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6.2 A waveform correlation procedure for detecting decoupled chemical explosions

6.2.1 Introduction

Between 1986 and 1989, a total of 11 decoupled chemical explosions were carried out in two underground chambers at a site in Älvdalen, central Sweden, by the Klotz Group of ammunition safety experts. Explosions with yields 10, 1000, and 5000 kg were performed in each of the two chambers, one with size 300 m^3 and one with size 200 m^3.

A complete list of these experiments is provided in Table 6.2.1 after Vretblad (1991), the date of each explosion being provided but without origin time. Both the NORES regional seismic array, central element a distance of 143 km from the test site, and the large aperture NORSAR teleseismic array, with instruments at distances between 123 and 175 km, were operational at the time. It should be noted, however, that the explosions were carried out prior to the NORSAR upgrade of 1995 and so this array only recorded data with a 20 Hz sampling rate. All NORES data is recorded with a 40 Hz sampling rate.

Our primary goal is to investigate the effects of seismic decoupling on the characteristics of seismograms recorded at regional distances. If we are to include these tests into the very small available database of such explosions, we need first to determine which part of the recorded data corresponds to the signals resulting from these experiments, or, equivalently, to determine the unknown origin times. An initial inspection of the NORES detection lists for the days in question does not produce any obvious candidates for the hitherto unidentified Klotz tests with the possible exception of shot number 4[1]. Gibbons et al. (2002) demonstrate that the Älvdalen signals are dominated by higher frequencies at which coherence between instruments is very poor, even over the small aperture NORES array; this makes it more difficult to determine the slowness and azimuth of detected phases using traditional array processing techniques.

We have at our disposal waveform data from four subsequent explosions from a third chamber at the same site which took place between December 2000 and June 2002 (see Gibbons et al., 2002, Stevens et al., 2003). In addition, the three largest of the experiments listed in Table 6.2.1 (shots 8, 9, and 11) have already been identified since they resulted in signals which are clearly visible in NORES and NORSAR data without filtering (Figure 6.2.1). These three shots are labelled 1987C146, 1987C259, and 1989C263 respectively in Stevens et al. (2003).

We aim to identify the data which corresponds to the unknown events by matching waveform data with signals resulting from the known events. We assess first the degree of correlation between waveforms from the events already identified and subsequently apply this to continuous data for the days on which the events in Table 6.2.1 are known to have taken place.

1. See http://www.norsar.no/NDC/bulletins/dpep/1986/177/NRS/NRS86177.html - automatic location ID number 135320 is ascribed an origin time of 1986-177:09.14.06.2, latitude 61.422°, longitude 13.901° a distance of 148 km from NORES at a backazimuth of 57.9°.

Table 6.2.1. The 11 Klotz group explosions at the Älvdalen site between 1986 and 1989. Information obtained from Vretblad (1991). Chambers A and B have volumes of 300m^3 and 200m^3 respectively.

Shot number	Date (yym-mdd)	Yield/ kg	Ammu-nition type	Site	Purpose of test
1	860611	10	TNT	A	Calibration
2	860610	10	TNT	B	Calibration
3	860617	1000	TNT	A	Study of large ejecta pieces
4	860626	1000	TNT	B	As (3) with debris trap
5	860917	1000	Shells	A	Comparison of pressures with and without casing. Study of fragment throw
6	860903	1000	Shells	B	As (5) but with debris trap
7	870521	1000	ANFO	A	Study of the effectiveness of ANFO for this type of simulation
8	870916	5000	ANFO	A	As (5) but with higher loading density and artificial debris
9	870916	5000	ANFO	B	As (6) but with higher loading density and with artificial debris.
10	890830	1000	Shells	A	As (5) but with a berm in front of the tunnel
11	890920	5000	ANFO	A	As (8) but with a berm in front of the tunnel.

