The Research Council of Norway (NFR)

NORSAR

NORSAR Scientific Report No. 1-93/94

Semiannual Technical Summary

1 April — 30 September 1993

Kjeller, November 1993

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

7.6 Generalized Beamforming as a tool in IDC processing of large earthquake sequences

Introduction

Generalized Beamforming (Ringdal and Kværna, 1989) is a technique for joint processing of time-aligned waveforms from a seismic network. The time-alignment is made for a grid of beampoints, and the density and spatial coverage of the beam deployment can be set without any restrictions.

The Generalized Beamforming (GBF) method has been applied successfully for phase association and event location, both at regional distances (Ringdal and Kværna, 1989; Kværna, 1990, 1992a) and in a teleseismic context (Taylor and Leonard, 1992; Kværna, 1992b). In this paper we investigate the potential of the GBF technique in achieving a rapid, preliminary association of phases for a large aftershock sequence. As is well known, such sequences are often problematic to process using conventional phase association techniques since there are so many individual phase detections that the number of possible combinations becomes very large.

The W. Caucasus earthquake sequence, April 1991

On 29 April 1991 a large earthquake (M_S =7.3) occurred in western Caucasus, with coordinates 42.453N, 43.673E, h = 17 km (NEIC).

The earthquake was followed by a large number of aftershocks. According to the catalogue of Starovoit et al (1992), 114 aftershocks were recorded on the day of the main shock (29 April) and 360 aftershocks had been recorded by the end of May.

The earthquake occurred early during the Group of Scientific Experts (GSE) Second Technical Test (GSETT-2, main phase, see GSE/CRP/190/Rev.4, 1991), and caused a considerable load at the National Data Centers (NDCs) as well as the four Experimental International Data Centers (EIDCs). The day 29 April was selected as one of the days for which reprocessing was to be made at EIDCs. Consequently, this day is useful for studying the performance of the experimental global system during a day of particularly high seismic activity. Moreover, it provides an excellent opportunity to evaluate the GBF technique applied to a large aftershock sequence.

Method

We selected 11 stations from the total of 60 participating in GSETT-2 for this analysis (see Fig. 7.6.1). These 11 stations comprised those that had the best detection performance for the W. Caucasus area. Table 7.6.1 lists the stations and summarizes the GBF parameters for this experiment. Note that only one generalized beam was formed, and it was steered to 42.5N 43.5E. The time and azimuth tolerances were set in accordance with the GSE requirements, and adjusted for the beam focus area of 0.5 degrees radius. These tolerances were narrow enough to avoid many false associations, while still allowing for the typical uncertainty in detection times and automatic parameter estimates. Detection threshold was set at 3 matching phases, and GBF detections less than 15 seconds apart were grouped together.

Table 7.6.2 shows the detection list generated by the automatic GBF process for the day in question. For each line our assessment of the detection is given (whether or not it was confirmed by the Starovoit et al bulletin and the number of EIDCs that reported the event). We note that more than 90% of the entries are in the confirmed category (either listed by Starovoit et al or reported by at least one EIDC).

Table 7.6.3 summarizes the number of detected events by the various systems. We note that the four EIDCs (reprocessed bulletins from Stockholm, Moscow, Canberra and Washington) had similar performances, and reported about half of the events in the reference catalogue. NEIC reported only one third of the reference events in their monthly bulletin. The rapid QED service (Quick Epicenter Determination) reported very few of the events.

The GBF association process reported more events than any of the four EIDCs, and also had the most events corresponding to the reference catalogue. In addition, the GBF method produced 17 reports that did not correspond to entries in Starovoit et al's bulletin. Each of the EIDCs also had events in this category, but not as many as the GBF process. It should be noted that one event reported by one EIDC and confirmed by Starovoit et al's bulletin was not reported by the GBF method. The reason was that the event had only two valid phases, and thus did not satisfy our GBF detection criterion. On the other hand, the GBF reported 4 confirmed events that were not in any of the EIDC bulletins.

We also conducted an experiment to test the likelihood of false associations. The GBF process with the parameters used in this study was run on a 7-day period prior to day 119. A false association would normally correspond to phases from a real event occurring somewhere else, but for which the phases happened to match our criteria. Table 7.6.4 shows the events associated for this 7-day period. Only six events were associated, two of which were in fact close to the beam steering point. Thus only four definite false alarms were observed during this one-week period. We conclude that the false alarm rate is very low for this processing method.

