ANNALI DI GEOFISICA, VOL. XXXVII, N. 3, June 1994

Intelligent post-processing of seismic events

Tormod Kværna and Frode Ringdal
NFR/NORSAR, Kjeller, Norway

Abstract
The Intelligent Monitoring System (IMS) currently provides for joint processing of data from six arrays located in Northern and Central Europe. From experience with analyst review of events automatically defined by the IMS, we have realized that the quality of the automatic event locations can be significantly improved if the event intervals are reprocessed with signal processing parameters tuned to phases from events in the given region. The tuned processing parameters are obtained from off-line analysis of events located in the region of interest. The primary goal of such intelligent post-processing is to provide event definitions of a quality that minimizes the need for subsequent manual analysis. The first step in this post-processing is to subdivide the area to be monitored in order to identify sites of interest. Clearly, calibration will be the easiest and potential savings in manpower are the largest for areas of high, recurring seismicity. We have identified 8 mining sites in Fennoscandia/NW Russia and noted that 65.6% of the events of $M_L > 2.0$ in this region can be associated with one of these sites. This result is based on 1 year and a half of data. The second step is to refine the phase arrival and azimuth estimates using frequency filters and processing parameters that are tuned to the initial event location provided by the IMS. In this study, we have analyzed a set of 52 mining explosions from the Khibiny Massif mining area in the Kola peninsula of Russia. Very accurate locations of these events have been provided by the seismologists from the Kola Regional Seismology Centre. Using an autoregressive likelihood technique we have been able to estimate onset times to an accuracy (standard deviation) of about 0.05 s for *P*-phases and 0.15-0.20 s for *S*-phases. Using fixed frequency bands, azimuth can be estimated to an accuracy (one standard deviation) of 0.9 degrees for the ARCESS array and 3-4 degrees for the small array recently established near Apatity on the Kola peninsula. The third step in the post-processing is a relocation of the event, using refined arrival times and recomputed azimuths from broad-band *f-k* analysis. By introducing region-specific travel-time corrections, a median error of 1.4 km from the reported location has been obtained. This should be compared to the median error of 10.8 km for the automatic IMS processing for these events. This improvement in location accuracy clearly demonstrates the usefulness of the intelligent post-processing approach.

Key words *seismology – signal processing – onset time – event location*

1. Introduction

From experience with analyst review of events automatically defined by the Intelligent Monitoring System (IMS) (Bache *et al.*, 1993), we have realized that the quality of the automatic event locations can be significantly improved if the event intervals are reprocessed with signal processing parameters tuned to phases from events in the given region.

In this paper we test an event relocation procedure that makes use of accurate retiming of seismic phases and accurate re-estimates of azimuth using broad-band analysis of array data. The key to obtain such accurate estimates is the knowledge, provided

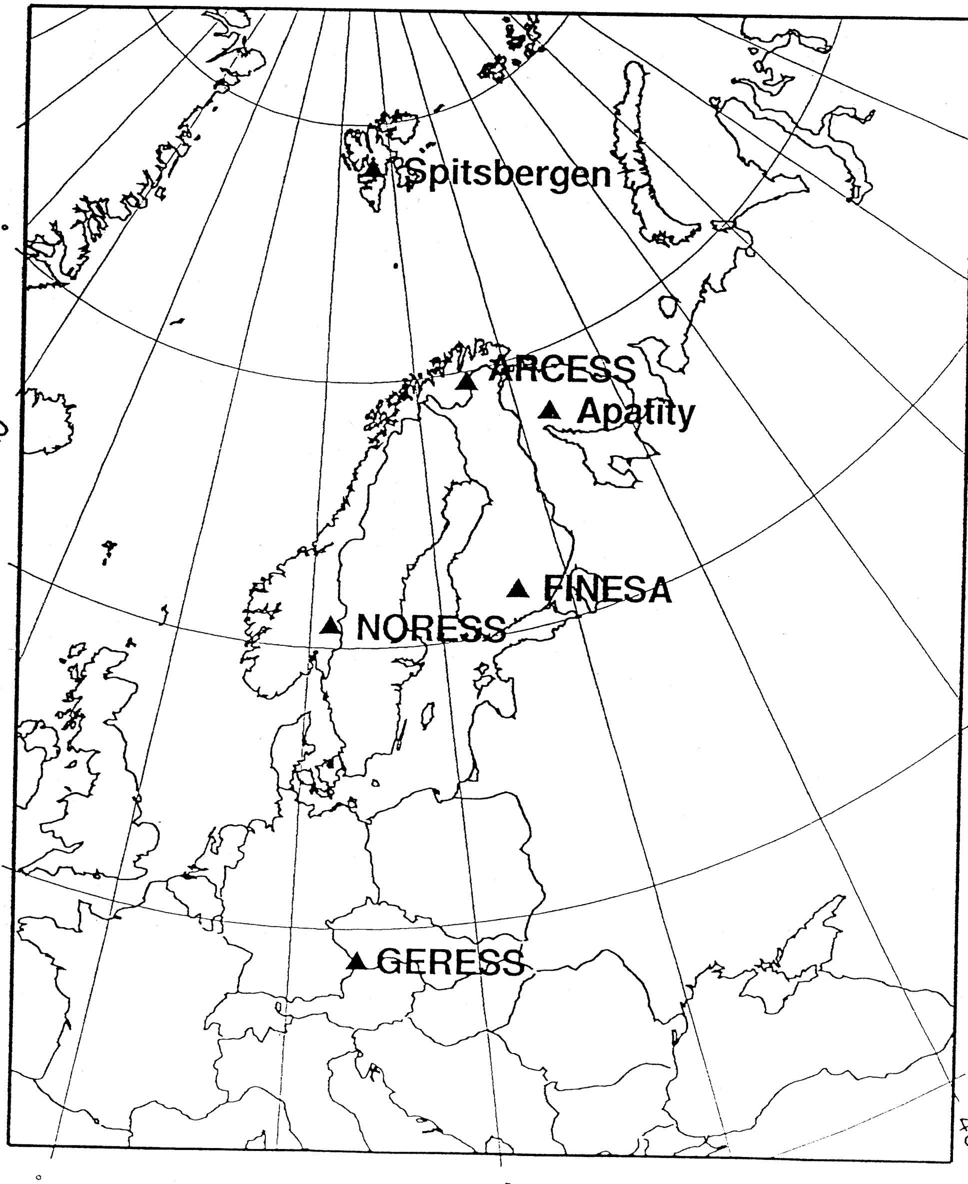

Fig. 1. Map showing the locations of the six regional arrays currently used by the Intelligent Monitoring System at the NORSAR processing center.

by the IMS, of an approximate event location in a known area with good event calibration information.

