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6.1 Detecting the aftershock of the 16 August 1997 Kara Sea event by waveform correlation

6.1.1 Introduction

On 16 August 1997, a small seismic disturbance occurred in the Kara Sea, approximately 100 km from the former Soviet nuclear test site on the island of Novaya Zemlya (see Figure 6.1.1). The event was recorded by several seismic stations and had an estimated magnitude m_b=3.5 (Ringdal et al., 1997). The close proximity of the event to the nuclear test site led to initial concerns that the event could have been a small clandestine nuclear explosion in violation of the Comprehensive Nuclear Test Ban Treaty (CTBT) which had been adopted by the United Nations eleven months previously. The event has been the subject of many subsequent publications (e.g. Richards and Kim, 1997; Hartse, 1998; Asming et al., 1998; Ringdal et al., 2002; Bowers et al., 2001; Kremenetskaya et al., 2001; Bowers, 2002; Schweitzer and Kennett, 2002) and the generally accepted conclusion, based upon location, spectral characteristics and other observations, is that the event was an offshore earthquake.

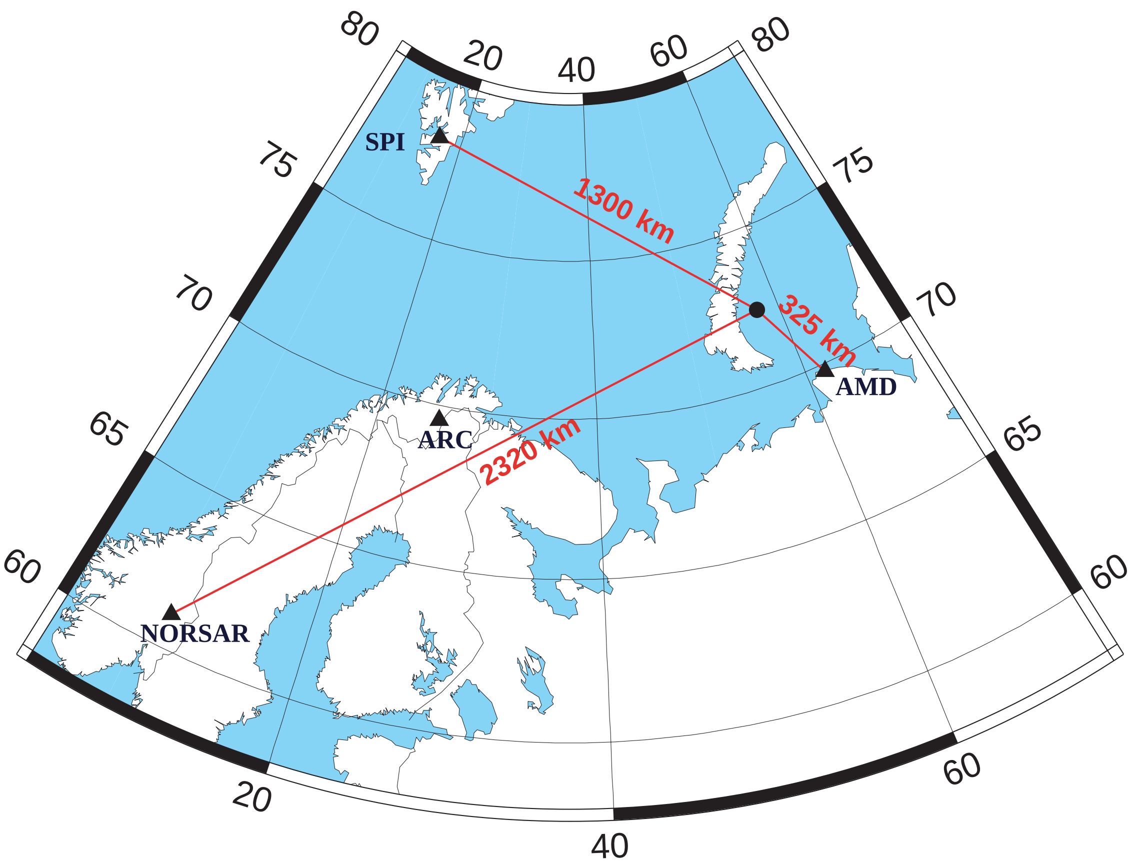

Fig. 6.1.1. Map indicating the location of the 16 August 1997 seismic disturbance in the vicinity of Novaya Zemlya. Also indicated are the locations of the SPITS and NORSAR seismometer arrays, the station at Amderma, Russia, and the ARCES array which was unusually and unfortunately not operational at the time of the event.

