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7.4 Multichannel statistical data processing algorithms in the framework of the NORSAR event processing program package

The NORSAR interactive data processing package was developed for the analysis of small aperture seismic array observations. This package, called the Event Processor (EP), has turned out to be a very convenient tool for the daily production of a seismic bulletin. The small aperture seismic arrays NORESS, ARCESS, FINESA and GERESS and their associated data processing facilities are constructed for automatic recording, location and classification of low magnitude regional events and medium magnitude teleseismic events. Signal detection is performed in an online mode, whereas parameter estimation can be performed as an offline procedure using recorded multichannel seismic wavetrains. Now, at NORSAR the automatic system is in full operation, providing seismic signal detection as well as signal parameter estimation. These parameters are: onset time, azimuth, apparent velocity, dominant frequency, signal-to-noise ratio and so on.

This automatic system is operated at a low threshold and inevitably produces numerous "false alarms", i.e., "events" caused by noise bursts. The current seismic bulletin is issued after an interpretation of the detection list, which may be effectively performed using the interactive Event Processing (EP) package. The EP program has a number of graphic routines and interfaces for work with NORSAR data bases. It also comprises some sophisticated and rather time-consuming data processing programs which at present cannot be used in automatic or online processing modes, i.e., without human control. In particular, adaptive statistical multichannel data processing programs have been installed recently in the framework of the EP package. These programs are based on optimal methods of multidimensional time series analysis described in Kushnir *et al* (1983), Kushnir and Lapshin (1984), Pisarenko *et al* (1987) and Kushnir *et al* (1990a, 1990b). They comprise the following procedures of seismic array data processing:

1. Selection of the array instruments and data time interval to be processed.
2. Filtering and resampling of the data.
3. Time-shifting of the channel waveforms with delays corresponding to a given azimuth and apparent velocity of a plane wave propagating across the array.
4. Summing of shifted waveforms, i.e., beamforming for a given azimuth and apparent velocity.
5. Whitening of the background noise by adaptive filtering of the beam output. This procedure provides signal-to-noise ratio (SNR) gain due

to differences in signal and noise frequency contents, but it distorts the signal waveform.

6. Adaptive optimal group filtering (multichannel Wiener filtering) of the array seismograms. This procedure permits high suppression of seismic noise due to its coherency. Theoretically it provides maximum SNR gain without any distortion of seismic signal waveform or frequency contents.

7. Adaptive detection of the distinct phases in single channel seismograms or in the output traces of beamforming and optimal group filtering procedures. The detection procedure takes into account the difference between noise on one hand, and signal plus noise on the other, not only in amplitude values but also in power spectra.

8. Seismic wave onset time estimation by detection of the moment in time when the wavetrain statistical features are abruptly changed.

Array data processing using the procedures listed above is accomplished in the framework of the EP system with the aid of a specially developed set of commands. The major commands are named GRFADAPT, GRFFILT, ESTDET, ESTON1, ESTON3. Description of these commands and examples of performance are given below.

GRFADAPT and GRFFILT commands

The procedures 1–6 are carried out sequentially by each of two EP system commands: GRFADAPT and GRFFILT. The GRFADAPT command, unlike the GRFFILT command, contains additional adaptation algorithms which have not been listed above. These algorithms are used before the execution of procedures 5 and 7 and accomplish adaptation to the current noise of the beam whitening filter and the optimal group filter. During GRFADAPT command execution, the processed data are regarded as "pure" seismic noise and the autoregressive (AR) model of the beam noise time series and the multidimensional AR model of the array noise time series are estimated. Based on these models, the whitening and optimal group filter coefficients are evaluated. They are stored and used later during GRFFILT command execution.

GRFADAPT and GRFFILT command execution produces seven output traces. The first four of them are the main resulting traces and the last three — auxiliary traces — are needed to check the adaptation quality. These seven output traces are placed on top of the EP system data stack (containing all input and output time series during the data processing). The main traces are:

1. Beam waveform composed of filtered and resampled channel traces for a given azimuth and apparent velocity (OGF beam),

2. Whitened beam waveform (OGF Wbeam),

3. Optimal group filter waveform calculated using filtered and resampled channel traces as input for a given azimuth and apparent velocity (OGF t-un),

4. Whitened optimal group filter waveform (OGF th-w).

The GRFADAPT and GRFFILT procedures also calculate the mean values and variances of the listed output traces and of the input channel traces. The important result of these calculations is the value of the ratios of the adapative optimal group filter (AOGF) output variance to the beam waveform variance and AOGF output variance to the averaged channel trace variance. After GRFADAPT command execution the first ratio characterizes the relative noise suppression by beamforming and optimal group filtering. Due to the signal undistorting feature of these procedures (provided a plane seismic signal wave is arriving with the given azimuth and apparent velocity), this ratio also characterizes the relative SNR gain due to beamforming and the AOG filtering.