Since 15 October 1991, the IMS has been processing seismic data from four high-frequency arrays in Northern Europe. These are NORESS and ARCESS in Norway, FINESA in Finland and GERESS in Germany. During October 1992 a small-aperture array was installed near Apatity on the Kola peninsula, and during late October/early November 1992 another small-aperture array on the island of Spitsbergen became operational. The data from these installations are now included in the IMS processing for the production of the event bulletin.

Since four of the arrays providing data to the IMS are located in Fennoscandia, see fig. 1, the IMS event bulletin shows an excellent event detection capability for this region. Ringdal (1991) found that for Fennoscandia/NW Russia, a network consisting of NORESS, ARCESS and FINESA has a 90% detection capability close to M_L 2.0. Near the individual arrays, the detection capability is considerably better, and consequently a large number of events less than M_L 1.0 are detected.

2. IMS event statistics

The basic principle of the post-processing method is to start by subdividing the area to be monitored into smaller areas, and subsequently apply a region-specific analysis to each area. As an example, we will consider in some detail the statistics of events in Fennoscandia and NW Russia for the 18-month time period 10/15/91-04/15/93.

For this time period the IMS bulletin contains 19503 analyst-accepted events. 65.6% (12799) of these events are located in the Fennoscandian/NW Russian region defined by the map of fig. 2, 15.8% (3089) are located within 5 degrees of the GERESS array, and the remaining 18.5% (3615) are distributed around the rest of the world, mostly at teleseismic distances from the regional array network.

Figures 2, 3 and 4 show the event distribution in Fennoscandia for all magnitudes, $M_L > 1$ and $M_L > 2$, respectively. In each figure, we have marked the approximate geographical extent of 8 main mining areas. Table I lists these mining sites and gives details on the number and percentages of events associated to the sites at various magnitudes.

From the three figures and table I we can make the following general observations:

— out of the total 12799 events, 6317 (49.4%) are above $M_L = 1$, and only 1131 (8.8%) are above $M_L = 2$;

— the total percentage of the events associated with the 8 mining sites is 47.88% (all magnitudes), 56.66% ($M_L > 1.0$) and 65.61% ($M_L > 2.0$). Thus, these sites become more dominant for the largest events, in terms of relative number of events reported;

— some mining sites have a relatively high proportion of large events ($M_L > 2.0$). This is particularly noticeable for the mining areas in Western Russia/Estonia. On the other hand, the Kiruna mine has the largest number of events altogether, but almost none of these are above $M_L = 2$.

Being based on about 1 year and a half of data, the statistics discussed here should be reasonably representative for the situation in the Fennoscandian/NW Russia region.

Thus, the analysis of recurring events from these mining areas is a significant workload for the analyst. An automatic method to improve the automatic analysis so as to obtain location precisions comparable with the analysts' results would be a significant development. In this paper, we will show that such an improvement is possible for a well-calibrated mining area (the Khibiny Massif of the Kola peninsula, Russia).

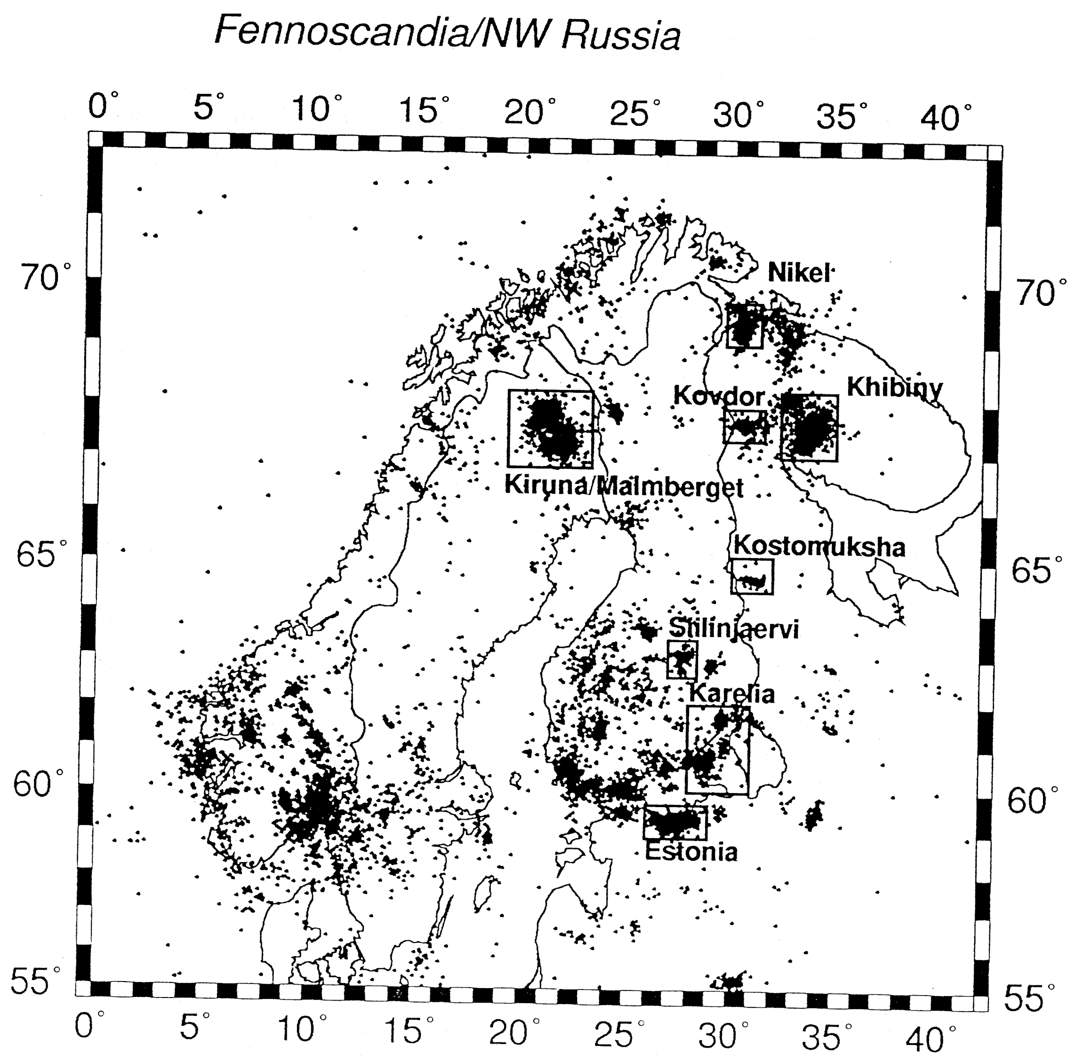

Fig. 2. Locations of 12 799 events (all magnitudes) processed by the IMS for an 18-month period. Note the concentration of events in selected mining areas.