As Richards and Kim (1997) point out, one of the most compelling pieces of evidence for the classification of the event as an earthquake was the occurrence of a small event (assumed to be an aftershock) approximately four hours following the main event. Crucial to the classification of this second event as an approximately co-located aftershock is the similarity of the waveforms between the two events observed at the Amderma station in Russia at a distance of 325 km (Ringdal and Kremenetskaya, 1999; Ringdal et al., 2002), the only station to have recorded both events with a high signal-to-noise ratio (SNR). The Amderma waveforms for both events are displayed in Figure 6.1.2.

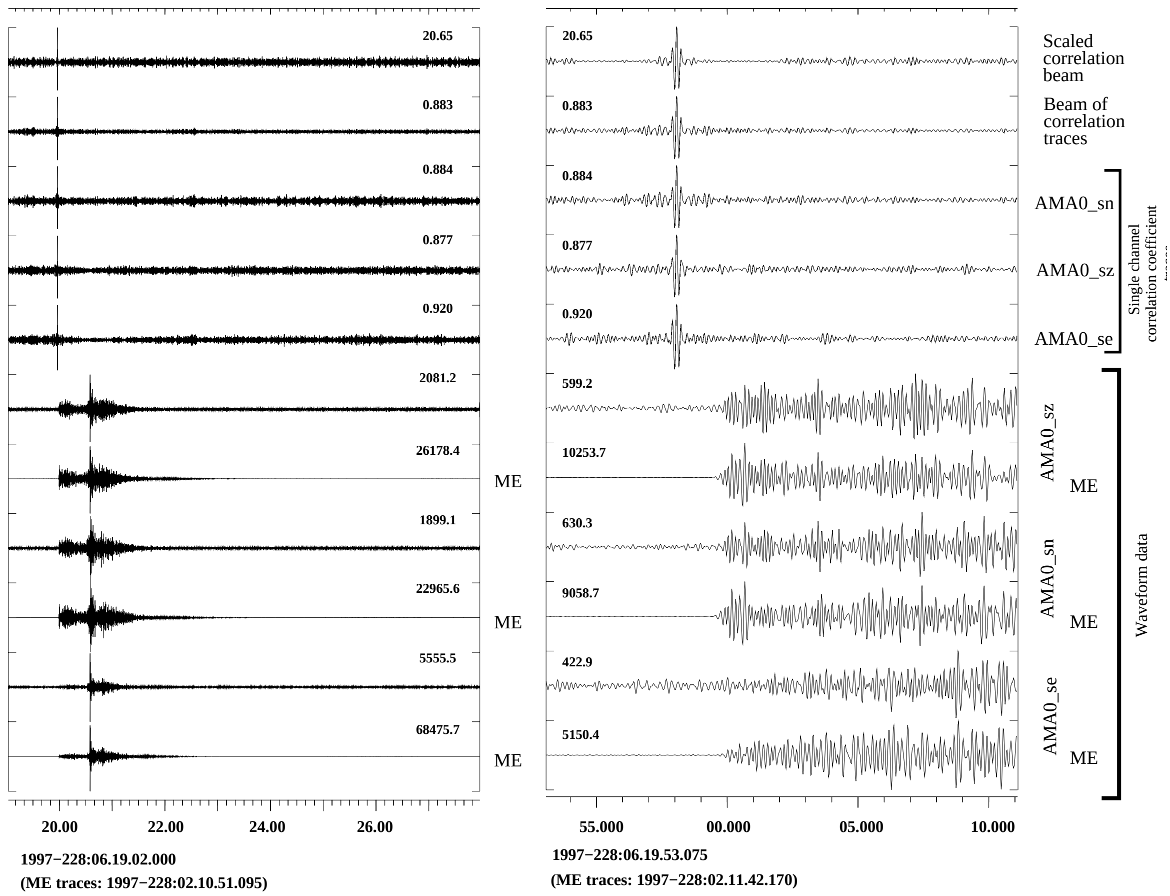

Fig. 6.1.2. The closest seismic station to record the event was the 4-site array at Amderma in Russia. The plots show the three components at the central AMA0 site. The traces labelled ME (master event) contain the signal from the main event and the remaining waveforms contain the signal from the presumed aftershock, aligned according to the time of maximum waveform-correlation. The correlation coefficient traces for the three components are displayed above the waveforms as labelled and the top two traces are the "beam" of the correlation traces and the rescaled beam (see Gibbons and Ringdal, 2005). All cross-correlation coefficients are obtained using data segments of length 60.0 seconds. The panel to the right is a close up of the P-arrival from the left panel. The waveform semblance between the two different events is clearest in these recordings given the high signal-to-noise-ratio (SNR) for both events. All waveforms bandpass filtered between 4.0 and 8.0 Hz.

The second event was of estimated magnitude $m_b = 2.5$ and was only detected by a single station of the International Monitoring System for the CTBT (IMS): the SPITS array on Spitsbergen at a distance of approximately 1300 km. Even at this station, only the P-arrival was detected and careful manual analysis was required for the identification of the signal. Given the importance of this second event to the conclusions drawn about the nature of the source, it is a cause of some concern that it was only barely detected by the global seismic network designated to monitor signals from such events. (The station at Amderma is not part of the IMS.)

The correlation coefficient between waveforms from the main event and the aftershock recorded at Amderma, using a 60.0 second waveform template bandpass filtered between 4.0 and 8.0 Hz, was approximately 0.9 for all of the available data channels (Figure 6.1.2). The segment of the waveform taken from the master event begins at a time 1997-228:02.11.47.170 and the time of maximum correlation coefficient was 1997-228:06.19.58.075; these two times are separated by 14890.905 seconds. Subtracting the template waveform multiplied by 0.06551 from the aftershock waveform results in the smallest residual in the least squares sense; this gives a scaling factor of approximately 15 between the amplitudes for the two events.

