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International Monitoring System Correlation Detection at the North Korean Nuclear Test Site at Punggye-ri with Insights from the Source Physics Experiment

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International Monitoring System Correlation Detection at the North Korean Nuclear Test Site at Punggye-ri with Insights from the Source Physics Experiment

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Introduction

Seismic waveform correlation offers the prospect of greatly reducing event detection thresholds when compared to more conventional processing methods. Correlation is applicable for seismic events that in some sense repeat, that is they have very similar waveforms (e.g., Gibbons and Ringdal, (2006)). A number of recent studies have shown that correlated seismic signals may form a significant fraction of seismicity at regional distances (e.g., Schaff and Richards, 2011; Slinkard et al., 2015; Dodge and Walter, 2015). For the particular case of multiple nuclear explosions at the same test site, regional distance correlation also allows very precise relative location measurements (e.g., Waldhauser et al., 2004; Wen and Long, 2010) and could offer the potential to lower thresholds when multiple events exist (e.g., NRC report, 2012). Gibbons and Ringdal (2012) have shown that using the Comprehensive Nuclear-Test-Ban Treaty (CTBT) International Monitoring System (IMS) seismic array at Matsushiro, Japan (MJAR) they were able to create a multi-channel correlation detector with a very low false alarm rate and a threshold below magnitude 3.0. They did this using the 2006 or 2009 DPRK nuclear explosion as a template to search through a data stream from the same station to find a match via waveform correlation.

In this paper, we extend the work of Gibbons and Ringdal (2012) and measure the correlation detection threshold at several other IMS arrays. We use this to address three main points. First we show the IMS array station at Mina, USA (NVAR), which is the closest to the Nevada National Security Site (NNSS), is able to detect a chemical explosion that is well under 1-ton with the right template. Second, we examine the two IMS arrays closest to the North Korean (Democratic People's Republic of Korea or DPRK) test site, at Ussuriysk, Russian Federation (USRK) and Wonju, Republic of Korea (KSRS), to show that similarly low thresholds are possible when the right templates exist. We also extend the work of Schaff et al. (2012) and measure the correlation detection threshold at the nearest Global Seismic Network (GSN) three-component station at Mudanjiang, Heilongjiang Province, China (MDJ) from the New China Digital Seismograph Network (IC). Finally we use these results to explore the recent claim by Zhang and Wen (2015) that the DPRK conducted "…a low-yield nuclear test…" on 12 May 2010.

Small explosion detection at a regional array: Insight from the Source Physics Experiment

The Source Physics Experiment (SPE) is carrying out a series of chemical explosions at the NNSS in southern Nevada as part of a program to develop a new, more physics-based paradigm for nuclear test monitoring (Snelson et al., 2013). To date there have been three small chemical explosions all conducted in the same granite borehole at NNSS. The three chemical explosions are: SPE-1, a 0.09 ton shot on 3 May 2011; SPE-2, a 1 ton shot on 25 October 2011 and SPE-3, a 0.9 ton shot on 24 July 2012. The data for these shots is available through the Incorporated Research Institutions for Seismology (IRIS) web site (www.iris.edu). The seismic data observed at the IMS array NVAR (Mina, Nevada) is shown in Figure 1 after filtering between 1-6 Hz. The two larger shots have regional P and S arrivals in the traces that are clearly visible to the eye, while the smaller SPE-1 signal is not easily observed.

If we use the 0.9 ton SPE-3 as a template at NVAR and then apply it to the data stream that contains the 0.09 ton SPE-1, we get a clear and strong detection using the stacked normalized cross-correlation (SCC) statistic of Gibbons and Ringdal (2012), as shown in Figure 2. The events are similar enough in size and location that no modification is needed to produce a strong correlation between these two events at NVAR. This is perhaps a particularly optimal case for which an excellent template event exists and we are able to use a very long signal window of about 60 seconds, resulting in a very large time bandwidth product. The result is a very strong detection of a very small, 0.09 ton, chemical explosion at a distance of more than 200 km.

If we consider the approximate factor of two difference in seismic amplitudes between chemical and nuclear explosions (e.g. Xu et al., 2014 calculation results), the chemical explosion SPE-1 signal would have an equivalent nuclear yield twice as large or about 0.18 tons, indicating a very low detection threshold indeed at NVAR for either chemical or nuclear explosions that correlate with the SPE chemical explosions. If the template and target events had a much larger difference in size, then we might have to take into account the different frequency content between events, an issue we take up in the next section. If the template event were located some distance away from the target event, we would expect the correlation coefficient to decrease as a function of the difference in Green's function. This Green's function difference at the two locations would depend upon the signal pass band being used. Correlation detection would be expected to fail if the separation between the events was large enough and/or the target event became too small relative to the background noise. A better understanding of these factors that affect correlation detection effectiveness is a subject of current research.

The 12 May 2010 North Korean Event

Zhang and Wen (2015) report the detection of a small (m_b(Lg) = 1.44) seismic event they locate at the DPRK Nuclear Test Site at Punggye-ri on 12 May 2010, based on records at stations in Jilin Province, China. Some of these stations are very close to the DPRK nuclear test site, approximately 75-200 km distant. They detect and locate this event based on correlation with the 2009 and 2013 declared nuclear explosions at the DPRK test site. We searched for this 12 May 2010 event in the records of USRK, KSRS, and MDJ. These stations are between 370 and 440 km from the DPRK test site. Figure 3 is a map of the station locations and region.

The interest in possible seismic events in May 2010 was stimulated by the detection of radionuclides at IMS stations in East Asia during that same time period (e.g. De Geer, 2012, 2013; Ihantola et al., 2013; Wotawa, 2013; Wright, 2013). Previously Schaff et al. (2012) examined five 24-hour time periods proposed by De Geer (2012) at station MDJ and concluded: "…no well-coupled explosion above about a ton occurred near the North Korean nuclear test site in the year 2010 on the five days hypothesized by De Geer". The event reported by Zhang and Wen (2015) occurs just past the last of the time periods examined by Schaff et al. (2012) and so is not necessarily covered by the conclusions of that paper.

We calculated the origin beams (beam with time delays between individual channels calculated with theoretical azimuth and slowness) for USRK and KSRS using the origin parameters reported in Zhang and Wen (2015). Figure 4 shows the beams, where there is no visible signal above noise.

In contrast, the 12 February 2013 nuclear explosion signals are clearly visible both in the individual elements and the beam as shown in Figure 5. We also used the 12 February 2013 explosion as a template and correlated it with the data stream from USRK, KSRS and MDJ near the predicted arrival time of the 12 May 2010 event at those arrays. The detection statistic is the stacked normalized correlation coefficient (SCC) described in Gibbons and Ringdal (2012). Figure 6 shows the streams and SCCs, where there are no significant detections. Similar results were found when we used the 2009 nuclear explosion as a template. To better understand the lack of signal detection for the 12 May 2010 event, either by direct examination of the beamed data or by correlating with past nuclear explosions, we performed a detailed examination of the detection threshold provided by these two IMS arrays and station MDJ.

Estimate of detection thresholds using the scaled 25 May 2009 explosion

To quantify the detection thresholds, we took records of the 25 May 2009 nuclear explosion and embedded their scaled signals in the USRK and KSRS streams. In order to transfer the recorded signal from the 25 May 2009 explosion to the predicted signal from the 12 May 2010 event, we calculate the spectral amplitude ratio of the two events using the yield and depth reported in Zhang and Wen (2013) for 2009: W=7.0±1.9 kt at 610 m and Zhang and Wen (2015) for 2010: W=0.0029±0.0008 kt at 230 m. The yield and depth are used to predict the spectral amplitude using the granite Mueller and Murphy (1971) model as described in Stevens and Day (1985). As discussed in Ford and Walter (2013), for small and/or over-buried events such as the SPE, it is necessary to correct the original Mueller and Murphy (1971) explosion model for linear yield scaling with depth, which we did using Murphy and Barker, (1994). The explosion model transfer function is shown in Figure 7 and is frequency dependent. The 2010 event P-wave amplitude varies from about 1500 times smaller than the 2009 explosion at frequencies below the modeled 2009 explosion corner frequency of about 4 Hz, to values of about 1/100 near 20 Hz as the ratio approaches the modeled 2010 event corner frequency. These means that at frequencies where array beam forming is coherent the expected signal will be quite small and depending upon the background noise such a small explosion may best be observed at very high frequencies > 10 Hz.