3. Location of regional events

Seismic event location has traditionally relied upon *P*-wave arrival times from a large number of stations. For small events observed only at regional distances, it has been necessary to include arrival times of later phases as well as arrival azimuths in order to obtain acceptable location accuracy (Bratt and Bache, 1988; Thurber *et al.*, 1989). With a sparse network, the number of arrival time observations may often be so low that azimuth information is given considerable weight in the location scheme. However, as the number of observations increases, the relative importance of the azimuths decreases

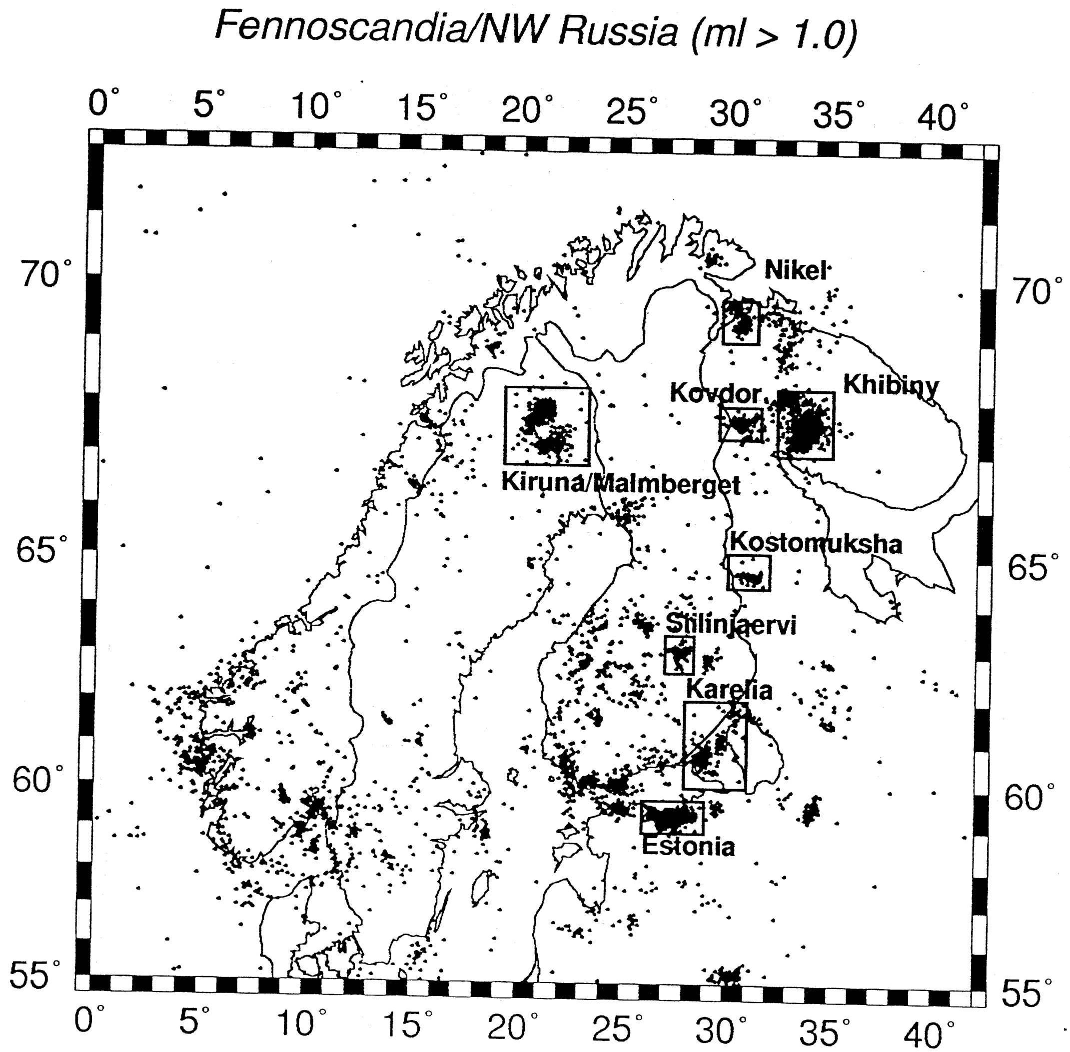

Fig. 3. Same as fig. 2, but showing only events of $M_L > 1.0$. The total number of events is 6317 for the 18-month period.

sharply, in view of the generally large uncertainties (10 degrees or more) that are associated with azimuth estimates (*e.g.*, Suteau-Henson, 1990; Bame *et al.*, 1990).

Kvaerna and Ringdal (1986) demonstrated that the uncertainty of azimuth estimates from regional arrays can be greatly reduced by applying a broad-band estimation scheme in which the frequency band is kept constant for a given epicentral region. Thus, for NORESS observations of explosions from Blåsjø in Southern Norway (distance 300 km) with high SNR, they found an azimuth standard deviation of only 1.0 degrees for *Pn* phases and 1.5 degrees for *Sn* and *Lg* phases.

