USArray Records the 9 October 2006 North Korean Nuclear Test

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Seismographic stations deployed as part of USArray (http://www.iris.edu/USArray/), a component of the National Science Foundation major research equipment project EarthScope (http://www.earthscope.org/), recorded teleseismic *P*-wave ground motions produced by the underground nuclear explosion detonated by North Korea on 9 October 2006. USArray includes a 400 broadband station Transportable Array (TA) being deployed over a regular grid with about 70 km station spacing, which will migrate across the United States over the next dozen years. The TA is currently undergoing its initial deployment in the western U.S., with ~240 operational stations at the time of the North Korean test (Figure 1). While USArray's primary objective is to record seismic signals for research applications addressing the structure, evolution and seismicity of the North American continent, the high quality of the installations allows data from small, distant events to be acquired and analyzed. We demonstrate the TA's small event detection capabilities here, extracting high fidelity signals produced by the North Korean explosion. We use simple waveform stacking approaches in our analysis; more sophisticated methods are viable when the array design allows more specific models of signal and noise characteristics (e.g., Douglas, 1998). Our primary focus is to illustrate USArray data quality, not to provide detailed analysis of the explosion.

Underground nuclear explosions generate shock waves in the encompassing rock, which produce outward propagating seismic *P* waves that are recorded at distant seismic stations. Seismometers, designed to continuously record ground motions, allow the *P* wave arrival time and amplitude to be determined at many positions on the Earth's surface. Given knowledge of the speed with which the waves travel, and combining information from a number of stations, the location and origin time of the source can be estimated. The vibration amplitudes can then be used to estimate the relative source strength, given prior determinations of how *P*-wave amplitudes vary with distance from the source. The U.S. Geological Survey used seismic waves recorded primarily at seismic stations in Asia to precisely estimate the hypocenter and magnitude of the North Korean event: 41.294°N, 129.094°E (Figure 1) 9 October 2006 at 01:35:28 (UTC); m_b 4.2 (*P*-wave magnitude; in this case based on 7 amplitude measurements) (USGS, 2006). Accurate location and event size estimates, acquired by various international seismological observation systems, play a key role in monitoring nuclear testing treaties and in characterizing the nature of underground explosions. Given independent calibration of the seismic magnitude versus known explosive yield for a particular rock environment, the measured seismic magnitude can be used to estimate the explosion energy. Several yield estimates of less than 1 kiloton for the North Korean event have been announced in the popular media, based on reported seismic magnitudes from different monitoring operations ranging from 4.0 to 4.2.

USArray TA stations operating in the western U.S. (Figure 1) are at epicentral distances of 66° to 95° from the North Korean test site. Although simple teleseismic *P* waveforms are expected for an underground explosion, a magnitude 4.2 event is expected to produce only about a 2-nm displacement in this distance range, so small that typically only exceptionally quiet sites or seismic arrays specially designed to reduce seismic background noise (e.g., *Douglas*, 1998) can make robust detections of teleseismic signals of this size. Small aperture seismic arrays are used routinely by the International Monitoring System (http://www.seismo.ethz.ch/bsv/ctbto/ims.html) and are being integrated into the USGS NEIC monitoring operations (Harley Benz, personal communication); very high quality recordings were obtained from several small permanent arrays for the North Korean test including the Pinedale and Mina arrays in the western U.S., which contribute to the IMS and to the USArray backbone network.

The TA, in contrast, is designed to record a broad spectrum of ground motions at isolated sensors with emphasis on uniform spatial coverage appropriate for seismic imaging of Earth's interior rather than multiple sensor stacking. The quality of the TA installations, however, allows some applications to seismological problems other than the primary design goals. Casual inspection of the broadband TA recordings (openly available, along with all other TA data, from the Incorporated Research Institutions for Seismology (IRIS) data management system, http://www.iris.edu/) reveals no discernible signal, but when the data are band-pass filtered between 1 and 4 Hz, 45 of the currently operating stations show a coherent *P* wave signal a few seconds later than the arrival time predicted for a standard Earth model. The stations recording clear *P* wave arrivals are identified in Figure 1. These stations tend to be far from the noisy Pacific coast, but are otherwise fairly uniformly dispersed throughout the current TA footprint.