The high degree of waveform semblance between the two events at the Amderma station indicates waveform correlation as a possible means of detecting signals at stations more distant from the event location. Gibbons and Ringdal (2004, 2005) have demonstrated the ability of waveform correlation (especially in the context of seismic arrays) to detect signals with SNR smaller than unity provided that a template signal exists from an event from a sufficiently close source location.

6.1.2 Detecting the Kara Sea event aftershock using waveform correlation on SPITS array data

The main event was detected with a high SNR for both P and S phases at the SPITS array (see the red-colored waveform in Figure 6.1.3). Waveforms from this master event were extracted and bandpass filtered between 4.0 and 8.0 Hz, a frequency band exhibiting a high SNR for this event. The filtered waveform was resampled to a frequency of 80 Hz and a 60.0 second long data segment was cut with a starting time of 02.13.44.915. Note that exactly the same time window was selected for all sensors of the array. The time-delays between the phase arrivals at the different sites do not constitute a problem; since we are attempting to detect another seismic event from the same source location, the sought signal will be associated with an identical time-delay at each of the receiver sites. Given the small aperture of the array, an incoming seismic wavefront will traverse all sites of the array within a second. The waveform template extracted was correlated with SPITS data over several hours both prior to and following the main event and a maximum of the array correlation coefficient beam was achieved at a time 1997-228:06.21.55.815, estimated using a spline interpolation of the discrete time series. The correlation results indicate that the origin time of the second event was 14890.9 seconds following the origin time of the main event.

The fully-normalised correlation coefficients for the single channels of the SPITS array are approximately 0.65. Although lower than the correlation coefficients observed for the data from Amderma, they are exceptionally high given the low SNR of the second event (blue traces in Figure 6.1.3). The peaks in the correlation coefficient traces are clearly visible for each of the individual channels; we conclude that the use of a seismic array was not actually necessary to able to detect this signal at SPITS using the signal from the first event as a template. However, it is important not to understate the importance of the observation that the correlation trace maxima occur simultaneously at each site. This observation provides evidence that the slowness vectors for phase arrivals from the two events are identical. A final observation from Figure 6.1.3 is that the arrival time of the P-phase from the second event can be estimated far more accurately given the presence of the master event waveform for comparison.

