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Frode Ringdal (ed.)

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6.3 A Case Study of Seismic Event Identification: Explosions in NW Russia using the ARCES seismic array

6.3.1 Introduction

There are many instances in which a full overview of seismic events from a given source region is required. In many cases of industrial seismic sources, such as mines and quarries, this may be solely for the purpose of event screening such that successive events from the same site may be associated confidently with the correct source. A description of an algorithm applying traditional regional array processing methods for identifying quarry blasts at regional distances from the ARCES array is provided by Gibbons et al. (2005). This method was extremely effective for blasts at the open-cast Kovdor mine in NW Russia. The events were characterized by very consistent slowness and azimuth measurements for the first Pn-phase arrivals, and events could be identified quite reliably by assessing the slowness and SNR in fixed time-windows following this initial arrival. The success of this case study was largely due to the high SNR of the initial arrival and the repeatability of f-k slowness vector measurements in calibrated fixed-frequency bands. Weaker events will result in a lower SNR which may lead to far poorer slowness estimates in short time-windows and subsequently limit the application of such algorithms.

Waveform correlation methods can be highly successful at identifying seismic sources (e.g. Harris, 1991) and, often matching the entire signal as opposed to a single transient phase arrival, can lower significantly the detection threshold for events from specific sources (e.g. Gibbons and Ringdal, 2006, and references therein). In recent years, several different case studies have demonstrated the advantages of applying waveform correlation to the detection of low-magnitude events. Gibbons and Ringdal (2004), Stevens et al. (2006) demonstrate how signals from cavity-decoupled chemical explosions buried deep in the background seismic noise could be detected with essentially a zero false-alarm rate by correlating against the signals from larger co-located (or almost co-located) explosions. Gibbons and Ringdal (2005) used correlation of SPITS array data to detect small mining-induced events at the Barentsburg mine at a distance of approximately 50 km. Gibbons et al. (2007) used the signals from a magnitude 3.5 earthquake in the Rana region of northern Norway to detect aftershocks and almost co-located earthquakes down to magnitude 0.5 at distances of over 600 km using the Nordic IMS array stations. An important characteristic common to each of these case studies, despite the different source mechanisms, is the similarity of waveforms from one event to the next.

Significant variation between the waveforms from event to event poses a significant difficulty for matched-filter detectors as described by Gibbons and Ringdal (2006). A case of interesting seismic events is described by Ringdal and Schweitzer (2005). The events are located close to the northern coast of the Kola Peninsula in Russia. The coordinates of the site are not known and events are only located to within the uncertainties of the location estimates obtained with the arrays in the region (c.f. Figure 12 of Ringdal and Schweitzer, 2005). The explosions were brought to the attention of researchers at NORSAR by residents of the Varanger region on the northern coast of Norway who felt and heard the events over a large geographical area. They have been of interest due to the generation of infrasound signals recorded both on the microbarograph mini-array at Apatity and on the ARCES seismic array. At the time, only 6 events had been identified and waveforms from these events, recorded at ARCES, are displayed in Figure 6.3.1.