Array processing methods generally involve summing signals from multiple sensors (e.g., Rost and Garnero, 2004), and we treat the TA as a large-aperture array. We consider a subset of the TA data that recorded both the North Korean underground test and a magnitude 5.9 deep earthquake that occurred on 16 September 2006, 366 km below the Sea of Japan (NEIC: 022250.59 UTC, 41.36°N, 135.70°E) (Figure 1). As described later, we use the deep event, which has impulsive P arrivals, to calibrate site effects that help extract the short-period signals produced by the North Korean test. Requiring each station to record at the time of the North Korean explosion and to record the deep event with a high signal-to-noise ratio, yields a 172 waveform subset that includes 36 of the 45 clear signals from the North Korean, which are shown in Figure 2. These traces have been picked manually and aligned on the largest pulse in the filtered *P* waveforms. Individual station signal-to-noise ratios are in the range 2 to 4 at these exceptionally quiet (in this pass band) stations.

We consider four different array sums of subsets of the 172 waveforms. For many stations it is not possible to pick the *P* wave arrival reliably. Simply aligning all 172 signals on theoretical *P* wave arrival times predicted for the Jeffreys-Bullen (JB) travel time tables, weighting each signal by the inverse of its RMS amplitude, and summing yields the top trace in Figure 3, which lacks any clear detection of the explosion signal. In this instance the explosion signal remains incoherent as a result of its short duration and the arrival time fluctuations relative to the JB predicted times caused by crust and upper mantle heterogeneity and station elevation variations across the large aperture array. To estimate station dependent travel time corrections for azimuths and incidence angles similar to those for the North Korean event we used picks of the impulsive *P*-wave arrivals for the much larger Sea of Japan event. The corrections have about a 2 s scatter around a systematic delay relative to the JB tables. The sum of all 172 traces aligned with these additional corrections, and again weighted using the inverse of the RMS amplitude of each trace, is shown in the second row of Figure 3. A clear arrival near the expected time is now apparent. The inverse RMS weighting reduces the influence of a modest number of stations with higher noise levels on the stack. If we restrict our attention to the 36 high signal-to-noise ratio TA observations in Figure 2, simple unweighted (true-ground displacement amplitude) stacks corrected for the Japan Sea event station statics give the third trace in Figure 3, which has a clear *P* wave detection. The aligned traces in Figure 2 sum to give an even cleaner stack, as shown in the bottom trace of Figure 3, with the peak-to-peak amplitude being about 2 nm, as expected. The overall affect of improved signal alignment is an increase in signal coherency reflected by increasing signal amplitude. The noise level is insensitive to time shifts and is below 0.25 nm, a remarkably low level that reflects the low noise levels of many of the TA stations and the effective suppression of incoherent noise. Secondary arrivals are observed in the stack within the first 6 s of the signal; these are most likely crustal reverberations generated near the source since they stack coherently across widely separated receivers.

Uniform installation procedures, which have evolved from extensive community experience with portable broadband seismic instrument deployments, are being followed for all TA stations (http://www.earthscope.org/usarray/site_char/trans_array_sites.php). The variations in TA noise properties are thus largely attributable to local seismic noise characteristics and site properties (detailed station information, including time varying power density function data that quantify the noise levels for each station is available from the USArray Network Facility site: http://anf.ucsd.edu/). While some sites are intrinsically noisier than others, the quality of many TA stations is comparable with that of the high-quality permanent sites within seismic monitoring networks.

While monitoring small nuclear tests is a well-developed capability and permanent small-aperture arrays that achieve comparably low detection thresholds are available, the general quality and capabilities of the TA data are illustrated by this example. As the EarthScope project progresses, there will be opportunities to use USArray for unexpected applications complementing the planned investigations of the North American continent (*e.g.* Moschetti *et al.*, 2005), including imaging earthquakes as well as deep and distant Earth structure (*e.g.*, Lay *et al.*, 2006).

