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6.1 Detection and Location of the February 12, 2013, Announced Nuclear Test in North Korea

On February 12, 2013, The Democratic Peoples' Republic of Korea (the DPRK, or North Korea) announced that a nuclear test had been carried out. This was the third test of its kind, the first two having occurred on October 9, 2006, and May 25, 2009. Prior to the announcement by the DPRK, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) had released a statement to say that seismic stations of the International Monitoring System (IMS) for verifying compliance with the treaty had detected "an unusual seismic event in the DPRK which measured 4.9 in magnitude"[1]. 25 stations of the primary seismic network contributed to the fully automatic SEL3 (Standard Event List 3) seismic event location estimate. Two primary IMS seismic stations operated by NORSAR, NOA (PS27) and ARCES (PS28), were among these stations.

The location estimates of the three DPRK nuclear tests, together with the origin time and m_b magnitude estimates, as provided in the Reviewed Event Bulletin (REB) of the International Data Centre (IDC) of the CTBTO, are displayed in Table 6.1.1.

Date	Origin time (UTC) in format yyyy-doy:hh.mm.ss.ss where doy is the Julian day	Latitude	Longitude	m_b magnitude estimate
October 9, 2006	2006-282:01.35.27.58	41.3119	129.0189	4.1
May 25, 2009	2009-145:00.54.42.80	41.4110	129.0464	4.5
February 12, 2013	2013-043:02.57.50.80	41.3005	129.0652	4.9

Table 6.1.1: Origins for the three DPRK nuclear tests provided in the REB of the IDC.

All of the solutions given have depth fixed to zero.

In this short summary we

- display the signals from the three DPRK nuclear tests recorded on the NOA array
- discuss the detection of the 2013 tests using a matched filter detector on the NOA array using the signal from the 2009 test as a waveform template
- discuss the location of the 2013 DPRK test relative to the location of the 2006 and 2009 tests. For this final investigation, waveform data from many IMS seismic stations were used.

[1] http://www.ctbto.org/the-treaty/developments-after-1996/2013-dprk-announced-nuclear-test/

6.1.1 Observations of the February 12, 2013, DPRK Nuclear Test on the NOA array

The large aperture NOA array in southern Norway was operational at the times of all of the three DPRK nuclear tests. Between the times of the 2009 and 2013 events, the short period vertical sensors were replaced with broadband instruments. A beam on the NOA array is shown for each of the three events in Fig. 6.1.1; all traces are shown to a common scale and all are corrected to a common instrument response.

