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7.1 A performance test of the generalized beamforming method applied to a data base of regional events

Introduction

In the real time processing of seismic network data, one of the most important aspects is to properly associate phases detected at individual stations. For a network of regional arrays, the current state-of-the-art is represented by the IAS system, where the Assess procedure is used for phase association and location estimation (Bache, 1987).

The generalized beamforming method introduced by Ringdal and Kværna (1989) is a different approach that has shown considerable promise as an efficient way to obtain phase grouping and initial epicenter estimates. In this paper, the method is applied to a data base of 77 regional and local events and compared to IAS results. It is found that the generalized beamforming is able to match the good results by Assess as far as phase grouping is concerned, and that the epicenter determinations are also quite accurate.

It is concluded from this study that the new method could be useful as a supplement to the expert systems techniques in future extensions of the IAS system. While some further testing would be required, it would appear that the method could be particularly valuable as a pre-processor in this regard. In this way, the results from the generalized beamforming could be taken as input to a procedure where the rule-based and script-based algorithms implemented in the IAS could be used to further refine the solutions.

Data analysis

The data set of event recordings from NORESS and ARCESS were first processed by the IAS detector program, called Sigpro, to generate detection lists for each array. The detection list was then processed by the IAS rule-based expert system, called Assess, to define event groups and event locations.

Subsequently the automatic Assess solutions were reviewed by an analyst, and if necessary, phases were retimed or new phases were picked to get more precise locations. When false events occurred, these were invalidated by the analyst.

As we consider the analyst-reviewed event definitions and locations to be correct, we will use those as a basis for evaluating the performance of the generalized beamforming method. For reference, we will also present the results produced by Assess.

1) Identification of event groups

After analyst review of the Assess solutions, 76 events were observed. Phase detections belonging to a common event, will be called an event group. 72 of the 76 event groups were validated or relocated after analyst review. The remaining 4 events can be divided into the following classes:

a) One multiple event that was observed as a separate event group, but with wrong phase id's. This event was not relocated by the analyst.
b) One triple event that was observed as one separate event group, but with wrong phase id's. These events were not relocated by the analyst.
c) One multiple event that was observed by analyst, but was not given any separate event group by Assess.

Both the generalized beamforming method and Assess in a few cases gave automatic locations that deviated considerably from the locations found after analyst review. But as long as a real event candidate is identified, the analyst can later make the necessary adjustments of phase id's and arrival times. We will therefore consider the event in 1a) as identified by Assess, one of the two events in 1b) as identified, whereas the second event in 1b) and the event in 1c) is missed.

The generalized beamforming method found 71 of the 72 events that were validated or relocated after analyst replacement. The events in 1a) and 1b) were missed, whereas the event in 1c) was identified. One new event was identified, so we set the number of events observed by analyst to 77.

If we discard the multiple events in 1a)-1c) from the statistics, the generalized beamforming method and Assess remain with one missing event each, both of these being small interfering events observed on one array only.

	Analyst	Generalized	Assess
Events identified	77	73	74
Excluding multiples	73	72	72

2) False events

An important factor in real-time operation of seismic networks is the number of false event groups created by the automatic system. If an analyst is going to review the automatic output, he will want the number of false events to be at a reasonable level. By split two-array events we mean that a single event was detected on two arrays, but the automatic algorithm created an extra event that was false. By split one-array event we mean that the event was detected on one array only, but the automatic algorithm created an extra event that was false. Implausible associations were decided on the basis of detection list information like amplitudes and frequency content of the different phases, knowledge of propagation characteristics and/or by inspecting the actual data.

	Generalized	Assess
Split two-array events	1	7
Split one-array events	0	4
Implausible associations	7	4
Number of false events	8	15

3) Phase identification

The generalized beamforming method takes advantage of the travel-time pattern of the detected phases when event groups and phase identifications are defined. For events with detections on one array only, we know that these patterns in many cases do not contain sufficient information for defining the individual phase identifications. In those situations a rule-based approach has to be invoked.

For 39 events in the sample data base with detections on two arrays, we have made some statistics for both the generalized beamforming method and Assess that reflect the ability to assign correct phase id's to the different detections. The reference will be the phase id's selected by analyst.