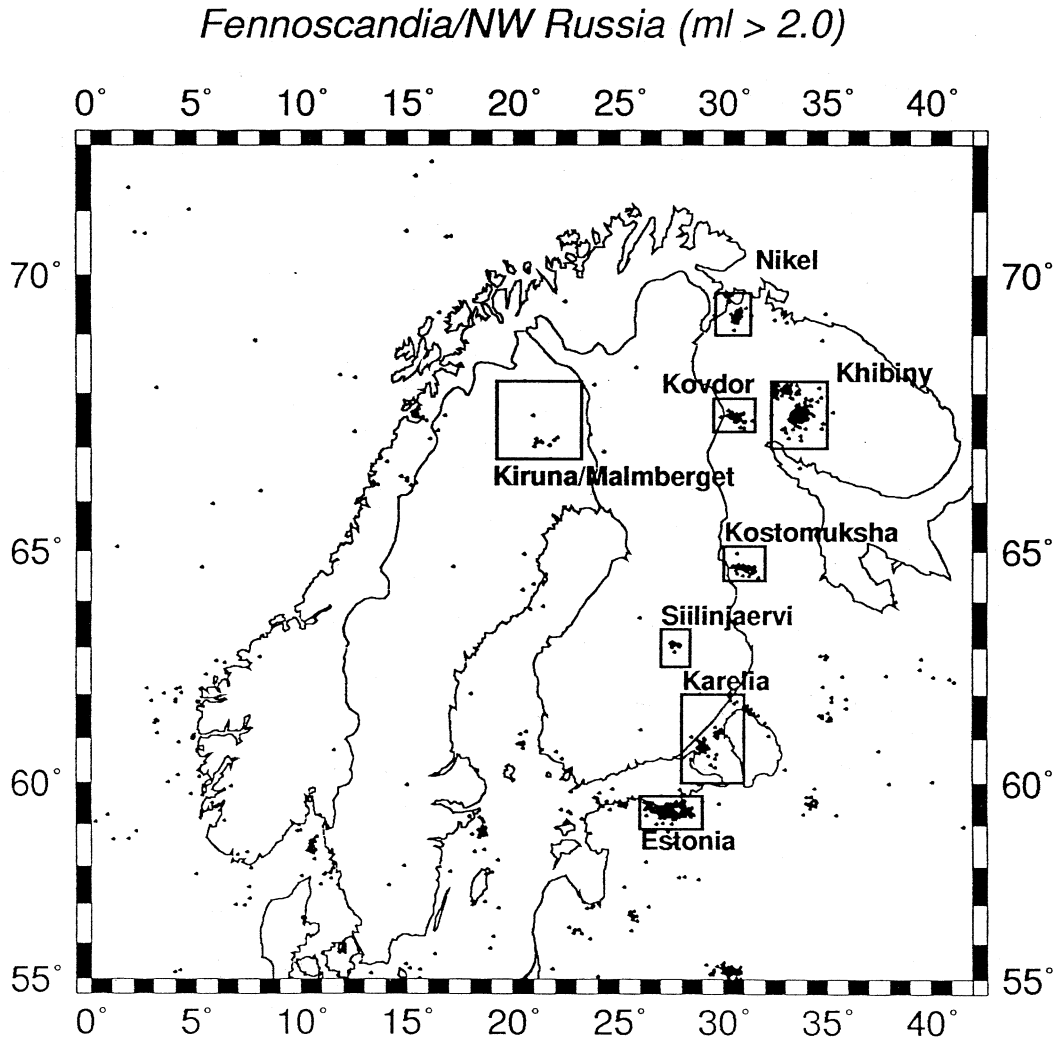

Fig. 4. Same as fig. 2, but showing only events of $M_L > 2.0$. The total number of events is 1131 for the 18-month period.

Kværna (1994) considered the problem of precise estimation of signal arrival time. Given that an event has occurred in a certain area, an automatic program selected a set of optimum filter bands and beam parameters for this area, prior to reassessing the arrival time estimate. It was shown that this can lead to a remarkable improvement in timing precision, by using an autoregressive likelihood technique (Pisarenko *et al.*, 1987; Kushnir *et al.*, 1990). It is noteworthy that this onset-time estimation method seems to require that the search be limited to a relatively short time window in order

Table I. Distribution of events in the mining regions of Fennoscandia and NW Russia.

Region	All Magnitudes		Magnitudes > 1.0		Magnitudes > 2.0	
	N.	%	N.	%	N.	%
Fennoscandia/NW Russia	12799	100.00	6317	49.36	1131	8.84
Estonia	1487	11.62	1159	18.36	225	19.89
Karelia	379	2.96	212	3.36	70	6.19
Khibiny	1374	10.74	1106	17.51	233	20.60
Kiruna	1953	15.26	634	10.04	11	0.97
Kostomuksha	69	0.54	69	1.09	47	4.16
Kovdor	112	0.88	99	1.57	34	3.01
Nikel	620	4.84	181	2.87	104	9.20
Siilinjaervi	134	1.05	119	1.88	18	1.59
Total for 8 mines	6128	47.88	3579	56.66	742	65.61

to work well. If an initial location and origin time is known, the required short time window for the search can be obtained.

The basic idea behind the post-processing technique described in this paper is to use, as a starting point, the initial event location provided by the Intelligent Monitoring System (IMS) and then use region-specific information to refine the solution. By applying this technique to areas with significant recurring seismic activity, such as mining areas, a considerable part of the analyst work can be eliminated.

The automatic method applied in this study is schematically shown in fig. 5 and consists of the following steps:

1) the IMS detects and locates a seismic event within a given distance from the target region;

2) for each phase detection by a station in the network, the estimated arrival time is refined using the autoregressive onset-time estimation method of Pisarenko *et al.*, (1987) (see Kværna, 1994). A standard deviation is assigned to each refined estimate;

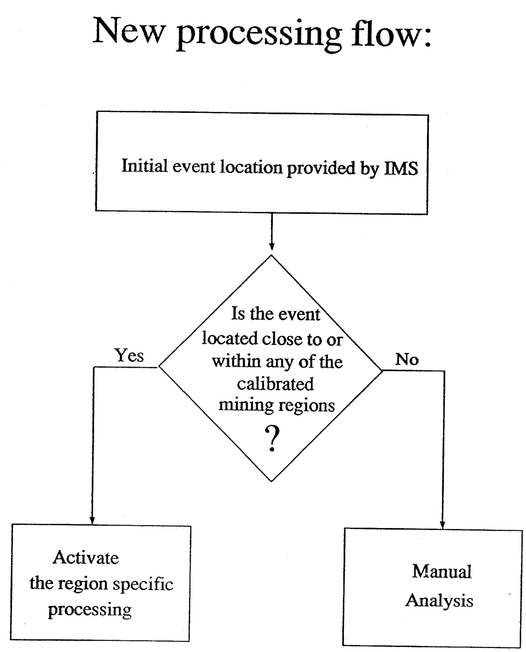

Fig. 5. Schematic view of the principle behind intelligent post-processing of seismic events.

3) for each phase detection by one of the arrays, an «optimum» frequency band for *f-k* analysis is extracted from a data base which, we assume, has been previously established and calibrated;

4) broad-band *f-k* analysis is then applied to each phase. The resulting values are corrected for systematic bias and assigned a standard deviation, based upon SNR, phase type and previously observed calibration information;

5) the LocSat program (Bratt and Bache, 1988) is then applied to the revised data set, and a new event location estimate is obtained. In practice, zero depth is assumed a priori in the automatic process.