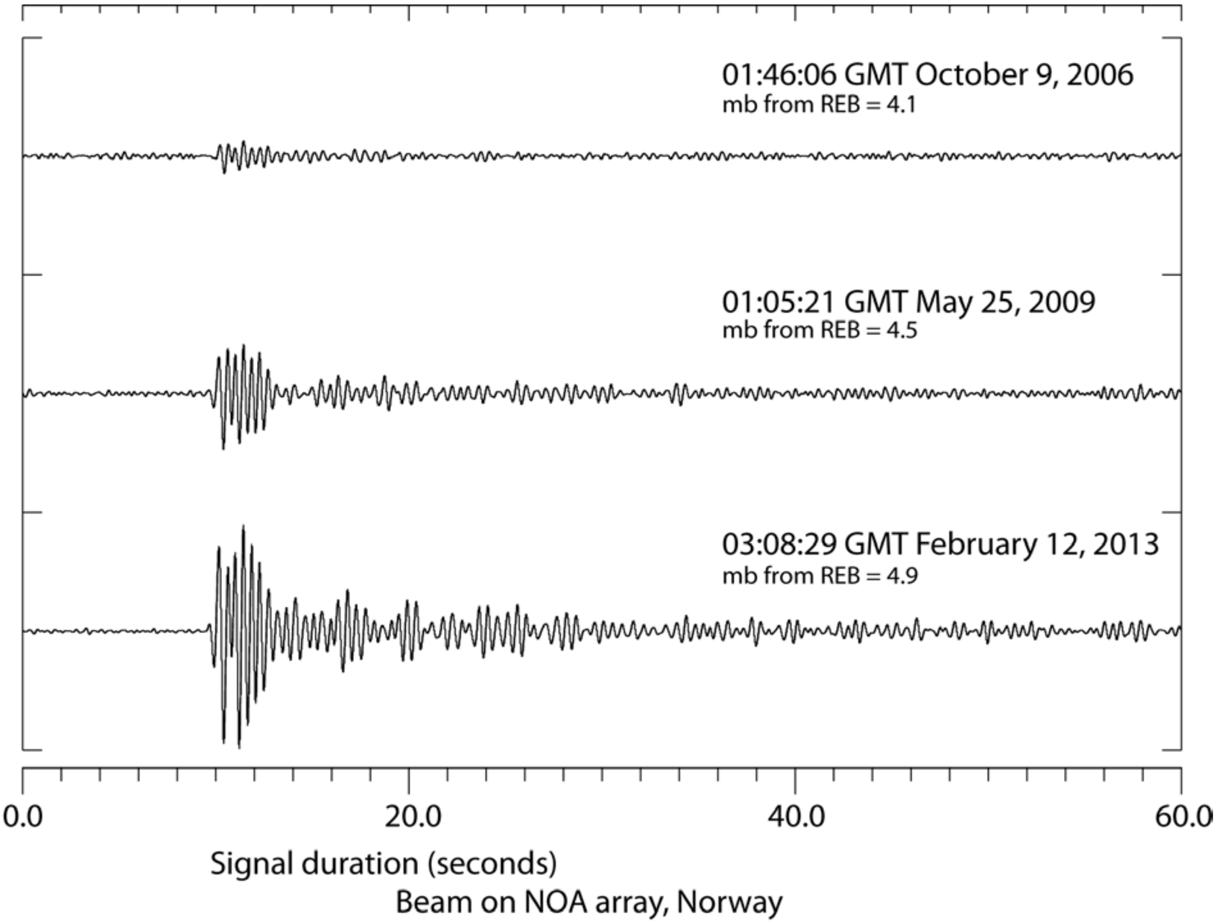

Fig. 6.1.1 Beam on the NOA array (PS27) for the three DPRK nuclear tests displayed to a common scale. A bandpass filter 1-5 Hz has been applied to all traces and the 2013 signal on the new broadband instruments has been transformed to the instrument response of the short period sensors which recorded the first two tests (so that the signal amplitudes for all 3 events are directly comparable). The times displayed give the starting times of the traces; the arrival of the P phase comes approximately 10 seconds later.

It has long been recognized that delay times over the large aperture NOA array based upon a plane-wave propagation model alone give poor signal alignment and result in significant destructive interference under the beamforming operation. The beams displayed in Fig. 6.1.1 are calculated using the semi-empirical time-delays provided in the Table 6.1.2 (see Gibbons et al., 2009, for further details).

Site	Predicted plane-wave time-delay (seconds) vel 17.3 km/s, azi 46.67^o	Estimated correction term (vel 17.3 km/s, azi 46.67 degrees)	Actual time-delay applied to channel (seconds)
NAO00	1.822	-0.348	1.474
NAO01	1.608	-0.308	1.299
NAO02	1.754	-0.344	1.410
NAO03	2.034	-0.346	1.688
NAO04	2.039	-0.337	1.702
NAO05	1.732	-0.274	1.458
NBO00	1.028	-0.075	0.953
NBO01	0.878	-0.054	0.824
NBO02	0.767	-0.085	0.682
NBO03	0.972	-0.128	0.845
NBO04	1.168	-0.100	1.068
NBO05	1.025	-0.034	0.991
NB200	0.000	0.000	0.000
NB201	-0.222	0.093	-0.129
NB202	0.002	0.005	0.007
NB203	0.234	0.102	0.336
NB204	0.084	0.093	0.177
NB205	-0.099	0.095	-0.004
NC200	-0.210	0.212	0.002
NC201	-0.466	0.221	-0.246
NC202	-0.264	0.220	-0.043
NC203	-0.039	0.164	0.125
NC204	-0.026	0.221	0.195
NC205	-0.370	0.272	-0.098
NC300	-1.425	0.109	-1.316
NC301	-1.660	0.092	-1.568
NC302	-1.429	0.103	-1.326
NC303	-1.163	0.103	-1.060
NC304	-1.314	0.116	-1.199
NC305	-1.560	0.130	-1.431
NC400	-1.311	0.099	-1.213
NC401	-1.499	0.146	-1.352
NC402	-1.248	0.054	-1.194
NC403	-1.086	0.017	-1.070
NC404	-1.230	0.070	-1.159
NC405	-1.451	0.132	-1.319
NC600	0.732	-0.310	0.422
NC601	0.423	-0.297	0.126
NC602	0.596	-0.325	0.270
NC603	0.867	-0.347	0.520
NC604	0.967	-0.339	0.628
NC605	0.711	-0.295	0.416

