semblance curves are quite similar to that of the Rasvumchorr mine events. The peak located 9 seconds after Pn corresponds to the Pg arrival. The mines in the Olenegorsk group are located 50-60 km closer to ARCES than the Khibiny mines, but, as seen from Figure 4, four of the stacked semblance traces are quite similar to those from the Khibiny mines. The only exception is the Oktjabrsk mine, but in this case only 14 GT events were available for stacking. Several of the Oktjabrsk events had a distinct signal arriving about 5 seconds after Pn, which is again seen in the corresponding panel of Figure 4.

Our comparisons of the stacked semblance traces for the different mines of the Khibiny and Olenegorsk groups have shown that the remaining, consistent features of the early part of the seismograms correspond to the first-arriving Pn and Pg arrivals. The remaining coherent energy pulses of the different events are due to the temporal and spatial distribution of the blasting sources within the mines.

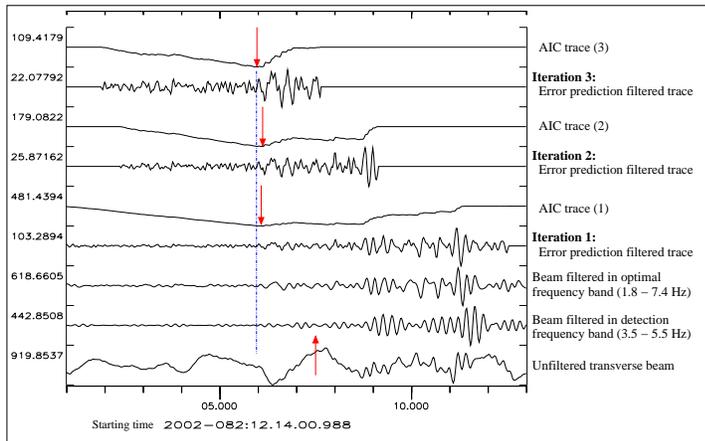


**Figure 4.** The blue curves show the stacked ARCES Pn semblance coefficients in the 4-8 Hz frequency band for the ground truth events in the Khibiny Central mine (upper left trace), and for the mines in the Olenegorsk group. The dashed red curve shows the stacked semblance coefficients for the compact underground shots in the Rasvumchorr mine.

### Improvement of automatic onset time estimates

The widely used AR-AIC (Auto-regressive Akaike Information Criterion) method for automatic arrival time determination has proved to be highly successful when applied to the types of regional phases being studied here, which are often dominated by high frequency seismic energy. The method is most effective when the signal and preceding noise exhibit a good contrast both in amplitude and in the spectral content. For this reason, it is important to make the analysis frequency band as broad as possible without too great a reduction in the SNR. Using the trigger time on the detecting beam (which has often been filtered in a narrow frequency band in order to improve the SNR) as an initial condition, an algorithm is followed which calculates an optimal frequency band and repeatedly applies the AR-AIC process in progressively shorter time windows in order to determine the most accurate automatic arrival time estimate. A strict set of safety checks reduces the likelihood that a good arrival time estimate is replaced by a spurious estimate, using SNR measurements made on both the actual waveforms and error-prediction channels. An example of this procedure is illustrated in Figure 5, where we re-estimate the onset time for a detection of a weak Sn phase.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring



**Figure 5.** Re-estimation of onset time using the AR-AIC method for a phase detection at ARCES. The lowermost arrow indicates the initial onset time estimate and the remaining arrows indicate modified times from autoregressive estimates in three successive iterations. The detected phase is an Sn arrival from a mining event in northern Sweden and the modified arrival time is within 0.5 seconds of the Sn onset time predicted by the barey model, based on a network location.

For the purpose of site-specific monitoring, the most important phase onset time estimate is that of the initial P-arrival. The first stage of the single array monitoring process described by Gibbons, Kväerna and Ringdal (2003) was the identification of detections which were likely to correspond to initial P-arrivals from the region being monitored. For all such phases, the onset time was re-estimated using an autoregressive method and all subsequent slowness and azimuth measurements were performed within time-windows fixed relative to this onset time. Starting values for secondary phase arrival time determinations are also based upon the initial P-arrival time.

