Cross comparison of four DPRK events
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Introduction. Seismic signals were detected by the IMS seismic network from four interested underground tests conducted by the DPRK in 2006, 2009, 2013, and 2016. These data allow thorough comparison of relative locations, including depth and time, and magnitudes using several techniques based on waveform cross correlations. The techniques are still in a development stage, and dedicated mostly to the Special Studies and Expert Technical Analysis specified in a Comprehensive Nuclear Test Ban Treaty (CTBT). Seismic signals from these events also provide waveform templates for detection of possible aftershocks with magnitudes by waveforms that are lower than the events themselves. We have processed one month of continuous data after each of four events and detected no aftershocks.

Conclusion. Four DPRK events were conducted within a few kilometres from each other and fall into a magnitude range of 4.5. Since the ground truth information about yields, depths and locations of these events is not available, several advanced methods were applied to estimate the observed differences in seismic waveforms from these events. Waveform cross correlation allows to precisely estimate relative locations and magnitudes of the events close in space. The relative locations of the 2006, 2009, and 2016 DPRK events can be placed within the same mountain. The 2008 event is located at a distance of 2.5 km to east from the 2008 explosion. The depth of burial for the 2006 event is estimated between 650 m and 1100 m by fitting with synthetic seismograms, phase method and coda analysis.

The depth of 2009 and 2013 are estimated between 400 m and 900 m, The 2008 event has also produced an LR wave with a higher amplitude relative to that measured from the 2013 event likely because of a larger CTSX component. The relative magnitude of four events measured as the logarithm of the RMS-amplitude in the cross correlation window serves as a reliable measure of the relative size of the DPRK explosions. The relative magnitude estimates are characterized by a lower uncertainty since the cross correlation coefficients for the signals from four events is higher than 0.18, except for few stations and for the smallest 2006 event.

Waveform comparison: Similarities and differences

Depth

We conducted a study of depth determinations based on cross-correlation techniques to improve the statistical accuracy. We performed a number of tests using synthetic seismograms and compared the results with the published locations of the膑pct events. The results show that the method is robust and can be used to locate earthquakes to within a few kilometres. The method is also applicable to other types of events, such as nuclear explosions.

A non-parametric test to determine the significance of differences in the depth estimates is presented. The test is based on the ranks of the depth estimates and can be used to test the null hypothesis that the true depths are the same for all events. The test was applied to the depth estimates of the four DPRK events and the results are consistent with the hypothesis that the true depths are the same for all events.

Relative location

The 2006 event was located within 100 m of the 2008 event, and the 2009 event was located within 200 m of the 2008 event. The 2013 event was located within 200 m of the 2006 event. The 2009 and 2013 events were located within a few kilometres of each other. The 2006 and 2013 events were located at the same depth, but the 2009 event was shallower.

The relative locations of the events were estimated using cross-correlation techniques and comparing the waveforms from the events. The relative locations of the events were estimated to within a few kilometres. The results are consistent with the hypothesis that the true locations are the same for all events.