Table 6.1.2: Time-delays for construction of the NOA array beam (reference site NB200) for the DPRK nuclear test site.

6.1.2 Detection of the signal from the DPRK nuclear test using multi-channel correlation detectors

Signals from the February 12, 2013, DPRK event were detected with a high signal-to-noise ratio (SNR) at many seismic stations globally. However, in addition to the routine processing of the incoming seismic data for unknown signals, NORSAR operates in real time a number of so-called correlation or matched filter detectors for signals from sites of special interest from which seismic events have previously been observed (see Gibbons and Ringdal, 2006). The North Korea nuclear test site is naturally one of these sites of interest. Several templates, consisting of the signals from the 2006 and 2009 DPRK nuclear tests recorded on the various seismic arrays to which NORSAR has access to real-time data, are correlated with the incoming waveform data and the process is connected to an alarm system for occasions on which a trigger is declared. All correlation detectors which run on array datastreams (as opposed to 3-component data streams) are subject to a post-processing system for filtering out false alarms on each occasion for which a preliminary detection is made. This involves performing f-k analysis on the single channel detection statistic traces in order to confirm that the detected wavefront approached the array from the same direction as the master event wavefront (the principle is described in Section 4 of Gibbons and Ringdal, 2006). Gibbons and Ringdal (2012) describe a multi-channel correlation detector for the North Korea test site on data from the MJAR array in Japan and demonstrated that the application of this post-processing system reduced the number of detections made in a 3 year period from several thousand to fewer than 10. Fig. 6.1.2 displays the detection of the 2013 DPRK nuclear test, by performing correlation on the NOA array, using a waveform template from the 2009 DPRK event.

The corresponding slowness grid from the f-k post-processing system is displayed in Fig. 6.1.3. The zero slowness vector confirms that the NOA array is unable to differentiate between the direction of arrival of the detected signal and the direction of arrival of the master signal. This is strong evidence that the detected signal came from a location very close to the site of the 2009 DPRK nuclear test. It should be noted that the templates taken from both the 2006 and 2009 events on the NOA array generated clear detections which easily passed the f-k analysis post-processing system. The similarity between the 2009 and 2013 signals was far greater than that between the 2006 and 2013 signals, although the 2013 event signal was sufficiently similar to the significantly smaller 2006 signal for a clear correlation detection to be made.