We note that waveform correlation methods have been applied in the past e.g. for detecting routine blasting operations at known industrial sites (Harris, 1991). These studies have shown considerable promise, but a major problem has been that seismograms from similar industrial explosions can differ significantly in waveform characteristics, both as a function of variations in blasting practice (see, for example, Stump et al., 2001) and because of differences in locations even within the same mine (Bonner et al., 2003). In our study, the explosion sources are very simple and of similar nature, and the shot points are closely spaced (the shots are detonated in a total of three chambers, separated by less than 200 meters). As will be shown in the following, this results in a significant improvement in the detection capability of such events by using waveform cross-correlation as compared with using conventional detectors. Furthermore, we will show that applying array processing to the correlation traces gives a considerable improvement over single-station correlation procedures.

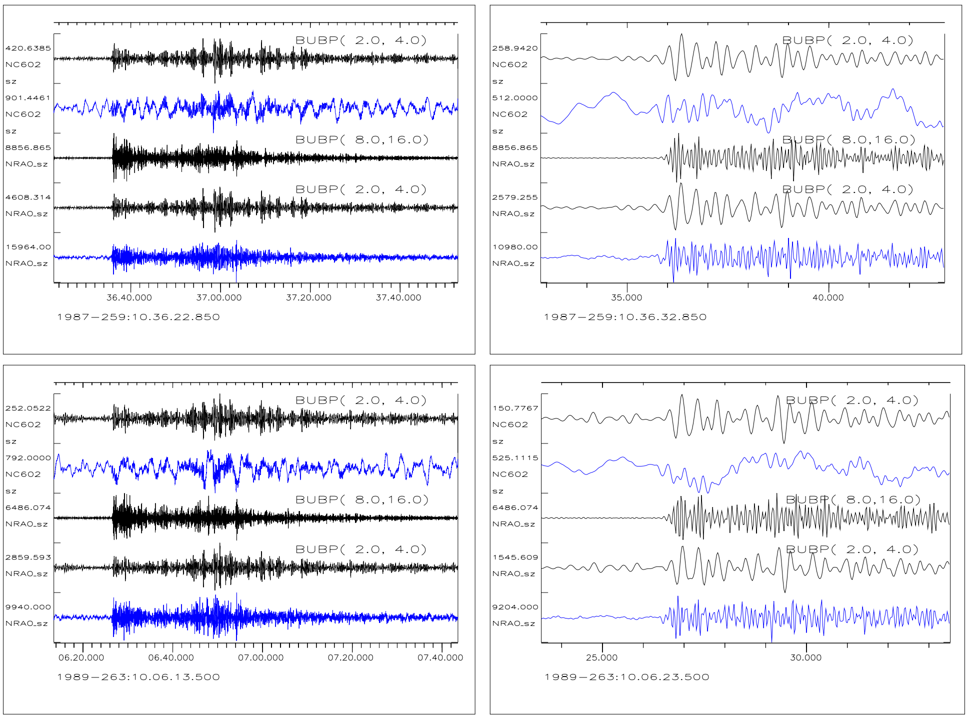


Fig. 6.2.1. Waveforms from two of the 5000 kg yield explosions recorded at the NORES central element NRA0 and the co-located NC602 element of the NORSAR array. The blue waveforms are unfiltered data and the black waveforms are bandpass filtered in the ranges indicated. The events are shots (9) and (11) in Table 6.2.1 respectively. Note the similarity between the waveforms from the events in the two different chambers.

6.2.2 Single-station correlation coefficients for the known events

Table 6.2.2 shows the fully normalized correlation coefficients for NRA0 data for explosions already known to have taken place in the various chambers at the Älvdalen site. Note that the final event from June 13th 2002 is not included as there is no NORES data for this explosion. When the broad frequency band (2.0-18.0 Hz) is used, the correlation coefficient is high for all of the event combinations except for those that include the 2001C150 event which was by far the weakest signal. However, when a higher frequency band (14.0-18.0 Hz) is used, even this event results in very high correlation coefficients since the signal to noise ratio is far better for these frequencies. All the data used here was resampled to 200 Hz in order to perform the cross-correlation.

Given that the signals that we are searching for are likely to be very weak, we proceed to use data filtered in a high frequency band for the correlation tests.