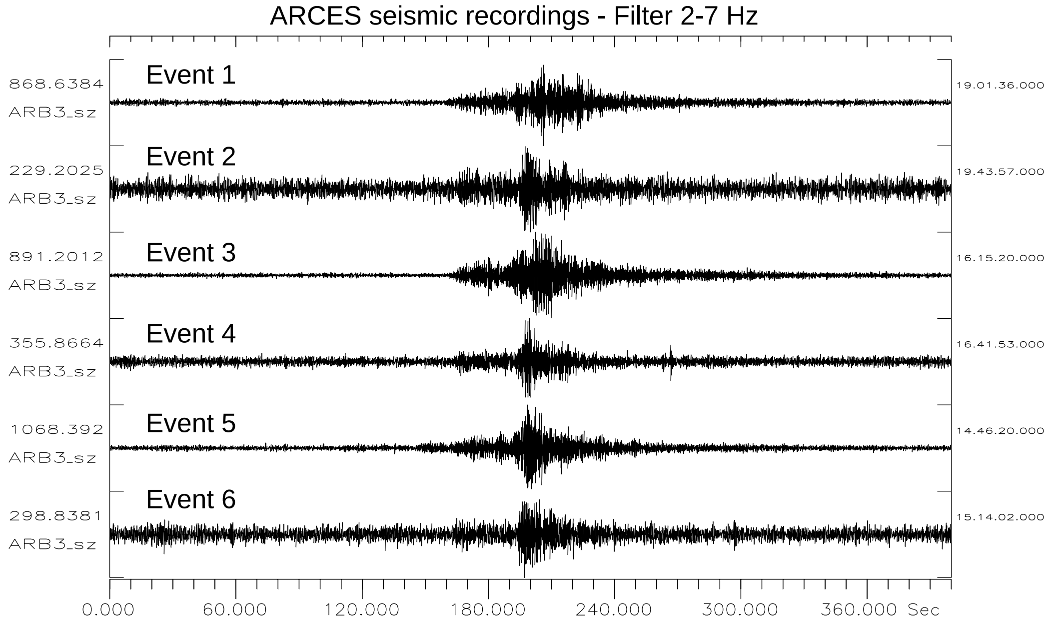

Fig. 6.3.1. Waveforms on a single sensor of the ARCES array for the six NW Russia events identified by Ringdal and Schweitzer (2005). Figure reproduced from Ringdal and Schweitzer (2005).

The six different signals in Figure 6.3.1 bear very little resemblance to each other and the lack of waveform similarity is confirmed by a calculation of correlation coefficients. The waveform dissimilarity is observed in a wide range of frequency bands and it is therefore assumed that (even if the events are closely located geographically) source-time histories are significantly different. How do we best proceed to identify other events related to this source? Using the fully-automatic GBF lists (Ringdal and Kværna, 1989) is not an option since the automatic location estimates for the (many hundreds of) events from the Zapoljarni ore mines (approximately 50 km from the assumed source location) cover an area of many thousands of square kilometers which encompass the region needing to be covered here (see Kværna et al., 2006). Is it possible to use full-waveform methods which take essentially all events from this site with an acceptable false-alarm rate?

6.3.2 A multi-channel correlation detector for the ARCES array

All of the events in Figure 6.3.1 appear to have either a low SNR or a waveform suggesting a complicated source-time function. It was judged that event number 5 appeared to have the best combination of a relatively simple waveform envelope and a reasonable SNR (bearing in mind that a large coda-amplitude is more helpful for correlation detectors than an impulsive initial arrival and a high STA:LTA value). The event is assumed to have an origin time of 2005-076:14.48.24.24 and coordinates 69.5508^o N, 31.8589^o E with zero depth. An empirical matched filter detector using a 60.0 second long template of ARCES array data, filtered between 3.0 and 8.0 Hz, was initiated and run over three years of continuous data.

The filtered and normalized waveform template was correlated against incoming waveform data segments with a length of approximately 10 minutes. Prior to the main run, the statistics of single-channel and array correlation coefficient traces were examined for different scenarios (no identified signal, unrelated signal, signal from close to the target area - in this case the Zapoljarni mines in NW Russia, signal from exactly the target area) in a similar way to that displayed in Figure 3 of Gibbons et al. (2006). On the basis of these studies, it was determined that a preliminary detection should be declared whenever a value on the array correlation coefficient beam (ACCB) exceeded by a factor for 10.0 the standard deviation of the most centrally distributed 95% of the values of the ACCB. For every occasion on which a local maximum of the ACCB satisfied these conditions, the 2.5 seconds preceeding and following this detection were associated with the detection in an attempt to preclude the recording of local maxima within the auto-correlation function as detections. Every occurrence of a correlation detection was followed by an f-k measurement of the single-channel correlation coefficient traces as described by Gibbons and Ringdal (2006) with the slowness vector and the relative beam-gain being recorded.

Between January 1, 2002, and December 31, 2005, a total of 17485 detections were made based upon the value of the (scaled) array correlation coefficient beam[1] alone. This is clearly far more detections than is likely to correspond to the actual events being monitored (this is approximately 20 detections per day). Each detection is associated with four measurements:

1. Value of the array correlation coefficient beam (ACCB)
2. Multiple by which the ACCB exceeds the standard deviation of values within the time-segment being investigated
3. The slowness vector pertaining to the maximum beam-gain from the single-channel correlation coefficient traces (using broadband f-k analysis with the assumption of a plane-wave propagation model)
4. The relative f-k power or beam-gain corresponding to this optimal slowness vector

The value of the correlation coefficient should of course be as large as possible to indicate the greatest possible waveform similarity.

The scaled correlation coefficient should also be large to indicate the significance of a detection.

The correlation coefficient slowness vector should be as close as possible to a zero vector to indicate that the detected incoming wavefield and the wavefield represented by the template come from a very similar direction.