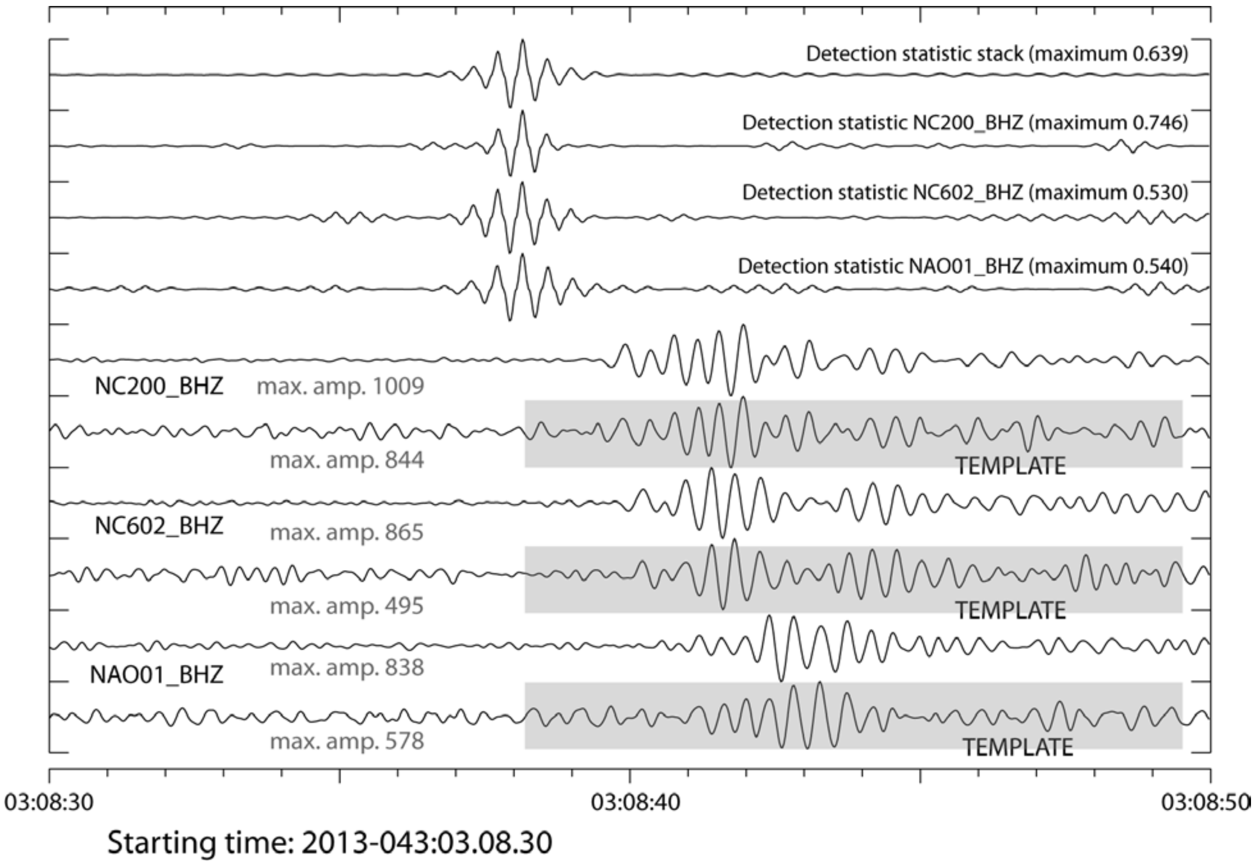

Fig. 6.1.2 Detection of the February 12, 2013, event on the NOA array using a signal template from the May 25, 2009, DPRK nuclear test. The 60 second long waveform template begins at a time 01.05.30 UTC on 2009-145 and the maximum value is reached at a time of 03.08.38.153 UTC on 2013-043. The "detection statistic" is the square of the correlation coefficient but preserving the sign (see Gibbons and Ringdal, 2012, for details).