Table 6.2.2. Correlation coefficients of waveforms recorded at the instrument NRA0_sz for events as labelled in Gibbons et al. (2002). All values are calculated for a five second time window beginning shortly after the P-onset time; values below the diagonal are for waveforms filtered in the frequency band (2.0-18.0 Hz) and those above the diagonal are for the frequency band (14.0-18.0 Hz). Values in red indicate that the two events took place within the same chamber.

Correlation coefficients (NRA0_sz)	1987C146	1987C259	1989C263	2000C348	2001C150	2001C186
1987C146	-	0.984	0.977	0.855	0.805	0.845
1987C259	0.919	-	0.987	0.877	0.821	0.871
1989C263	0.981	0.914	-	0.862	0.796	0.853
2000C348	0.852	0.862	0.851	-	0.902	0.997
2001C150	0.310	0.293	0.318	0.423	-	0.900
2001C186	0.846	0.846	0.843	0.971	0.448	-

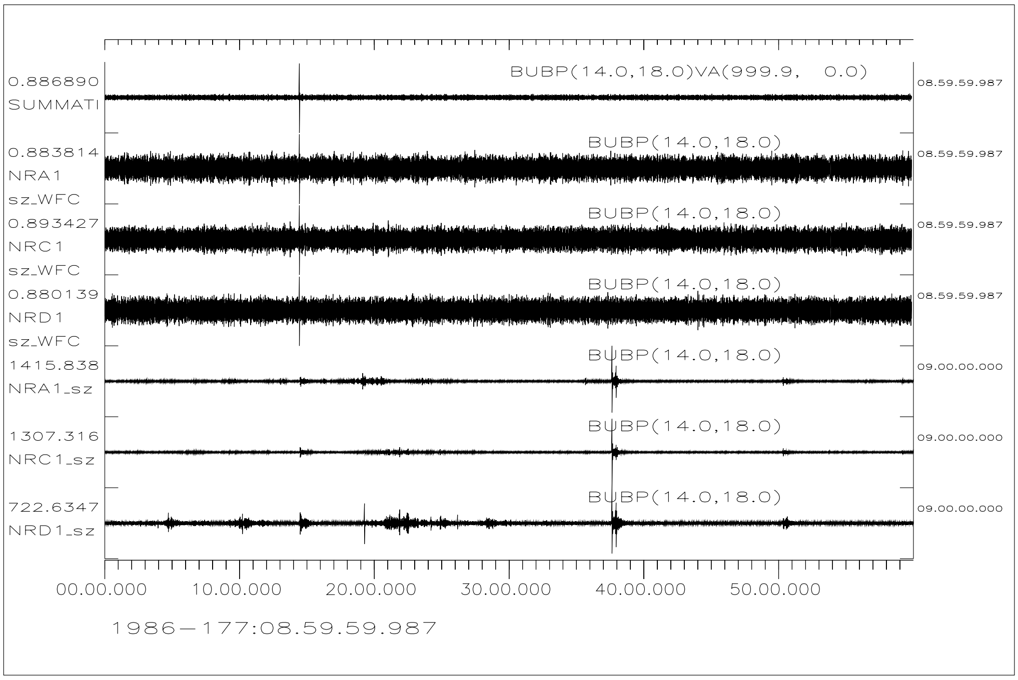
6.2.3 Multiple channel waveform correlation for the detection of the unknown events

The correlation coefficients provided in Table 6.2.2 refer only to a single channel. Each of these coefficients is in fact the maximum value of a trace produced by correlating a short, fixed time window from a ‘master event’ with consecutive sections of a much longer time series. This trace would reach a maximum value of 1.0 should the master event time window be an exact (positive) multiple of the corresponding segment of the longer seismogram. Otherwise the waveform correlation trace will vary between 1.0 and -1.0, fluctuating about a zero mean depending upon whether the contribution from the in-phase parts of the waveform exceeds the contribution from the out-of-phase parts or not.

Given that we have array data available, we ought to be able identify correlation maxima more easily by an appropriate stacking of the individual correlation traces. Deterministic correlation will occur simultaneously for all channels used (subject to any time-shift imposed when defining the master event time-windows) whereas other local maxima and minima of the individual waveform correlation (WFC) traces are assumed to occur randomly.

