Automated Processing of Seismograms by *SparseNet*

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Introduction

SparseNet is a suite of programs designed to produce an automated bulletin of seismic events. It operates on sparse seismic networks or arrays limited to a maximum of eight stations. *SparseNet* is an application of Artificial Intelligence techniques to seismic monitoring; a more general survey on AI approaches is given in Joswig (1996). Currently, *SparseNet* consists of the three modules: SONODET, COASSEIN and COAEBULL. SONODET performs pattern recognition on single traces, COASSEIN evaluates their coincidence by rules, and COAEBULL eases comparison with ground truth bulletins summarized in different performance statistics. The restriction to eight stations was made to avoid the problem of "combinatorial explosion" for our very simple rule-based approach in COASSEIN, since n events at k stations may cause $(n!)^{k-1}$ permutations for phase association.

The current results of *SparseNet* processing are first identifications of seismic events by source region and with magnitude estimates. These approximate event parameters do *not* represent the final event bulletin, but they stay reliable even when the amplitudes of weak seismic signals are just above the background noise. The creation of the final bulletin needs additional, specialized modules for the precise picking of P and S-onsets on three-component traces and for a standard magnitude determination. Some of these additional modules are already prototyped and will be included in future versions of *SparseNet* (Joswig, 1993).

All programs can either be evoked interactively or in batch-mode, as sketched in Fig. 1. Interactively, you may manipulate many parameters; this mode is best suited for single events and for adjusting the knowledge base. Batch-mode proceeds without interruption and displays some restricted graphics; the results are compiled into lists for single-trace detections, network voting and the optional comparison with reference bulletins. Selecting other data sets with potentially different knowledge bases is handled via editing the *Environment* file.

Single-trace Detection

The program SONODET contains two detectors, the classical STA/LTA and the SONOGRAM detector. Both algorithms can be independently enabled or disabled; they work on seismogram segments or continuous data. Three parameter sets tune the overall behavior, one for each detector and the third for selecting the plot mode. With *automove* you may scan large data volumes of continuous records; SONODET stops whenever a detection is found. By the *fixed scale* option, the sequence of proceeding seismogram segments is plotted with constant magnification as in old-fashioned ink records. This mode will clip at larger amplitudes and gives an immediate impression of signal amplitude, while the requantization of the filter output unveils the true ADC resolution. An example is given in Fig. 2. The Quanterra data logger at the CTBT *International Monitoring System* (IMS) auxiliary station EIL in the Negev, Israel, digitized a weak local event using just four bits from the broadband STS-2 seismometer.

The STA/LTA is an implementation of seismology's most widely used detection algorithm. Its performance can be tuned by the standard options for (1) bandpass filter before STA/LTA, (2) lengths of the two summation windows in the short-term and the long-term averages, and (3) the minimum rise time that the STA/LTA must be above threshold. Our less-common approach explicitly parameterizes the detection threshold by an independent estimation of mean μ and standard deviation σ by

$$S_i > \beta_1 \cdot \mu(S_{i-1},...) + \beta_2 \cdot \sigma(S_{i-1},...) , \qquad S_i = STA \quad or \quad \log(STA) . \qquad (1)$$

Both values μ and variance σ^2 are calculated over earlier values of S_i and replace the simple LTA estimate. The factors β_1 and β_2 are constants while μ and σ^2 are updated recursively. Typical values for a robust detection threshold are $\beta_1 = 1$ and $\beta_2 = 3$; in Fig. 2 the detector triggered on both the P and the Lg onset. The noise statistics in Eq. (1) is based on the STA although its distribution is not GAUSSIAN. Alternatively, one can run the detector on *log*(STA). This conforms to the plausible assumption of a *log*-normal distribution of noise energy, where the smaller variations of S_i demand $\beta_2 =$ 1.5 for comparable sensitivity. The detection results exhibit a more constant false alarm rate for the diurnal and seasonal changes in the stationary noise level. However, none of both choices reliably excludes false alarms caused by short-term bursts from local noise sources.