To create synthetic data for the Zhang and Wen (2015) reported 2.9 ton 2010 event, we take the 2009 nuclear explosion data at each station, calculate its Fourier transform and multiply the amplitude spectra by the ratio in Figure 7. We then use the modified amplitude spectra and the original phase spectra to create synthetic seismograms, which have the correct timing and amplitudes. We show in Figure 8 the band-pass filtered data observed at the USRK station for May 2010 compared to the expected explosion signals from scaling the 2009 nuclear explosion. If the May 2010 event resulted from a 2.9 ton explosion at the North Korean test site then the gray synthetic signals are hidden in the noisy traces in Figure 8. The expected signal to noise is close to one and after we add the synthetic signals to the actual traces then destructive interference makes them just a little too small to be detected by eye after filtering. At the high frequencies necessary to get the better signal to noise, the array is incoherent so beam forming does not improve the detectability. The result appears to be that if the expected signal were a little larger we should be able to see it at high frequencies even without using correlation, but no signal is observed.

We can generalize this 2010/2009 event ratio calculation in order to explore a range of potential explosion yields for the 2010 event. We scale the 25 May 2009 nuclear explosion signal by calculating the spectral amplitude ratio of a nominal 5 kt explosion in granite at a depth of burial of 500 m to an explosion at the same depth with a reduced yield as shown in Figure 9. We note the absolute values assumed are less important than the ratio. We tried a range of scaling such as a nominal 10 kt event at 260m depth to smaller explosions at the same depth and get very similar results. The dark black curve in Figure 9 shows the specific parameters reported by Zhang and Wen (2013, 2015) for the 2009 and 2010 events and this falls in the middle of the scaling curves. The 5 kt to 5 ton transfer function is consistent with the average amplitude ratio (in the WWSSN short period band) of 8×10^{-4} reported in Table S2 of Zhang and Wen (2015); we plot this with a circle at the instrument response peak in Figure 9. This corresponds to a reduction of about a factor of 1000 in the 2009 nuclear explosion yield.

To test the correlation detection we use the 2013 nuclear explosion as the template and correlate against the 2009 nuclear explosion scaled down by a yield factor of 1000 after it is embedded in the signals at the time of the 12 May 2010 event. As shown in Figure 10 we find clear detections at KSRS, USRK and MDJ. The results are similar if we scale the 25 May 2009 nuclear explosion using the Zhang and Wen (2013) yield estimate of 7 kt and a depth of 610m, however the scaling is larger. In this case the 2.9 ton scaled event is reduced from the original 2009 explosion by about a factor of 1500, which is different than the straight yield factor difference of about 2400, due to the different depths, as was shown in Figure 7. Embedding the scaled data in the 12 May 2010 noise and using the 2013 nuclear explosion as a template we get a clear detection at USRK, and detections just above the 3σ threshold at KSAR and MDJ as shown in Figure 11.

Given these results it is somewhat surprising that as shown in Figure 6 there is no correlation detection of the 12 May 2010 event. Zhang and Wen (2015) locate the 2010 event about as close to the 2013 nuclear explosion as the 2013 and 2009 nuclear explosions are located to each other. If this location is correct, we should be able to assume the 2010 event would correlate with the 2013 explosion about as well as the 2009 and 2013 explosions correlate with each other. In this case the clear implication of the lack of a 2013 explosion template correlation detection at USRK, KSRS and MDJ as shown in Figure 6, is the 2010 event must be smaller than the 2.9±0.8 tons estimated by Zhang and Wen (2015) using their modified Lg-magnitude-yield depth relationship.

We focus first on the USRK array, as it appears to have the best predicted correlation for the 12 May 2010 event. Using the scaled 2009 nuclear explosion embedded in the 12 May 2010 noise and the 2013 nuclear explosion as a template, the stacked correlation coefficient for a range of scaled 2009 explosion yield ratios is plotted in Figure 12. This figure makes clear that an explosion more than 5000 times smaller than the 2009 explosion would be detectable at USRK at the time of the 12 May 2010 event. It implies that if the Zhang and Wen (2015) location of the 12 May 2010 event is correct, then their reported yield needs to be at least 3 to 5 times lower in order to explain the non-detection of the 2010 event at USRK when using the 2013 nuclear explosion as a template.

Single and Multiple Array Correlation Detection Thresholds

Next we work to generalize the results of Gibbons and Ringdal (2012) for multiple array correlation detection as applied to the DPRK test site. We employ a detection statistic formulation similar to the one described in Gibbons and Ringdal (2012) where the multicomponent detection statistic C at time t is the average normalized correlation coefficient for M sensors (SCC) divided by the standard deviation σ of SCC that begins two window lengths before C(t). We call this detection statistic the correlation score due to its similarity to the standard score or Z-score where the mean value in the noise population is zero.

The correlation score can be thought of as the number of standard deviations above the background noise that the detection signal has. In practice the noise levels across multiple arrays are not necessarily Gaussian, and so the actual standard deviation can be larger. For these reasons we use high scores of 3 and 6 as initial thresholds and then test the results using multiple realizations.

We first calculate the correlation score for array USRK for a range of frequency pass bands and window lengths as shown in Figure 13 as a function of simulated yield for the 12 May 2010 event. We again scale the 2009 nuclear explosion, embed it in the noise at the time of the 2010 event and correlate using the 2013 nuclear explosion as a template. It is clear that using shorter windows of less than 30 seconds and frequency bands that start below 2 Hz leads to worse results than longer windows and higher frequencies. Using windows greater than 30 seconds and frequency bands of 2 Hz and higher leads to USRK array correlation yield detection thresholds of less than 1 ton using correlation scores of 3 or 6 as bounds.

The correlation score or Z at each array or three-component station can be combined via a Mahalnobis distance so that each correlation value is normalized by its local noise environment. A significant advantage of using two or more arrays with some azimuthal separation is a greatly reduced potential for false alarms from events with similar back azimuths, such as the example shown by Gibbons and Ringdal (2012). Given sufficient station/array separation, only events near the template event would correlate at the multiple stations.

In Figure 14 we show the two-array result for USRK and KSRS for the 2010 event using a 120 s window and a 2-8 Hz passband. These results again use the scaled 2009 explosion embedded in the 2010 event noise with the 2013 explosion template. We can see that an event between ½ and 1 ton should be detectable at both arrays on 12 May 2010 and no such event is detected.

To explore the more general IMS multiple array correlation detection threshold for the DPRK test site we embedded the scaled 2009 explosion signal at 75 different points in time during 2010 to more accurately sample the background noise level variation. These median results for a series of explosion sizes at USRK and KSRS are shown in Figure 15 as large solid dots. We can see that in all cases the median score at USRK is higher than for KSRS, so USRK on average has a lower detection threshold at the DPRK test site. The 75 individual realizations are shown as small points for each yield. For example focusing on the cloud of 75 realizations around the 5 ton median point, we can see that sometimes the two stations have nearly equal scores on the order of 40 and sometimes USRK has a score ten times higher. The noise level at the time of the 12 May 2010 event (circled point) is such a case. Thus while we can confidently say the 12 May 2010 event must be below 1 ton if the Zhang and Wen (2015) location is correct, for the more general case of an explosion at the DPRK test site, the joint USRK and KSRS conservative threshold would be between 1 and 2 tons to keep the joint score above 6.

Discussion

This study and others like it (e.g., Gibbons and Ringdal, 2012; Schaff et al., 2012) show the tremendous potential of correlation techniques to lower event detection, location and identification thresholds at regional stations and arrays where the right templates exist. We show that in the case of the SPE chemical explosions in Nevada and scaled versions of the DPRK nuclear explosions, that templates at the nearest CTBT IMS array stations exist and can confidently detect events down to the level of a few tons or less. What is much less well defined, and is an area of current research, is when and how these methods break down. For example it is well known that as the template event and target events are increasingly separated spatially, their correlation coefficient will diminish, as the difference in the Green's function between the two events grows larger. This is likely to be related to the event separation in terms of wavelength, the heterogeneity of the Earth structure, and the time-bandwidth of the correlation parameters used, but it has not been well quantified.