Using the GRFADAPT and GRFFILT commands, a report file is created containing the input and output numerical parameter values and description of the processed channel traces. Particularly, this report contains the value of AOGF and the beamforming SNR gain ratio. An example of such a report is shown in Fig. 7.4.1.

The format of the GRFADAPT command is given below:

```
grfadapt vel [apparent velocity, km/sec] azi [azimuth, degrees]
{filter type} [cutoff frequencies, Hz] factor [resampling factor]
```

where {filter type} is one of the three character strings: lp, bp, hp, which means low-pass, band-pass and high-pass filter types.

Before the GRFADAPT command is initiated, values of the associated parameters have to be assigned. There are additional numerical parameters which are not specified with the command, and which have the following default vaules:

1. Filter frequency response decay factor: ALPHA = 10^{-4},

2. Filter impulse response one-side length: IRL = 15;

3. Order of beam noise AR model (number of beam-whitening filter coefficients): DARB = 10,

4. Number of input array data matrix autocovariance coefficients: LCRC = 6,

5. Regularizator of matrix autocovariance function: REG = 10^{-6},
6. Order of input array data multidimensional AR model (one-side length of the optimal group filter): DARGRF = 6,
7. Auxiliary parameters: DARARF = 10, DMARF = 20.

Assigning of alternative values for the parameters listed above can be done by the

EP command:

```
gr [parameter name] [parameter value]
```

To check the current parameter setting before GRFADAPT and GRFFILT command execution, one should use the EP command:

```
q gr
```

There is no need to enter any parameter values before the GRFFILT command execution. The computations are carried out with numerical parameter values and whitening and optimal group filter coefficients stored during the previous GRFADAPT command exeuction.

The numerical results of the GRFADAPT command execution are written to the disk file GRFREPORT.OUTPUT by the command:

```
grfreport
```

The purpose of the array data processing using the GRFADAPT and GRFFILT procedures is to compute the adaptive, statistically optimal beam which suppresses coherent and incoherent array noise, thus providing the maximum SNR gain without distortion of the signal waveform. These procedures are especially efficient in the case when the signal and coherent noise power spectra are overlapping. In this case they can provide much higher SNR gain than bandpass filtering after conventional beamforming.

For this reason, in the first experiments with the GRFADAPT and GRFFILT procedures in the framework of the EP system, we tried to learn how the program parameter values influence the AOGF SNR gain relative to conventional beamforming SNR gain, when data are processed in a broad frequency band. The main program parameters which influence the quality of the optimal group filter adaptation are 1) the order of the input data multidimensional

AR model, 2) the data frequency band and 3) regularizator of the data matrix covariance function. Table 7.4.1 comprises the results of NORESS noise processing. The 120 sec interval of array noise shown in Fig. 7.4.2 has been used for optimal group filter adaptation.

As one can see from this table, increasing the input data multidimensional AR model order leads to a strong increase of AOGF SNR gain. Nevertheless, it does not seem worthwhile to use a multidimensional AR model order greater than 10–12 because the adaptation procedure becomes time consuming and less stable (especially when a large number of array channels are used). Choosing a higher frequency band leads to diminishing of AOGF SNR gain. This can be explained by the strong coherency of the NORESS noise mainly at low frequencies. Varying the regularizator value from 0 to 10^{-4} practically does not affect the AOGF SNR gain.