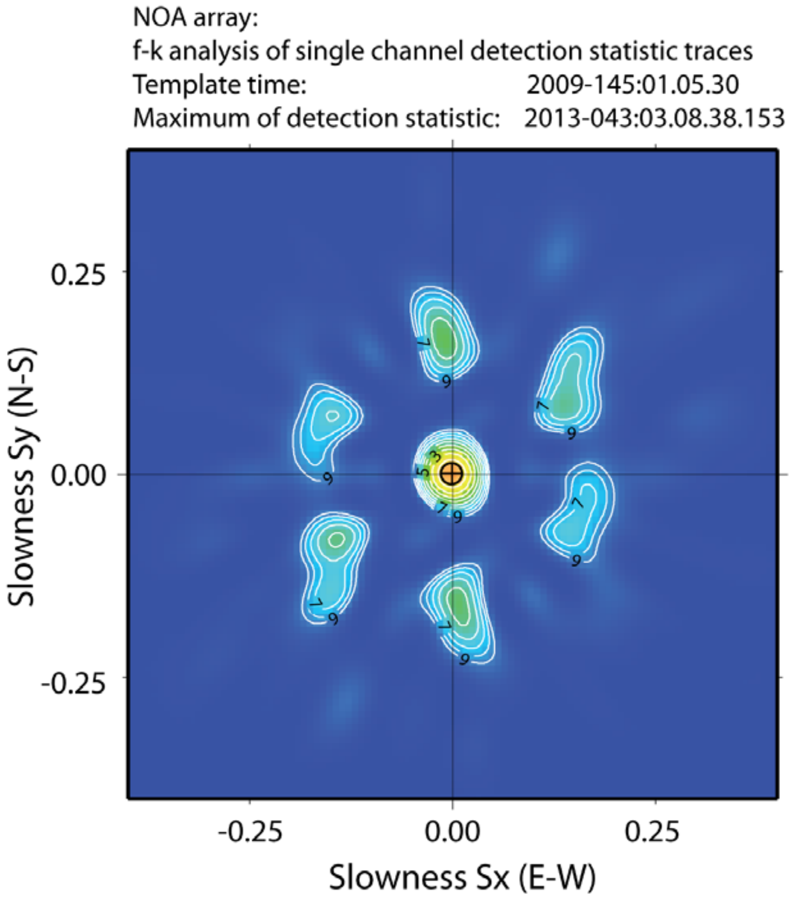

Fig. 6.1.3 f-k analysis of the detection statistic traces in a 2-second long window centered on a time 2013-043:03.08.38.153 for each of the 42 vertical channels of the NOA array. The maximum beam-gain is for the zero slowness vector (i.e. with zero time-delay), the implication being that the detected wavefront approached the array from exactly the same direction as the wavefront in the waveform template. See Gibbons and Ringdal (2006) for details.

6.1.3 Location of the 2013 DPRK nuclear test relative to the 2006 and 2009 events

When two seismic events occur very close to each other, there may be sufficient similarity between the signals generated at any given station that very accurate relative times may be calculated by cross-correlating the one waveform against the other. The accuracy in these relative arrival times can exceed greatly the accuracy with which the arrival of a seismic phase can be read on a seismogram and, by measuring these very small time differences at many seismic stations observing the event from different directions, we may be able to locate the two events relative to each other with a high level of confidence. This principle forms the basis of the double difference location algorithms (e.g. Richards et al., 2006; Waldhauser and Ellsworth, 2000) which have been used to create earthquake catalogs of unprecedented detail.

When North Korea carried out their second nuclear test in 2009, it was evident that the signals generated by this explosion were very similar to those generated by the test in 2006. Several independent studies (Murphy et al., 2010; Selby, 2010; Wen and Long, 2010) examined closely the time differences between stations, both regional and global, and there is general agreement that the location of the explosion in 2009 is approximately 2 km to the West and slightly to the North of the 2006 test. These high precision relative location estimates have also been examined in relation to high-resolution satellite imagery of the test-site region (see also Schlittenhardt et al., 2010). Fig. 6.1.4 shows the locations that Wen and Long (2010) provide for the 2006 and 2009 tests based on both precision seismology and analysis of satellite imagery. The symbol to the right is the location of the 2006 explosion.