Conclusions

The GBF technique provides a simple and rapid way to associate large numbers of phases from an aftershock sequence with a very low false alarm rate. In fact, the GBF aftershock processing of 24 hours of data for the day in question (29 April 1991) took only 5 minutes on a SUN sparcstation2.

We consider that the GBF would be very useful as a preprocessor to the expert system algorithm to be applied at a future International Data Center (IDC). By first using the GBF to extract aftershock sequences, and remove the corresponding phase detections, the remaining task of associating events from other locations would be much simplified. Other applications of GBF in the context of IDC processing can also be envisaged. Furthermore, the interaction between GBF and threshold monitoring, in terms of eliminating "unlikely" phase associations, deserves to be studied in detail.

F. Ringdal
T. Kværna

References

GSE/CRP/190/Rev. 4 (1991): *Instructions for the conduct of Phase 3 of GSETT-2*, Group of Scientific Experts, UN Conference of Disarmament, Geneva, Switzerland.

Kværna, T. (1990): Generalized beamforming using a network of four regional arrays, *Semiann. Tech. Summary, 1 April - 30 September 1990*, NORSAR Sci. Rep. No. 1-90/91, Kjeller, Norway.

Kværna, T. (1992a): Automatic phase association and event location using data from a network of seismic microarrays, *Semiann. Tech. Summary, 1 October 1991 - 31 March 1992*, NORSAR Sci. Rep. No. 2-91/92, Kjeller, Norway.

Kværna, T. (1992b): On the use of regionalized wave propagation characteristics in automatic global phase association, *Semiann. Tech. Summary, 1 April - 30 September 1992*, NORSAR Sci. Rep. No. 1-92/93, Kjeller, Norway.

Ringdal, F. and T. Kværna (1989): A multi-channel processing approach to real time network detection, phase association, and threshold monitoring, *Bull. Seism. Soc. Am.*, **79**, 1927-1940.

Starovoit et al (1992): Catalog of aftershocks of the West Caucasus earthquake of 29 April 1991.

Taylor, D.W.A. and S.K. Leonard (1992): Generalized beamforming for automatic association, in Papers presented at the 14th Annual PL/DARPA Seismic Research Symposium, 16-18 September 1992, Loews Ventana Canyon Resort, Tucson, AZ, USA.

Station	Type	Lat	Lon	Distance	Phase	Trtime	Azimuth	Slowness
KIV	Single	43.95	42.68	1.57	Pn	28.87	157.33	13.73
KIV	Single	43.95	42.68	1.57	Sn	50.21	157.33	24.17
ARU	Single	56.40	58.60	16.47	P	236.95	221.31	12.66
GAR	Single	39.00	70.30	20.57	P	279.67	288.38	11.01
FIN	Hfarray	61.44	26.07	21.66	P	291.44	143.15	10.52
GER	Hfarray	48.85	13.70	21.68	P	291.58	95.77	10.51
OSS	Single	46.69	10.13	24.02	P	315.08	87.84	9.61
HFS	Sparray	60.13	13.68	25.33	P	327.43	120.73	9.28
NRS	Hfarray	60.73	11.54	26.55	P	338.63	118.86	9.07
ARC	Hfarray	69.54	25.51	28.66	P	353.11	151.55	8.92
GBA	Sparray	13.62	77.59	41.16	P	465.27	320.96	8.23
YKA	Sparray	62.49	-114.61	73.89	P	696.14	16.68	5.87

Table 7.6.1. Station and phase parameters used for GBF processing of the Caucasus aftershock sequence (42.5N, 43.5E, Depth 0).