In the case study discussed in detail in this paper, we will analyze events in the Khibiny Massif recorded by the IMS, for which we have independent location information. We will primarily make use of the Apatity array, using arrival times for the *P* and *S* phases and azimuths derived from the *Rg* phase in order to refine the location estimates as described above. In addition, we will consider possible improvements in the location accuracy when using additional available stations.

4. Data

The data for this study comprises 52 events at 6 mines in the Khibiny Massif. The mines are only a few kilometers apart (Mykkeltveit, 1992), and each mine has a dimension ranging from a few hundred meters to about 1 km. These dimensions are small enough so that we ignore the areal extent of each mine.

To obtain an initial location, we have used the automatic IMS epicenter solution for each event. The automatic IMS solution relative to the «true» epicenter for each of the events is displayed graphically in fig. 6. Although many of the events are very accurately located (to within a few km), there is a fair amount of scatter in the location estimates. The median «error» is 10.8 km. In a few cases, the location is wrong by several tens of km; this is due to occasional erroneous phase identification by the automatic process.

The Apatity array has been described by Mykkeltveit *et al.* (1992), and initial data analysis results have been presented by Ringdal and Fyen (1992). The latter paper discusses in particular the high stability of azimuth estimates using the *Rg* phase for shallow events at local distances.

Kværna (1994) shows an example of Apatity array recordings of events in the Khibiny Massif. The filtered recordings (0.8-2.0 Hz) are dominated by the *Rg* phase. In contrast, the *P* and *S* phases are far more high-frequent, as is to be expected at such close distances. Because of the low frequency of the *Rg* phase, this phase has a high coherency across the array and it provides a stable and very robust slowness estimate in the sense that «side-lobe» peaks in the frequency-wavenumber diagram are easily avoided.

For the present study, we have used Apatity (APA0) array recordings for all 52 events. These constitute a subset of the 58 events analyzed in the study of Kværna (1994), but six events were discarded from this study due to missing three-component data at the array site. Furthermore, all events have associated three-component broadband recordings from the station installed in the town of Apatity (APZ9), 15 km from the array site. ARCESS array data have been available for all but one of the events.

5. Results

In table II, the mean and the standard deviation of the azimuth residuals relative to the Khibiny mine locations of the phases recorded at the arrays APA0 and ARCESS are presented. We see from the table that the *P* and *Rg* azimuths at APA0 have about the same standard deviation (3.9 and 3.4 degrees, respectively), but that the *P* azimuths have a systematic bias of 8.2 de-

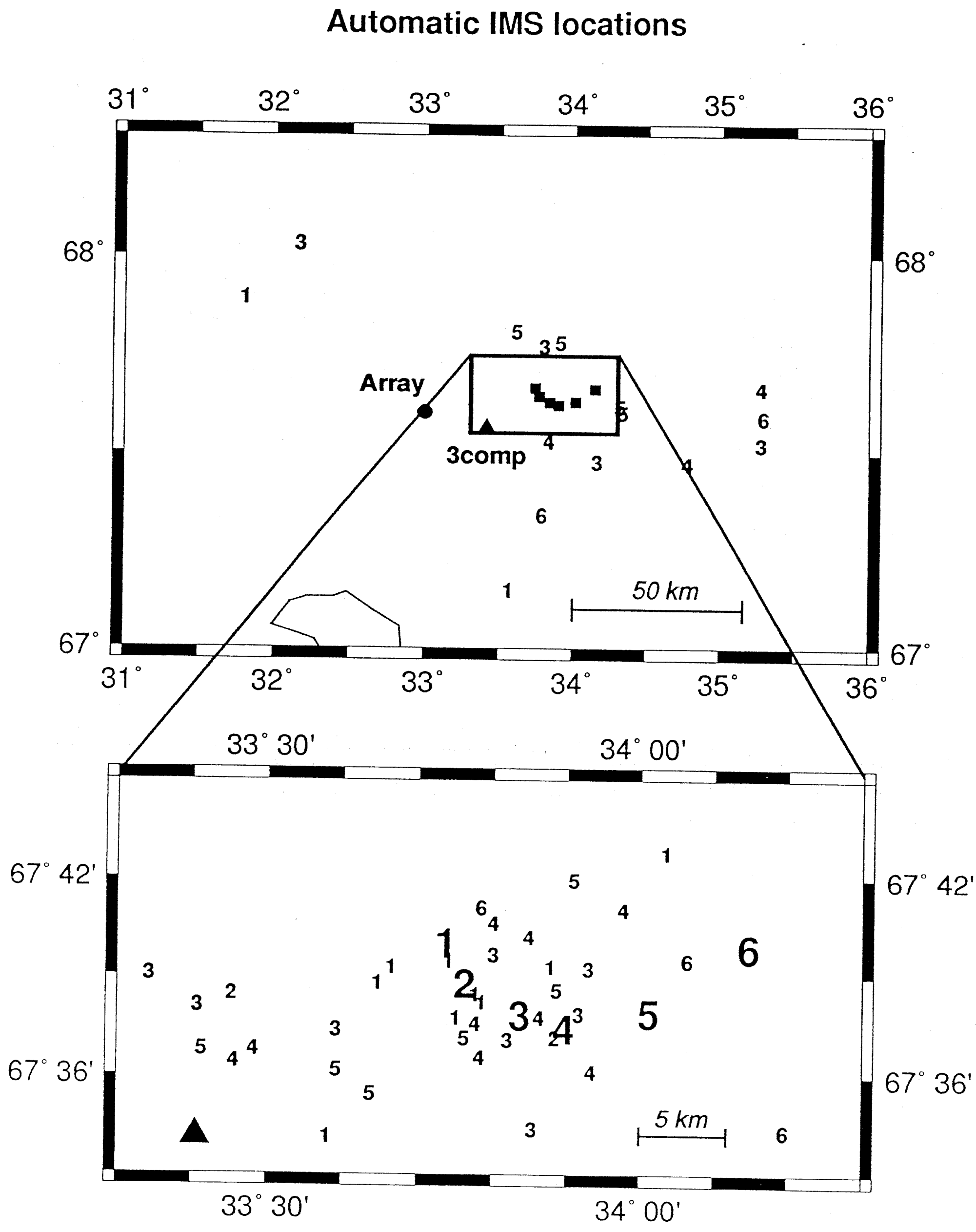

Fig. 6. Locations of the six mining sites in the Khibiny Massif (large numbers 1-6) and the locations of the 52 reference events (small numbers 1-6) as given by the automatic IMS processing. In the upper part, a large reference area is shown, with the mines plotted as filled squares. The lower part shows a detailed picture for the area near the mines. The small number (1-6) associated with each event represents the mine in which the event actually occurred. The Apatity array (APA0) is shown as a filled circle and the three-component station in the town of Apatity (APZ9) is shown as a filled triangle. The median location error is 10.8 km, the 90% quantile is 48.4 km and the maximum error is 86.1 km.