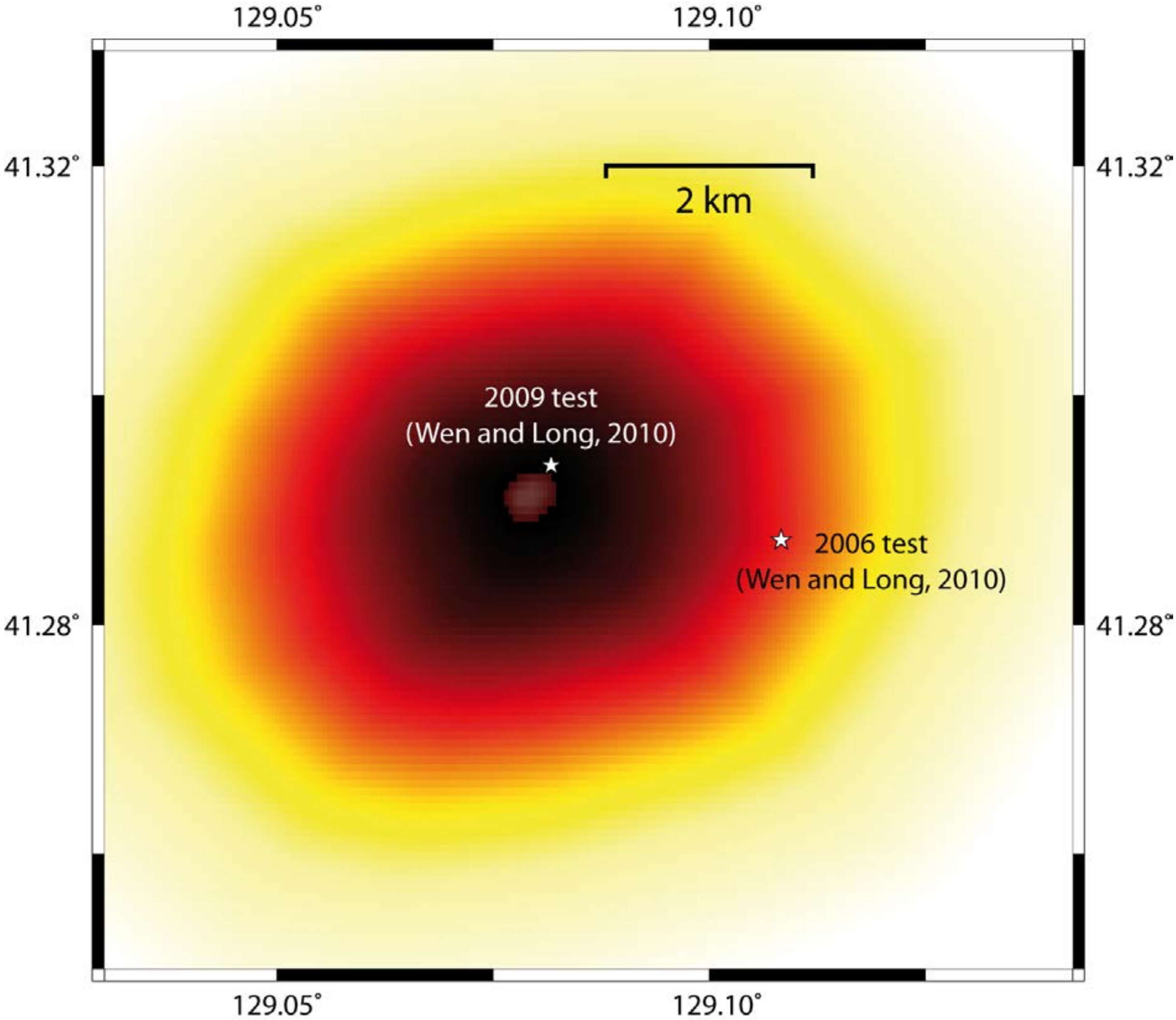

Fig. 6.1.4 A grid of trial epicenters for the 2013 test scanned for goodness-of-fit between the predicted and observed traveltime differences using the method of Selby (2010). The white stars indicate the locations of the 2009 and 2006 explosions as provided by Wen and Long (2010). The location of the May 25, 2009, DPRK explosion is fixed at 41.2939°N and 129.0817°E and the colours indicate the size of the misfit. The minimum residual is associated with a location very close to the assumed site of the 2009 explosion: within 500 meters and to the South West. The depth was held constant for all trial hypocenters.

The signals generated by the test on February 12, 2013, are remarkably similar to those generated by the test in 2009. Using correlation-based travel-time differences from selected IMS seismic stations (see Fig. 6.1.5), and applying the grid-search method of Selby (2010), we fixed the location of the 2009 test at 41.2939° N and 129.0817° E and calculated a residual or misfit for a grid of trial epicenters for the location of the 2013 explosion. The location with the smallest misfit value is located within 500 meters of the assumed site of the 2009 explosion and somewhat to the South West (Fig. 6.1.4). The geometrical distribution of observing stations is very good and the location of this optimal fit appears to be quite stable to the removal of selected stations from the inverse problem.