The SONOGRAM detector performs pattern recognition on time-frequency images. These "sonograms" are calculated per frequency band; different from simple spectrograms, they "blank" the stationary part of pure noise. Thus, these images appear as adaptive filters for the best possible signal-to-noise ratio. The "blanking" is determined by an estimation of spectral background noise, which is given in the upper right corner of Fig. 2. The vertical axis displays *log* frequency as in the sonogram to the left of it, while the horizontal axis represents dynamic range instead of time as in the sonogram. The gray or color scale starts above the noise variance. We can see the increase of low frequency microseisms due to the nearby Gulf of Eilat; the high frequency noise is very low since station EIL is a desert site in the Negev. The horizontal lines mark the maximum amplitude per frequency band, confirming the observation from the seismogram plot. Above 3 Hz, the event is resolved by just four bits. Below 3 Hz, the signal energy is not visible in the sonogram since it is masked by the noise fluctuations. Dedicated CTBT primary stations like ARCES would record the same signal with forty times more resolution, i.e. 9 to 10 bits of the ADC.

The pattern recognition module compares actual events with some ten to twenty predefined patterns and rates its recognition result as {*Clear, Probable, Possible*}. In case any other pattern comes close to the first match, the detector may issue one additional "*2ndGuess*". Over the years, different algorithms for the SONOGRAM detector have evolved. The first uses *generic* patterns that describe just the shape of the energy distribution by {-1,0,+1} coding {*no energy, don't care, signal energy*} (Joswig, 1990). Generic patterns are quite generally applicable and form a default knowledge. However, better results are achieved with *specific* patterns, which are simply the sample sonograms of typical seismicity. The recognition is based on a sophisticated pattern adaptation to the actual, spectral noise conditions and the signal maximum. The calculation of *fits* using 2-D cross correlation compares all patterns with the actual signal, rating (I) the contour of the sonogram and (II) the amplitude distribution (Joswig, 1995). For regional seismograms with a more monochromatic signal content, like that typically observed in Scandinavia, a slightly different correlation scheme emphasizing amplitude ratios over contour once again improves the results (Joswig, 2000). In Fig. 2 the event is recognized by the generic pattern `Far_ooOO` with a correct P onset time despite the high quantization noise. The distance range `Far_` describes patterns with some 8 pixels S-P difference. This converts to an epicentral distance of about 150 km for the actual sample rate. All patterns with extension `_ooOO` describe local events causing prominent surface waves; in the specific geology of Israel this indicates an explosion source.

The detection messages of SONODET running in batch-mode have a common part containing station, component, detection time, duration, and maximum SNR, but they differ in later parts for the STA/LTA and the SONOGRAM detector. The latter also reports on the process of pattern adaptation (percentage of valid pattern, up/down shift of pattern maximum), the pattern fit (normalized to unity), the quality of recognition {*possible, probable, clear* and *2ndGuess*}, the pattern name, and a magnitude estimate (determined by the pattern shift). Fig. 3 displays the detection list of both options for the same set of data from one ARCES station in northern Norway.

Coincidence Evaluation

COASSEIN is a rule-based system for evaluating the single-trace detections (SE's) produced in seismic networks or arrays. For STA/LTA it performs a simple voting on coincidence while for SONODET it tries to choose event identifications that are common at all network stations. This processing is based on a list of possible network events (NE's) constructed by permuting all reported SE's. The rules of Fig. 4 guide the ranking of solutions and help to resolve various types of possible contradictions. The quality of coincidence is characterized by *, **, and *** like a hotel rating. Fig. 5 shows the results for the four-partite subarray ARA1, ARC1, ARC3, ARC6 of ARCES corresponding to the single trace input ARA1 of Fig. 3.

The full set of rules is permanently stored in the program, but it may selectively be enabled or disabled by the user. Also, the order of rule execution may be changed. Both manipulations will influence the final result. A full description of this behavior is given in Joswig (1995). COASSEIN starts with default knowledge that includes rules for associating secondary STA/LTA detections, for suppressing known noise patterns and for performing an increasingly rigorous rule-out scheme to exclude contradicting patterns from a minority of stations. However, better results demand site-specific information which is coded into "cluster exchange" pairs. An example for the ARCES data is given in Fig. 6, e.g. COASSEIN may substitute an initial `Kovdor` identification by the pattern type `Kiruna_II`. This extra knowledge is applied to resolve the most common contradiction in the NEs, which is caused by the typical error of SONOGRAM detection: events from different backazimuths but same distance range or from neighboring source regions have similar signatures and may be confused in the pattern identification.