The GRFADAPT and GRFFILT commands were also tested by processing some low magnitude local event records from the NORESS, ARCESS and FINESA arrays. In these experiments the optimal group and whitening filter adaptations were made using the array noise records preceding the seismic signal wavetrains. The duration of the noise time intervals used for adaptation were from 100 to 150 sec. The main purpose of these experiments was to learn about possible differences in P, S and Lg wave phase extraction by different array data processing algorithms such as conventional beamforming, beam output noise whitening, adaptive optimal group filtering and AOGF output noise whitening. What distinguishes these experiments from those described in our previous reports (Kushnir *et al*, 1990a; Kushnir *et al*, 1990b) is the processing of array data in different frequency bands: 0.2–5 Hz, 0.2–10 Hz, and 0.2–20 Hz. Table 7.4.2 comprises the ratios of AOGF output SNR relative to beamforming output SNR and AOGF output SNR relative to averaged channel SNR for different phases being extracted from 7 small local event records. Each phase has been extracted from the noise by the conventional beam and AOGF adjusted for the azimuth and apparent velocity of this phase arrival as given in the NORSAR detection list. One can see that in these experiments the AOGF SNR gain relative to the conventional beamforming gain was betwen 16.2 and 24.5 dB for the 0.2–5 Hz frequency band, between 12.3 and 24.2 dB for the 0.2–10 Hz frequency band and around 10–11 dB for the 0.2–20 Hz frequency band. Note that the highest AOGF SNR gain of more than 24 dB was achieved on the FINESA records. This is due to the presence in these records of strong, highly coherent, low frequency background noise possibly caused by stormy seashore waves. This noise has been suppressed by the AOGF procedure, but not by conventional beamforming.

Examples of GRFADAPT and GRFFILT output traces as the result of event wavetrain and preceding noise processing are given in Figs. 7.4.3–7.4.5. In some of these examples, the AOGF and whitened beam output wavetrains are similar. One may conclude that the adaptive whitening procedure after conventional beamforming can provide the same results as the AOGF procedure (while being less time consuming). But this inference is true only for body waves of local low magnitude events, which as a rule have high frequency contents. Power spectra of surface waves and teleseismic body waves are often overlapping with those of coherent seismic noise. In this case, the AOGF procedure has a strong advantage over other filtering procedures since it retains the signal undistorted.

ESTDET command

Adaptive detection of distinct phases in the wavetrain is accomplished by the EP command ESTDET. This procedure is based on the optimal statistical algorithm described in Pisarenko *et al* (1987). During the ESTDET command execution the time interval of the data being processed is divided into two parts. The data in the first interval are regarded as "pure" noise and its AR model is estimated ("noise AR model"). The data in the second interval are presumed to contain the seismic phases. The detection of these phases is carried out using a moving time window. The detection algorithm consists of calculation of the simplified Bayesian test statistic for the hypothesis: a) the AR model of time series inside the moving time window is the same as the noise AR model versus the hypothesis: b) these two models are different (Kushnir *et al*, 1983). The ESTDET program takes as input the wavetrain at the top of the EP system data stack and produces nine new traces which in turn are placed on the top of this data stack. Eight of these traces contain the values versus time of the detection statistics calculated using data in a moving time window. These statistics are derived from four slightly different versions of the simplified Bayesian test described above. The first four traces are the statistical values in logarithmic scale, the next four are the same values in linear scale. The ninth output trace is the auxiliary trace for noise AR modelling checking. The detection triggering of the seismic phases is now performed in an interactive mode by comparing the detection statistic value with the threshold chosen to provide the acceptable false alarm rate. But it would clearly be straightforward to develop a special EP command for automatic phase detection triggering.

The ESTDET command format is

```
estdet start [first point, sec.] end [last point, sec.]
w [window length, sec.] o [AR model order] noise
[noise interval length, sec.]
```

where "start" and "end" are the first and last points of the trace being processed (in sec. relative to the initial point of this trace); "w" is the width of the moving time window, "noise" is the length of the first part of the data time interval used for the noise AR model estimation.

Examples of ESTDET command output traces and input wavetrains are given in Figs. 7.4.6–7.4.8.