The beam-gain parameter should be high to indicate the significance of an “almost zero” slowness vector.

1. Whilst the actual beam of correlation coefficients was used rather than a scaled trace as described by Gibbons and Ringdal (2006), the threshold was always set as a multiple of the standard deviation of the correlation coefficients being considered. This provided an experimental dynamic threshold. It will be the subject of further investigations as to which detection statistics are likely to provide the most sensitive and the most robust correlation detectors.

Selection criteria for detections which are likely to correspond to signals from events in the source region being monitored need to assess this parameter space and determine values for each of the measurements which define a threshold of plausibility. A decision was made to remove all preliminary detections which did not satsify the following three conditions:

- Value of maximum ACCB must exceed 20.0 times the standard deviation of ACCB values in the time segment considered
- The magnitude of the CC-trace slowness vector must not exceed 0.02 s/km
- The beam-gain of the CC-traces must exceed 0.2

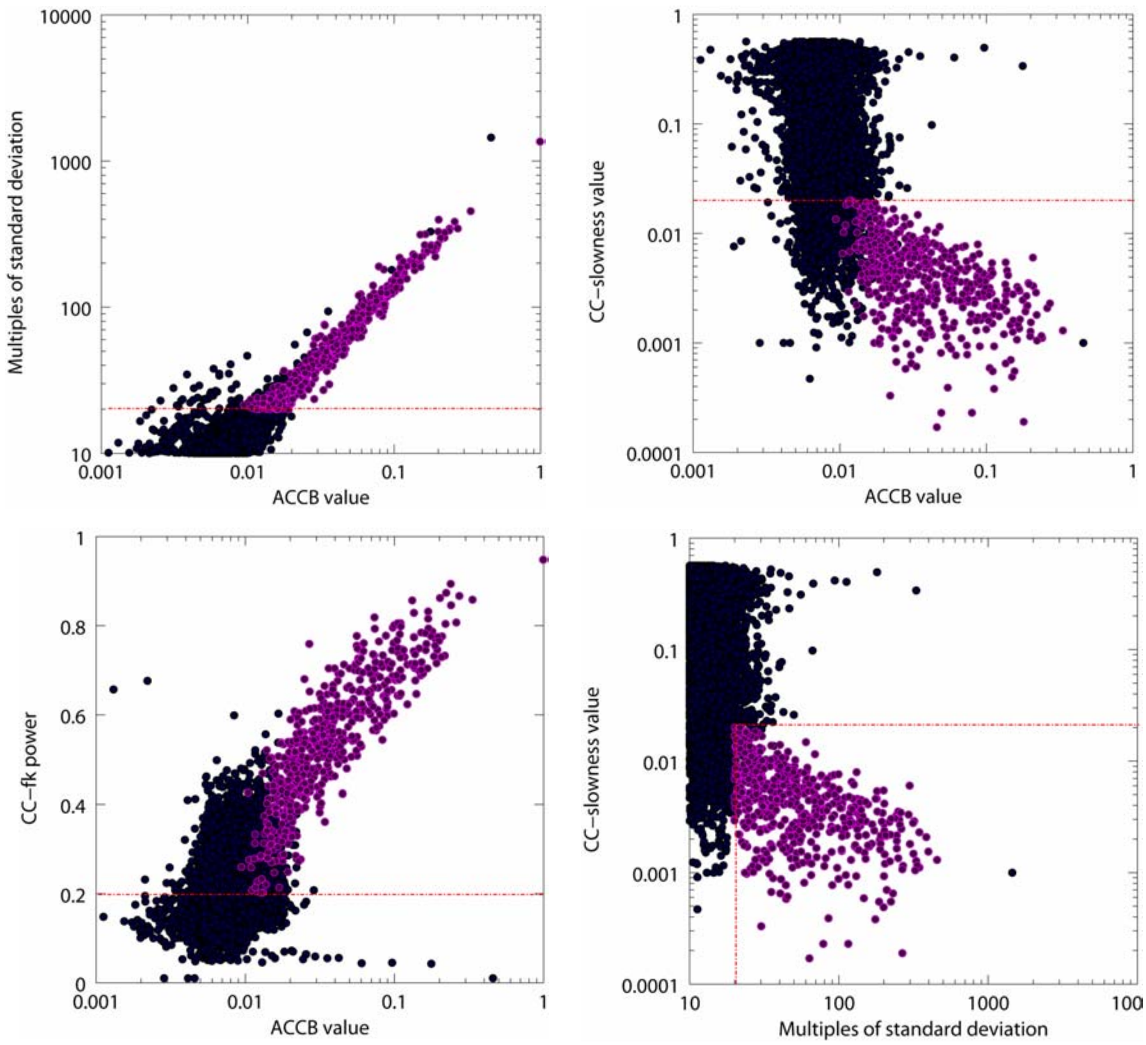

Fig. 6.3.2. Properties of the 17485 preliminary correlation detections for the ARCES Russian Explosion site template. The brighter colored symbols indicate the 557 detections which passed the three conditions listed above. ACCB stands for "Array Correlation Coefficient Beam". The dashed red lines indicate the cut off points in each parameter space for the acceptance of correlation detections.

Figure 6.3.2 displays the listed properties of the full set of preliminary detections together with the detections which passed the subsequent post-processing tests highlighted. The new conditions placed upon the correlation detections have reduced the number of detections under consideration from 17485 to 557.

A closer inspection of the detection lists reveals that almost all of these 557 detections in the reduced list consist of multiple detections in rapid succession. The reason for this becomes apparent when inspecting the waveforms and correlation traces for an example detection (Figure 6.3.3). Instead of a single maximum of the correlation beam, surrounded by diminishing sidelobes, the correlation beam contains approximately 15 seconds of values which are approximately an order of magnitude higher than the background values. Close inspection of the waveforms reveal that signals are not particularly similar. For example, the correlation coefficient traces in this example could not be used to measure relative delay times for double-difference relocation. We cannot yet be certain how far apart the source locations for these two events are. However, the emergence of a high amplitude signal with sound velocity from the same direction at a similar time to that corresponding to the master event is an indication that the source type at least might be similar and that the distance separating the events is probably not very large.