Comparison with Ground Truth

COAEBULL is a utility program that provides support in the comparison of automated event listings to ground truth given by up to four bulletins and by an editable reference list. COAEBULL is currently linked to the design of SONODET and COASSEIN, i.e., the basis for event comparison is the concept of source regions. The regions must be defined by name and by rectangle as in Fig. 7. Regions may overlap like the well-constrained quarry areas `Kovdor` and `Khibiny` over peninsula `Kola`; in this case a priority factor determines the selected region. The comparison proceeds by constructing *event sets* comprising all list entries within an adjustable time window. An event set may be triggered by a variety of conditions, e.g. one option excludes all teleseisms. The trigger criterion can be linked to a completeness threshold *Mc*(100), specified for a 100 km distance. The correction of *Mc* to other distances resembles the calculation of ML. Once an event set is triggered, entries from all lists are included regardless of magnitude; those below [*Mc*] are marked explicitly by * in the last column of Fig. 8. This helps to distinguish between relevant events and mutually coincident signals with weaker seismogram amplitude. In Fig. 8 eight event sets are shown that correspond to the information of Figs. 3 and 4; mutual coincidence happened in the first and last event set.

The result of bulletin comparison is currently derived from a very simple idea. COAEBULL takes an entry from the event list to be evaluated and looks for the best of any matches in all bulletins that constitute ground truth. This rule mirrors our heuristic assumption that if the questionable entry does show up in any reference bulletin, it will be correct. Eventually it may be necessary to correct some given bulletins to achieve the correct ground truth, as those bulletins can contain errors too. Instead of changing the original bulletins, COAEBULL offers another choice by considering a separate reference list. Any entry here will override all other info - thus the comparison result exclusively depends on the reference list. One may use this feature to correct wrong epicenter coordinates or magnitudes, add events, declare bulletin entries to be false alarms, and ignore them for the statistics. In Fig. 8 the detection at 09:16:57 in the EPX listing of ARCES is considered a false alarm; its "miss" by *SparseNet* must not be counted as an error.

The quality measure for counting the comparison results is based on source regions. This information is immediately reported by SONODET / COASSEIN, or it must be derived from the epicenter coordinates by the scheme of Fig. 7. If an actual epicenter of the evaluated list is within the target source region of ground truth, this counts as *right*. If the actual epicenter falls into a gray zone surrounding the target source region, it is rated *close*. If the actual event has a different backazimuth but its distance is within the limits of the target source region, it counts as *equidistant*. In any other case it is a *wrong* identification. Additional counters take care of *false alarms* and *missed events*; all this information is compiled into a final performance statistics.

Conclusions

SparseNet is a complete software package for automated detection and preliminary location. It implements the standard processing schemes and AI techniques, which may deliver substantially improved results by tuned knowledge bases. *SparseNet* has evolved to Version 2.1 with extended documentation, compiled data sets with ground truth, and tutorials. It is a contribution to the IASPEI shareware library and can be obtained from `ftp://snow.tau.ac.il/pub/joswig/SparseNetV3.0`.

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Literature

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Joswig, M. (2000). Automated event location by seismic arrays and recent methods for enhancement, in *Advances in seismic event location*, eds. C. H. Thurber & N. Rabinowitz, Kluwer, Dordrecht, 205-230.