The columns of the following tables need some explanation.

correct - gives the number of correctly identified detections.
early - gives the number of cases where a detection preceding the correct one is selected.
late - gives the number of cases where a detection following the correct one is selected.

missed - gives the number of cases were a detection is identified by the analyst, but missed by the automatic method.

phases - means number of detections identified as defining phases by the analyst. # phases=correct+early+late+missed

The number of events analyzed is 39, as indicated earlier.

false - gives number of cases where the automatic method picked a defining phase that was not identified by the analyst.

For both the generalized beamforming method and Assess, we give tables for the phase identification performance on Noress and Arcess detections. By adding the two tables, we also indicate the overall performance.

Generalized beamforming

NORESS

	correct	early	late	missed	# phases	false
nrs-pn	31	0	5	1	37	0
nrs-pg	0	0	0	0	0	1
nrs-sn	23	0	6	0	29	0
nrs-lg	24	1	4	1	30	2
sum	78	1	15	2	96	3

ARCESS

	correct	early	late	missed	# phases	false
arc-pn	34	0	4	1	39	0
arc-pg	3	0	0	0	3	11
arc-sn	15	1	12	2	30	3
arc-lg	13	2	10	1	26	3
sum	65	3	26	4	98	17

NORESS and ARCESS

	correct	early	late	missed	# phases	false
sum-pn	65	0	9	2	76	0
sum-pg	3	0	0	0	3	12
sum-sn	38	1	18	2	59	3
sum-lg	37	3	14	2	56	5
sum	143	4	41	6	194	20

Assess

NORESS

	correct	early	late	missed	# phases	false
nrs-pn	30	0	1	6	37	0
nrs-pg	0	0	0	0	0	0
nrs-sn	21	0	0	8	29	1
nrs-lg	20	1	2	7	30	2
sum	71	1	3	21	96	3

ARCESS

	correct	early	late	missed	# phases	false
arc-pn	34	0	3	2	39	0
arc-pg	1	0	0	2	3	0
arc-sn	12	1	3	14	30	1
arc-lg	14	2	4	6	26	4
sum	61	3	10	24	98	5

NORESS and ARCESS

	correct	early	late	missed	# phases	false
sum-pn	64	0	4	8	76	0
sum-pg	1	0	0	2	3	0
sum-sn	33	1	3	22	59	2
sum-lg	34	3	6	13	56	6
sum	132	4	13	45	194	8

Within the data base there were 9 one-array events with three or more defining phases. That all of these events were observed on ARCESS, reflect the fact that very few events within the data base had epicenters close to NORESS. In cases with one-array events defined by three or more phases, there is a possibility that the generalized beamforming method can utilize the travel-time pattern to come up with correct phase id's.

The following two tables indicate the performance of the two methods on this data set.

Generalized beamforming

	correct	early	late	missed	# phases	false
arc-pn	6	0	3	0	9	0
arc-pg	2	0	1	0	3	5
arc-sn	7	0	1	0	8	1
arc-lg	5	0	0	1	6	1
sum	20	0	5	1	26	7

Assess

	correct	early	late	missed	# phases	false
arc-pn	8	1	0	0	9	0
arc-pg	1	0	0	2	3	0
arc-sn	5	0	0	3	8	0
arc-lg	1	1	2	2	6	1
sum	15	2	2	7	26	1

4) Initial location estimates

Although the generalized beamforming method gave reasonable phase id's for the 9 one-array events considered above, we can not give very much confidence to the initial event locations. Within the predefined azimuth acceptance limits, all points with the same radius from the observation point will be equally good location candidates. As we have not run any location program on the phases identified by the generalized beamforming method, the location estimates for these events will not be very accurate. But for completeness, we present the results.

For the epicenter estimates obtained by the generalized beamforming method and Assess, we calculated the deviations from the epicenters computed after analyst review. These deviations were grouped into different intervals, as shown below.

Deviation from analyst reviewed epicenter solutions for all one-array events with three or more defining phases.

Deviation in km	Number of events within distance interval Generalized	Assess
d≤10	0	3
10<d≤25	0	2
25<d≤50	4	1
50<d≤100	2	2
100<d≤200	3	1
200<d	0	0
events	9	9

In the following table we consider the 39 events that were detected on two arrays.