This implies that an alternative reason for the lack of correlation detection of the 12 May 2010 event at the IMS arrays USRK and KSRS could be due to an error in the Zhang and Wen (2015) location. If the true location were farther from the 2013 and 2009 explosions than reported, the correlation between the signals could degrade and cause the observed lack of detection. Given the good correlation between the 2006 DPRK nuclear explosion and the 2009 and 2013 explosions at KSRS (USRK was not running at the time of the 2006 event) the location would likely need to move several km to explain the lack of detection. Such a change in location could also potentially change the Zhang and Wen (2015) assessed connection between the 12 May 2010 event and the 2006, 2009 and 2013 nuclear explosions and opens the possibility of other source types such as industrial blasting or tectonic earthquakes.

At the magnitude 1.44 level of the Zhang and Wen (2015) event there is likely to be significant natural and man-made seismicity in and around North Korea that is not currently cataloged. We note that the stations in Jilin Province, China used by Zhang and Wen (2015) are not in the public domain and this limits our ability to hypothesis test the causes of the differences between the results of that study and this one. Releasing this data to the community could help significantly in sorting out the nature of the 12 May 2010 event. In the absence of that data, we looked for other local and near-regional data. The NorthEast China Extended SeiSmic Array (NECESS Array) is a temporary seismic deployment in northeast China (e.g., Tao et al., 2014) whose data is available through IRIS. Examination of that data shows a clear detection of the 12 May 2010 event at one station, and perhaps marginal detections at a few other stations. Unfortunately none of the declared DPRK nuclear explosions are available at these stations, so we cannot examine correlation detection at NECESS Array. We looked for events that appear similar to the 12 May 2010 and show one with similar S-P times that occurred in 6 June 2010 in Figure 16. We note this time period is outside of the two months of April and May 2010 data examined by Zhang and Wen (2015). We believe this shows that events that have the potential to be false alarms exist, as was also shown by Gibbons and Ringdal (2012). Given the potentially important nature of the 12 May 2010 event as reported by Zhang and Wen (2015), we believe a more thorough examination of the nature of low magnitude (M_L <2) seismicity in the area and more thorough error analysis of the correlation detection is needed.

Conclusions

We demonstrate that if the right templates exist, it is possible to use data from the CTBT IMS arrays and publicly available GSN stations to detect seismic explosions on the order of a few tons or less at nuclear test sites in Nevada and North Korea. We use and extend the results of Gibbons and Ringdal (2012) and Schaff et al. (2012) to create combined multiple station/array correlation detection thresholds. We use these results to analyze the Zhang and Wen (2015) conclusion that they: "…detect and locate a low-yield nuclear test conducted on 12 May 2010 by North Korea." We show that if the Zhang and Wen (2015) parameters were correct, this event should be detected via correlation with the 2013 nuclear explosion at the IMS arrays USRK and KSRS, whereas no detected signal is found. If the Zhang and Wen (2015) location is correct, we show the explosion must be less than a ton, which is below their estimate of 2.9±0.8 tons. Alternatively it is possible to explain the lack of correlation detection at USRK and KSRS if the event is not located near the DPRK test site, such that the correlation between it and the 2009 and 2013 nuclear explosion signals at the IMS arrays are poor. In either case we believe this implies the true nature of the 12 May 2010 seismic event needs further elucidation as to its source. We note that there is both natural and mining related seismicity in North Korea below current catalog thresholds and these sources must be better cataloged and then more confidently ruled out as possible causes of the 12 May 2010 seismic signal.

Acknowledgments

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Figures

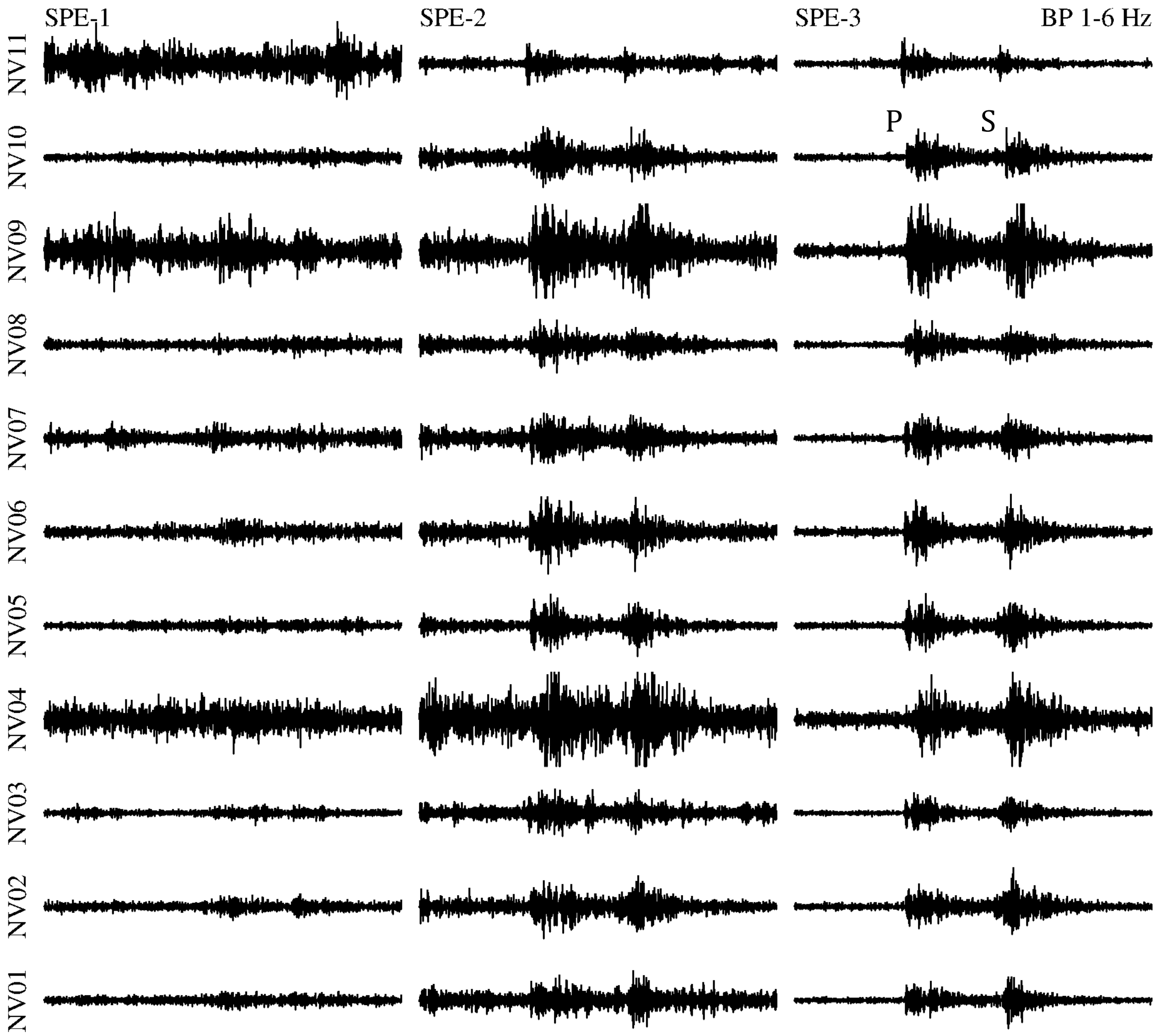

Figure 1. SPE-1, -2 and -3 chemical explosions of approximately 0.09, 1, and 0.9 ton observed at the NVAR array in the 1-6 Hz passband. The regional P and S arrivals are clearly seen for the two larger explosions but are not evident for the much smaller SPE-1 explosion. NVAR is approximately 238 km from the SPE event location and the timeseries are 120 s in duration.