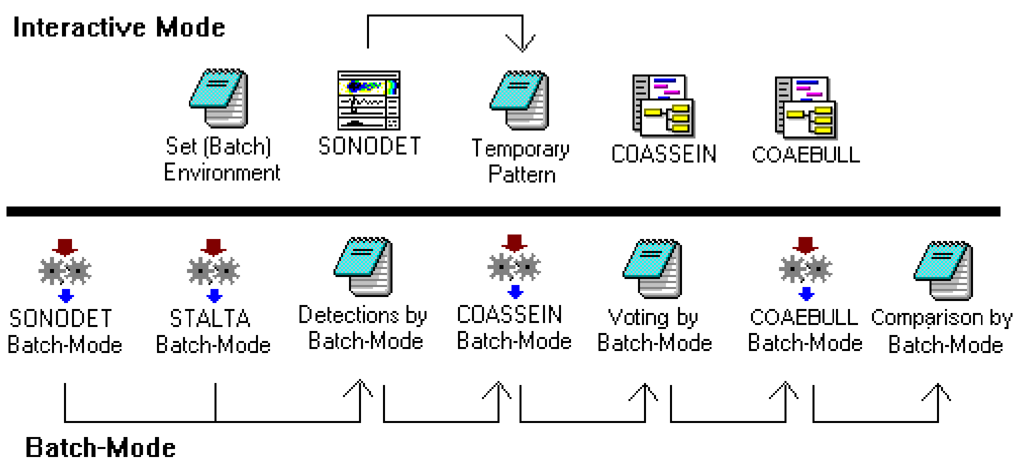


Fig. 1 *SparseNet* Modules for Interactive and Batch Processing

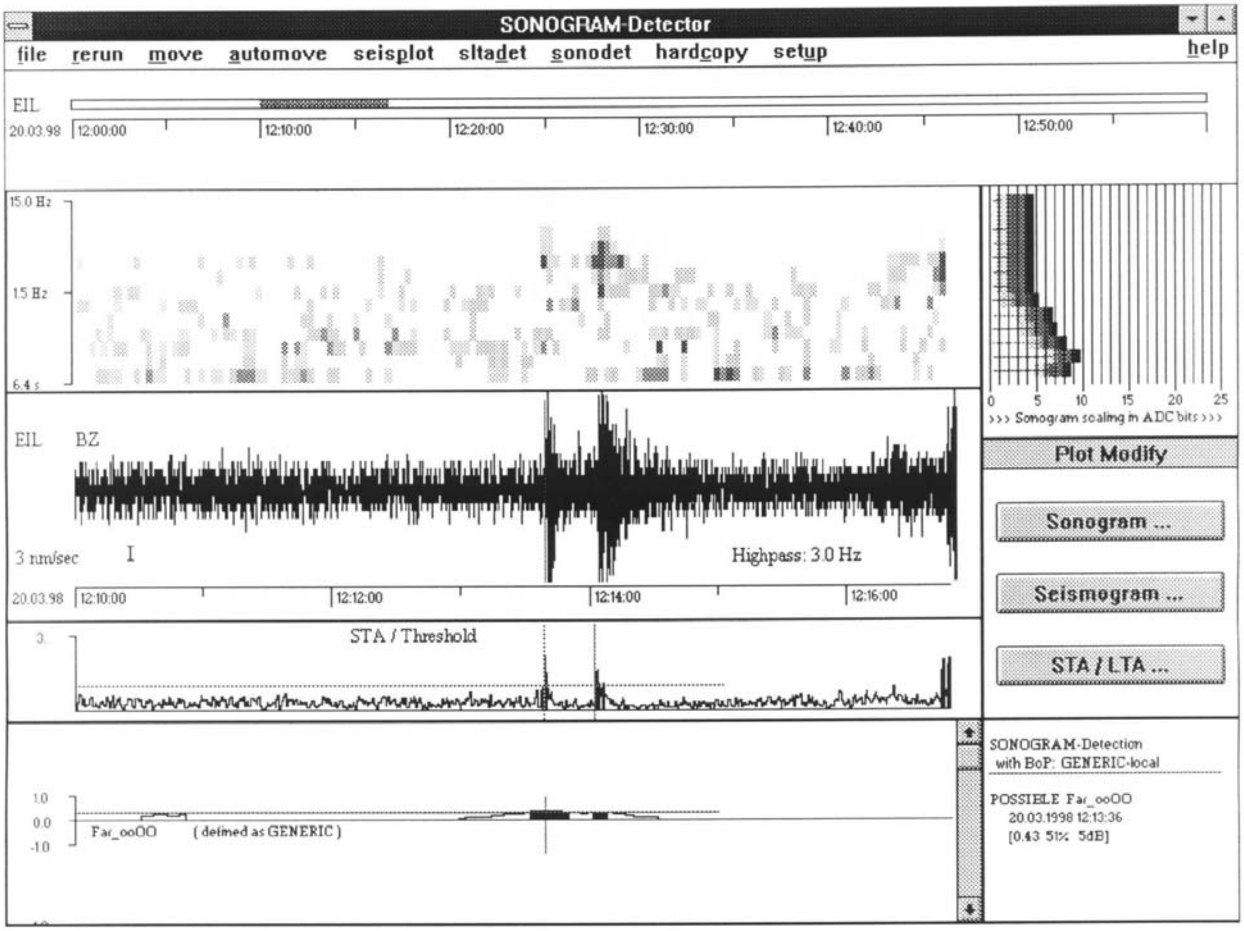


Fig. 2 SONODET Screendump. The weak local event is sampled by 4 bits of ADC but the sonogram well resolves any detectable signal energy in the *f*-*t* plane. In top-right, the plot of noise spectrum with same vertical *f* axis is typical for low-noise BRB stations. The event is timed on P and Lg by the STA/LTA and identified as `Far_ooOO` by the SONOGRAM detector (see text for more details).

```
# Log-File for Batchmode #
#
# ARA1   ------------------------------------------------------------------------------------------
#        -station-  ----onset time-----   dur  snr perc fit shift Mss  quality  type/source region
#        ---------  -------------------  ----  ---- --- ---- --- ----  -------- ------------------
STALTA   ARA1   sz  12.04.1996 08:34:50    3s  50dB
STALTA   ARA1   sz  12.04.1996 08:35:45    7s  10dB
STALTA   ARA1   sz  12.04.1996 09:01:24    6s  21dB
STALTA   ARA1   sz  12.04.1996 09:02:26    4s   8dB
STALTA   ARA1   sz  12.04.1996 09:08:33    5s  15dB
STALTA   ARA1   sz  12.04.1996 09:09:07    8s  24dB
STALTA   ARA1   sz  12.04.1996 09:30:34    4s   3dB
STALTA   ARA1   sz  12.04.1996 09:51:21    3s  16dB
STALTA   ARA1   sz  12.04.1996 09:56:59   10s  16dB
```

Fig. 3a SONODET Batch Output: STA/LTA

```
# Log-File for Batchmode #
#
# ARA1   ------------------------------------------------------------------------------------------
#        -station-  ----onset time-----   dur  snr perc fit shift Mss  quality  type/source region
#        ---------  -------------------  ----  ---- --- ---- --- ----  -------- ------------------
SONODET  ARA1   sz  12.04.1996 08:34:47   81s  19dB 99% 0.93  00  2.2  CLEAR    Khibiny_II
SONODET  ARA1   sz  12.04.1996 09:01:22  111s   3dB 78% 0.83 -01  1.8  PROBABLE Kostomuksha