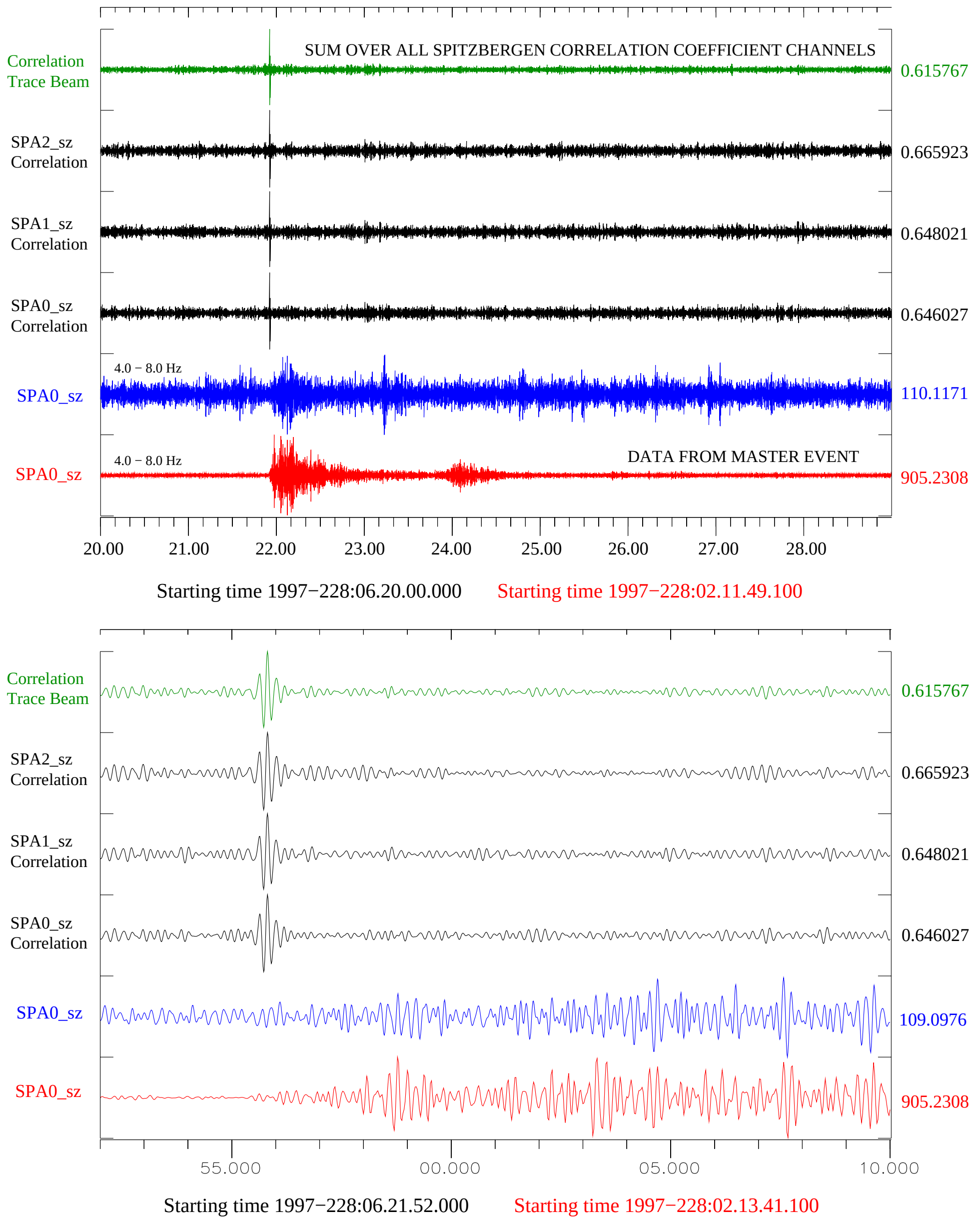

Fig. 6.1.3. Detection of an aftershock from the 16 August 1997 Kara Sea event using waveform correlation on the short period vertical channels of the Spitsbergen array. Each channel was bandpass filtered between 4.0 and 8.0 Hz and a 60 second long data segment was extracted from the master event signal (shown in red for SPA0 sz) with the first data segment beginning at 1997-228:02.13.44.913. The data containing the presumed aftershock was filtered in the same band (shown in blue for SPA0) and a trace of fully normalized correlation coefficients was calculated for each channel. The green channel is the summation of the 9 correlation coefficient traces. A clear peak is observed on the correlation beam at a time 1997-228:06.21.55.815. The lower panel is a zoom-in of the upper panel.

6.1.3 Detecting the Kara Sea event aftershock using waveform correlation on NORSAR array data

The closest IMS station to the site of the 16 August 1997 event was the regional array ARCES in the north of Norway. This station was unfortunately inoperational at the time of this event and, in such cases, every kind of observation possible from other (more distant) stations is potentially important. The large-aperture NORSAR array in the south of Norway is approximately 2300 km from the site of the Kara Sea event and recorded the main event with a reasonably high SNR. The signals are very different from those observed at the Spitsbergen array; the attenuation of energy at high frequencies means that the optimal SNR is obtained in a far lower frequency band: between approximately 2.5 and 5.0 Hz. It is noteworthy that, even at these somewhat lower frequencies, the waveforms from the various array sites are highly dissimilar.

Waveform data from the main event (recorded at the site NC602) is displayed in red in Figure 6.1.4 and the corresponding segment at the time of the aftershock is displayed above in blue. Given that these waveforms were filtered in approximately the optimal frequency band, it is quite evident that there is no chance of detecting the signal from the aftershock at NORSAR using a conventional energy detector. The data