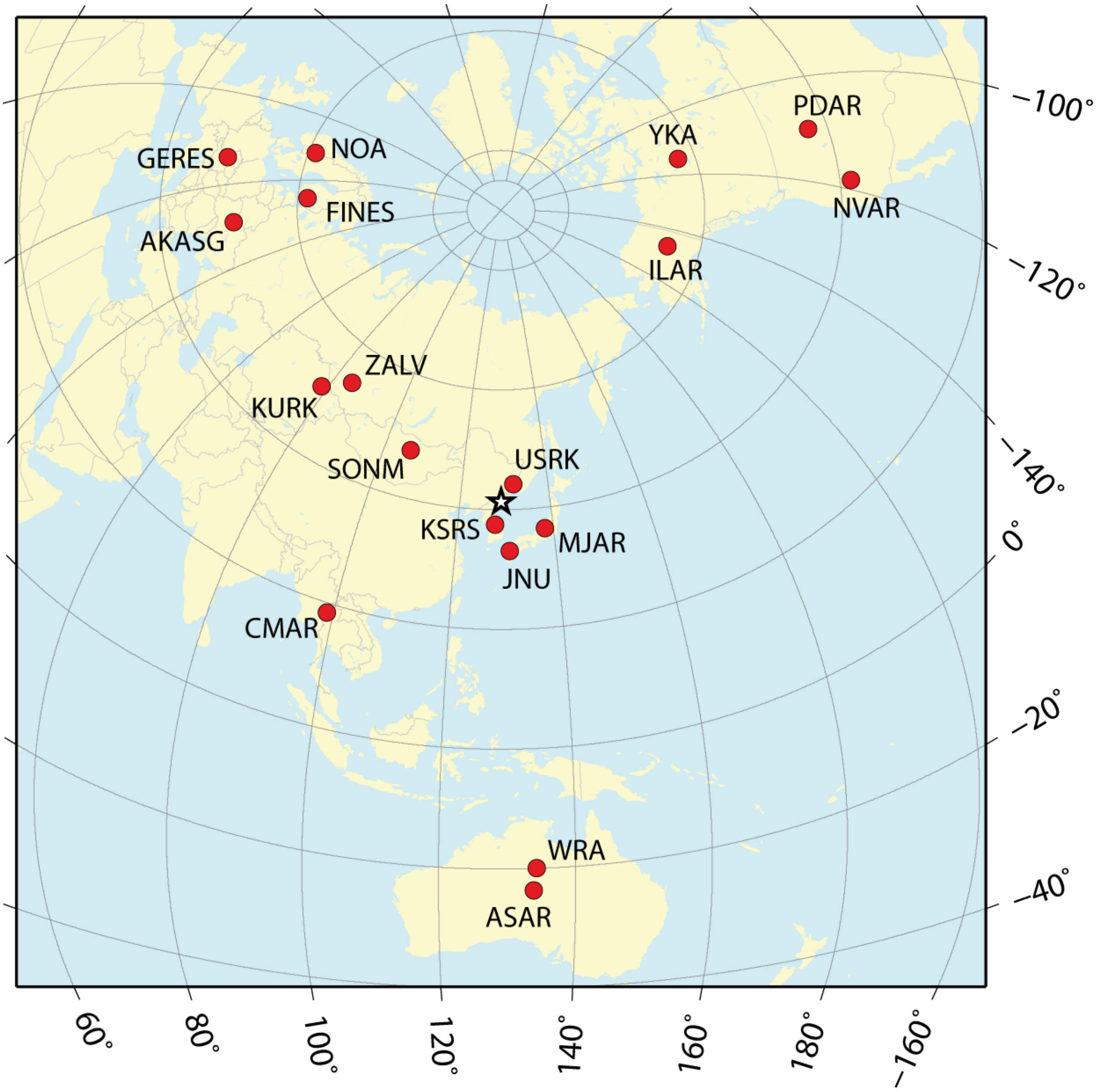

Fig. 6.1.5 IMS stations used in the relative location of the 2009 and 2013 DPRK nuclear tests.

6.1.4 Summary

The seismic signals generated by the February 12, 2013, nuclear test in the DPRK were detected clearly by seismic stations globally. The primary IMS stations in Norway, NOA and ARCES, both recorded the signals from this event with a high SNR.

In addition, the 2013 DPRK nuclear test was readily detected on the NOA array with a correlation detector using waveform templates from both the 2006 and 2009 DPRK events. Both detections passed the f-k post-processing screen which we deem to be essential for running correlation detectors at aggressively low detection thresholds with exceedingly low false alarm rates.

Using cross-correlation based relative time estimates on a selection of IMS seismic stations, using the method of Selby (2010), we estimate the location of the 2013 event to be approximately 400 to 500 meters to the South West of the 2009 event.

Acknowledgements

Data from IMS seismic stations was obtained from the International Data Center (IDC) in Vienna.

Steven J. Gibbons

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