SONODET  ARA1   sz  12.04.1996 09:01:22  120s   3dB 97% 0.82  01  2.2  2ndGUESS Norwegian_Sea_II
SONODET  ARA1   sz  12.04.1996 09:08:31   57s   5dB 97% 0.91  00  1.7  PROBABLE Murmansk
SONODET  ARA1   sz  12.04.1996 09:08:28   63s   5dB 90% 0.85  00  1.6  2ndGUESS Kiruna_II
SONODET  ARA1   sz  12.04.1996 09:11:07   45s   2dB 75% 0.73 -99 -9.9  PROBABLE Noise_Car
SONODET  ARA1   sz  12.04.1996 09:56:53   30s   9dB 96% 0.79  00 -9.9  PROBABLE Teleseism_emergent
```

Fig. 3b SONODET Batch Output: Sonogram detector

```
----1/0-----type--------actual ruleset in order of execution----------------
A:  (1)   Create_o         create original NE's
B:  (1)   Create_m         create modified NE's
C:  (1)   Selection    *** pattern matching for NE
D:  (1)   Selection     ** pattern matching for NE
E:  (1)   Selection      * pattern matching for NE
I:  (1)   Selection    --- coincidence of 3+ noise burst SE's
J:  (1)   Selection     -- coincidence of 2+ noise burst SE's
K:  (1)   Selection      - ignore (multiple) SE's from single station
P:  (1)   Resolution       ignore contradicting noise burst SE
O:  (1)   Resolution       cluster exchange gives new SE's
Q:  (1)   Resolution       rule-out contradicting   SE  : 4+ modified SE's
R:  (1)   Resolution       rule-out contradicting n SE's: 4+ original SE's
S:  (1)   Resolution       rule-out contradicting   SE  : 3  modified SE's
T:  (1)   Resolution       rule-out contradicting n SE's: 3  original SE's
U:  (1)   Resolution       rule-out contradicting   SE  : 2  original SE's
F:  (1)   Selection    +++ time coincidence 4+ of N stations
G:  (1)   Selection     ++ time coincidence 3  of N stations
H:  (0)   Selection      + time coincidence 2  of N stations
X:  (0)   Evaluation       reevaluate initial pattern match
Y:  (1)   Evaluation       reevaluate voting for 2nd phase
Z:  (1)   DEFAULT          no solution found in rule base
```