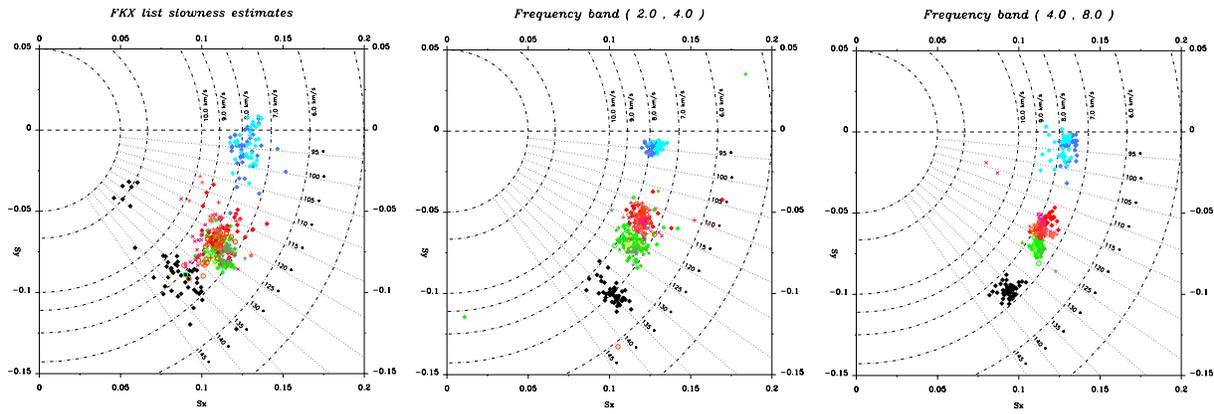
### Calibration of processing parameters for improved event location using Ground-Truth information from active mines in NW Russia.

Each detected arrival is subject to an estimation of the slowness and azimuth in order to classify and associate the phase. Inaccuracies in such estimates may lead to the exclusion of valid phases and/or the inclusion of spurious phases in the association process and a decrease in location accuracy. Accuracy in azimuth is of the greatest importance for single station locations.

It has been demonstrated (Kväerna and Ringdal, 1986) that slowness estimates for phases from repeated events at a given site are far more stable when calculated in a fixed frequency band than in variable bands calculated to maximize the SNR. For the test-period October 1st 2001 to September 30th 2002, each phase detected by ARCES was subject to an auto-regressive arrival time re-estimation and subsequent slowness estimation by broadband f-k analysis in each of ten fixed frequency bands: (0.5-1.5 Hz), (1.5-3.5 Hz), (2.0-4.0 Hz), (2.0-5.0 Hz), (3.0-6.0 Hz), (3.0-8.0 Hz), (4.0-8.0 Hz), (5.0-10.0 Hz), (6.0-12.0 Hz), and (8.0-16.0 Hz). For each frequency band is associated a set of parameters defining the time window and an array configuration; for example, the D-ring instruments are not included in the f-k analysis for the highest frequencies in order to mitigate the effects of signal incoherence. Tapering is applied to the data segments to prevent edge effects in the Fourier transforms.

The extensive database of GT mining events provides an excellent natural laboratory for the testing of this re-processing. Figure 6 displays the slowness estimates for the initial P-arrivals for all the GT-events during the test-period in two of the fixed frequency bands, together with those from the existing variable band processing. The black, red, green, and blue symbols correspond to slowness estimates from P-arrivals from the four main Kola mining regions indicated in Figure 1 and it is clear that the estimates from the different sources show a far better separation and smaller variance for the fixed bands. One example of the problems with the variable band processing is the false interpretation of many of the P-arrivals from Kovdor events. The signals are dominated by frequencies over 10.0 Hz and so the existing procedure estimates slowness in high-frequency bands. Probably a result of the specific ripple-firing practices at this mine, compounded by poor signal coherence over the array, slowness estimates were consistently too low and azimuth estimates misleading. Such results were also observed for the reprocessing in the highest frequency bands, despite the absence of the more distant D-ring sensors.