Table II. Mean and standard deviation of azimuth residuals relative to Khibiny mine locations.

	Mean (°)	σ(°)
P – Apatity array	8.2	3.9
Pn – ARCESS	4.6	0.9
S – Apatity array	−1.0	19.8
Rg – Apatity array	−1.8	3.4

grees. The *Rg* azimuth bias is as low as −1.8 degrees. The ARCESS *Pn* azimuths have a very low standard deviation (0.9 degrees), but a systematic bias of 4.6 degrees is consistently observed. The *S*-azimuths at APA0 show a very large scatter. These observations indicate that if the Khibiny events are located without introducing corrections for the azimuth biases, the *Rg* azimuths should be given the smallest a priori uncertainty. If the systematic biases are removed, the a priori uncertainty of *P* and *Rg* at APA0 become comparable. With the systematic bias removed, the a priori uncertainty of ARCESS *Pn* is very small, but it should be noticed that in the event location procedure (Bratt and Bache, 1988) the a priori azimuth uncertainty is scaled by the source-receiver distance, such that an azimuth observation at 400 km distance with an uncertainty of 0.9 degrees (ARCESS *Pn*) is given less weight than an azimuth observation at 40 km distance with an uncertainty of 3.9 degrees (APA0 *P*).

In the following, we present location results from analyzing the 52 events in the data base under various scenarios. Each scenario assumes that we have an operational situation in which a certain amount of calibration information has been assembled.

a) Use of Apatity array only; *P* and *S* arrival times, *Rg* azimuth, no calibration. In this scenario, we assume no prior knowledge except for the «optimum» frequency bands for timing and azimuth estimation. The travel-time tables are those that the IMS uses for Fennoscandia in general, with no regional corrections. The results are displayed in fig. 7. We note that there is a small systematic bias, as there seems to be a trend of events being located to the north and east of the sites. This indicates that some improvement could be obtained by introducing a regional velocity model for the Khibiny area, together with regional azimuthal corrections. Nevertheless, the scatter relative to the 6 mines in this plot (using uncalibrated Apatity array data only) is significantly reduced compared to the IMS results plotted in fig. 6. The improvement can be quantified by considering that the median «error» is only 3.1 km, with a worst case «error» of 6.7 km. This can be compared to the IMS results of 10.8 km and 86.1 km, respectively. Thus the reprocessing, even without regional correction, could significantly improve the precision in the epicenter solutions if incorporated into the automatic IMS processing.

b) Use of Apatity array data only, with regional *P* and *S* travel-time bias correction and a correction for systematic *P* and *Rg* azimuth bias. The resulting location plot is shown in fig. 8. The median error is reduced to 2.1 km, and the «worst case» error is 6.1 km.

c) Use of Apatity array data plus *P* and *S* times from the three-component station in Apatity. Regional corrections have been applied both for the array and the three-component station. The resulting location plot (fig. 9) shows that the median error is 1.4 km, and the maximum error is 5.4 km.

d) This final scenario includes both Apatity array data, Apatity three-component data and ARCESS *Pn* arrival times. Regional corrections have been applied for all the data. The resulting location plot (fig. 10) shows a median error of 1.6 km, and a maximum error of 7.1 km. It is interesting to note that this is not quite as good as case c). Thus, it is not necessarily an improve-

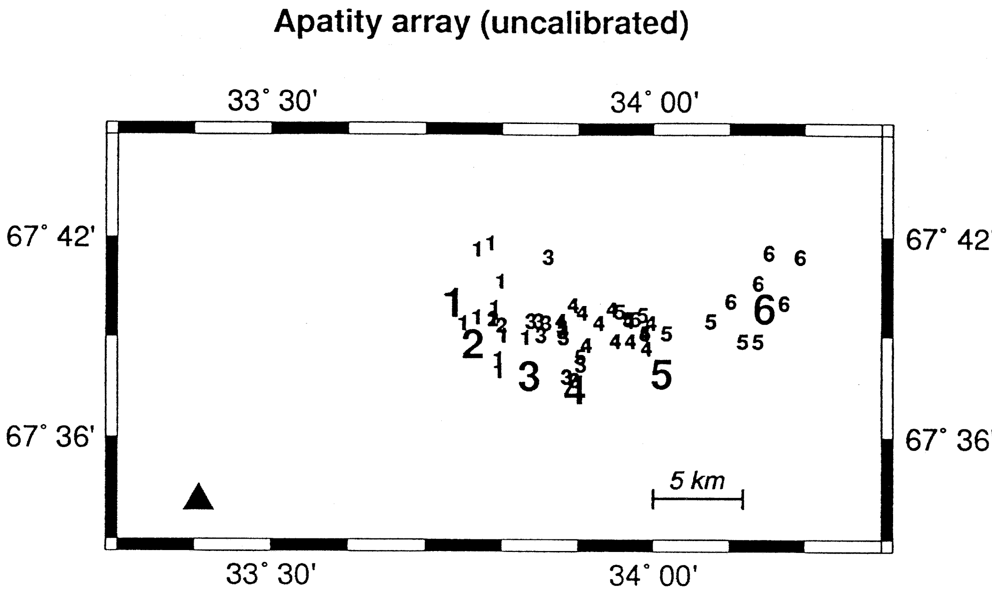

Fig. 7. Same as lower part of fig. 6, but the event locations (small numbers) have now been taken from the post-processing results using uncalibrated Apatity array data only. The median location error is 3.1 km, the 90% quantile is 4.9 km and the maximum error is 6.7 km.