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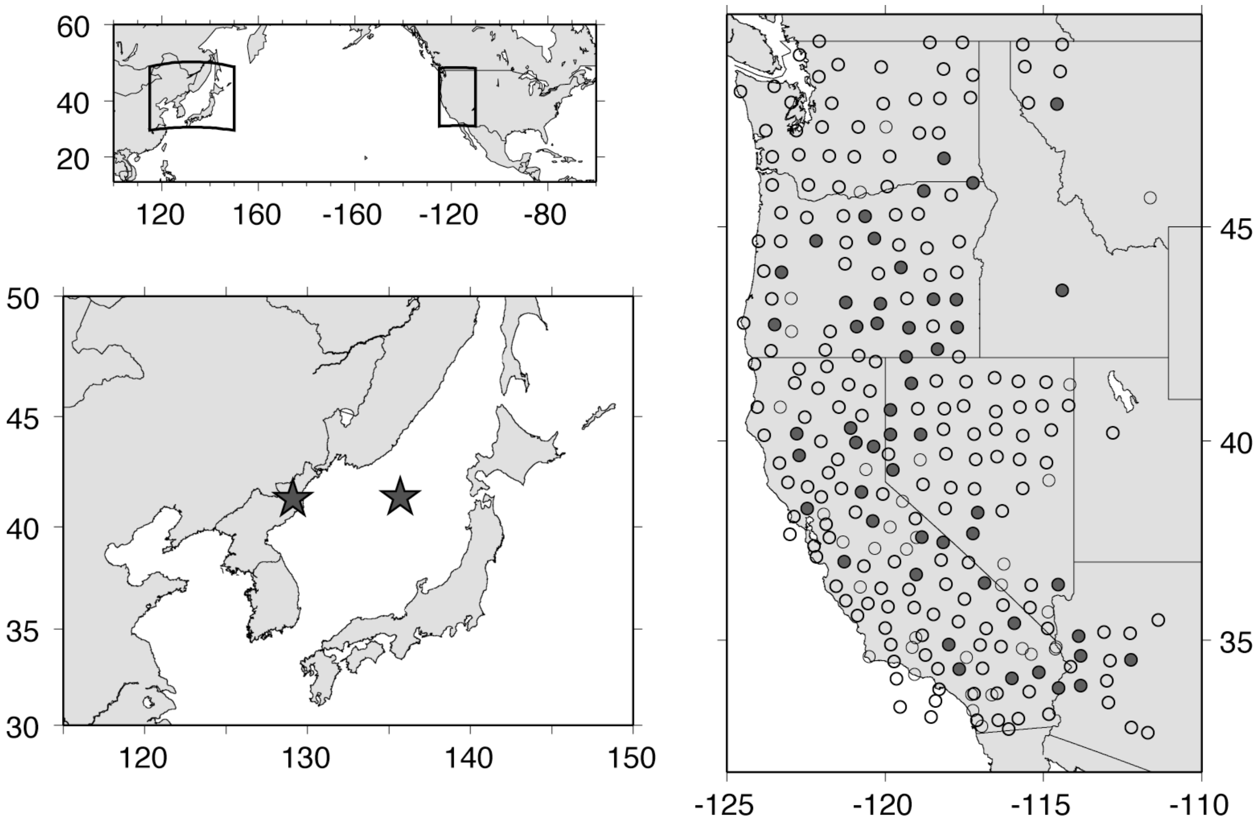

Figure 1. (Upper left) Outlined regions show event and station map locations. (Lower left) Map showing the location of the North Korean nuclear test and a deep event beneath the Sea of Japan that we used as a calibration event. (Right) Locations of unavailable TA station signals (light gray circles), stations with usable, but low signal-to-noise records (dark gray unfilled circles), and stations with clear *P* wave arrivals for the North Korean test (dark gray filled circles).