An 8 second long time-window was selected from the signal from event 1987C259 (the event with best SNR) for each sz channel of the NORES array. For simplicity these windows started simultaneously, removing the need to apply time-shifts when stacking the WFC traces. The master event traces were subsequently filtered in the frequency band 14.0-18.0 Hz and resampled to 200 Hz. The resulting waveforms were correlated against the corresponding filtered data for the days of the unknown events.

Figure 6.2.2 indicates the results of this procedure for an hour of data beginning at 1986-177:09.00.00.0. A clear and unique peak is observed for all of the WFC traces at a time 1986-177:09.14.28.61 and therefore also on the summation channel. Note (a) the degree of noise suppression which results from the stacking of the WFC traces and (b) the fact that several other regional signals are observed in this one hour long data segment and that none of them have a noticeable effect upon the fully normalized correlation coefficient traces.



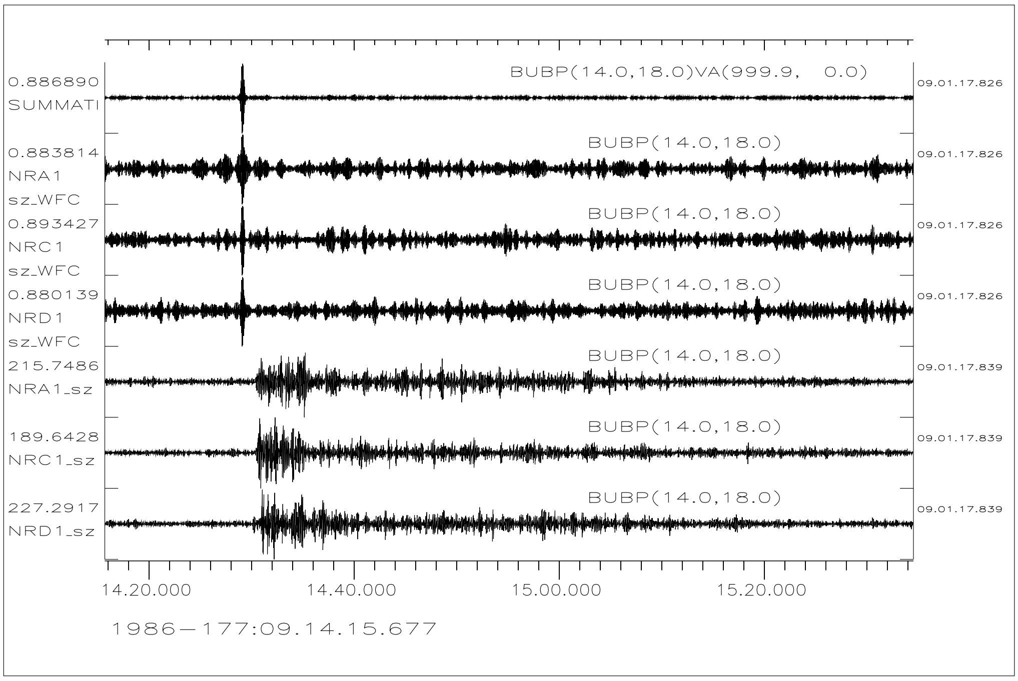


Fig. 6.2.2. Results of a waveform correlation between the filtered master event waveforms and an hour of NORES data on the day on which shot 4 in Table 6.2.1 is reported to have taken place. The upper frame shows a full hour of data and the lower frame a zoom in. The lowermost three traces indicate the filtered data, the traces labelled WFC, the corresponding correlation coefficient traces and the upper trace gives the summation of all NORES waveform correlation traces.

The process was also applied to the days 1986-168, 1986-177, 1986-260, 1986-246, 1987-141, and 1989-242. For all but one of these days, a single correlation peak was observed and corresponding event origin times (deduced from the times of these peaks, the definitions of the master event time windows, and the source to receiver travel times) are tabulated in Table 6.2.3. It is worthy of note that, with the exception of shot 4, no NORES detection was made using the standard on-line processing (shot 4 resulted in the strongest signals given the higher charge density due to the smaller size of chamber B).

