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Real-time detection and characterization of nuclear explosion using broadband analyses of regional seismic stations

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Abstract. This preliminary study aims to propose a new method of real-time detection and characterization of nuclear explosions by analyzing broadband seismic waveforms acquired from a network of regional seismic stations. Signal identification generated by a nuclear test was differentiated from natural sources of either earthquakes or other natural seismo-tectonic events by verifying crucial parameters, namely source depth, type of first motion, and *P*-wave domination of the broadband seismic waves under consideration. We examined and analyzed a recently hypothetical nuclear test performed by the North Korean government that occurred on September 3, 2017 as a vital point to study. From spectral analyses, we found that the source of corresponding signals associated with detonations of the latest underground nuclear test was at a much shallower depth below the surface relatively compared with that of natural earthquakes, the suspected nuclear explosions produced compressional waves with radially directed outward from the source for their first motions, and the waves were only dominated by *P*-components. The results are then discussed in the context of potential uses of the proposed methodology for human-induced disaster early warning system and/or the need of rapid response purposes for minimizing the disaster risks.

1. Introduction

Identification of large seismic signals in magnitude whether they are generated by natural earthquakes of either volcanic or tectonic origin, or induced by nuclear explosions has long been an important issue for some reasons. When an underground nuclear bomb is tested, its impacts upon the environment is spread out within minutes posing fatalities that may last for a long time. Interested readers may refer to a good review of nuclear explosions modelled from underground nuclear tests [1] and a further study of recent work on direct comparison between nuclear explosions and natural earthquakes [2].

Underground nuclear explosions could be monitored in the same manner as natural seismic events. In cases where rock layers beneath the surface rupture owing to the passage of an elastic seismic wave, intensive shaking of the rocks produces seismic signals that are recorded by nearby stations equipped with sensitive instruments. One way of distinguishing between nuclear tests and natural earthquakes is thus to analyze broadband seismograms from either a network of regional seismic stations [3, 4, 5] or teleseismic events [6]. Using this technique, scientists are able to trace the propagating waves back to the source location as well as to determine the focal depth and its corresponding source mechanisms. With respect to this technique, the depth of a nuclear test has been restricted to only



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several kilometres below the ground with the energy is radially released outward away from the source.

Another way of separating underground detonations of a nuclear weapon from earthquakes is to use a P/S ratio, describing direct comparison of P - and S -seismic wave amplitudes hence their energies. Using observations from nuclear test sites around the world, [7, 8] demonstrated that the P/S ratio, despite its dependence on the frequency, is a good indicator for explosion-earthquake discrimination. In this method, the P/S ratio derived from nuclear explosions is commonly larger than that obtained from natural events, suggesting that the nuclear detonations are primarily dominated by P -waves only. In contrast, the energy in earthquakes is in balance distributed over body and surface waves, and even in some cases most of the energy is taken by the S -component over the P -component [8].

Considering the importance of the nuclear test issue in relation to the development of world nuclear weapons and their potential destruction of all living things on earth, we here propose a rapid method of real-time monitoring for underground nuclear explosions by analyzing broadband seismic waveforms acquired from regional station network. In this study, we use the suspicious North Korean nuclear test with a measured magnitude of M 6.3 performed on Sunday in September 3, 2017 at 03:30:01 UTC as a case study to complete examinations of earlier nuclear tests arranged by the same government within a time period of 3-4 years from 2006 to date with increasing magnitudes: on October 9, 2006 with M 4.3 [9], on May 25, 2009 with M 4.7 [10], on February 12, 2013 with M 5.1 [11], on January 6, 2016 with M 5.1 [12]. Complete information about these underground nuclear tests can be freely accessed at <https://ds.iris.edu/ds/nodes/dms/specialevents/>. The primary aim of the present work is to determine whether the latest detonation has been a nuclear bomb. The methodology developed in this study is also examined for possible applications to other man-made explosions, such as rock-bursts in mines and chemical explosions.

2. Methods

Among major differences in the characteristics of generated signals between nuclear explosions and natural earthquakes, the source location or the depth of the hypocenter, type of the first motion, and the relative dominance of P -component over the S -component are of fundamental interest to determine to first order for the latest explosion with M 6.3 geographically located at 41.34°N and 129.04°E on September 3, 2017 at 03:30:01 UTC.

2.1. Real-Time Monitoring Explosion

We provide here in figure 1 a research design of Real-Time Monitoring Nuclear Explosion (RTMNE) developed for this study to distinguish signals of nuclear explosions from those of natural earthquakes.