Origin time	Lat	Lon	Depth	Nph	Nsta	Tres	Nazi	Azres	Nslow	Slres	Nslv	Slvres	Starov	EIDCs
1991-119:09.12.49.0	42.50	43.50	0.00	11	11	1.45	7	4.53	7	1.15	7	1.45	Yes	4
1991-119:09.27.48.0	42.50	43.50	0.00	3	3	2.84	2	4.10	2	1.71	2	1.87	Yes	3
1991-119:09.31.05.0	42.50	43.50	0.00	3	3	1.12	3	7.45	3	1.09	3	1.74	No	3
1991-119:09.37.39.0	42.50	43.50	0.00	11	10	2.29	7	4.86	7	1.24	7	1.64	Yes	2
1991-119:09.38.08.0	42.50	43.50	0.00	5	5	3.53	4	4.48	3	0.93	3	1.17	No	4
1991-119:09.38.34.0	42.50	43.50	0.00	4	4	2.32	4	3.23	3	1.92	3	2.00	No	3
1991-119:09.41.52.0	42.50	43.50	0.00	4	3	1.23	2	7.25	1	0.93	1	2.02	Yes	3
1991-119:09.50.49.0	42.50	43.50	0.00	3	2	1.22	1	4.27	0	0.00	0	0.00	No	2
1991-119:09.54.37.0	42.50	43.50	0.00	6	5	2.87	4	5.33	3	1.01	3	1.42	Yes	4
1991-119:09.59.24.0	42.50	43.50	0.00	11	10	1.12	6	4.43	6	0.90	6	1.19	Yes	4
1991-119:10.01.15.0	42.50	43.50	0.00	9	8	2.32	5	2.94	5	0.94	5	1.05	Yes	4
1991-119:10.06.23.0	42.50	43.50	0.00	4	3	3.93	2	2.84	2	1.70	2	1.77	Yes	3
1991-119:10.08.37.0	42.50	43.50	0.00	3	2	1.02	1	4.27	0	0.00	0	0.00	Yes	-
1991-119:10.15.35.0	42.50	43.50	0.00	10	9	1.84	5	5.72	4	1.16	4	1.65	Yes	4
1991-119:10.15.57.0	42.50	43.50	0.00	5	5	2.26	4	4.98	3	0.98	3	1.35	No	4
1991-119:10.19.42.0	42.50	43.50	0.00	9	8	1.52	5	4.44	5	0.93	5	1.24	Yes	4
1991-119:10.30.42.0	42.50	43.50	0.00	6	5	1.21	4	6.01	3	0.91	3	1.54	Yes	4
1991-119:10.35.33.0	42.50	43.50	0.00	5	4	6.83	2	2.48	1	0.42	1	0.43	Yes	3
1991-119:10.41.00.0	42.50	43.50	0.00	4	3	1.35	2	3.48	1	0.43	1	0.52	Yes	3
1991-119:10.52.43.0	42.50	43.50	0.00	11	10	2.03	6	2.47	6	0.85	6	1.05	Yes	4
1991-119:10.53.05.0	42.50	43.50	0.00	3	3	4.25	2	10.16	2	1.30	2	2.19	No	-
1991-119:10.56.12.0	42.50	43.50	0.00	5	4	0.90	3	4.79	2	1.10	2	1.69	Yes	3