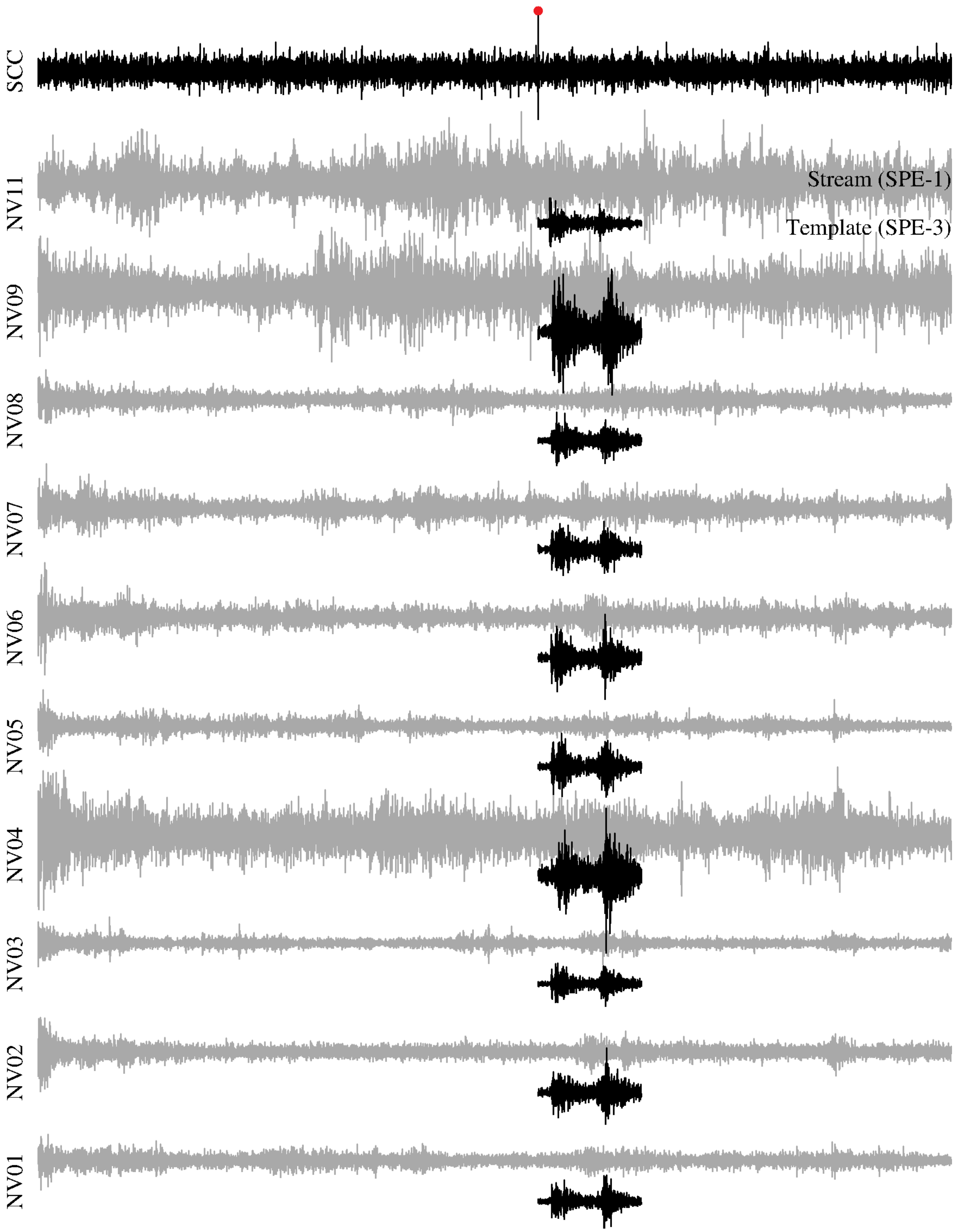

Figure 2. The SPE-3 recording is used as a 60 s long template (short black traces) to scan for signals in the 10 minute long SPE-1 data stream. Although the SPE-1 signal is not visible to the eye, there is a good correlation found for it as shown by the stacked normalized correlation coefficient (SCC) statistic as indicated by the red dot on the top trace.

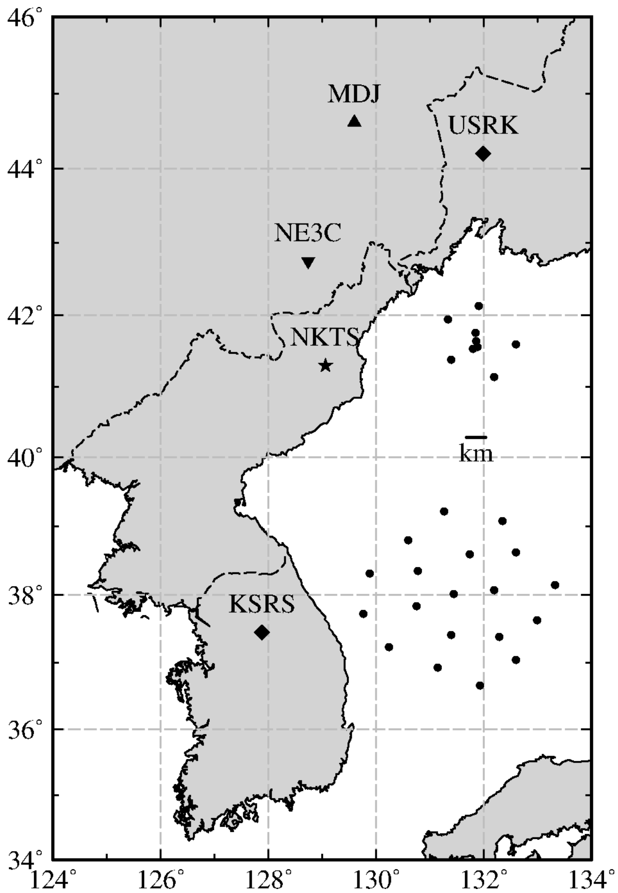

Figure 3. Location of three-component GSN station MDJ, the short-period IMS arrays, USRK and KSRS, and the NECESSArray station NE3C, along with the location of the North Korea Test Site at Punggye-Ri (NKTS). The array element configurations are shown as blowups near the arrays.

