A Seismo-Acoustic Analysis of the 2017 North Korean Nuclear Test

by Jelle Assink, Gil Averbuch, Shahar Shani-Kadmiel, Pieter Smets, and Läslo Evers

ABSTRACT

The 2017 North Korean nuclear test gave rise to seismic and low-frequency acoustic signals, that is, infrasound. The infrasonic signals are due to seismo-acoustic coupling and have been detected on microbarometer array I45RU in the Russian Federation at 401 km from the test site. I45RU is part of the International Monitoring System for the verification of the Comprehensive Nuclear-Test-Ban Treaty. We analyze the seismo-acoustic coupling by making use of array-processing and backprojection techniques. The backprojections show that infrasound radiation is not confined to the epicentral region. More distant regions are found to be consistent with locations of topography, sedimentary basins, and underwater evanescent sources. The backprojections can be used to estimate the average infrasonic propagation speed through the atmosphere. We discuss these findings in the context of infrasound propagation conditions during the sixth nuclear test. It is suggested that propagation from the test site to I45RU may have occurred along unexpected paths instead of typical stratospheric propagation. We present several scenarios that could be considered in the interpretation of the observations.

Electronic Supplement: Details on signal characterization and infrasound propagation conditions.

INTRODUCTION

The Democratic People’s Republic of Korea (DPRK) has performed six underground nuclear tests since 2006. Seismic signals from these tests have been detected globally and have been used to estimate the epicenter, origin time, and seismic magnitude. The seismic measurements indicate that the DPRK has tested larger nuclear weapons over time. The facilities of the International Monitoring System (IMS) that is in place for the verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) have been instrumental in the accurate localization and characterization of the tests (e.g., Gibbons et al., 2017). The yield estimate of the explosions strongly trades off with their depth, which is difficult to estimate from teleseismic arrivals alone (Bowers and Selby, 2009).

Large seismic sources also generate observable infrasound in the atmosphere. The coupling of seismic waves to atmospheric infrasound waves can occur due to various mechanisms. Generation of acoustic waves from surface waves in a solid–fluid system is a well-known phenomenon (Stoneley, 1926; Scholte, 1947). It has been shown that air-coupled surface waves also contribute to the observed acoustic signal in the atmosphere (Ewing et al., 1957; Ben-Menahem and Singh, 1981). It follows that the solid earth-atmosphere and ocean-atmosphere interfaces are transparent for the inhomogeneous part of the wavefield. This spectrum includes low phase velocities that are evanescent in the solid earth or oceans but can be propagating in the atmosphere (Godin, 2008, 2011). Evanescently coupled infrasound has been observed from the 2004 Mw 8.1 Macquarie ridge earthquake as acoustic signals with relatively large wavelengths coupled from shallow underwater features (Evers et al., 2014).

Previous studies of infrasound from earthquakes have shown that most of the coupled seismo-acoustic signals originate from the epicentral region. This is referred to as epicentral infrasound. In addition, secondary infrasonic signals have been observed from the movement of mountain ranges, away from the epicenter (Young and Greene, 1982; Le Pichon et al., 2003; Green et al., 2009). In an analysis of the 2016 central Italy earthquakes, it was shown that seismo-acoustic coupling occurs over an even larger extent. The detection of these signals was dependent on the ground-to-air coupling and atmospheric propagation conditions to a distant array (Shani-Kadmiel et al., 2018).

The detection of infrasound at a remote station is strongly dependent on the noise levels due to the local wind and turbulence and the propagation conditions along the source–receiver path. Long-range infrasound propagation, that is, propagation over distances longer than 100 km, is facilitated by atmospheric waveguides. These waveguides are formed between the ground and atmospheric layers aloft and are much dependent on the prevailing vertical temperature and wind distribution. The stratospheric waveguide is particularly
important in the detection of long-range infrasound and is sustained by a strong wind jet around 50 km altitude, that is, the stratospheric vortex. Because the direction of the flow reverses during the equinoxes, the propagation efficiency of the stratospheric waveguide reduces. A thermospheric waveguide always exists because of a strong temperature gradient in the lower thermosphere. The low density in the upper atmosphere leads to non-linear propagation effects and significant absorption (e.g., Lonzaga et al., 2014; Wxler et al., 2017).

