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Estimating and exploiting the outgoing seismic wavefield at the North Korean nuclear test site

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Between October 2006 and September 2016, 5 declared underground nuclear explosions were carried out at the Punggye-ri test-site in North Korea. All events were detected clearly both at regional and teleseismic distances. Waveform similarity allows us to estimate relative locations of all 5 events using classical double-difference techniques. However, using a simple 1D velocity model, these estimates are quite sensitive to the set of stations used with inter-event distances estimated using regional Pn phases consistently longer than those estimated using teleseismic P-phases; the seismic wavefield leaving the test-site is more complicated than the 1D velocity model description. We seek perturbations to the horizontal slownesses of each of the rays leaving the source region which ultimately reach the sensors at which the correlations are performed. We find spatially consistent perturbations which reduce the double-difference time residuals and provide relative location estimates which are consistent on both regional and teleseismic measurements. The perturbations are almost sinusoidal with azimuth, as is frequently observed with the observation of incoming wavefronts at seismic arrays. The spatial form of the outgoing wavefield can also be estimated using classical array processing methods on a virtual source array. The source-array analysis supports independently the perturbations to the outgoing wavefield obtained previously and, given the number of events now recorded at this site, may allow accurate relative location estimates for subsequent events which are recorded by a less favorable set of stations. One such scenario is a lower magnitude event recorded only at regional distances, with the associated limitations in azimuthal coverage. Another scenario is of a test in a different part of the test site for which the waveform similarity at some stations, a particularly acute problem for regional phases, may be significantly diminished.