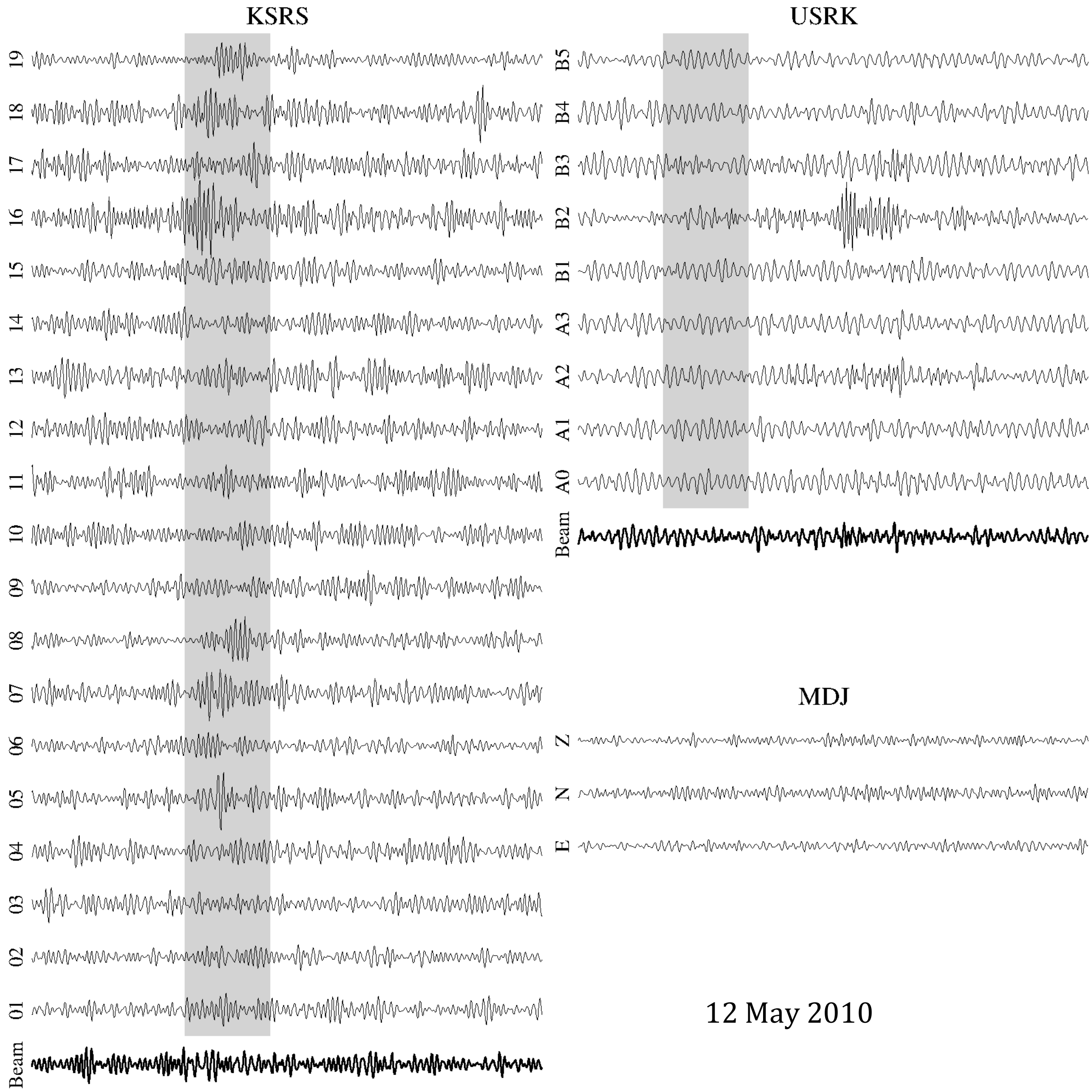

Figure 4. This figure shows the beam formed traces at the two closest IMS arrays to the DPRK test site for the Zhang and Wen (2015) reported 12 May 2010 event. Each trace is filtered between 2 and 4 Hz and begins 51 s after their reported origin and is 30 s in duration and normalized to the maximum amplitude at the array or station. The gray region shows the theoretical P-window.

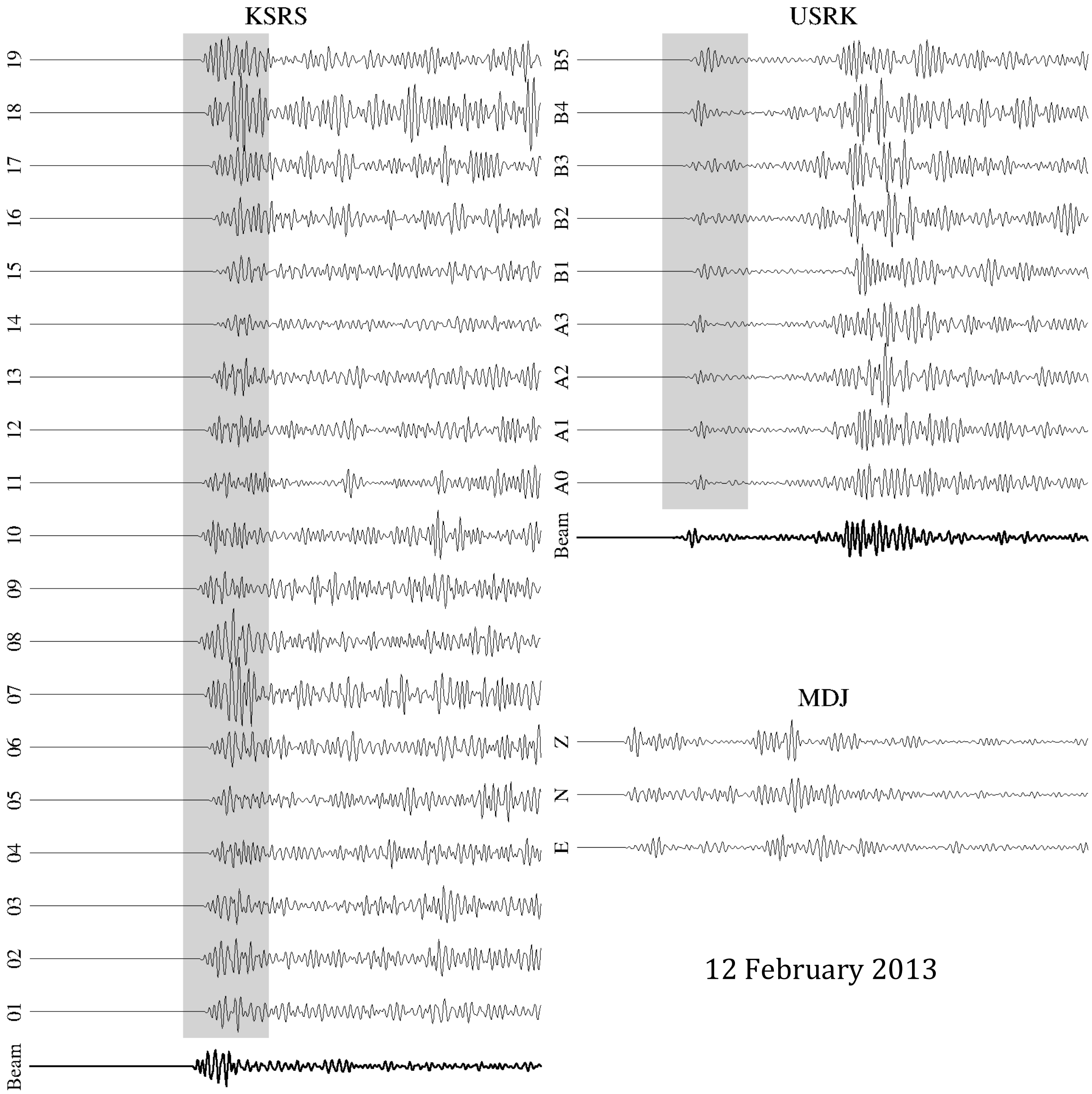

Figure 5. Same as Figure 4, but for the origin of the 12 February 2013 declared nuclear explosion at Pungyye-Ri.

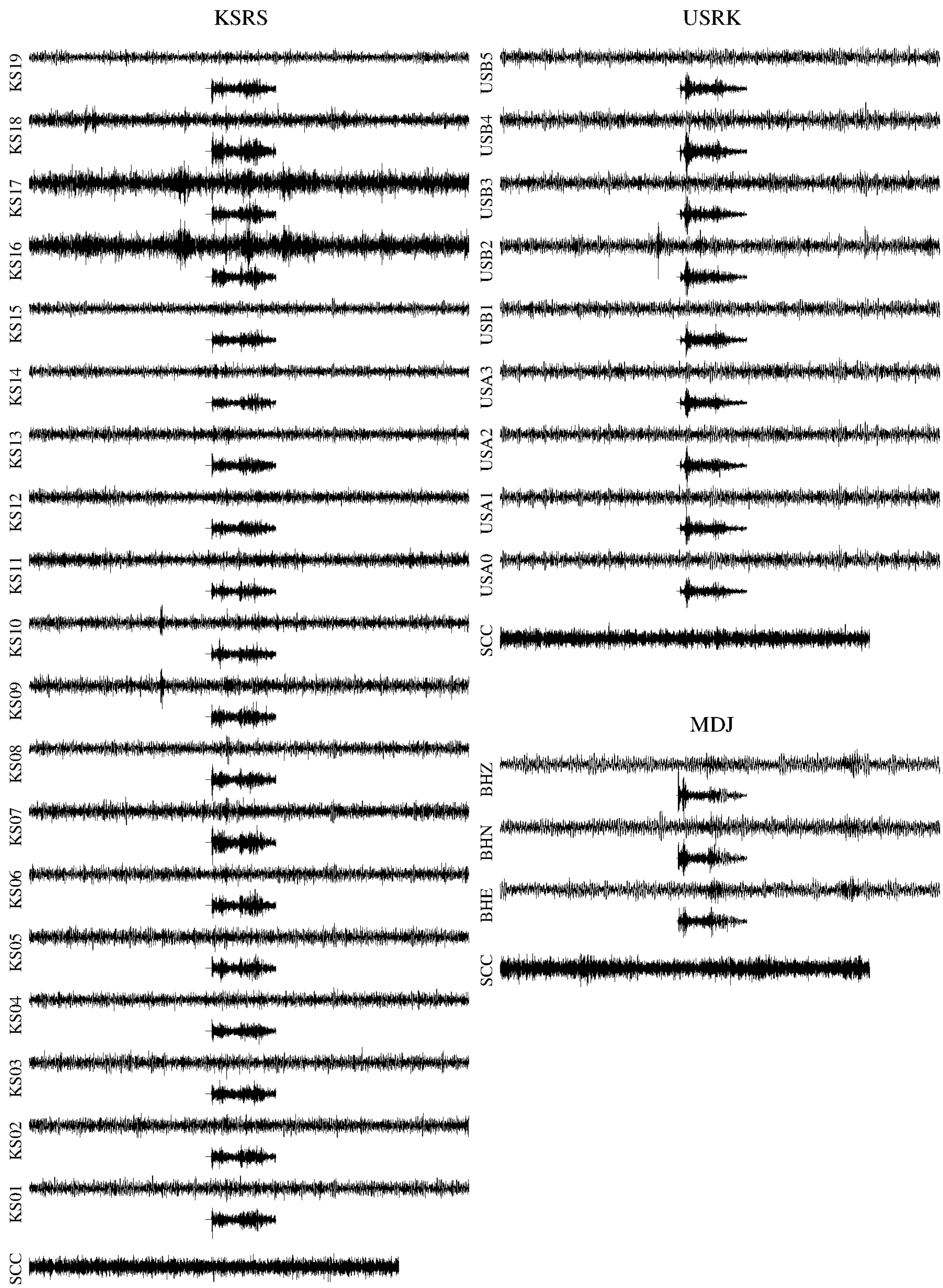

Figure 6. The 12 February 2013 explosion at Pungyye-Ri (120 s duration short traces) correlated with the stream (750 s duration long traces) during the predicted arrival of the event reported in Zhang and Wen (2015). The stacked correlation coefficient (SCC) is