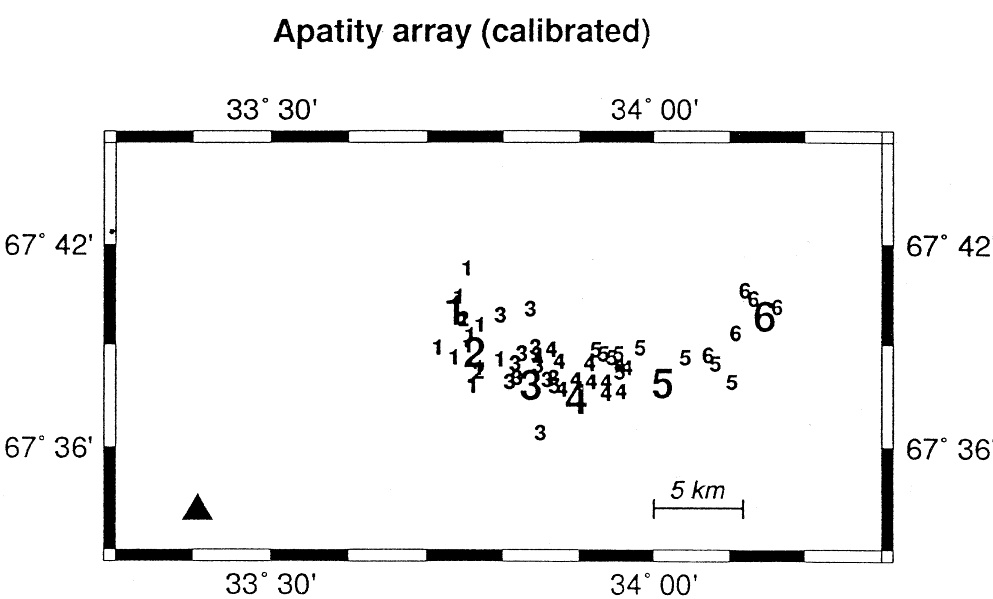

Fig. 8. Same as lower part of fig. 6, but with the event locations resulting from post-processing of calibrated Apatity array data (see text for details). The median location error is 2.1 km, the 90% quantile is 3.9 km and the maximum error is 6.1 km.

Apatity array and 3comp. (calibrated)

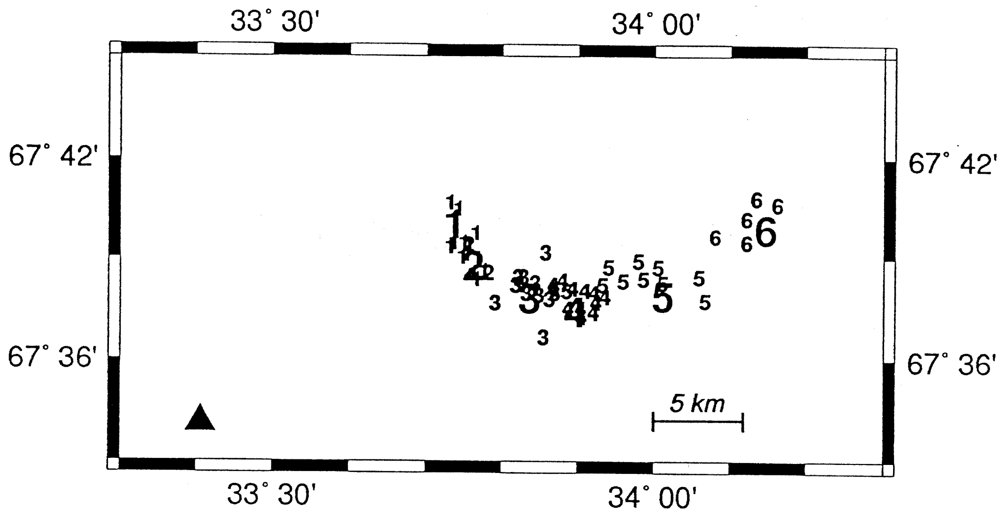

Fig. 9. Same as lower part of fig. 6, but with the event locations resulting from combining Apatity array data and three-component data (both calibrated) in the post-processing. The median location error is 1.4 km, the 90% quantile is 2.7 km and the maximum error is 5.4 km

ARCESS, Apatity array and 3comp. (calibrated)

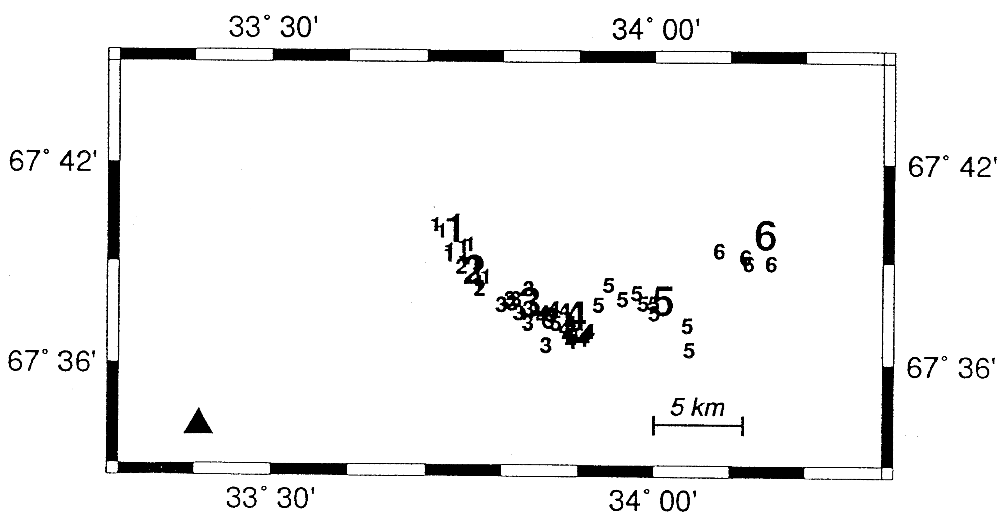

Fig. 10. Same as lower part of fig. 6, but with the event locations resulting from combining Apatity array, Apatity three-component and ARCESS array data (all calibrated) in the post-processing. The median location error is 1.6 km, the 90% quantile is 3.0 km and the maximum error is 7.1 km.

Table III. Travel-time corrections used in this study.

Phase	Station	Correction
P	APZ9	0 s (fixed)
P	APA0	−0.10 s
Pn	ARCESS	−0.31 s
S	APZ9	0.22 s
S	APA0	0.09 s

ment to add data, even if (as in this case) the additional data are extremely accurate (error ⩽ ± 0.05 s for *P*-recordings).

We should note that the travel-time corrections used in this paper (table III) are *relative* and based upon the same data set that we have evaluated. In view of the large number of events, the possible bias introduced by this procedure should be negligible. As the origin time of the Khibiny events are unknown, we have fixed the travel-time correction of *P* at the Apatity three-component station APZ9 to 0. The *P* phase at APZ9 has travelled a shorter distance and spent less time in the Earth than the other phases used in the event locations. Thus, the influence of an erroneous travel-time model is likely to be the least for this phase.