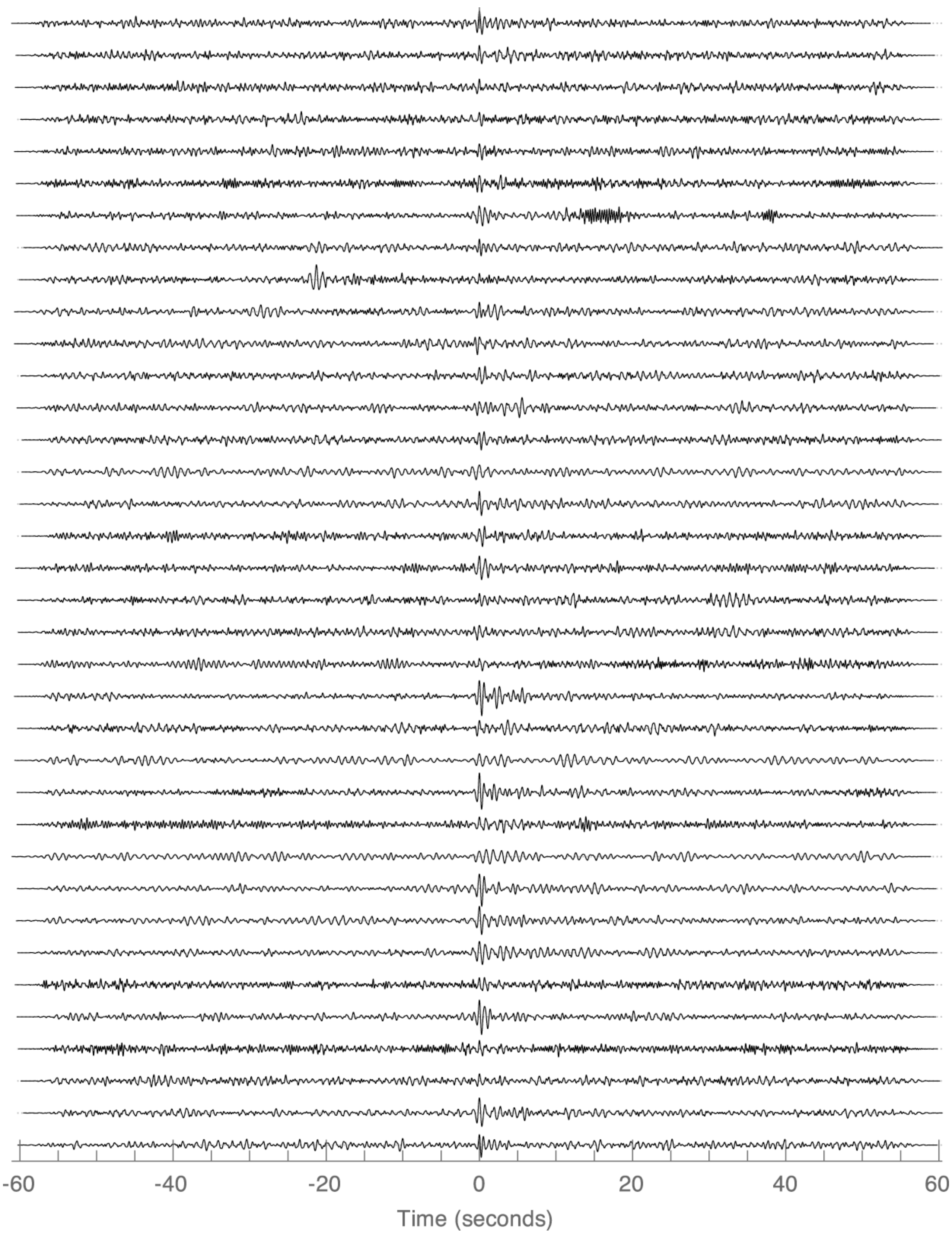

Figure 2. Ground displacement recordings of the 9 October 2006 North Korean Nuclear test from TA stations, manually aligned on the peak of the *P* waves. The signals are RMS amplitude equalized for display and filtered between 1 and 4 Hz.