ESTON1 and ESTON3 commands

The moving window detection procedure points out those time intervals where seismic wave phases are present. The next stage of the signal processing is an estimation of phase parameters. Among the most important parameters needed for event source location are the wave phase onset times. For rough estimates of these times, the moments of detection triggering may be used. But for precise estimation of each phase onset time, special statistical procedures have been developed (Pisarenko *et al*, 1987). In the framework of the EP system, this procedure is realized as two commands: ESTON1 and ESTON3. The first command is intended for single component trace processing. This may be the beam or AOGF output trace or a "raw" array single channel wavetrain. The second command is intended for 3-component seismogram processing with the purpose of onset time estimation. Both procedures are based on maximum likelihood algorithms for estimation of the moment in time when the time series AR model parameter values abruptly change. The ESTON1 procedure takes into account changing of the time series variance and frequency contents at the moment in time when the seismic phase arrives. The ESTON3 procedure also takes into account changs in the 3-dimensional time series polarization features at this moment.

Both commands use the traces at the top of the EP system data stack as input: ESTON1 takes the upper trace, ESTON3 — the three upper traces. Both commands produce one output trace containing the onset time likelihood function calculated for data inside a given time interval. After command execution, this trace is placed on the top of the EP data stack.

The ESTON1 and ESTON3 command format is:

```
eston1(3) start [first point, sec.] end [last point, sec.]
w [min. window length] o [AR model order]
```

where "start" and "end" are the first and last points of the wavetrain being processed (in sec. relative to the initial point of the trace); "w" is the minimum width of the data window for the AR model estimation. The onset time likelihood function is calculated for the data inside the time interval (start + w, end - w) (in sec. relative to the trace initial point).

Examples of ESTON1 output traces for different types of seismic wave phases are given in Figs. 7.4.9–7.4.11. The onset time values given in these figures as the arguments of the likelihood function absolute maximums coincide very well with the results of visual interactive analysis using the EP system's graphic options.

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Frequency Band (Hz)	Order of Multidimensional AR Model 6	8	12
0.2 – 5	16.7 (20.3)	17.9 (21.5)	18.8 (22.4)
0.2 – 10	13.2 (16.8)	—	16.5 (20.2)
0.2 – 20	—	—	14.0 (17.5)

Frequency Band (Hz)	Regularizator Value 0	10^{-6}	10^{-5}	10^{-4}
0.2 – 5	18.9 (22.5)	18.8 (22.4)	18.7 (22.3)	—
0.2 – 10	—	16.5 (20.2)	—	—
0.2 – 20	—	14.0 (17.5)	—	14.2 (17.6)

Table 7.4.1. Adaptive optimal group filtering SNR gain relative to beamforming for different values of the GRFADAPT procedure main parameters. Gain values are given in dB, values in brackets are AOGF SNR gains relative to average single array channel. The results are based upon using 120 sec NORESS noise recordings shown in Fig. 7.4.2. The results of the upper table are obtained with a regularizator value of 10^{-6}, whereas an AR model order of 12 has been used for obtaining the results in the lower table.

Event Origin Time	Array, Distance (km)	Phase (AR Model Order)	Gain Relative to Beam (dB)	Gain Relative to Single Chan. (dB)	Frequency Band (Hz)
298:17.51.50	ARCESS 508.4	P (12)	16.2	18.8	0.2–5
282:12.04.13	FINESA 287.9	P (12)	21.7	23.3	0.2–5
		P (12)	19.3	21.0	0.2–10
		S (12)	19.6	21.6	0.2–5
		S (12)	17.2	19.3	0.2–10
		Lg (12)	17.3	19.4	0.2–10
294:09.13.00	FINESA 772.3	P (12)	23.6	25.7	0.2–5
		S (12)	21.0	23.7	0.2–5
		Lg (12)	20.3	23.1	0.2–5
	NORESS 1302.7	P (12)	18.8	22.9	0.2–5
		S (12)	16.6	21.1	0.2–5
		Lg (12)	16.5	21.3	0.2–5
28:09.38.09	NORESS 1219.0	P (6)	16.0	19.6	0.2–5
		P (6)	12.3	16.1	0.2–10
		P (6)	10.1	13.8	0.2–20
		P (8)	10.9	14.6	0.2–20
	FINESA 1771.0	P (12)	23.1	24.3	0.2–5

Table 7.4.2. SNR gains of adaptive optimal group filtering relative to beamforming based on processing of local event phases.