6. Conclusions

In this study we have conducted extensive off-line analysis of 52 mining explosions in the Khibiny Massif recorded at the Apatity array. Independent locations of these explosions are provided by seismologists from the Kola Regional Seismology Centre. Most of these events show clear *P*, *S* and *Rg* phases at the nearby Apatity array located 30-50 km away from the mining areas and the events have also been detected by the ARCESS array. By using the autoregressive onset-time estimator of Pisarenko *et al.* (1987) and comparing to the best manual pick, we have found that *P*-onsets can be automatically estimated with an accuracy of better than 0.1 s, and *S*-onsets with an accuracy better than 0.5 s. In addition, the azimuth estimates from *f-k* analysis of the *P* and *Rg* phases show to be accurate well within ± 5 degrees after removing the biases. The key to achieve stable azimuth estimates is to process the data in a fixed frequency band, using a fixed time window positioning, as demonstrated by Kværna and Ringdal (1986).

Our observations suggest that based on data from the Apatity array alone, we are able to locate these events (assuming 0 depth) with a median error of about 3 km relative to the true location. Even better accuracy can be achieved using calibration information, *i.e.*, correcting the azimuth and arrival time observations for systematic bias. The excellent precision of the automatic phase onsets and azimuth estimates also indicate that the need for subsequent manual analysis of these events may be eliminated.

In conclusion, we have demonstrated that the approach of doing post-processing based on IMS initial solutions has the potential of providing an order-of-magnitude improvement in location precision, at least in certain cases such as the Khibiny Massif near the Apatity array. The improvement may be less if no network station is located close to the source, but it should still be significant. For example, the data from Kværna and Ringdal (1986) indicate that a single array (NORESS) would be capable of locating the Blåsjø explosions within an accuracy of 10 km or better at a distance of 300 km. This is compared to the typical uncertainty of about 30 km in traditional single-array location estimates at this distance (Mykkeltveit and Ringdal, 1981).

In general, it is true that regional corrections are required in order to compute an optimum location. Again, the post-processing analysis is well suited toward this end, because the corrections can be tied to the general area, to which the initial IMS processing assigns the event.

In this context, it is important to note that no regional travel-time tables need to be involved as long as an adequate set of calibration events for the general area are available. The corrections for systematic biases may be made both to the phase arrival times and to the estimated azimuths as has been demonstrated in this paper.

Acknowledgements

This research is sponsored by the Advanced Research Projects Agency of the US Department of Defense, and monitored by the Air Force Technical Applications Center under Contract N. F08606-93-C-0002. We would also like to thank Dr. V.M. Trjapitsin of the Kola Regional Seismological Centre for providing the information on the Khibiny Massif events. The help of Ulf Baadshaug in preparing the figures is much appreciated.

NORSAR Contribution N. 502.

REFERENCES

BACHE, T.C., S.R. BRATT, H.J. SWANGER, G.W. BEALL and F.K. DASHIELL (1993): Knowledge-based interpretation of seismic data in the Intelligent Monitoring System, *Bull. Seismol. Soc. Am.*, **83**, 1507-1526.

BAME, D.A., M.C. WALCK and K.L. HIEBERT-DODD (1990): Azimuth estimation capabilities of the NORESS regional seismic array, *Bull. Seismol. Soc. Am.*, **80** (part B), 1999-2015.

BRATT, S.R. and T.C. BACHE (1988): Locating events with a sparse network of regional arrays, *Bull. Seismol. Soc. Am.*, **78**, 780-798.

KUSHNIR, A.F., V.M. LAPSHIN, V. I. PINSKY and J. FYEN (1990): Statistically optimal event detection using small array data, *Bull. Seismol. Soc. Am.*, **80** (6), special issue, 1934-1950.

KVÆRNA, T. (1987): Wide-band slowness estimation using a small-aperture seismic array, in *NORSAR Semiannual Tech. Summ. 1 October 1986-31 March 1987*, Scientific Rep. N. 2-86/87, Kjeller, Norway, 38-45.

KVÆRNA, T. (1994): Accurate determination of phase arrival times using autoregressive likelihood estimation, *Annali di Geofisica*, **37** (3), 287-300.

KVÆRNA, T. and F. RINGDAL (1986): Stability of various *f-k* estimation techniques, in *NORSAR Semiannual Tech. Summ. 1 April-30 September 1986*, Scientific Rep. N. 1-86/87, Kjeller, Norway, 29-40.

MYKKELTVEIT, S. (1992): Mining explosions in the Khibiny Massif (Kola peninsula of Russia) recorded at the Apatity three-component station, Report PL-TR-92-2253, Phillips Laboratory, Hanscom AFB, MA., U.S.A.

MYKKELTVEIT, S. and F. RINGDAL (1981): Phase identification and event location at regional distances using small-aperture array data, in *Identification of Seismic Sources – Earthquake or Underground Explosions*, edited by E.S. HUSEBYE and S. MYKKELTVEIT, Dordrecht, Holland, 467-481.

MYKKELTVEIT, S., A. DAHLE, J. FYEN, T. KVÆRNA, P.W. LARSEN, R. PAULSEN, F. RINGDAL and I. KUZMIN (1992): Extensions of the Northern Europe Regional Network – new small-aperture arrays at Apatity, Russia, and on the Arctic island of Spitsbergen, *NORSAR Semiannual Tech. Summ. 1 April-30 September 1992*, Scientific Rep. N. 1-92/93, Kjeller, Norway, 58-71.

PISARENKO, V.F., A.F. KUSHNIR and I. V. SAVIN (1987): Statistical adaptive algorithms for estimation of onset moments of seismic phases, *Phys. Earth Planet. Int.*, **47**, 4-10.

RINGDAL, F. (1991): Regional detection performance during GSETT-2. Initial results for the Fennoscandian array network, in *NORSAR Semiannual Tech. Summ. 1 April - 30 September 1991*, Scientific Rep. N. 1-91/92, Kjeller, Norway, 127-133.

RINGDAL, F. and J. FYEN (1992): Initial processing results from the Apatity small-aperture array, *NORSAR Semiannual Tech. Summ. 1 April - 30 September 1992*, Scientific Rep. N. 1-92/93, Kjeller, Norway, 72-85.

SUTEAU-HENSON, A. (1990): Estimating azimuth and slowness from three-component and array stations, *Bull. Seismol. Soc. Am.*, **80** (part B), 1987-1998.

THURBER, C., H. GIVEN and J. BERGER (1989): Regional seismic event location with a sparse network: application to Eastern Kazakhstan, U.S.S.R., *J. Geophys. Res.*, **94**, 17767-17780.