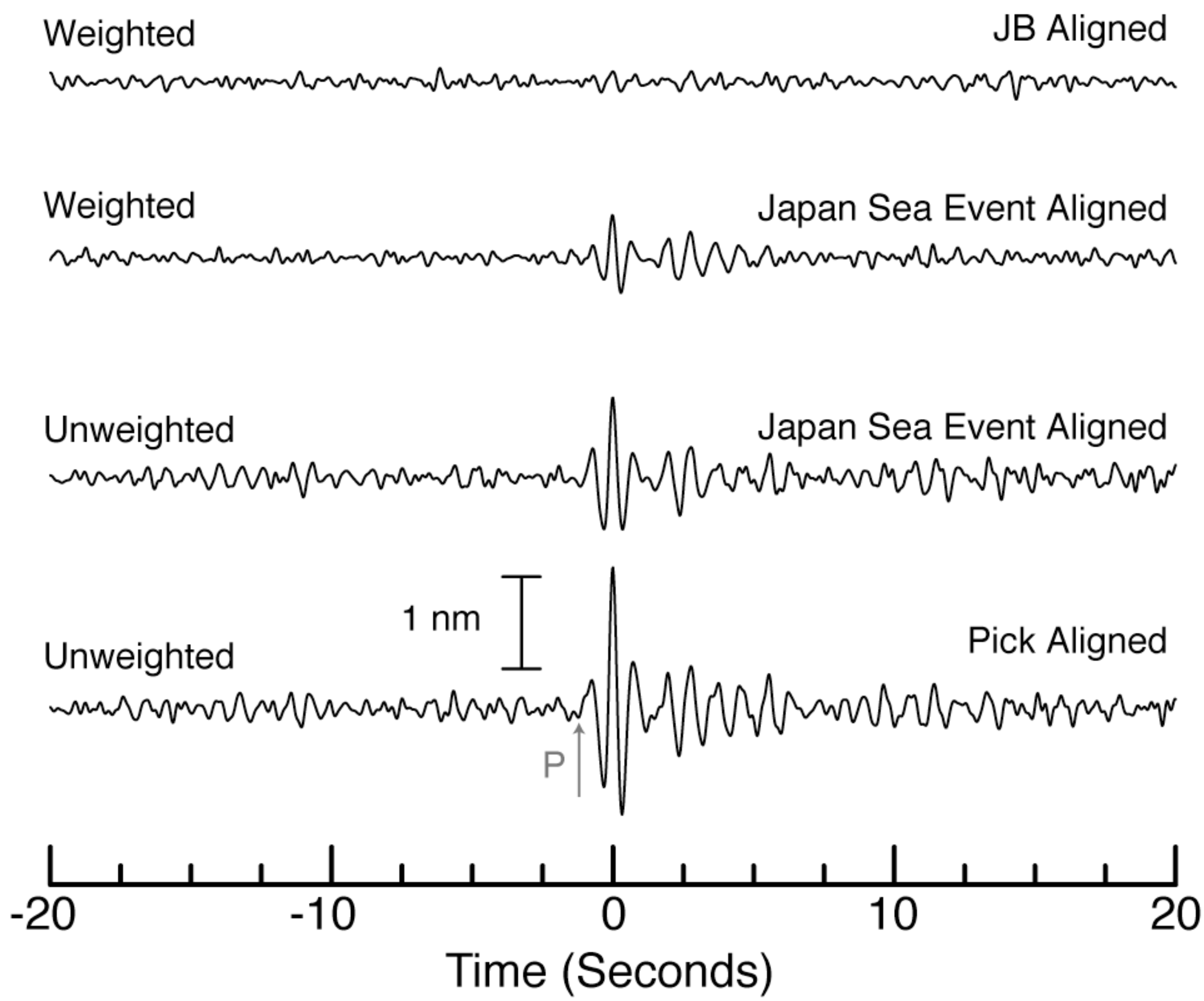

Figure 3. Linear stacks of *P* wave signals from TA stations for the North Korean event. All stacks are shown on the same amplitude scale – the weighted averages are scaled by the sum of the weights to produce displacements. The top trace is the result of aligning 172 signals using only a standard travel time reference before averaging; the second trace from the top is the result of adjusting the alignment of the same 172 signals using station-dependent travel time corrections measured from the deep Sea of Japan event; the third is a stack using the Sea-of-Japan-event time corrections on the 36 high-quality signals in Figure 2; the bottom trace is a stack of the same 36 signals aligned by picking the peak arrival time directly. The top two stacks were computed using signal weights equal to the inverse of the signal's RMS amplitude; the lower two stacks were constructed using observed ground displacements. The first, emergent upward polarity, indicated by the arrow labeled P, is the compressional first arrival. In all cases, the incoherent noise between stations is very effectively suppressed, down to levels of 0.25 nm, which indicates exceptionally quiet sites and suppression of incoherent noise.