was filtered between 2.5 and 8.0 hz and data segments of length 60.0 seconds were extracted for each channel of the array using time-windows staggered to capture the initial P-arrival and the most energetic part of the signal for each site. These waveform segments were cross-correlated with filtered waveform data surrounding the time of the aftershock. Inspection of the single channel cross-correlation traces indicates no discernible peak values. However, a zero time-delay stacking of all of the available correlation channels results in an array correlation beam with a clear maximum at a time 1997-228:06.23.49.999: 14890.9 seconds following the reference time for the main event.

The signal from the second event is so weak at this distant station that it cannot be detected using a traditional energy detector. The signal to noise ratio is so low that cross-correlation using a single channel does not give a detection of the kind observed in Figure 6.1.3. However, beamforming of the correlation coefficient channels results in a spectacular array gain; local maxima of the single-channel correlation traces which result from coincidental similarity of unrelated seismic noise cancel out under the stacking operation, leaving only a superposition of the correlation maxima which result from the same deterministic waveform similarity. It is a remarkable result that such a detection is possible over a large aperture array where the waveforms themselves are largely incoherent. In traditional array processing, a requirement for array gain is incoherent noise and coherent signal. In contrast, array-based waveform correlation requires only incoherent noise in order to be applied successfully. The requirement for waveform coherency over the array is replaced by a requirement for coherency between the master waveform and the target waveform. The “signals” in this case are the cross correlation traces for each sensor, and the peaks of these traces occur simultaneously when the master event and the target event are co-located. Therefore, a zero-delay array beam of the correlation traces can be calculated without loss due to missteering or lack of signal coherence.