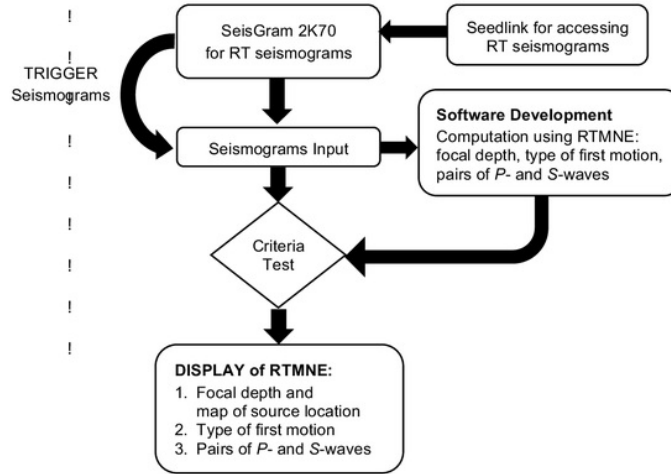


Figure 1. Simple research design, showing steps used for RTMNE.

2.2. Source location and data collection

Datasets used in the study of RTMNE were obtained from a network of regional seismic stations organized by International Federation of Digital Seismograph Network (FDSN) in collaboration with the central government of China through New China Digital Seismograph Network (NCDSN) to provide 3 stations, namely MDJ, BJT, and HIA coded by IC and the North Korean government through Global Seismograph Network (GSN-IRIS/USGS) to provide only INCN station coded by IU. The 4 stations from which the datasets are obtained with their corresponding geographical positions relative to the source location are listed in table 1 below. In addition, FDSN code II with a network of IRIS/IDA seismic stations was also used for comparison. All the datasets used in this study are freely downloaded from https://ds.iris.edu/wilber3/find_event.

Table 1. Names of stations used in this study with their epicentral distances.

FDSN code	Station	Latitude	Longitude	Epicentral Distance	
				in degree	in km
IC	MDJ	44.62° N	129.59° E	3.31°	364
	BJT	40.02° N	116.17° E	9.81°	1,081
	HIA	49.27° N	119.74° E	10.26°	1,129
IU	INCN	37.48° N	126.62° E	4.28°	471

Figure 2 below provides a geographical map of the source location, including all the four stations used for characterizing the explosion on September 3, 2017. The yellow star indicates the source location while the red triangles represent the ground-based observatories listed in table 1, which are positioned within a radius of 10 degrees (one degree is approximately 110 km) away from the source epicenter. Other triangles, green colored, are stations that are not used in this study, some of them are located outside the circle of 10 degrees or positioned less than 10 degrees away from the source but giving unclear seismic waveforms with which we distinguish nuclear explosions from natural earthquakes. Hence, as previously stated we only provide 4 stations for monitoring the explosion.

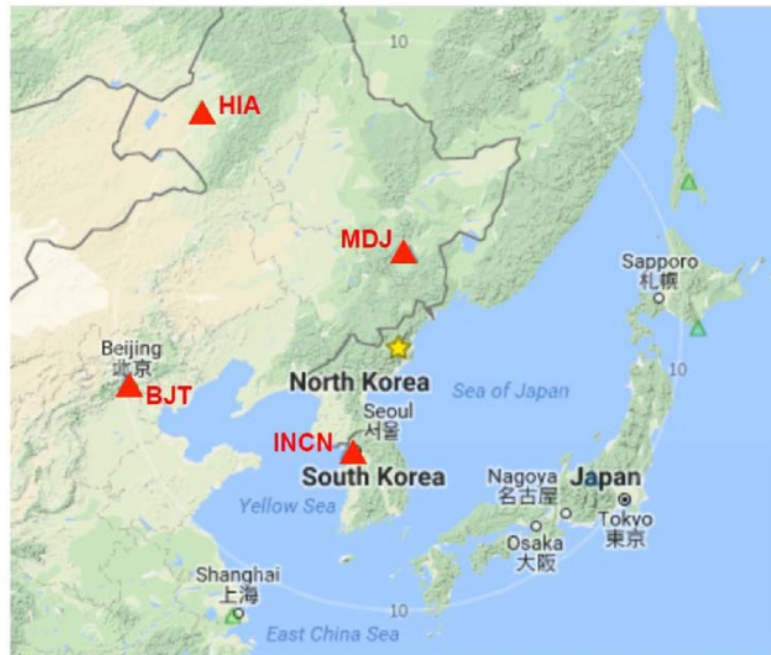


Figure 2. Map of the source location and regional station network used in this study.