We proceed to attempt to identify which of the 557 detections correspond to seismic events close to the source of our master event.

The first step is to separate out multiple detections. This was performed using a simple association algorithm by which detections were eliminated if they occurred within 60.0 seconds of a detection with a higher value of the scaled correlation coefficient. Given a sequence of associated detections, the one corresponding to the highest scaled correlation coefficient often occurs later in the sequence. The resulting list of detections contained 244 hypothetical events.

The second step is to attempt to associate these hypothetical events with events in the automatic GBF event bulletin. Out of the 244 event hypotheses, 220 were associated uniquely with an automatic GBF event solution. These event location estimates are displayed in Figure 6.3.4. These estimates cover an area of many thousands of square kilometers and GBF estimates for events from many other sites in this part of the world show a similar distribution (see, for example, Kværna et al. 2006). Comparing the times of detections with times of confirmed events at mines in Zapoljarni confirms that none of the event hypotheses resulting from the current detector coincided with known mining events from this region. We conclude that, despite the waveform dissimilarity between the different signals from these events, the waveform correlation procedure described provides a highly effective method for identifying the source region.

Three of the 244 event hypotheses corresponded to multiple GBF solutions falling within the region displayed in Figure 6.3.4. Only 21 of the event hypotheses did not correspond to events in the GBF. These are summarised in Table 1. Four of these appear to be convincing correlation detections but for which the signal is too weak to be detected by the online system. Vespagram analysis of the waveforms did provide indications of coherent energy with the appropriate apparent velocity and azimuth at the appropriate times, although the weak signal made it impossible to estimate arrival times for the primary and secondary phases. A further three were convincing correlation detections which did not appear on the GBF due to interfering signals or other exceptional reasons.