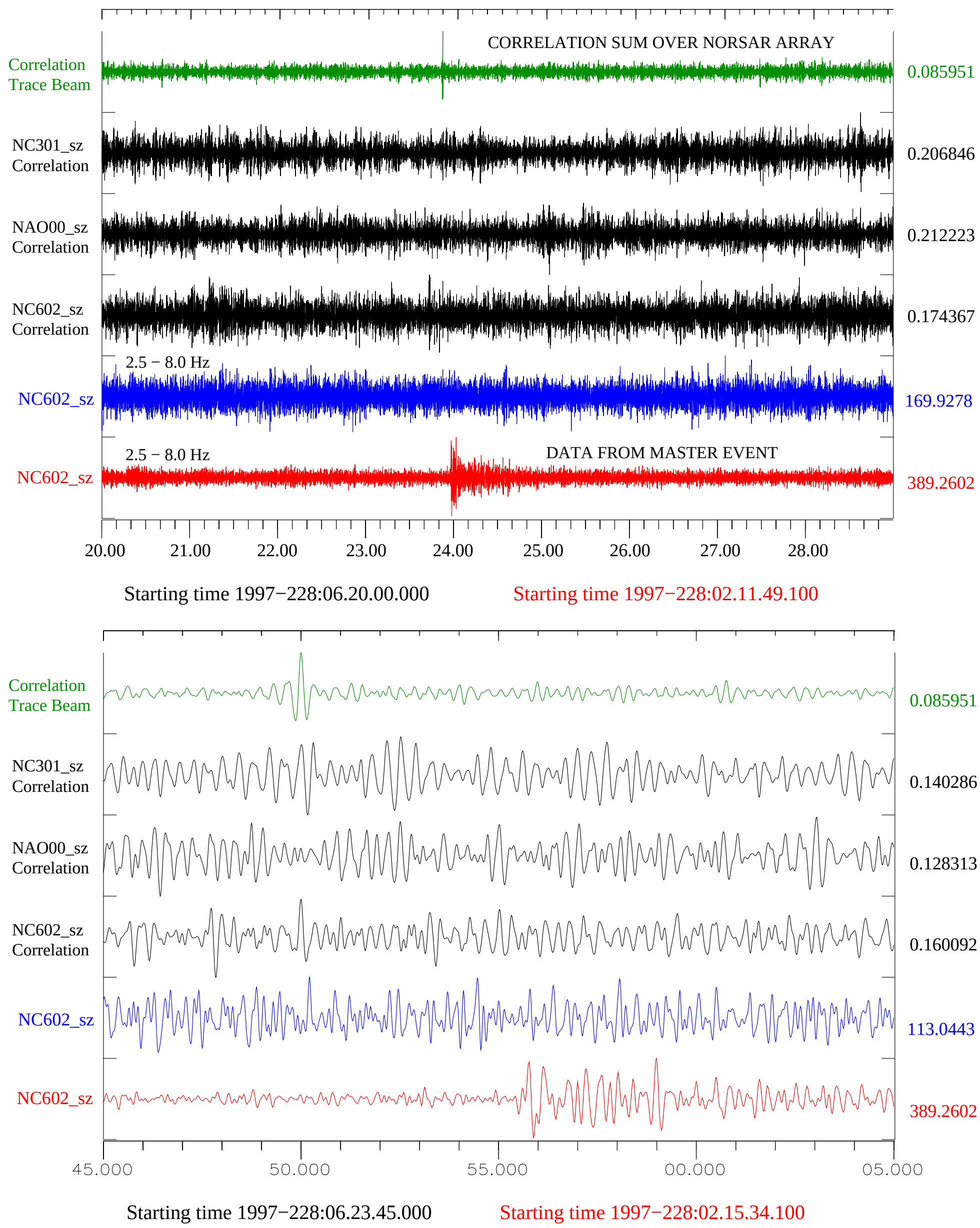

Fig. 6.1.4. Detection of the Kara Sea event aftershock by waveform correlation using the NORSAR array. The frequency band applied in this calculation is 2.5 - 8.0 Hz. The 60 second long time windows containing the master event signal are staggered by several seconds to account for the significant time delays across the array; the first master event time-window begins at 1997-228:02.15.39.087 for instrument NC301. The signal at this far more distant array is buried in the noise to a far greater extent than at SPI and in no filter band could this signal be detected with a conventional STA/LTA detector. While the SPI signal is very coherent over the array in the frequency band for which the SNR is optimal facilitating a reasonable SNR gain by conventional beamforming; this is not the case for the NOA signal. In contrast to the correlation displayed in Figure 3, the individual sensor correlation traces do not indicate clear simultaneous maxima. However, the beam (formed by applying the appropriate time-shifts to the individual correlation traces) displays a clear peak at time 1997-228:06.23.49.999.