2.3. Data analysis

Following the method suggested by [13], we then applied the same method of Real-Time Location (RTL_{oc}) to the case of September 3, 2017 explosion to determine whether the explosion was sourced at a shallow depth near the surface. Analysis of type of first wave motion as well as a test of *P*- and *S*-components was performed using SeisGram2K.70.jar, freely available at alomax.free.fr/seisgram/beta. Calculation of the source depth, analysis of the first wave motion, and the paired test of *P*- and *S*-wave components were all used to decide whether the latest detonation that occurred on September 3, 2017 (see geographical map in figure 2) was a nuclear bomb.

3. Results and discussion

3.1. Source depth determination

As stated in the methodology, the first stage of doing RTMNE is to determine the source location or precisely the focal depth. We used a grid-search technique in combination with a real-time inversion method for seismic wave travel-time with which we obtained the precise location of the source with adequately high confidence, as shown as the white star in figure 3. Projected onto the vertical axis *z* and measured in kilometres, we then estimate the depth of the explosive detonation to be no more than 2 km deep from the surface. It follows that the source depth is at a shallow point beneath the ground. This finding is supported by previous results of similar explosions identified as nuclear tests using nuclear test sites at Nevada, US [4] although high uncertainties in the depth measurement were found by [9, 10, 11, 12] for the earlier North Korean underground detonations.

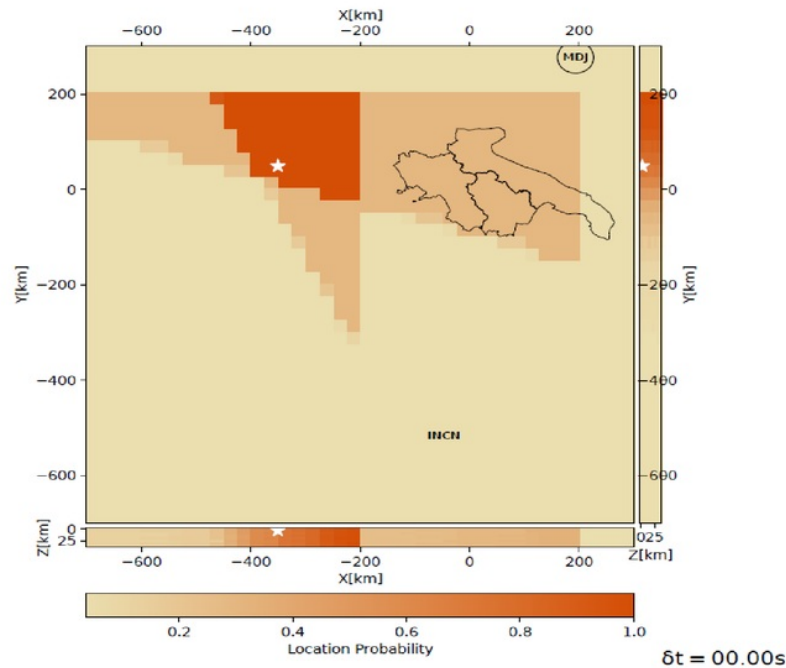


Figure 3. Depth determination using real-time inversion method for wave travel-time.

The relative high uncertainty found in previous work of the source depth estimation [9, 10, 11, 12] is probably caused by difficulties in discriminating nuclear explosions from natural earthquakes using broadband analysis of waveforms acquired from regional stations for small to moderate events, as claimed by [4]. This argument is confirmed by seismological institutions that prefer a P/S ratio or a similar method, namely a body-surface wave amplitude ratio to the source depth determination for characterizing a particular explosion. However, our finding about the depth using the methodology in this study is supported by a release of the depth given by GEOFON GFZ as shown in figure 4.