shown for each array and the three-component station MDJ. No significant detection is observed.

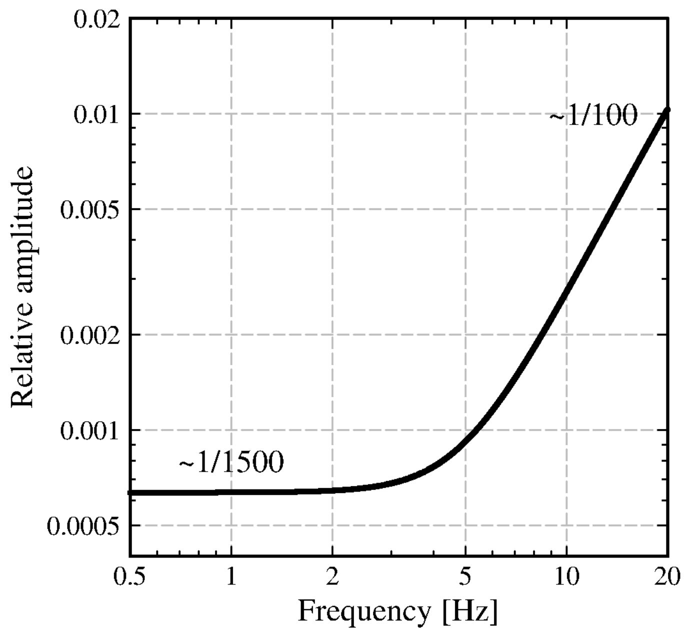

Figure 7. P-wave spectral amplitude ratio of a 2.9 ton explosion at 230 m depth divided by the amplitude of a 7.0 kt explosion at 610 m depth (parameters from Zhang and Wen, 2013 and 2015). We note that the different depth of the two shots changes the long period ratio from about 1/2400 to about 1/1500. As frequency increases the ratio diminishes above the corner frequency of the large shot until the ratio is much lower, on the order of only 1/100 at 20 Hz. For this reason the small event may best be detected at high frequencies.

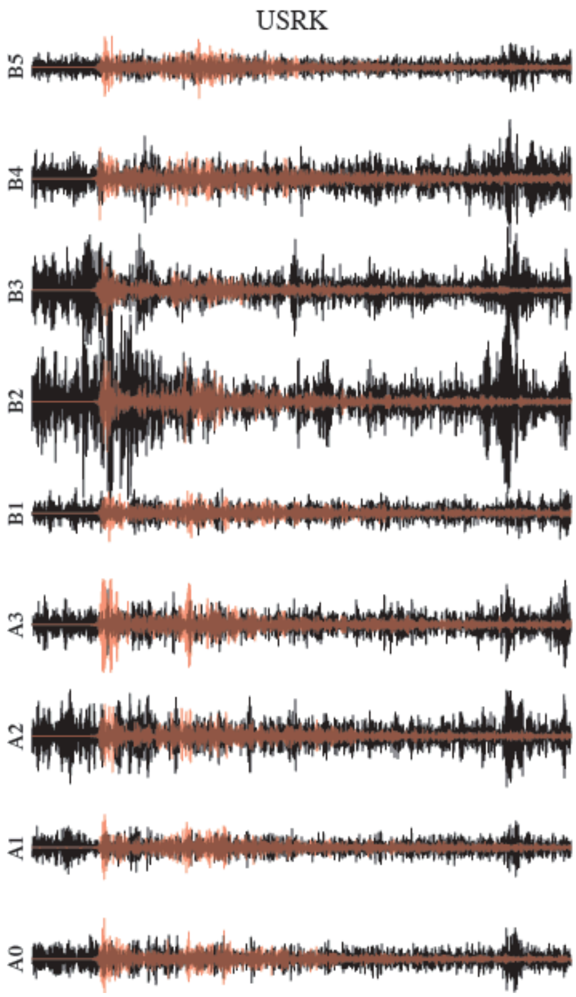

Figure 8. Plot of 8-16 Hz band-passed USRK array seismograms from May 2010 data (black) and the expected signals from a 2.9 ton explosion at the same scale if there were no background noise (red). The expected SNR is near one and the predicted signals would be difficult to observe by eye when embedded in the background noise. No signal is observed in the actual data.

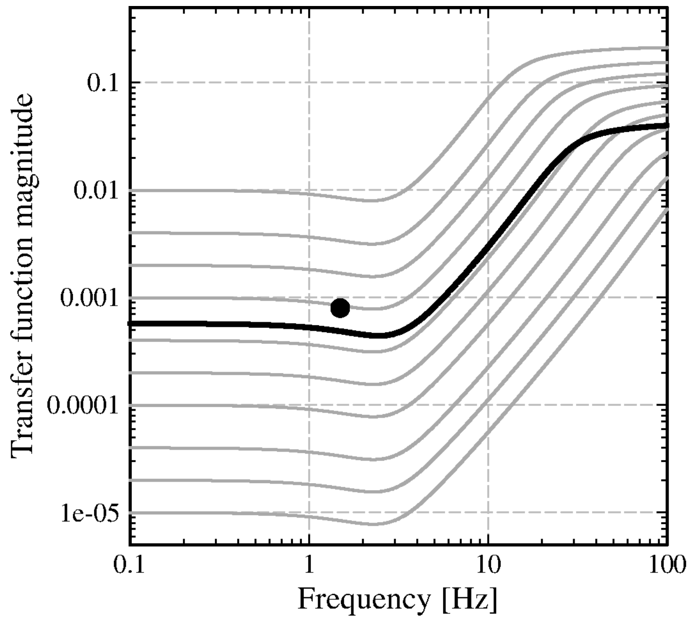

Figure 9. Transfer function used to scale the 25 May 2009 explosion for detection threshold testing. The circle is the average amplitude ratio reported in Zhang and Wen (2015) at the peak of the WWSSN short period response (~1.5 Hz) used to calculate the spectral amplitude in that study.