Deviation from analyst-reviewed epicenter solutions for all two-array events

Deviation in km	Number of events within distance interval Generalized	Assess
d≤10	3	8
10<d≤25	8	5
25<d≤50	15	12
50<d≤100	7	7
100<d≤200	4	2
200<d	2	5
events	39	39

Discussion

We have in the preceding section shown that when processing data from two arrays, the generalized beamforming method identified 73 out of 77 event groups. When discarding multiple events from the same location, only one small interfering one-array event was missed.

Some false event groups were created, and this requires some attention. In the cases were two phases from two arrays are erroneously associated together, a check on the amplitude (magnitude) of the two phases would remove some of the event candidates.

One of the main problems in automatic identification of seismic phases, is the relatively large number of detections in the coda of the seismic signals. If the travel-time functions of the different phases do not fit with what we acually observe, there is a possibility that the generalized beamforming method will assign a phase id to one of the coda detections. For the 39 two-array events, we find that this happened in 41 cases.

As an additional test, we wanted to check if we could improve the performance by introducing some simple rules to the procedure. They were as follows:

a) If a phase is assigned the id Pn, and the event group contains a preceding Pn candidate (within some given time interval), the preceding phase is given the id Pn.
b) If a phase is assigned the id Sn, and the event group contains a preceding Sn candidate (within some given time interval), the preceding phase is given the id Sn.
c) If a phase is assigned the id Lg, and the event group contains an Lg candidate with a larger STA value (within some given time interval), that phase is given the id Lg.

The time intervals were for all 3 phases set to 10 seconds, and we did of course also check how these rules affected the previously correct phase assignments. The results are shown in the tables below.

Generalized beamforming

NORESS

	correct	early	late	missed	# phases	false
nrs-pn	36	0	0	1	37	0
nrs-pg	0	0	0	0	0	1
nrs-sn	27	0	2	0	29	0
nrs-lg	26	0	3	1	30	2
sum	89	0	5	2	96	3

ARCESS

	correct	early	late	missed	# phases	false
arc-pn	36	0	2	1	39	0
arc-pg	3	0	0	0	3	11
arc-sn	23	1	4	2	30	3
arc-lg	14	2	9	1	26	3
sum	76	3	15	4	98	17

NORESS and ARCESS

	correct	early	late	missed	# phases	false
sum-pn	72	0	2	2	76	0
sum-pg	3	0	0	0	3	12
sum-sn	50	1	6	2	59	3
sum-lg	40	2	12	2	56	5
sum	165	3	20	6	194	20

What we found was that these simple rules improved the performance on Pn and Sn considerably, but the Lg-rule did not provide almost any improvement. Another approach that could possibly be used to better identify Lg is to compute an event location based on the identified phases and thereafter reselect Lg from the detection that best fitted the predicted Lg arrival time.

But the fundamental problem is that for many regions, we do not have the correct travel-time functions, so to further improve the performance of the generalized beamforming method, we need to introduce regionalized travel-time functions that reflect the automatic picks.

For the 9 one-array events with three or more defining phases, 5 out of 26 phase id's were assigned to coda detections. By introducing the same rules as outlined for the two-array events, this number was reduced to 2, as shown in the table below.

Generalized beamforming

	correct	early	late	missed	# phases	false
arc-pn	9	0	0	0	9	0
arc-pg	2	0	1	0	3	5
arc-sn	8	0	0	0	8	1
arc-lg	4	0	1	1	6	1
sum	23	0	2	1	26	7

For the two-array data set, the analyst only identified 3 Pg phases, all on ARCESS. The generalized beamforming method correctly identified these phases, but in addition, 12 Pn coda detections were assigned the id Pg. Some of these false Pg identifications may be removed by giving this phase some stronger constraints on apparent velocity and/or polarization attributes.

The generalized beamforming produced initial locations that were consistent with the relatively good performance on phase identification. The natural next step would be to run a location program on the identified phases, and then compare to the location obtained after analyst review.

In this study we have presented results on the performance of the generalized beamforming method on a network of two arrays. The next step will be to get detection data (real or synthetic) for a larger network of arrays and single stations, and test the method on this data set. Since the computer programs for this method is almost fully parameterized, only minor modifications are needed for such an experiment.

References

Bache, T.C. (1987): A knowledge-based system for analyzing data from a network of NORESS-type arrays. Papers presented at 9th DARPA/AFGL Research Symposium, 15-18 June, 167-172.

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