Event Origin Time	Array Distance (km)	Phase (AR Model Order)	Gain Relative to Beam (dB)	Gain Relative to Single Chan. (dB)	Frequency Band (Hz)
292:12.31.45	FINESA 164.4	P (6)	14.6	17.6	0.2–1
		P (12)	16.3	19.4	0.2–10
	ARCESS 390.4	P (12)	16.4	20.8	0.2–10
294:19.32.03	FINESA 259.0	P (12)	24.5	26.0	0.2–10
	NORESS 564.6	P (12)	17.9	21.8	0.2–5
		S (12)	16.0	19.8	0.2–5
		Lg (12)	15.7	20.0	0.2–5

Table 7.4.2. cont.

```
Output from GRFADAPT:                    (P_n- phase, 0.2-5. Hz)

Start time: 1990-282:12.02.50.0   Seconds:  120.00 (Data time interval)

Input rarmeters:

Filter type:-1         (low pass(lp)=-1,band pass(bp)=0,high pass(hp)=1)
FCH         : 5.25     (lp,hp-filters cut frequency, hz)
FLH         : 20.00    (up-filter low cut frequency, hz)
FHH         : 20.00    (up-filter-high cut frequency, hz)
IRL         : 15       (one-side length of the filter impulse response)
ALPHA       : 0.00010  (decay factor of the filter frequency response)
AZIMUTH     : 153.80   (azimuth of the seismic phase to be extracted)
VELOCITY    : 7.80     (apparent velocity of this seismic phase)
DARB        : 10       (order of a beam noise AR-model)
LCRC        : 6        (number of autocovariance matrises)
REG         : 0.000001(regularizator value)
DARGRF      : 6        (order of the data multidimensional AR-model)
DARARF      : 10       (auxiliary parameter)
DMARF       : 20       (auxiliary parameter)
K           : 4        (resampling factor)

Output parameters:

NP          :  1193    (number of the data samples being processed)

AVCHPOW     :  0.1380 (averaged dispersion of the channel traces)
BMEAN       :  0.0000 (mean value of the beam trace, m)
BPOW        :  0.0946 (dispersion of the beam trace, σ^2 )
IERLBLD     :  0      ⎫
IERMLD      :  0      ⎬ (computation errors, error=1, otherwise=0)
IERGLD      :  0      ⎭
GRTUN (M/P):   0.0003   0.0006 (m and σ^2 of the AOGF output trace)
GRTW  (M/P):   0.0098   1.0128 (m and σ^2 of the whitened output trace)
GRAUN (M/P):   0.0000   0.0007 (m and σ^2 of the auxiliary output trace)
GRMUN (M/P):   0.0006   0.0006 (m and σ^2 of the auxiliary output trace)
Gain (avch):   214.33   23.311 (AOGF SNR gain relative averaged channel)
Gain (beam);   146.95   21.672 (AOGF SNR gain relative beam, times, db )
```

(Description of the array data being processed)

Channel	X(E-W)	X(N-S)	ELEV	TDEL	CHMEAN	CHPOW
FIN_A0_sz	-180.0	-85.0	138.0	0.211	-0.0070	0.1287
FIN_A1_sz	0.0	0.0	138.0	0.211	-0.0181	0.1421
FIN_A2_sz	-308.0	-353.0	162.0	0.262	-0.0085	0.1308
FIN_B1_sz	275.0	-37.0	165.0	0.252	-0.0074	0.1264
FIN_B2_sz	121.0	-599.0	159.0	0.371	-0.0053	0.1280
FIN_B3_sz	-474.0	-555.0	176.0	0.292	0.0071	0.1258
FIN_B4_sz	-764.0	-85.0	158.0	0.143	-0.0167	0.1171
FIN_B5_sz	-436.0	257.0	143.0	0.098	0.0206	0.0913
FIN_B6_sz	83.0	277.0	147.0	0.153	-0.0255	0.1501
FIN_C1_sz	-1064.0	-657.0	158.0	0.248	-0.0223	0.1398
FIN_C2_sz	-1110.0	226.0	138.0	0.027	-0.0460	0.1368
FIN_C3_sz	-162.0	788.0	138.0	0.000	-0.0100	0.1507
FIN_C4_sz	629.0	420.0	138.0	0.182	-0.0373	0.1256
FIN_C5_sz	653.0	-518.0	138.0	0.413	-0.0160	0.1374
FIN_C6_sz	-185.0	-1108.0	138.0	0.460	-0.0329	0.2375

Fig. 7.4.1. Example of a GRFREPORT.OUTPUT file.