Fig. 4 COASSEIN Rule Set (see text for details)

```
# Start of Batch processing ####
#
#----onset time----   Mss qual type/source region
#-----------------   ---  --- ------------------
12.04.1996 08:34:50  -9.9  +++ VOTING
12.04.1996 08:35:34  -9.9    + VOTING 2nd Phase
>
12.04.1996 09:01:24  -9.9  +++ VOTING
12.04.1996 09:02:26  -9.9   ++ VOTING 2nd Phase
>
12.04.1996 09:08:33  -9.9  +++ VOTING
12.04.1996 09:09:08  -9.9  +++ VOTING 2nd Phase
>
12.04.1996 09:56:59  -9.9  +++ VOTING
```

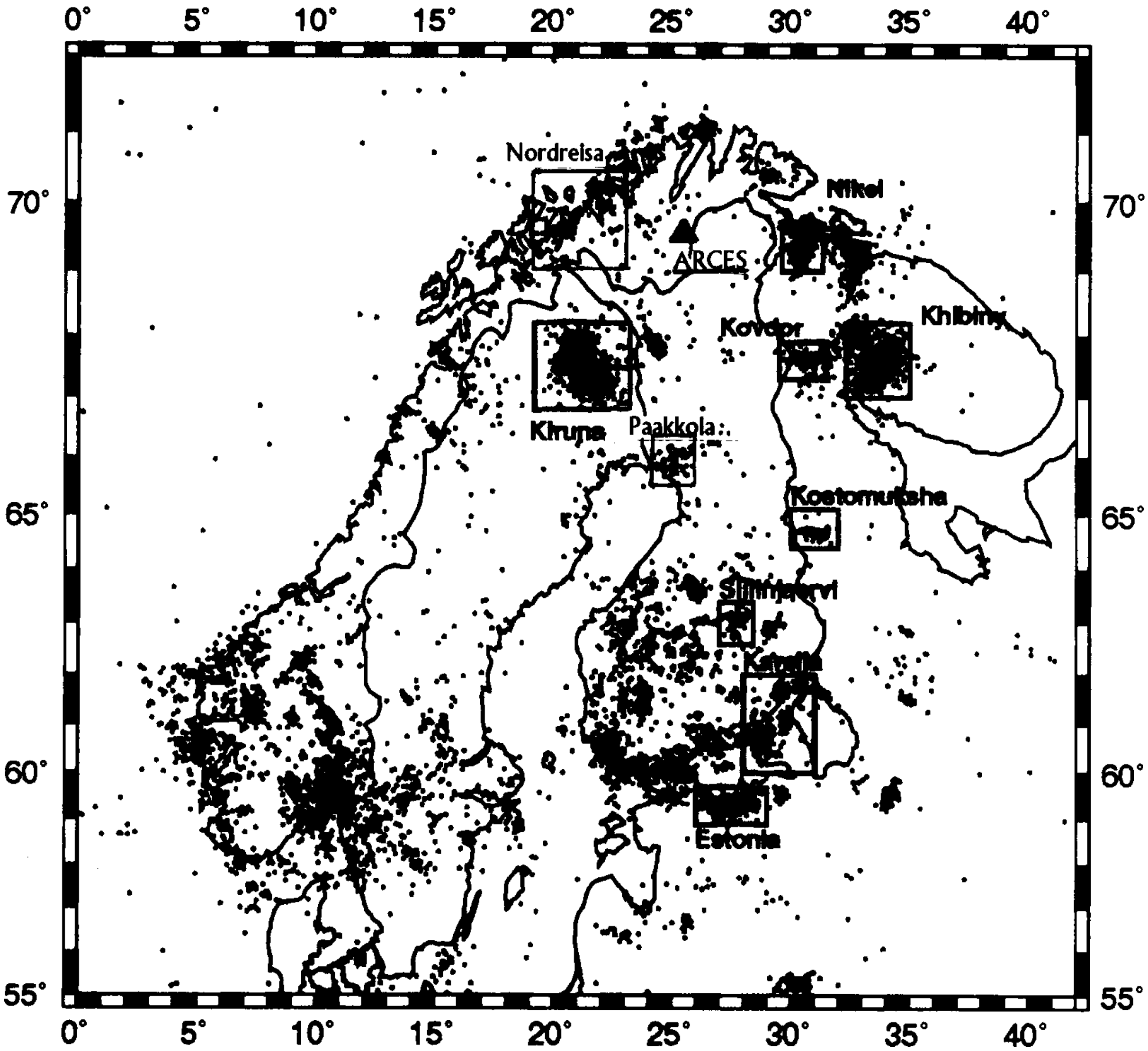
Fig. 5a COASSEIN Batch Output: STA/LTA & Voting

```
# Start of Batch processing ####
#
#----onset time----   Mss qual type/source region
#-----------------   ---  --- ------------------
12.04.1996 08:34:47   2.2  *** Khibiny_II
12.04.1996 09:01:22   1.8  *** Kostomuksha
12.04.1996 09:08:30   1.6  *** Murmansk
12.04.1996 09:56:53  -9.9  *** Teleseism_emergent
```