1991-119:11.04.31.0	42.50	43.50	0.00	9	8	2.01	4	4.34	4	0.60	4	0.94	Yes	4
1991-119:11.08.04.0	42.50	43.50	0.00	3	3	1.22	3	2.21	2	1.30	2	1.32	No	2
1991-119:11.10.14.0	42.50	43.50	0.00	10	9	2.34	5	6.35	4	0.72	4	1.42	Yes	4
1991-119:11.12.21.0	42.50	43.50	0.00	3	3	0.39	2	7.52	1	0.94	1	2.26	Yes	3
1991-119:11.38.38.0	42.50	43.50	0.00	4	3	0.46	2	2.29	1	0.14	1	0.14	Yes	3
1991-119:11.43.19.0	42.50	43.50	0.00	5	4	2.02	2	2.48	2	0.66	2	0.81	Yes	4
1991-119:11.51.13.0	42.50	43.50	0.00	9	8	2.41	5	3.53	4	1.04	4	1.28	Yes	4
1991-119:11.59.56.0	42.50	43.50	0.00	10	9	2.98	6	6.76	5	0.77	5	1.57	Yes	4
1991-119:13.02.12.0	42.50	43.50	0.00	4	3	1.13	2	3.29	2	0.41	2	0.64	Yes	4
1991-119:13.12.38.0	42.50	43.50	0.00	6	5	1.79	3	5.06	3	0.23	3	0.97	Yes	4
1991-119:13.13.26.0	42.50	43.50	0.00	4	3	2.05	2	6.46	2	1.01	2	1.50	No	4
1991-119:13.19.50.0	42.50	43.50	0.00	6	5	0.80	2	2.29	1	0.14	1	0.14	Yes	4
1991-119:13.27.17.0	42.50	43.50	0.00	9	8	2.64	4	7.83	3	0.33	3	1.67	Yes	4
1991-119:13.49.59.0	42.50	43.50	0.00	7	6	0.67	3	2.94	2	0.66	2	0.73	Yes	4
1991-119:13.53.10.0	42.50	43.50	0.00	5	4	0.82	2	2.93	2	0.72	2	1.03	Yes	4
1991-119:14.00.28.0	42.50	43.50	0.00	4	3	2.38	1	0.68	1	0.20	1	0.21	Yes	4
1991-119:14.20.57.0	42.50	43.50	0.00	3	2	0.49	1	4.27	1	0.82	1	1.10	No	2
1991-119:14.43.08.0	42.50	43.50	0.00	11	10	2.34	6	2.84	6	0.80	6	1.03	Yes	4
1991-119:14.43.30.0	42.50	43.50	0.00	3	3	4.90	2	6.21	2	0.31	2	1.11	No	-
1991-119:15.28.48.0	42.50	43.50	0.00	6	5	1.29	4	7.45	4	0.95	4	1.75	Yes	4
1991-119:15.38.56.0	42.50	43.50	0.00	4	3	2.38	1	11.77	1	1.90	1	2.73	Yes	2
1991-119:16.03.09.0	42.50	43.50	0.00	6	6	5.62	3	2.55	3	1.03	3	1.14	Yes	3
1991-119:16.12.49.0	42.50	43.50	0.00	5	4	1.55	2	5.70	2	1.06	2	1.47	Yes	3
1991-119:16.22.27.0	42.50	43.50	0.00	5	4	1.45	2	2.29	1	0.64	1	0.64	Yes	4