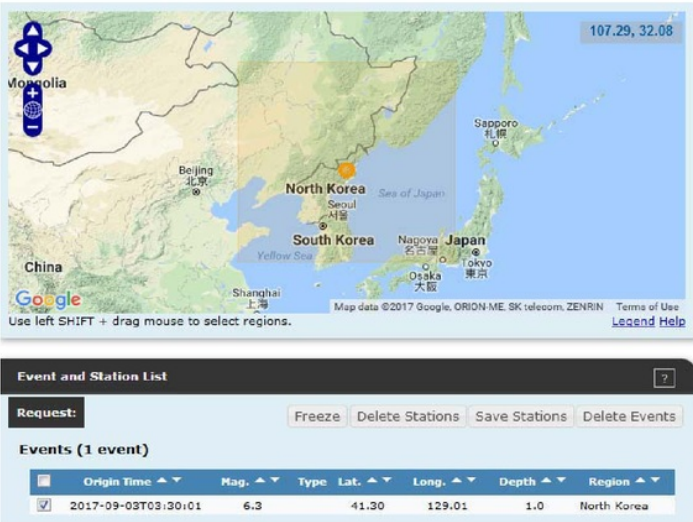


Figure 4. Interface of GEOFON showing information about the latest explosion on September 3, 2017 including the corresponding event origin time and magnitude, the source epicenter and depth location.

3.2. Type of first wave motion

In this section, we provide seismograms recorded at 4 nearby stations with respect to the source used in this study for monitoring the September 3, 2017 explosion. In consecutive, figures 5, 6, 7, and 8 describe body and surface seismic wave patterns by sensitive geophysical instruments employed in stations MDJ, BJT, HIA all positioned in China and station INCN landed in South Korea.

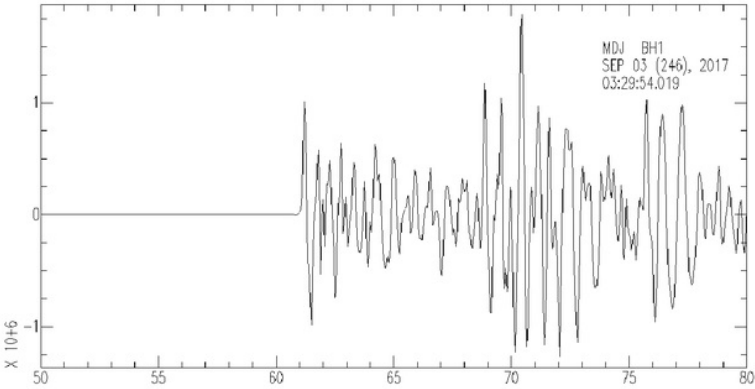


Figure 5. Recorded seismogram for the September 3, 2017 explosion given by station MDJ.

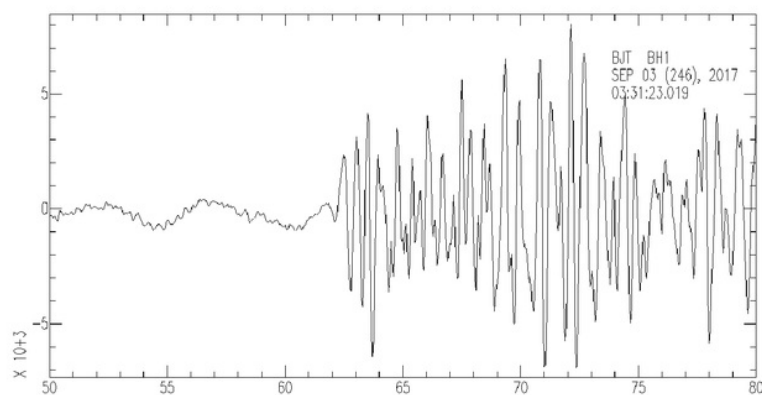


Figure 6. Recorded seismogram for the September 3, 2017 explosion given by station BJT.

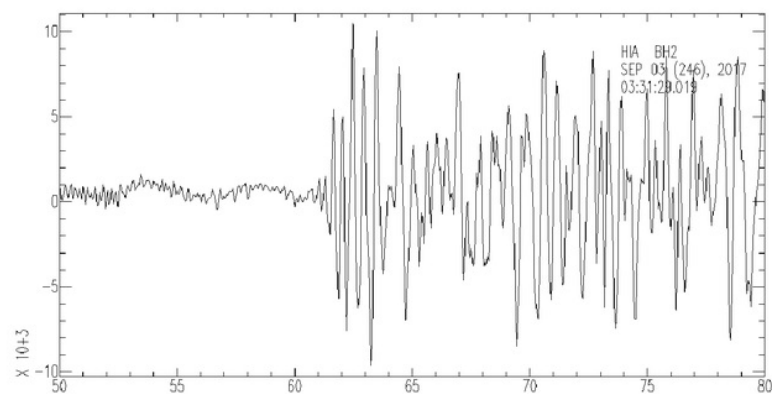


Figure 7. Recorded seismogram for the September 3, 2017 explosion given by station HIA.