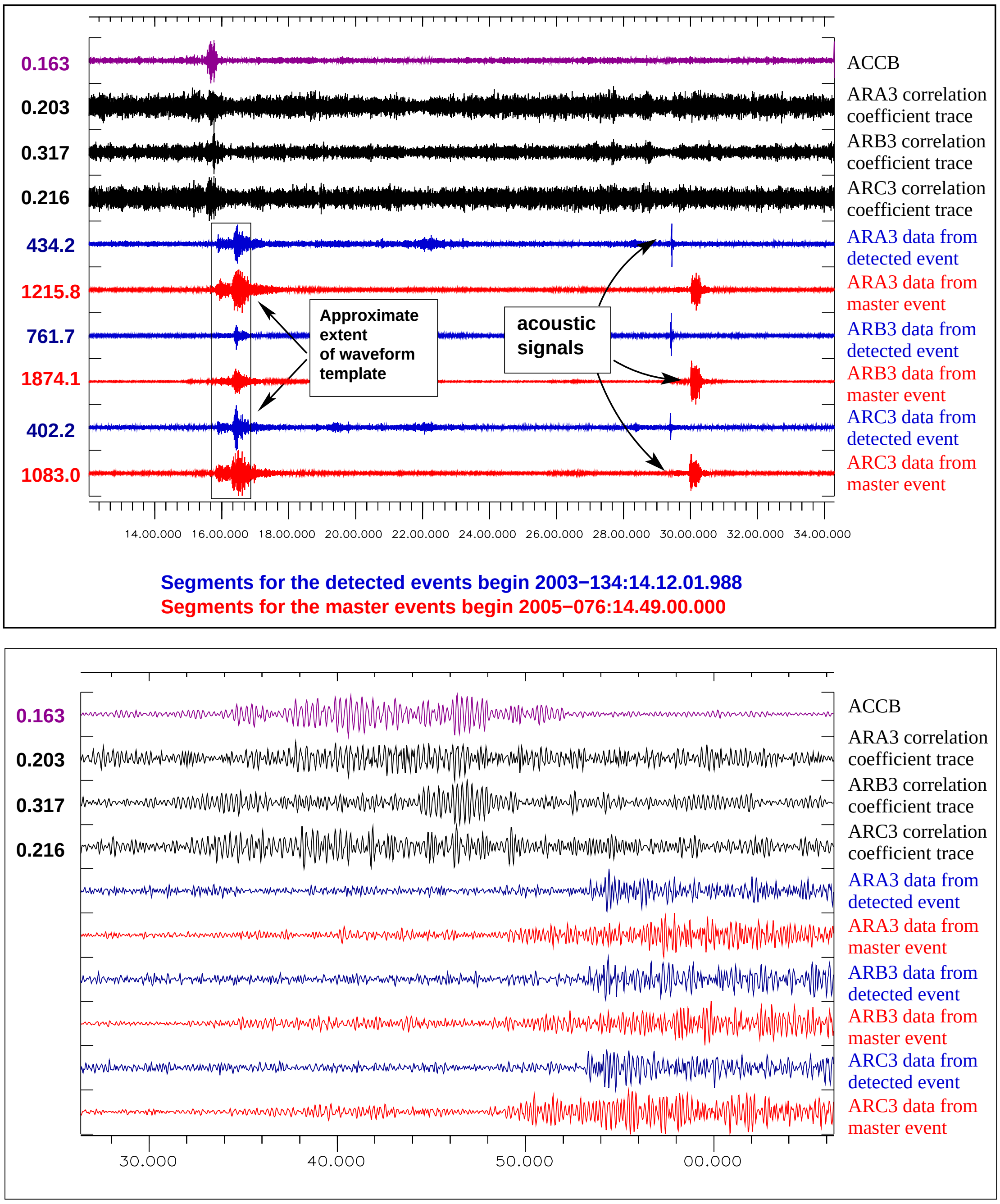

Fig. 6.3.3. A typical correlation detection on the ARCES array for the Russian surface explosions. Whilst there is no single correlation maximum (as was the case for the examples provided in Gibbons and Ringdal, 2006, and Gibbons et al., 2006) the alignment of the single site correlation coefficient traces reduces the suppression of the single channel values under the stacking operation. This alignment becomes clear when the broadband f-k analysis is performed upon the single channel values. Under the detection reduction algorithm presented, this event appears as two distinct detections.