Nph - Number of associated phases
Nsta - Number of stations
Tres - Mean absolute time residual
Nazi - Number of azimuth observations
Azres - Mean absolute azimuth residual
Nslow - Number of slowness observations
Slres - Mean absolute slowness residual
Nslv - Number of horizontal slowness vector observations
Slvres - Mean absolute horizontal slowness vector residual
Starov - Event confirmed by Starovoit et al catalogue (Yes/No)
EIDCs - Number of confirming EIDCs

Table 7.6.2. List of event parameters for the events detected on the generalized beam steered to 42.5°N, 43.5°E for day 119 (29 April) 1991. See text for details. (Page 1 of 2)

1991-119:16.48.43.0	42.50	43.50	0.00	10	9	2.73	5	2.11	5	1.20	5	1.34	Yes	4
1991-119:16.49.59.0	42.50	43.50	0.00	8	7	2.03	3	7.88	2	1.59	2	2.58	Yes	4
1991-119:16.58.51.0	42.50	43.50	0.00	7	6	2.30	3	4.27	2	1.52	2	1.67	Yes	4
1991-119:17.10.29.0	42.50	43.50	0.00	6	5	1.42	2	2.98	1	0.43	1	0.47	Yes	4
1991-119:17.20.40.0	42.50	43.50	0.00	3	3	0.57	3	6.21	2	0.89	2	1.55	No	4
1991-119:17.21.27.0	42.50	43.50	0.00	7	6	1.99	4	3.32	3	1.48	3	1.63	Yes	4
1991-119:17.34.43.0	42.50	43.50	0.00	4	3	2.01	1	3.77	1	1.83	1	1.94	Yes	3
1991-119:17.55.01.0	42.50	43.50	0.00	9	8	2.07	4	3.45	3	1.17	3	1.28	Yes	4
1991-119:18.14.44.0	42.50	43.50	0.00	5	4	3.85	2	5.75	1	1.19	1	1.83	Yes	4
1991-119:18.17.22.0	42.50	43.50	0.00	4	3	2.92	1	1.73	1	1.05	1	1.09	Yes	2
1991-119:18.23.18.0	42.50	43.50	0.00	10	10	2.62	6	4.09	6	1.11	6	1.36	Yes	4
1991-119:18.30.43.0	42.50	43.50	0.00	9	9	2.37	5	3.86	4	1.22	4	1.38	Yes	4
1991-119:18.51.37.0	42.50	43.50	0.00	4	3	1.88	2	5.78	2	0.65	2	1.36	Yes	4
1991-119:19.07.05.0	42.50	43.50	0.00	12	11	1.59	7	3.81	6	1.17	6	1.38	Yes	4
1991-119:19.16.06.0	42.50	43.50	0.00	6	5	1.91	2	4.96	2	0.74	2	1.06	Yes	4
1991-119:19.19.58.0	42.50	43.50	0.00	10	9	2.78	5	4.10	4	0.77	4	1.22	Yes	4
1991-119:19.26.52.0	42.50	43.50	0.00	3	2	0.18	0	0.00	0	0.00	0	0.00	Yes	-
1991-119:19.44.56.0	42.50	43.50	0.00	9	8	2.26	4	1.85	4	0.50	4	0.69	Yes	4
1991-119:19.52.52.0	42.50	43.50	0.00	4	4	1.40	3	2.24	2	0.18	2	0.24	Yes	4
1991-119:20.01.42.0	42.50	43.50	0.00	3	2	0.21	1	7.85	1	2.17	1	2.52	Yes	-
1991-119:20.12.08.0	42.50	43.50	0.00	9	8	1.77	4	5.59	4	0.84	4	1.33	No	4
1991-119:20.19.47.0	42.50	43.50	0.00	5	4	1.91	3	3.06	3	0.99	3	1.16	Yes	4
1991-119:20.24.45.0	42.50	43.50	0.00	10	9	1.88	5	4.13	4	1.07	4	1.34	Yes	4
1991-119:20.32.54.0	42.50	43.50	0.00	9	9	0.87	5	3.50	4	1.48	4	1.63	Yes	4
1991-119:21.23.16.0	42.50	43.50	0.00	4	3	1.93	1	1.27	1	0.41	1	0.46	No	2
1991-119:21.24.11.0	42.50	43.50	0.00	8	8	1.34	5	7.72	4	1.07	4	1.91	Yes	4
1991-119:21.25.24.0	42.50	43.50	0.00	4	4	0.95	3	8.45	2	0.77	2	1.96	No	4
1991-119:21.30.32.0	42.50	43.50	0.00	3	2	2.58	0	0.00	0	0.00	0	0.00	No	3
1991-119:22.25.07.0	42.50	43.50	0.00	3	2	1.54	0	0.00	0	0.00	0	0.00	No	2
1991-119:22.28.25.0	42.50	43.50	0.00	10	9	2.62	5	5.00	4	0.61	4	1.29	Yes	4
1991-119:23.10.54.0	42.50	43.50	0.00	4	3	0.70	1	4.27	0	0.00	0	0.00	Yes	2
1991-119:23.17.56.0	42.50	43.50	0.00	3	2	1.13	1	4.27	0	0.00	0	0.00	Yes	-
1991-119:23.32.32.0	42.50	43.50	0.00	9	8	2.68	4	5.26	3	0.87	3	1.27	Yes	4
1991-119:23.32.50.0	42.50	43.50	0.00	3	3	6.58	2	4.89	2	0.70	2	1.27	No	-
1991-119:23.34.18.0	42.50	43.50	0.00	3	3	0.55	2	7.25	1	0.03	1	1.87	No	4

Table 7.6.2 (cont.). (Page 2 of 2)

Source	Total number of events	Confirmed by Starovoit et al's catalogue	Not in Starovoit et al's catalogue
Starovoit et al catalogue	115	115	0
Canberra EIDC (reprocessed)	57	48	9
Stockholm EIDC (reprocessed	73	62	11
Moscow EIDC (reprocessed)	76	61	15
Washington EIDC (reprocessed)	71	58	13
GBF (automatic)	82	65	17
NEIC monthly list	35	35	0
QED list	6	6	0

Table 7.6.3. Number of events reported by various sources for the W. Caucasus sequence of 29 April 1991. From our analysis, all reported GBF events for that day were real (no false alarms). A few events reported by the EIDCs or GBF were close in time (possibly multiple events) and therefore not included as separate events in Starovoit et al's catalogue.