Fig. 5b COASSEIN Batch Output: Sonogram detector & Rules

```
# Cluster exchange pairs with correction factors for time and magnitude
#  applied to any specific station (* = all) below Mthres (-9.9 = disable)
#
#         type/source region -> type/source region  td    md  station  Mthres
EXCHANGE  Kiruna_I              Kiruna_II           -5   0.0     *      -9.9
EXCHANGE  Kiruna_II             Kiruna_I            +5   0.0     *      -9.9
EXCHANGE  Kovdor                Kiruna_II           +5   0.4     *       3.0
#
EXCHANGE  Khibiny_I             Khibiny_II           0   0.0     *      -9.9
EXCHANGE  Khibiny_II            Khibiny_I            0   0.0     *      -9.9
EXCHANGE  Norwegian_Sea_I       Khibiny_II           0  -0.7     *       3.0
#
EXCHANGE  Paakkola              Noise_assume         0   0.0     *       0.8
EXCHANGE  Nordreisa             Noise_assume         0   0.0     *       0.6
#
EXCHANGE  Teleseism_impulsiv    Teleseism_emergent   0  -9.9     *      -9.9
EXCHANGE  Teleseism_emergent    Teleseism_impulsiv   0  -9.9     *      -9.9
```

Fig. 6 COASSEIN Cluster Exchange Pairs (see text for details)




```
# Evaluation is based on regions instead of simple distance measure. They are
#     defined by Region Qualifiers (RQ). Any event within Box [LATs,n LONw,e]
#     belongs to that Region. When boxes overlap, Priority decides.
#    For inverse association of PR detections, (LATc,LONc) describes the
#     typical epicenter. when converting a source region back to coordinates
#    Grayzone [km] is the upper limit for a CLOSE hit instead of full match,
#     the nominal value is 0.6 times the box extension in NS or EW.
#
#        NAME                LAT  -  LAT    LON  -  LON   LATc   LONc   GZ  Pri
REGION   Kiruna              66.8   68.2    19.2   23.2   67.2   21.2  100    1
REGION   Kovdor              67.3   67.9    30.5   31.5   67.6   31.0  100    1
REGION   Khibiny             67.0   68.3    32.2   35.0   67.6   33.6  100    1
REGION   Nikel               68.9   69.7    29.5   31.2   69.3   30.3  100    1
REGION   Murmansk            68.5   69.7    31.2   33.5   69.2   32.3  100    1
#
REGION   Kola                66.0   70.0    30.0   42.0   68.5   32.0  100    2
REGION   North-Finland       64.0   69.0    23.0   30.0   66.5   26.5  100    2
REGION   South-Finland       60.0   64.0    20.0   30.0   62.3   27.0  100    2
REGION   West-Russia         60.0   66.0    30.0   42.0   60.5   36.0  150    2
REGION   West-Russia         55.0   60.0    28.0   42.0   60.5   36.0  150    2
#
REGION   Barents_Sea         70.0   76.0    20.0   50.0   73.0   40.0  200    3
REGION   European_Russia     50.0   70.0    30.0   60.0   60.0   45.0  200    3
```