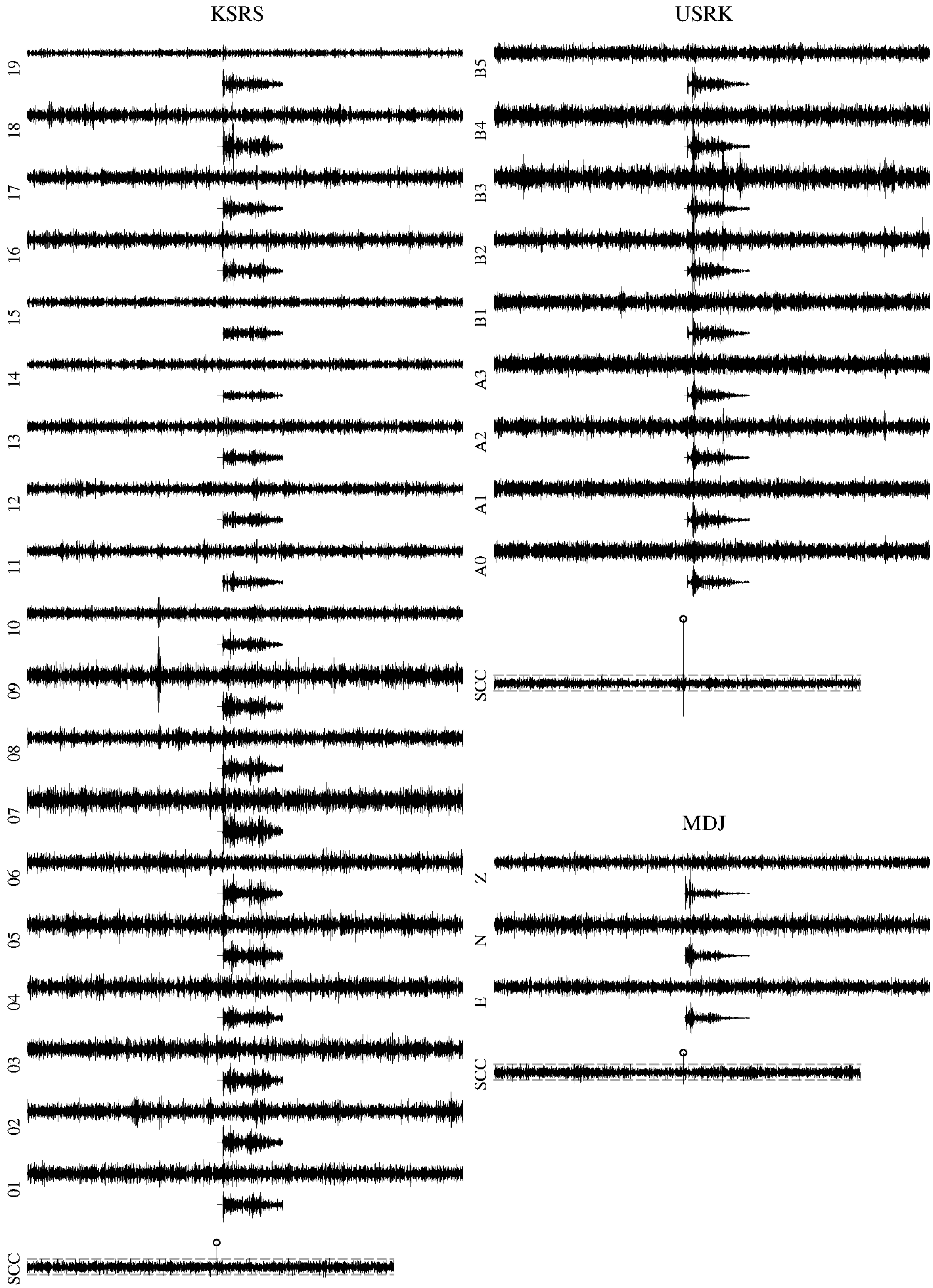

Figure 10. DPRK13 correlated with DPRK09 ⊗ 5t@500m/5kt@500m (factor of 1000 in yield) embedded in the timeframe of the event reported in Zhang and Wen (2015). All detections (circles in SCC traces) are above the 3σ threshold (dashed line).

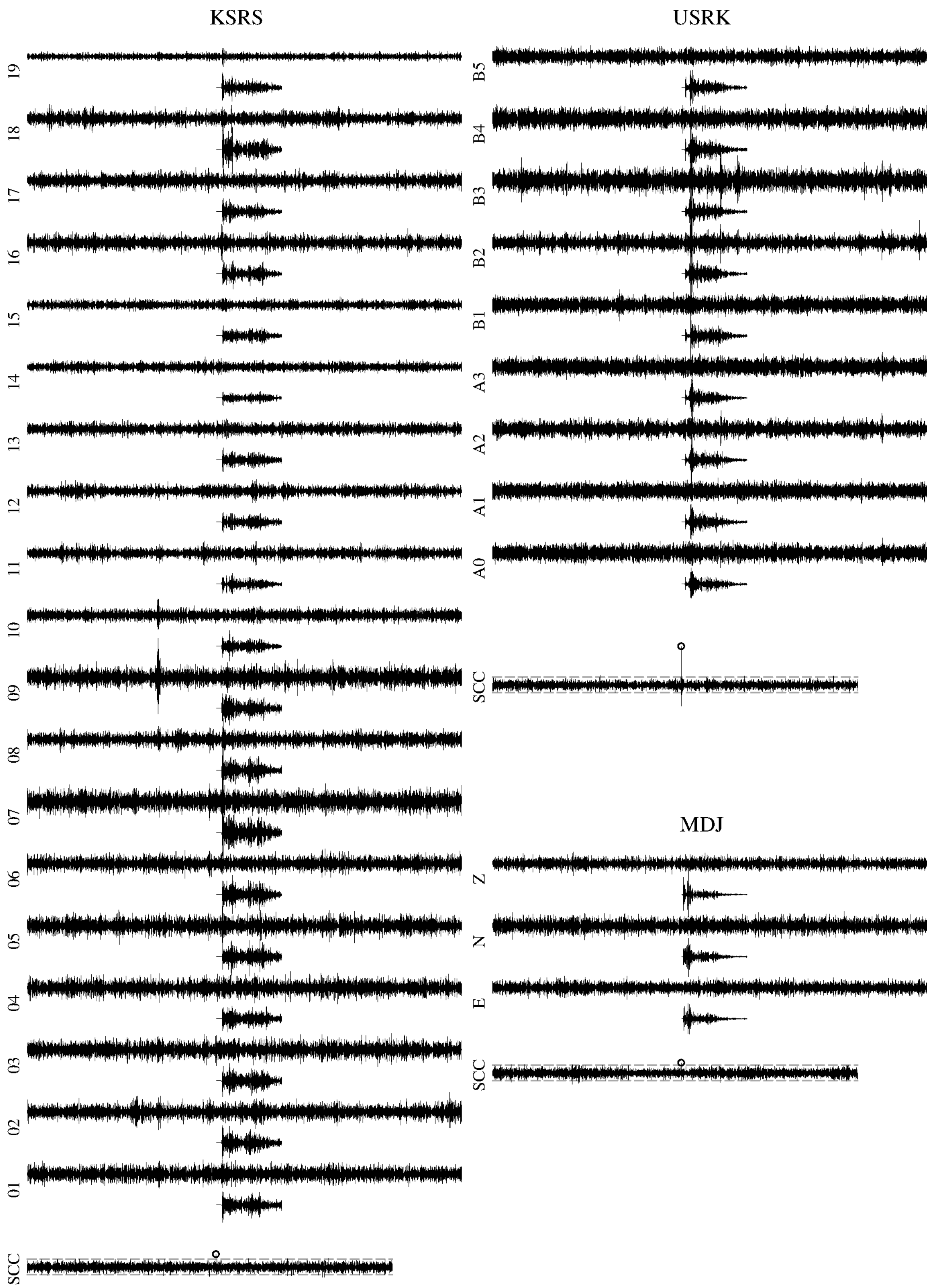

Figure 11. DPRK correlated with DPRK09 ⊗ 2.9t@230m/7kt@610m (proposed yield and depth of the Zhang and Wen (2015) event). All detections (circle in SCC trace) are above the 3σ level (dashed line), but only USRK has a detection much greater than 3σ.

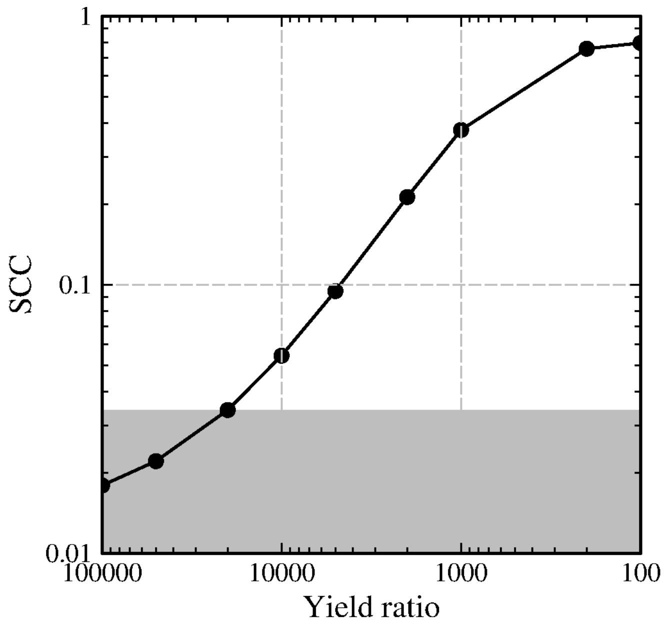

Figure 12. Stacked correlation coefficient (SCC) at USRK versus the 2009 explosion scaled down by the yield ratio. The gray region is 3σ noise level.