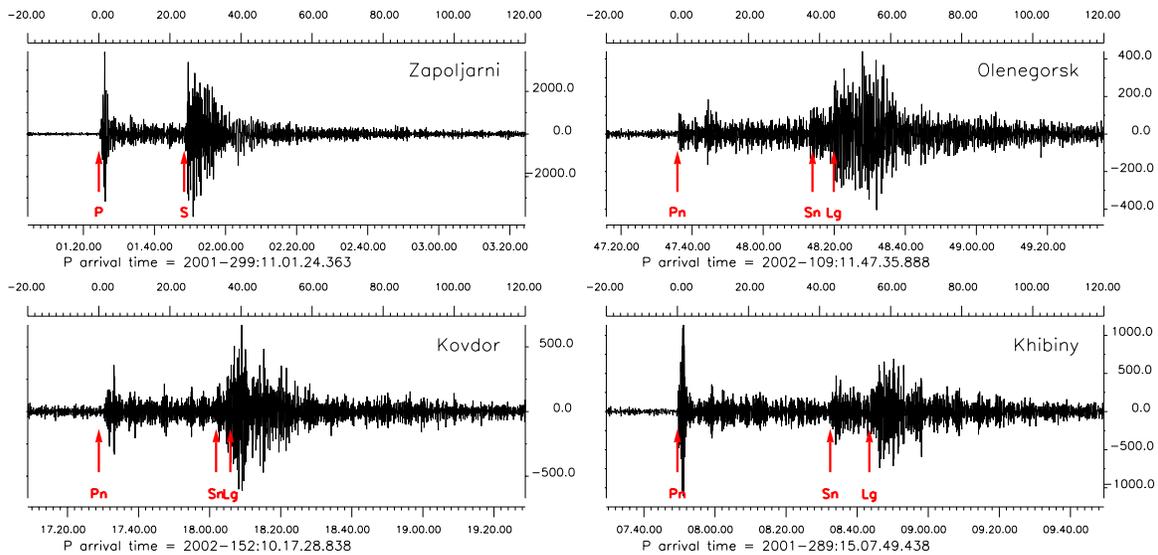
## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring



**Figure 6.** Slowness estimates for the initial P-phases from each of the Ground Truth events in the database between October 1st 2001 and September 30th 2002 in an optimal frequency band (ARCES online processing: left), the 2.0-4.0Hz frequency band (center) and the 4.0-8.0 Hz band (right). The mines are indicated by symbols as shown.

KEY		
◆	Zapadni	zp1
◆	Central	zp2
◆	Olenegorsk	ol1
○	Kirovogradsk	ol2
×	Bauman	ol3
+	Oktjabrsk	ol4
★	Komsomolsk	ol5
◆	Kirovsk	kh1
★	Rasvumchorr	kh3
★	Central	kh4
○	Koashva	kh5
○	Norpakh	kh6
◆	Kovdor	kv1

The slowness estimates in the band (4.0-8.0 Hz) are far more stable than those in the (2.0-4.0 Hz) band for the three more distant mining regions; the opposite is true for slowness estimates from the Zapoljarni mines. Many smaller events in the database have a very low SNR in the lower of these frequency bands which often leads to an fk-result dominated by coherent background noise.

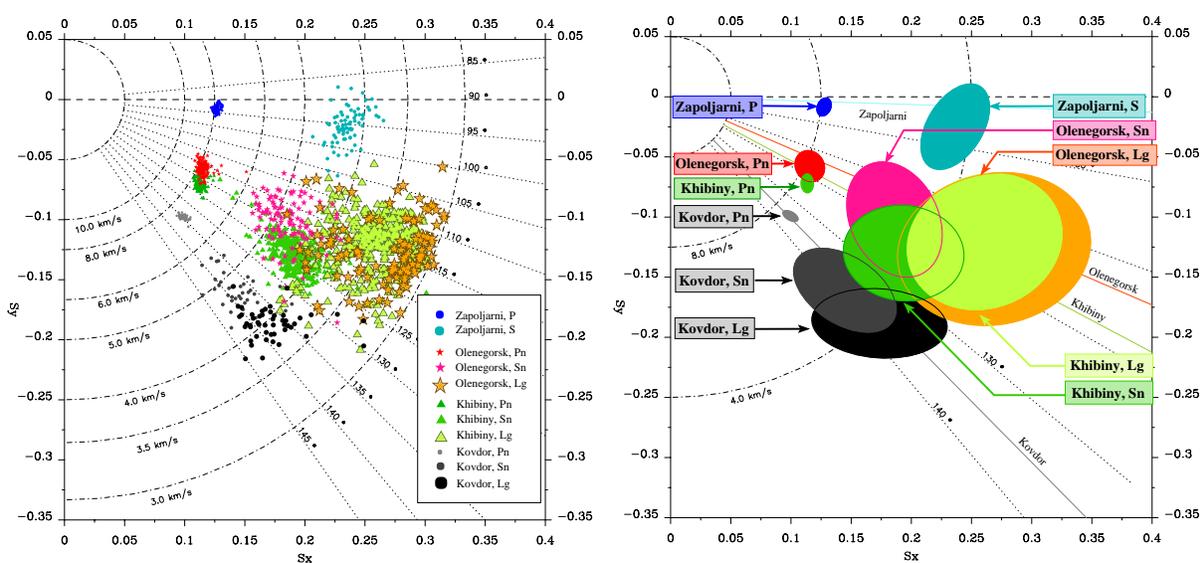


**Figure 7.** A typical event from each of the four mining areas studied. The ARA0\_sz trace is displayed for each event, filtered in the frequency band 2.0-5.0 Hz. According to the “barey” velocity model, the Pb, Pg, and Pn phases all arrive within a second of each other for events from the Zapoljarni mines (distance 204 km from ARCES), as do the Sb, Sg, and Sn phases; we therefore simply denote first arrivals P and S. For the more distant mines at 298 km (Kovdor), 345 km (Olenegorsk), and 400 km (Rasvumchorr, Khibiny), Pn and Sn are the first arrivals and are indicated as predicted by “barey”. The time for the Lg phase cannot be directly predicted from the barey model and is based upon group-velocity measurements from the Ground Truth events.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

