

**Abstract**

The accuracy of earthquake location is controlled by several factors, including the network geometry, available phases, arrival-time reading accuracy, and knowledge of the crustal structure. At 00:30 (UTC) on 09 September 2016, the North Korea conducted its fifth nuclear test. Because lack of near station and poor network geometry, it's difficult to determine the location of the fifth nuclear test in North Korea with routine earthquake location method. In this study, we improve the double-difference relocation algorithm which can fix the focal depth and only invert the epicenter and occurrence time. We correct the positions of the double-difference relocation results with reference events. Synthetic tests indicate that the method has little effect on velocity model and the location error is less than 100 m. We determined the locations of the four nuclear tests with the new method. The fifth nuclear test is located to the northeastern of the fourth test. The distance between the two tests is about 400 m.

**Data and Method**

The waveform data used in this research are provided by the Data Management Centre of China National Seismic Network at the Institute of Geophysics (Fig. 1). We selected 20 from 71 permanent seismic stations with high SNR near North Korean nuclear test sites to pick the arrival times (Fig.1). The epicentral distance varies from 210 km to 500 km. Due to the small number of stations in 2006, we only processed waveforms of 2009/05/25, 2013/02/12, 2016/01/06 and 2016/09/09 nuclear test. P-wave arrivals are manually picked for these four events at all stations. Waveform cross correlation are then adopted to refine the arrival times.

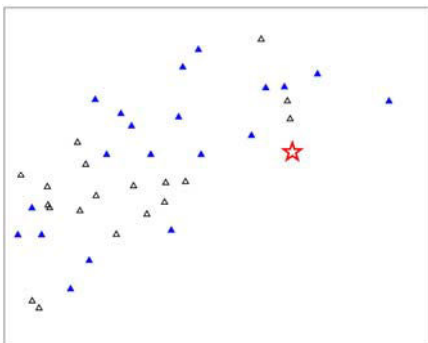


Figure 1. Seismic stations used in this study. The red star show the location of the nuclear test. The blue triangle indicates station with high SNR. The white triangle represents station not used in the study.

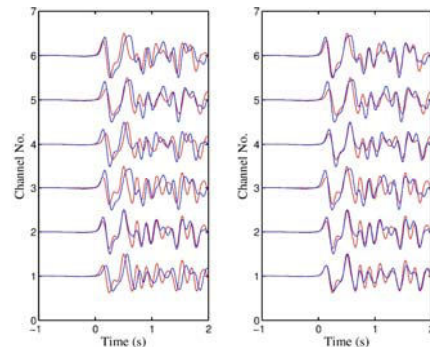


Fig 2. Waveforms from different event pairs recorded at the MDJ station. In the left panel, the waveforms are aligned according to manually picked arrival time. The right panel shows waveforms aligned according to cross correlation.

Double-difference location method was widely applied to relocate aftershocks and earthquake swarms (Waldhauser & Ellsworth, 2000; Fang et al., 2013). In this research, we improved the double-difference relocation algorithm. The new method can fix the focal depth and occurrence time. The 1-D velocity model used in relocation is modified from a deep seismic sounding profile. The  $V_p/V_s$  ratio is set according to receiver function  $h-k$  study.

**Synthetic tests**

In order to evaluate the performance of the new method, we conduct a series of synthetic tests. We calculate the traveltimes of 100 reference events. The events are evenly distributed in space with  $0.01^\circ \times 0.01^\circ$  grid. We use the location difference before and after relocation to estimate the location error. Figure 3 shows an example. When the traveltime error is 0.02s, the semi-major and semi-minor axes of the error ellipse is 80 m and 51 m respectively.

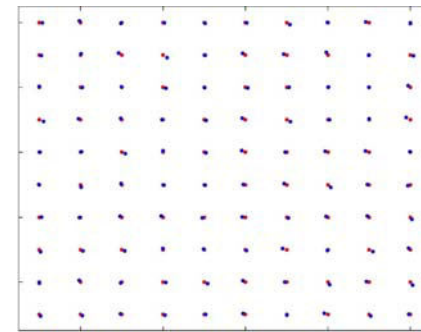


Fig 3. Distribution of reference event before (red dot) and after (blue dot) relocation.

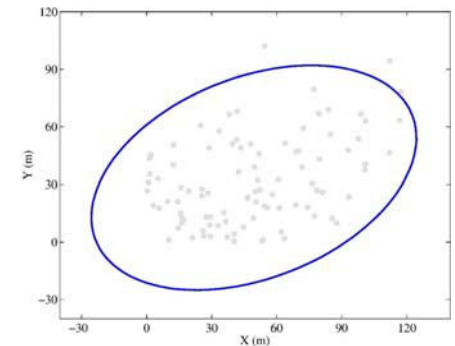


Fig 4. Error ellipse of the relocation

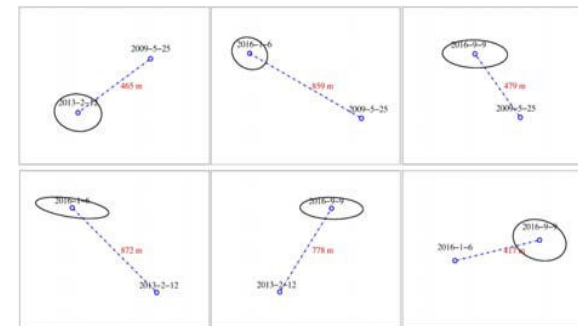


Fig 5. Relative location between each event pair.

Test	Date (year/mm/dd)	Origin Time (hh:mm:ss)	Latitude ( $^\circ$ N)	Longitude ( $^\circ$ E)
2009	2009/05/25	00:54:43.17	41.2944	129.0798
2013	2013/02/12	02:57:51.32	41.2914	129.0759
2016	2016/01/06	01:30:01.00	41.2973	129.0735
2016	2016/09/09	00:30:01.32	41.2981	129.0783

Table 1. Time and location of the four nuclear tests in North Korea.

**References**

Fang L H, Wu J P, Wang W L, et al. Relocation of the mainshock and aftershock sequences of Ms7.0 Sichuan Lushan earthquake. *Chin Sci Bull*, 2013, 58: 3451-3459.  
 Waldhauser F, Ellsworth W L. A double-difference earthquake location algorithm: Method and application to the Northern Hayward Fault, California. *Bull Seismol Soc Am*, 2000, 90: 1353-136.  
 Zhao L F, Xie X B, Wang W M, et al. Seismological investigation of the 2016 January 6 North Korean underground nuclear test. *Geophysical Journal International*, 2016, 206(3): 1487-1491.  
 Wen L, Long H. High-precision location of North Korea's 2009 nuclear test. *Seismological Research Letters*, 2010, 81(1): 26-29.  
 Zhang M, Wen L. High-precision location and yield of North Korea's 2016 nuclear test. <http://seis.ustc.edu.cn/2016/09/09/c10094a113704/page.htm>.

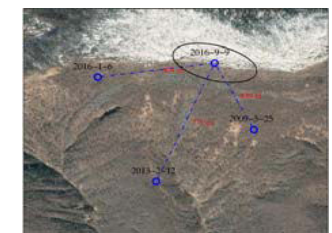
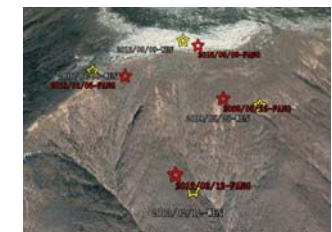


Fig 6. Locations of the four nuclear tests in North Korea plotted on a Google Earth map.