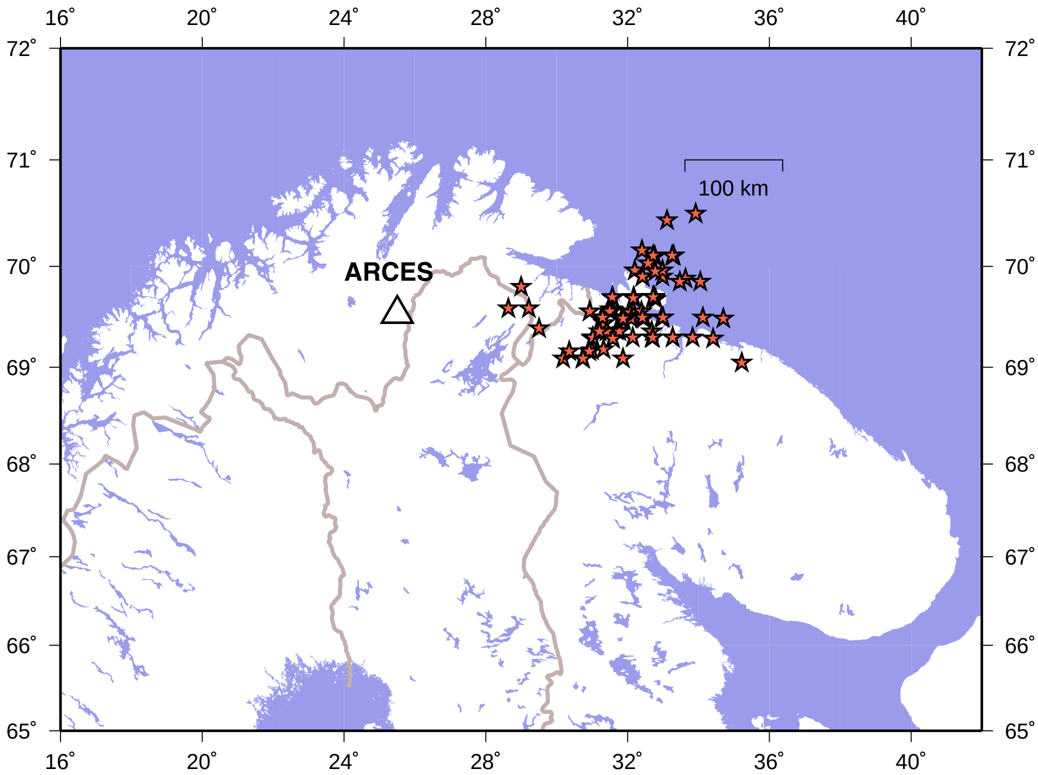

Fig. 6.3.4. Fully automatic GBF location estimates for events corresponding to 220 of 244 event hypotheses for Russian explosions resulting from the correlation detector described.

All times in Table 6.3.1 labelled "False alarm" were followed by a high amplitude Rg phase in the ARCES data some 70 seconds later. Visual inspection of the f-k plots of the correlation traces reveals a very different pattern of side-lobes to those observed for the more convincing detections - this may at a later stage be incorporated into more sophisticated selection criteria. The presence of the high-amplitude Rg phase is a very promising screening criterion due to the consistency of the time at which it occurs in relation to the event hypothesis and the stability of the f-k estimates using this signal.

6.3.3 Summary

We have demonstrated in this study that the rank-1 waveform correlation detector on an array has proved to be a very effective tool for the detection and approximate location of events from a given source region despite the lack of similarity between signals from subsequent events. Of paramount importance is the alignment of the correlation coefficient traces which facilitates a powerful screening criterion.

We do not yet have Ground Truth confirmation of these events and some unrelated events from a similar direction may have been included. However, this procedure has created a shortlist of events for analyst review which has far fewer possible false alarms than any other procedure currently available.

Acknowledgement

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Table 6.3.1. Summary of the 21 event hypotheses for the presumed Kola Peninsula explosions not associated with an automatic GBF event location.

Event time hypothesis	Evaluation
2002-015:10.03.27.813	False alarm
2002-231:14.32.05.388	Convincing signal correlation: signal too weak for STA:LTA detection
2002-254:14.49.16.963	Convincing signal correlation: signal too weak for STA:LTA detection
2002-255:16.25.09.788	Convincing signal correlation: signal too weak for STA:LTA detection
2002-304:05.05.54.688	False alarm
2002-321:14.38.25.013	False alarm
2002-361:08.52.51.488	False alarm
2002-362:23.06.45.138	False alarm
2003-090:02.36.36.463	False alarm
2003-226:15.15.56.213	Convincing signal correlation: signal too weak for STA:LTA detection
2003-313:19.08.51.838	False alarm
2003-322:19.38.47.688	Convincing correlation: strong Sg phase detected by STA;LTA detector but P-phase obscured by strong unrelated Rg signal
2003-328:18.39.06.338	Convincing correlation: Strong signal located by single station process.[a] Presumed absent from GBF list due to a one-off technical fault.
2003-334:00.54.21.225	False alarm
2004-292:02.18.41.750	False alarm
2004-319:04.45.05.300	False alarm
2005-059:04.39.54.700	False alarm
2005-075:08.46.56.875	False alarm
2005-272:16.56.54.325	Convincing correlation: in coda of an unrelated high amplitude regional phase.
2005-310:12.12.35.325	False alarm
2005-328:19.12.14.550	False alarm

a. http://www.norsar.no/NDC/bulletins/dpep/2003/328/ARC/ARC03328.html

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S. J. Gibbons
F. Ringdal