For the seismic monitoring of specific source locations, it is probably best to measure slowness and azimuth for the anticipated secondary phases in time-windows fixed relative to the initial P-arrival which almost certainly will have the most reliably determined onset time. We demonstrated in Figure 3 how, due to the complexity of the firing sequences for events from these mines, there were unpredictable pulses of coherent energy throughout the coda which compound the frequent problem of low SNR for the onset-time determination of weak secondary phase arrivals.

Figure 7 shows a selected seismogram for an event from each of the four main mining regions, together with phase onset times predicted by the “barey” model (Schweitzer and Kennett, 2002). For each event in the GT database, f-k analysis was performed for each of the indicated secondary phases with time-windows set at the appropriate delays following the P-onset. Slowness estimates in the 2.0-5.0 Hz frequency band for each phase for each GT event during the test period are displayed in Figure 8. The first observation is that the slowness estimates for the secondary phases are far less consistent than those for the first P-arrivals for all source regions considered. In this frequency band, it is almost possible to determine from which of the four regions a signal comes based on the P-phase slowness estimate alone. The Olenegorsk and Khibiny regions are poorly separated in azimuth from ARCES and this results in a small overlap in the slowness estimate populations; this overlap is greater in some frequency bands and smaller in others.



**Figure 8.** ARCES slowness estimates in the 2.0 - 5.0 Hz frequency band for phases as indicated for Ground Truth confirmed mining events between October 1st 2001 and September 30th 2002 (left) and 95% confidence error-ellipses for these populations (right) together with the geographically expected backazimuth values. Note the small spread of the slowness estimates for initial P-arrivals compared with that of the secondary phases from all of the mines considered. Other frequency bands lead to an improvement in the distribution of slowness estimates for some phases and a deterioration for others. A few outliers which were evidently the result of a low signal to noise ratio were omitted for the calculation of the error ellipses.

In calculating these confidence intervals, it was necessary to remove some data points for which slowness estimates had clearly been dominated by background noise, coda signals, or other unrelated events. As reported by Gibbons et al. (2003), many Kovdor Sn phases were attributed a slowness value consistent with a Kovdor Pn/Pg phase due to repeat blasting at the same site. Many of the underground explosions on the Khibiny massif have weak associated signals which are dominated by background noise in this frequency band.

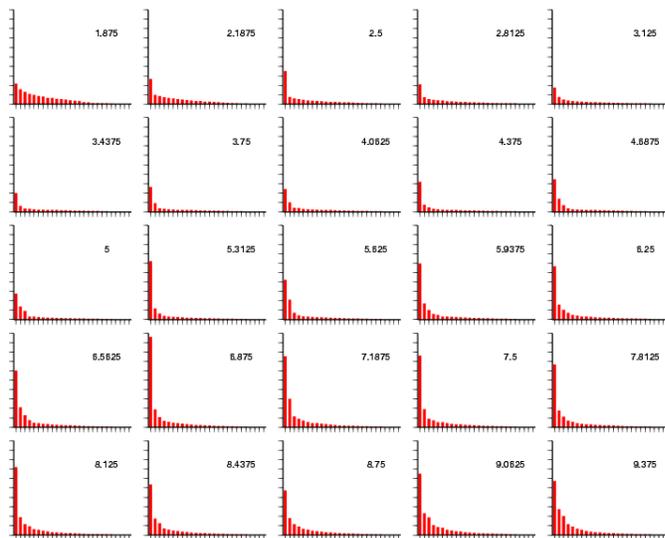
The overlap between Sn and Lg slowness determinations from the Khibiny and Olenegorsk mines is very large. These measurements should correspond to different time-windows relative to the P-arrival although Sn-type slowness values can be anticipated long into the S-coda and fortuitous firing sequences may lead to Sn or Lg from delayed blasts being observed at unexpected times. Lg is not observed in higher frequency bands and slowness estimates in the Lg time-window only measure the S-coda.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

In addition to useful information about the variance of these slowness estimates, we observe how these distributions relate to the anticipated azimuth values. Slowness estimates from the initial P-arrivals generally over-estimate the backazimuth, with the exception of the Kovdor events (although, in other frequency bands, the backazimuth is also overestimated for these events: Gibbons and Kvaerna, 2002). The large variance in slowness estimates is probably a consequence of the broad-band f-k analysis with the slowness corresponding to maximum coherence being determined according to the relative strength of high and low frequency energy within the given band.