Table 6.2.3. Estimated origin times for the 1000 kg Klotz explosions determined from NORES data.

Shot number	Estimated origin time from NORES data
3	1986-168:10.06.15.9
4	1986-177:09.14.07.1
5	1986-260:11.34.17.4
6	No correspondance found in existing NORES data
7	1987-141:10.16.08.3
10	1989-242:10.12.21.0

On day 1986-246, the day of shot number 6 in Table 6.2.1, there is no NORES data until approximately 12.50 GMT and there are no clear correlations following this time. NORSAR data does exist for the whole of this period although it is not clear that this data would allow us to identify this event given; the Nyquist frequency of this data is 10 Hz and the anti-aliasing filter cutoff frequency is 4.5 Hz, well below the frequencies where these signals achieve their optimal SNR. Nevertheless, the slope of the anti-aliasing filter is such that useful energy is recorded up to the Nyquist frequency for high-frequency signals.

In order to increase the likelihood that a positive correlation could be achieved using the 1987C259 event, a full minute of NORSAR data was taken from the master event thus including secondary phases (especially Lg) which are likely to feature better at low frequencies. The data was filtered in the frequency band 6.0-9.5 Hz.

As indicated by Figure 6.2.3, a positive correlation was indeed observed indicating an origin time for this last remaining event of 1986-246:11.50.45.1. This positive identification is remarkable in that the waveforms themselves do not (in the available frequency band) display a signal which can be identified by an analyst or, consequently, detected by a standard STA/LTA detector. Figure 6.2.3 purposefully displays the closest station to the origin (NC301) and the most distant (NAO03). The WFC trace for NAO03 does not even achieve a global maximum at this time, the corresponding correlation coefficient being 0.232. The other stations of the NORSAR array generally give higher correlation coefficients the closer they are to the source and, indeed, the WFC trace for NC301 does give a higher correlation coefficient at this time than at any other during this one hour period. When creating the summation trace, all WFC traces are included since even those which do not have a global maximum at this time do interfere constructively to produce the summation maximum at the point indicated (see the lowermost panel).