a) GBF detection list, day 112-118

Origin time	Lat	Lon	Depth	Nph	Nsta	Tres	Nazi	Azres	Nslow	Slres	Nslv	Slvres	Actual event location	
1991-114:10.54.48.0	42.50	43.50	0.00	3	3	3.07	3	5.01	3	0.32	3	0.78	Turkey	(40N 41E)
1991-116:17.09.43.0	42.50	43.50	0.00	5	5	3.52	5	4.50	5	1.81	5	1.98	S. Iran	(28N 55E)
1991-116:22.28.43.0	42.50	43.50	0.00	3	2	1.93	1	3.77	1	2.52	1	2.60	Tadzik	(39N 71E)
1991-117:03.32.11.0	42.50	43.50	0.00	5	5	5.82	2	4.04	2	0.92	2	1.13	Turkey	(40N 44E)
1991-117:09.54.01.0	42.50	43.50	0.00	3	3	4.68	2	12.81	2	1.48	2	2.71	Hindu Kush	(37N 71E)
1991-118:03.46.32.0	42.50	43.50	0.00	3	3	1.16	3	2.86	3	1.13	3	1.28	Pers. Gulf	(28W 51E)

b) Number of GBF detections by day

Day	Number of Detections
112	0
113	0
114	1
115	0
116	2
117	2
118	1
Total	6

Table 7.6.4. Detection statistics for the W. Caucasus GBF beam covering the one-week period prior to day 119. 1991. Note that two of the six events were actually in the Caucasus area, while the four remaining detections were "side lobes" from large events elsewhere in Eurasia. Consequently, there were only 4 "false alarms" for the entire 7-day period.

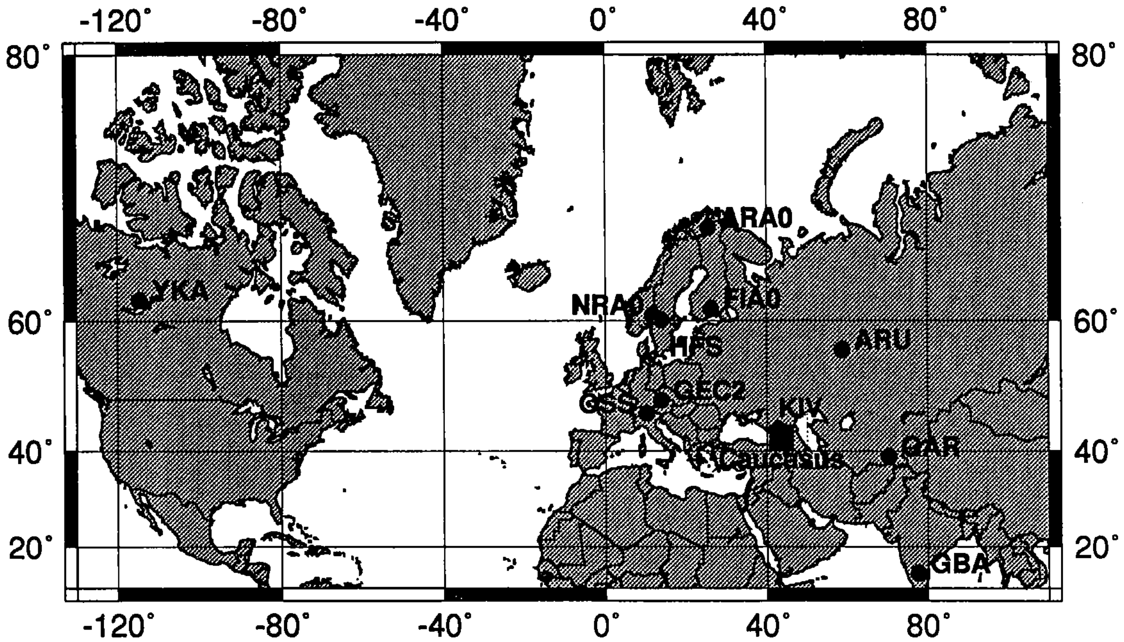

Fig. 7.6.1. Map showing the stations used for GBF processing of the Caucasus aftershock sequence.