6.1.4 Concluding remarks

We have examined waveforms from the main (m_b=3.5) Kara Sea event of 16 August 1997, and the m_b=2.5 event which occurred approximately 4 hours later, recorded at the Amderma station in Russia at a distance of approximately 325 km from the source location. At this station, the waveforms for both events exhibit a high SNR and a remarkable degree of waveform similarity between the two events. High correlation coefficients (~0.9) are obtained by correlating 60.0 second long data segments from the two events filtered between 4.0 and 8.0 Hz.

The detection of the second event using traditional array processing at the SPITS array (at a distance of approximately 1100 km) was marginal, resulting only in weak P-phase detections. We demonstrate that, using the signal from the main event as a waveform template, the second event is easily detected at SPITS using waveform correlation on a single seismometer channel. The correlation coefficients observed on the individual channels are approximately 0.65 for one minute long data segments (between 4 and 8 Hz) which is remarkably high considering the low SNR of the signal from the second event. Performing waveform correlation over the whole array provides us with the useful observation that the times of maximum cross-correlation are the same for each site which supports the claim that both signals come from approximately the same site.

The main event was also recorded by the large aperture NORSAR array at a distance of approximately 2300 km from the source; no detection by traditional processing is possible for the signal from the second event. Cross-correlating one minute long data segments from the main event with the corresponding waveforms from the time of the second event does not result in peaks on single-sensor correlation-traces which allow detection of the event. However, the event is clearly detectable on the NORSAR array by stacking the correlation coefficient traces from the various sites. This is a superb demonstration of how the cross-correlation functions are coherent across a large array or network even when the actual waveforms are not.

A time separation between the two events of approximately 14890.9 seconds was obtained from each of the three sites.

References

Asming, V. E., E. Kremenetskaya, and F. Ringdal (1998). Monitoring seismic events in the Barents/Kara Sea region, NORSAR Scientific Report: Semiannual Technical Summary No. 2 - 1997/1998. NORSAR, Kjeller, Norway. pp. 106-120.

Bowers, D. (2002). Was the 16 August 1997 Seismic Disturbance near Novaya Zemlya an Earthquake? Bull. seism. Soc. Am., 92, pp. 2400-2409.

Bowers, D., P. D. Marshall, and A. Douglas (2001). The level of deterrence provided by data from the SPITS seismometer array to possible violations of the Comprehensive Test Ban in the Novaya Zemlya region, *Geophys. J. Int.*, 146, pp. 425-438.

Gibbons, S. J. and F. Ringdal (2004). A waveform correlation procedure for detecting decoupled chemical explosions, NORSAR Scientific Report: Semiannual Technical Summary No. 2 - 2004. NORSAR, Kjeller, Norway. pp. 41-50.

Gibbons, S. J. and F. Ringdal (2005). The detection of rockbursts at the Barentsburg coal mine, Spitsbergen, using waveform correlation on SPITS array data, NORSAR Scientific Report: Semiannual Technical Summary No. 1 - 2005. NORSAR, Kjeller, Norway. pp. 35-48.

Hartse, H. E. (1998). The 16 August 1997 Novaya Zemlya Seismic Event as Viewed from GSN Stations KEV and KBS, Seism. Res. Lett., 69, pp. 206-215.

Richards, P. G. and W. Y. (1997). Testing the nuclear test-ban treaty, *Nature*, 389, pp. 781-782.

Ringdal, F., T. Kværna, E. Krementskaya, and V. Asming (1997). The seismic event near Novaya Zemlya on 16 August 1997, NORSAR Scientific Report: Semiannual Technical Summary No. 1 - 1997/1998. NORSAR, Kjeller, Norway. pp. 110-127.

Ringdal, F., E. Kremenetskaya, and V. Asming (2002). Observed characteristics of regional seismic phases and implications for P/S discrimination in the European Arctic, *Pure appl. geophys.*, 159, 701-719.

Schweitzer, J and B. L. N. Kennett (2002). Comparison of Location Procedures - The Kara Sea event of 16 August 1997, NORSAR Scientific Report: Semiannual Technical Summary No. 1 - 2002. NORSAR, Kjeller, Norway. pp. 97-103.

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