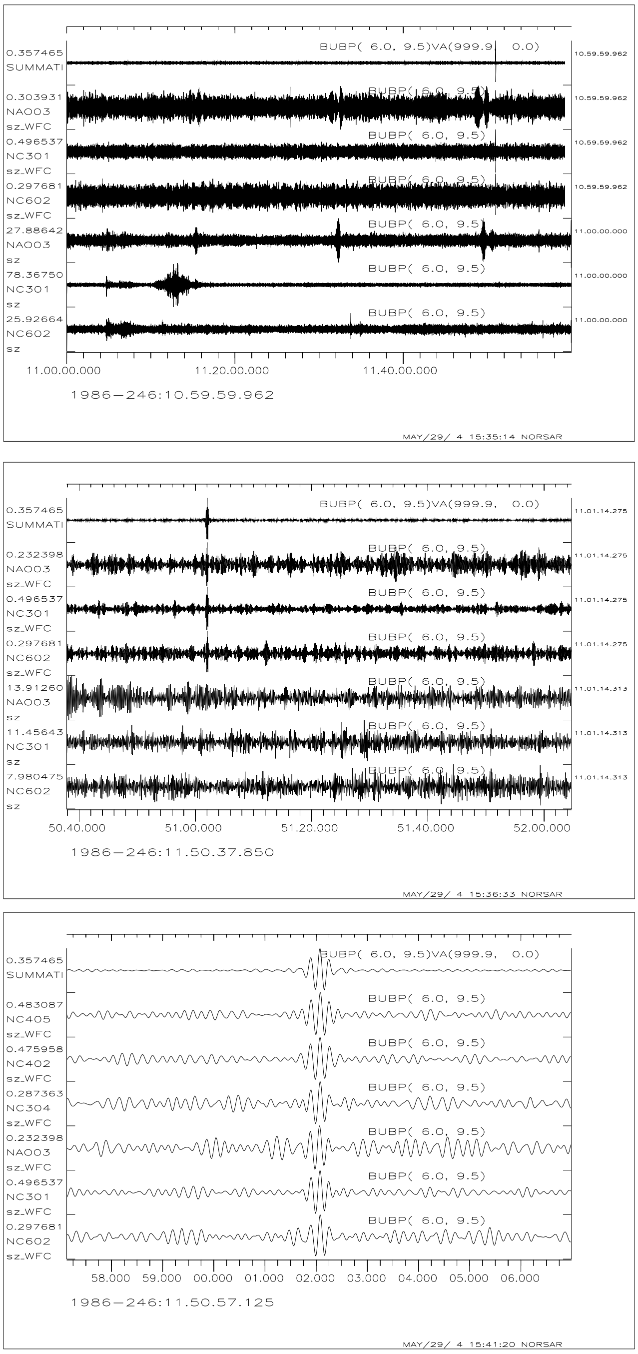


Fig. 6.2.3. Illustration of how we were able to detect shot number 6 in Table 6.2.1 using data from the large aperture NORSAR array (no NORES data exists for this time period). Waveforms, WFC traces, and summation trace for an hour long segment (top), a close up view (centre), and a zoom of the stacking of the WFC traces (lowermost) are shown.

6.2.4 Identification of a 500 kg explosion in the 1000 m^3 chamber at Älvdalen.

Five days prior to the December 13th 2000 Älvdalen explosion, in which 10000 kg of pure TNT was detonated within a chamber of size 1000 m^3, a detonation of 500 kg TNT took place in the same chamber (Wu et al., 2003). No signals from this events were detected at the nearby seismic arrays. In addition to NORES and NOA (now with data at 40 Hz sampling rate), there is also data from the Hagfors array in Sweden. Segments of signal were extracted from each of the short period instruments for the 2000-348 event and filtered in the frequency band 14.0-18.0 Hz. The cross-correlation procedure was applied to data from each of the three arrays separately.