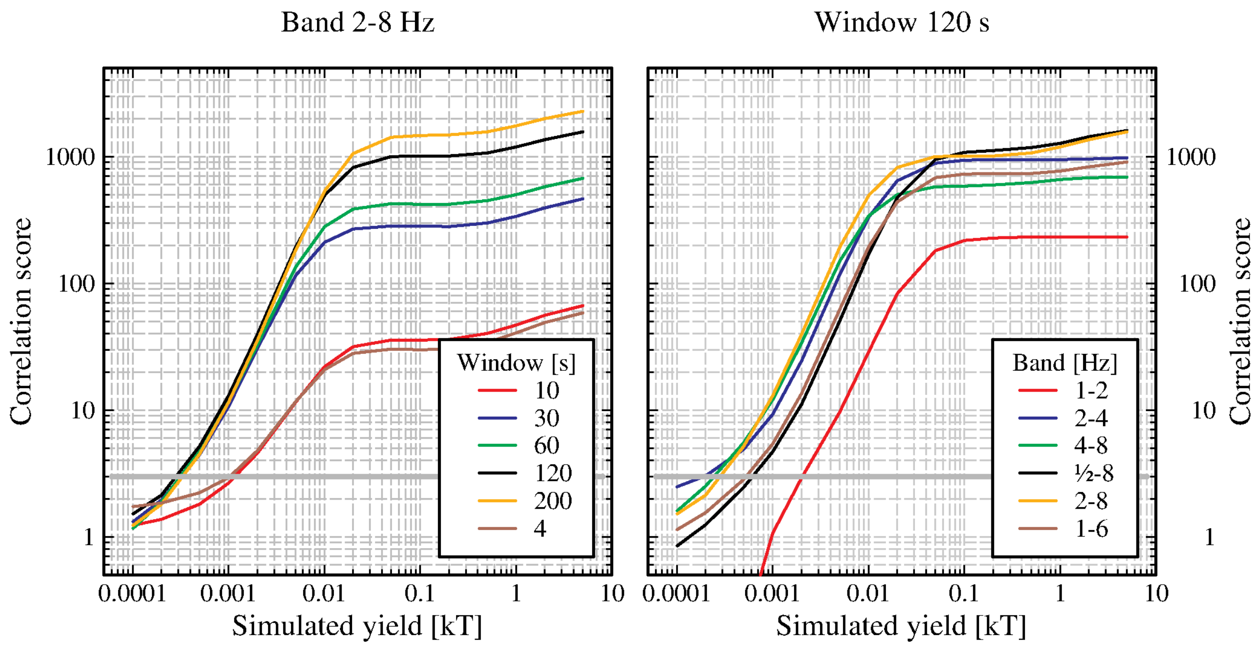

Figure 13. Correlation score at USRK where data is time period of the Zhang & Wen (2015) event added to reduced DPRK09 and template is DPRK13.

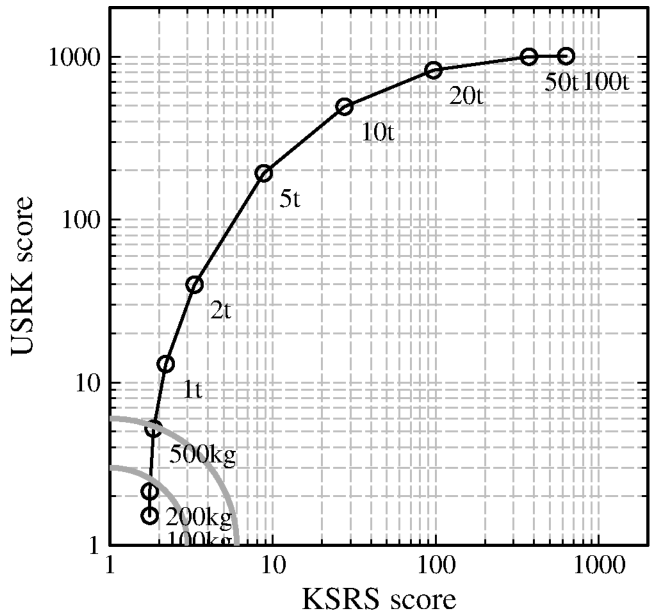

Figure 14. Joint USRK and KSRS detection thresholds for 120s at 2-8Hz at the time of the 12 May 2010 event. Circles show working thresholds of 3σ and 6σ.

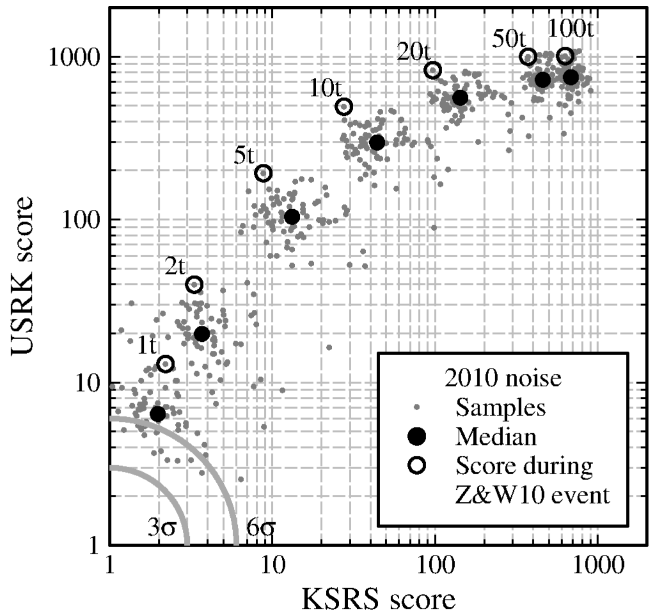

Figure 15. The scaled explosions were embedded in data steams at 75 different times over a one-year time period to explore the detection threshold variability. The median results are shown as large solid dots and the individual results are shown as small dots. The results for the 12 May 2010 time period are shown as open circles and are the same as in Figure 14.

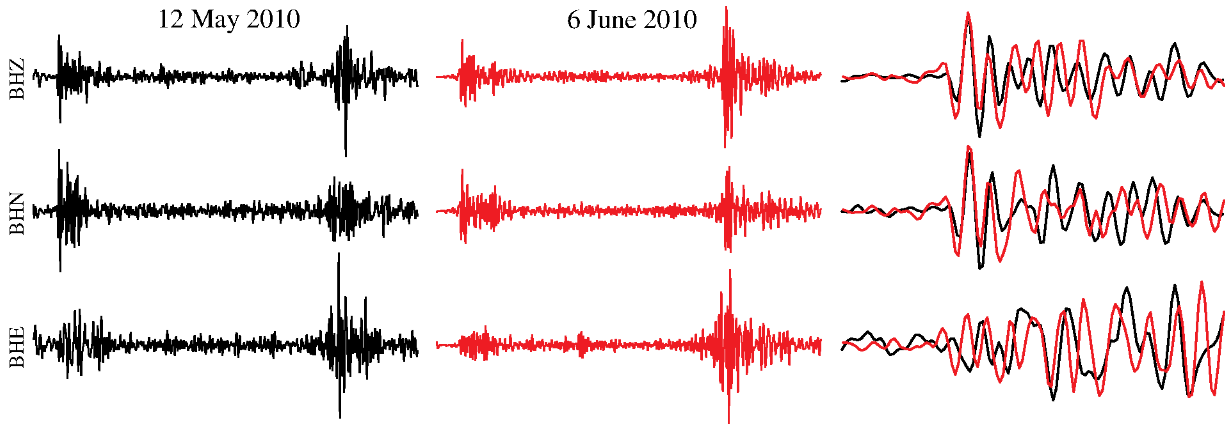

Figure 16. 12 May 2010 event (black) and 6 June 2010 event (red) recorded at NECESS Array temporary station NE3C which is ~165 km from the test site at Punggye-Ri. The right-most pane is 3 s of the P-wave filtered between 1-6 Hz.