Fig. 7 COAEBULL Source Regions by Map and Table

```
         +----RESULTS legend:   *  right     c  close     s  same_dist  -  wrong_ident---+
         |                      .  no_event  d  detected  m  missed     f  false_alarm   |
         |                      i  ignored   r  rejected  @  overwritten_by_reference    |
         +-------------------------------------------------------------------------------+---+
                                                                                             |
t_onset    ARCES-EPX       NORSAR-GBF      IDC-REB         Helsinki        SparseNet         |
           ignored ------> considered ---> considered ---> considered ---> evaluated ---> RESULTS

12.04.1996==========================================================================================
08:34:47   Kola            Khibiny         Khibiny         Estonia         Khibiny        i***=*
              .            Estonia            .            Khibiny            .
------------------------t_origin--t_onset----dist----lat----lon---------------------Mag--Mthres
ARCES-EPX    12.04.1996  08:34:07  08:34:49    305    68.05  31.90  Kola                2.2  [ 0.8]
NORSAR-GBF   12.04.1996  08:33:59  08:34:53    384    67.75  33.65  Khibiny             2.2  [ 1.0]
NORSAR-GBF   12.04.1996  08:33:06  08:35:23   1097    59.69  27.17  Estonia             1.5 *[ 2.3]
IDC-REB      12.04.1996  08:33:55  08:34:48    376    67.55  33.02  Khibiny             3.4  [ 1.6]
Helsinki     12.04.1996  08:32:57  08:35:19   1141    59.31  27.74  Estonia             1.9 *[ 2.6]
Helsinki     12.04.1996  08:33:53  08:34:50    405    67.63  34.05  Khibiny             3.0  [ 1.4]
SparseNet    12.04.1996  08:33:52  08:34:47    392    67.60  33.60  Khibiny             2.2  [ 1.1]
12.04.1996==========================================================================================
09:01:22   North-Finland   West-Russia     Kostomuksha     Kostomuksha     Kostomuksha    ic**=*
------------------------t_origin--t_onset----dist----lat----lon---------------------Mag--Mthres
ARCES-EPX    12.04.1996  09:00:24  09:01:23    419    66.07  29.45  North-Finland       1.1  [ 1.1]
NORSAR-GBF   12.04.1996  09:00:12  09:01:24    528    65.15  30.29  West-Russia         2.0  [ 1.4]
IDC-REB      12.04.1996  09:00:05  09:01:23    576    64.77  30.78  Kostomuksha         2.6  [ 2.1]
Helsinki     12.04.1996  09:00:04  09:01:23    581    64.72  30.78  Kostomuksha         2.1  [ 1.8]
SparseNet    12.04.1996  09:00:02  09:01:22    587    64.70  31.00  Kostomuksha         1.8  [ 1.5]
12.04.1996==========================================================================================
09:08:30   Murmansk        Murmansk           .               .            Murmansk       i*..=*
------------------------t_origin--t_onset----dist----lat----lon---------------------Mag--Mthres
ARCES-EPX    12.04.1996  09:07:49  09:08:32    286    68.99  32.62  Murmansk            1.7  [ 0.7]
NORSAR-GBF   12.04.1996  09:07:47  09:08:31    293    69.05  32.86  Murmansk            1.5  [ 0.7]
SparseNet    12.04.1996  09:07:50  09:08:30    268    69.20  32.30  Murmansk            1.6  [ 0.6]
12.04.1996==========================================================================================
09:16:57   Barents_Sea        .               .               .               .          @rrrr= r
------------------------t_origin--t_onset----dist----lat----lon---------------------Mag--Mthres
ARCES-EPX    12.04.1996  09:15:36  09:16:57    610    74.96  28.12  Barents_Sea         1.8  [ 1.6]
@reference   12.04.1996            09:16:57                         <False Alarm>
12.04.1996==========================================================================================
09:29:23   Khibiny         Khibiny            .               .               .           im..= m
------------------------t_origin--t_onset----dist----lat----lon---------------------Mag--Mthres
ARCES-EPX    12.04.1996  09:28:22  09:29:23    452    67.10  34.35  Khibiny             1.5  [ 1.2]
NORSAR-GBF   12.04.1996  09:28:38  09:29:36    412    67.75  34.44  Khibiny             1.3  [ 1.1]
12.04.1996==========================================================================================
09:56:53      .            South-Finland      .            South-Finland   Teleseism     @iiii=ii
------------------------t_origin--t_onset----dist----lat----lon---------------------Mag--Mthres
NORSAR-GBF   12.04.1996  09:54:34  09:56:14    757    62.79  23.14  South-Finland       1.6 *[ 1.8]
Helsinki     12.04.1996  09:54:32  09:56:13    758    62.80  22.90  South-Finland       1.9 *[ 2.1]
SparseNet    12.04.1996            09:56:53  3000+                  Teleseism
@reference   12.04.1996            09:56:53  3000+                  Teleseism           0.0  [-0.5]
```

Fig. 8 COAEBULL Batch Output