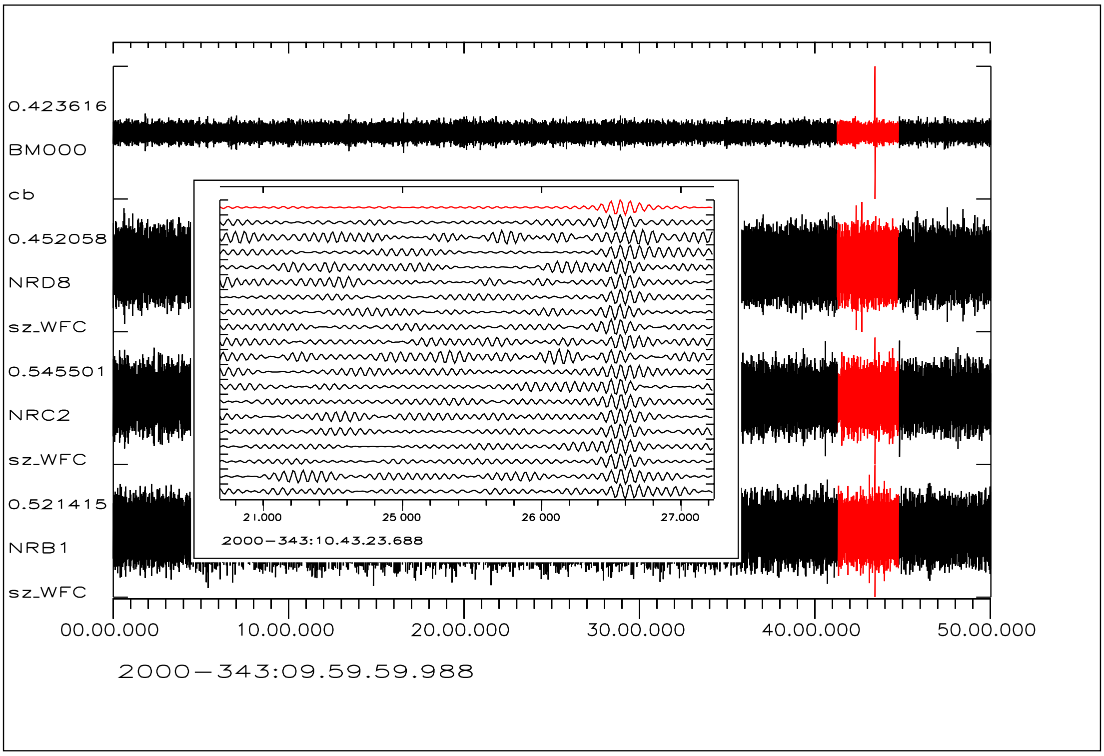


Fig. 6.2.4. Results of waveform correlation for the 8th December 2000 explosion using NORES data. The inset panel indicates how the constructive interference from the individual WFC traces leads to the significant global maximum despite the fact that this time is a global maximum for very few of the single station WFC traces.

Each of the arrays NRS, NOA, and HFS produced a unique WFC summation peak at a time consistent with an origin time of 2000-343:10.43.04.5. On none of the waveforms is it possible for an analyst to identify the direct signal from this small explosion, even filtered in this high frequency band. There are very few stations which produced a global maximum correlation coefficient at this time; a stacking of the WFC traces from each of the full arrays did however lead to clear peaks corresponding to this time.

It is important to emphasize that the three different arrays all resulted in times of maximum cross-correlation which were consistent with one single source at the Älvdalen test site.

6.2.5 Conclusions

- The waveforms resulting from subsequent explosions in the various chambers at the Älvdalen site correlate very well, even at very high frequencies. Unlike many mining explosions where source characteristics can vary greatly between events, these decoupled chemical explosions have a simple source function which has been almost identical for each of the tests.
- A further seven events from this site have been identified by finding the data which best matches waveforms from larger events confirmed to have taken place at Älvdalen.
- Only one of these events had been detected by the standard on-line processing. The 1000 kg Klotz explosions from 1986 to 1989 could probably have all been detected and processed in this way given sufficient modifications to the detection and processing recipes. Any such modifications would, however, lead to far more false alarms with limited returns in detectability given the poor coherence of the weakest signals from these events.
- A 500 kg explosion in the 10000 m^3 chamber was detected by applying the same process to data from the NRS, HFS, and NOA arrays. The signal is only observable in the sense that the waveform correlation traces stack to maximum values for all three arrays, independently implying the same origin time for a hypothetical event at the Älvdalen site.
- The noise suppression obtained by stacking the waveform correlation traces over the arrays was significant. The teleseismic NORSAR array is as effective as the NORES and Hagfors regional seismic arrays for these detections by cross-correlation since the interstation coherency of the waveforms themselves is of no consequence. A similar result could be achieved using a network of many stations.

An online process was set up to test continuous NOA data, correlating with the master event 2002C164 (see Stevens et al., 2003). Waveform correlation channels were calculated and stacked as described here and an optimal STA/LTA detector run on the WFC summation channel. The SNR threshold for this detector was set to 3.5 (following extensive tests whereby it was shown that, within any given hour, the maximum SNR value would probably be between 2.0 and 2.8 and would very rarely exceed 3.2). The process was performed for selected days from 2000, 2001, and 2002, and run on continuous data from July 1st 2003 to the present.

For all the data processed so far, the STA/LTA detector has only triggered 5 times: each time for a confirmed event from the Älvdalen site. The smallest event from December 8th, 2000, produced a stacked correlation coefficient of 0.31 and a corresponding signal to noise ratio of 6.91. For the 10000 kg explosion in the same chamber 5 days later, a correlation coefficient of 0.98 was achieved with a corresponding SNR of 24.55. The May 30th, 2001, test (2001C150, which was the weakest of the events detected by normal processing) resulted in a mean correlation coefficient of 0.76 and a corresponding SNR of 15.39. No Älvdalen explosion which the authors know of has failed to be detected by this test, and on no occasion did the test produce a detection without there having been a confirmed explosion at Älvdalen.

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