### Empirical Matched Field Processing

We are investigating the application of matched field processing to seismic array data. Matched field processing is a narrowband technique borrowed from underwater acoustics (Baggeroer et al., 1993) that generalizes the notion of beamforming to non-planar wave structure. Recall that narrowband beamforming and FK measurements may be interpreted as a spatial inner product operation with a vector of complex numbers (called a steering vector) representing phase delays at a given processing frequency under a plane-wave propagation assumption. Matched field processing most often substitutes theoretical predictions of the steering vector structure computed from a model of propagation in the medium. The complex components of the steering vector consequently may have non-planar phase structure and non-uniform amplitudes. An empirical approach to matched field processing measures the wavefield structure, rather than calculating it from a model (Fialkowski et al., 2000). In this approach, sample covariance matrices are measured from narrowband data for sources of known location, and empirical steering vectors are extracted as the eigenvectors corresponding to the largest eigenvalues. Steering vectors derived this way are tied to particular source locations. This approach may be adaptable to producing narrowband, aperture-level calibrations for seismic arrays. The quality of the calibrated steering vector is determined by the quality of the narrowband covariance matrix. In the seismic case, high-quality covariance matrices may be estimated by stacking many observations of a particular phase (especially from repeating sources, such as mines).



**Figure 9.** Eigenvalue structure (square-root scaling) of Pn spatial covariance matrices (ARCES array) made by averaging sample covariance matrices from 28 observations of events at the Olenegorsk mine.

In situations where a single incident wave is anticipated the quality of the covariance matrix may be assessed from the matrix eigenstructure, which should be dominated by a single large eigenvalue. An example of this situation is shown in Figure 9. These are results of preliminary covariance matrix estimates for Pn phases generated by explosions in the Olenegorsk mine and recorded by the ARCES array. In this example, Pn covariance matrices were averaged for 28 GT events in each of 25 narrow (0.3125 Hz bandwidth) frequency bands. The plot shows the square root (to compress dynamic range) of the eigenvalues in each frequency band, and demonstrates that a single eigenvalue does indeed predominate in most frequency bands. Generally this observation breaks down at the very low frequencies (where noise flattens the eigenstructure) and the very high frequencies (where scattering spreads signal energy over multiple wavenumbers and eigenvalues). To date, we have completed software to efficiently calculate average covariance matrices for a large number of events on a regular set of frequencies and extract eigenvalues and eigenvectors. We plan next to use the eigenvectors as empirical steering vectors in narrowband beamforming and FK operations.

## 26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

### CONCLUSIONS AND RECOMMENDATIONS

Our initial results have confirmed that application of a fixed frequency band for f-k analysis provides a greatly improved stability of slowness estimates of regional events, compared with the conventional procedure which uses a variable frequency band (i.e. the frequency band with the highest SNR). The application of broadband f-k analysis in parallel in a number of fixed frequency bands has been shown to provide a convenient method to select the best frequency band for a particular station-site configuration. From our initial studies of ARCES data for several mining sites in the Kola Peninsula, we have found that the “optimum” frequency band varies with site and phase type, and the selection of such a band for operational processing therefore requires careful calibration for each case. The stability for the slowness estimates for the first P-phase is much more stable than for secondary phases (S and Lg), and gives an azimuth estimate with a typical scatter as low as +/- 2 degrees for the events studied.

Semblance analysis of ARCES recordings from different mining sites has been investigated in detail, and has revealed significant variations even for signals from the same mine. Thus, it may be difficult to successfully apply waveform correlation techniques for these mining explosions in general, but some promise is seen for the simple “compact” explosions. Further progress will require detailed analysis by taking into account relative location of the explosions as well as the different firing practices.

Further work will focus on applying automatic one-array location processing to the mines in Fennoscandia, expanding upon the procedure introduced by Gibbons et al. (2003). We will also develop and apply an initial multi-array process for detecting and locating recurring mining explosions in Fennoscandia, and compare the results to the current experimental regional monitoring system in operation at NORSAR. Furthermore, in the second year of this project, we will apply the analysis procedures to selected mining sites in Kazakhstan. This work, which will include calibration of specific station-site configurations will be carried out in cooperation with the Kazakhstan NDC.

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