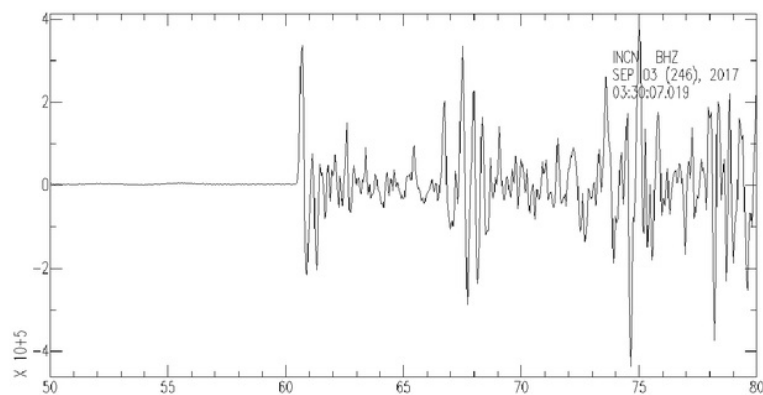


Figure 8. Recorded seismogram for the September 3, 2017 explosion given by station INCN.

As shown in each seismic wave pattern in figures 5, 6, 7, and 8, the first motion is upward vertical displacement, suggesting the *P*-component to be the dominant part for tens of seconds after the first shock. At the initial stage, a large part of the seismic wave energy is taken by the *P*-wave propagation before Rayleigh waves come into play by bringing maximum wave amplitudes away from the source location. These common features for underground nuclear explosions are also found by some of previous researchers working on explosion-earthquake discriminant [6, 7, 8] for cases outside the North Korean test sites and those recently detonated in the North Korea region [9, 10, 11, 12]. All of these studies also confirm that the *P/S* ratio as well as the body to surface wave energy ratio hence the associated wave amplitude ratio is a good indicator whether the explosion is a nuclear bomb test.

Note also that there is a clear difference in the appearance of surface (Rayleigh) waves between seismograms recorded by MDJ in China and INCN in South Korea and those recorded by BJT and HIA both in China. As listed in table 1, MDJ and INCN are seismic stations located within the range of less than 500 km away from the source, making it possible to have short periods, within seconds, of the *P*-waves before releasing the large part of the energy through the propagation of surface waves. Different from these stations, BJT and HIA are relatively far away from the source located at a radius of greater than a thousand kilometres. This gives more times for the *P*-wave to bring the energy with it before the appearance of the surface Rayleigh waves, in several minutes after the *P*-wave life time, takes the lead to transfer the energy radially outward in isotropic propagation [1, 2, 4, 8].

It seems that broadband analysis of waveforms observed at regional distances remains useful but providing a clear clue for complexity of the problem when this method is applied to near-field observations. Instead, as also previously prompted by [4, 6] the separation of underground nuclear explosions from naturally occurring events becomes significant for stations located at far distances from the source although the clarity of the generated waveforms is also influenced by the distance of which a station is located from the source as well as by the sensitivity of the instruments employed. Considering the applicability of the method proposed in this work for examining and characterizing nuclear explosions to far observations, we then argue that the developed method is also applicable for the development of existing disaster early warning system, particularly the man-made disaster, such as explosions induced by nuclear tests. Therefore, specific targetson explosion-earthquake discriminant for minimizing the disaster risks using the current method are necessary to identify for future work.

4. Conclusions

We have proposed the RTMNE method to distinguish seismic signals generated by nuclear explosions from those induced by natural events. Among all the differences, 3 seismic parameters: source depth, first vertical displacement, and appearance of *P*- and *S*- components recorded by seismometer are used in this study for characterizing the suspicious large detonation with a magnitude of 6.3 that exploded on September 3, 2017 in the North Korea region, shocking the world about a possible nuclear war. Using broadband analysis of waveforms obtained from regional stations nearby the source location, the propagated signals were identified as a nuclear bomb due to its characteristics: the depth is sourced within a kilometer below the surface, all the seismic stations observe upward vertical displacement for the first motion, and none of the observatories records the *S*-component, indicating the dominance of the *P*-component. These findings are consistent with the results released by some institutions around the world, suggesting that the methodology in the present work is reliable for detecting a nuclear test. In the case of seismic events with smaller magnitudes, future work may possibly use this method for distinguishing chemical explosions and rock-bursts from natural earthquakes.

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