Previous underground nuclear tests by the DPRK generated infrasound that has been observed on IMS stations (Assink et al., 2016) and infrasound arrays in South Korea (Che et al., 2014). As seismo-acoustic coupling is related to source depth, this motivates a synergy between seismology and acoustics, for example, to improve depth-yield estimates of (nuclear) explosions. The relation between source depth and seismo-acoustic coupling has been studied previously (Arrowsmith et al., 2011; Ford et al., 2014). Assink et al. (2016) hypothesized that a relative source depth between two events can be estimated from infrasonic observations. In this procedure, (1) the coupling of seismic waves to infrasound is quantified, and (2) the propagation paths are known to estimate the relative transmission loss from the Earth surface to the receiver.

In this article, we focus on a seismo-acoustic analysis of the 3 September 2017 nuclear test. Besides a main event at 03:30:01 UTC, a non-tectonic aftershock occurred at 03:38:32 in the vicinity of the test site, possibly related to collapse of the underground cavity (Liu et al., 2018). The source characteristics are summarized in Table 1 and are derived from seismic stations from the IMS. Infrasound was detected on a nearby IMS infrasound array in the Russian Federation, 145RU (see Fig. 1), as well as in South Korea. This analysis focuses on seismo-acoustic signals that have been detected on 145RU. This array is located at a distance of 401 km distance to the northeast of the Punggye-ri nuclear test site. We show that array-processing and backprojections using recorded data from this IMS array provide unprecedented insight into seismo-acoustic coupling.

Furthermore, we discuss the infrasound propagation conditions during the sixth nuclear test, during which the stratosphere was in a state of transition from summer to winter and the stratospheric vortex was relatively weak. As long-range infrasound propagation is largely conditioned by the strength and the direction of the stratospheric vortex, this implies that propagation from the test site to 145RU may have occurred along unexpected paths (Kulichkov, 2010; Green et al., 2011; Chunchuzov et al., 2015). We present several scenarios that could be considered in the interpretation of the observations.

<p>| Table 1 |
| Details from the Events Associated with the 2017 North Korean Nuclear Test from the Revised Event Bulletin (REB) Published by the Comprehensive Nuclear-Test-Ban Treaty (CTBT) Organization |</p>
<table>
<thead>
<tr>
<th><strong>Time</strong> (hh:mm:ss.ss)</th>
<th><strong>Latitude</strong> (°)</th>
<th><strong>Longitude</strong> (°)</th>
<th><strong>m_b</strong></th>
<th><strong>Magnitude</strong></th>
<th><strong>Estimated Yield (kt)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear test</td>
<td>03:30:01.08</td>
<td>41.3205</td>
<td>129.0349</td>
<td>6.1</td>
<td>200–300</td>
</tr>
<tr>
<td>Nontectonic aftershock</td>
<td>03:38:32.08</td>
<td>41.3206</td>
<td>129.0615</td>
<td>4.1</td>
<td>—</td>
</tr>
</tbody>
</table>

The yield estimates are estimated by Norwegian Seismic Array (NORSAR), as published at NORSAR's website (see Data and Resources).
DATA ACQUISITION AND PROCESSING

I45RU is a triangular array with a central element and has an aperture of 2.1 km. The array is equipped with four MB2000 absolute microbarometers that have a flat frequency response between 0.01 and 8 Hz. A rosette wind-noise reduction system is used to reduce wind noise over the infrasonic frequency band by spatially averaging the pressure field in the vicinity of each infrasound sensor. The MB2000 sensors sample the pressure field at 20 Hz. The microbarometers are primarily sensitive to pressure fluctuations but appear to be responsive to mechanical vibrations as well (Alcoverro et al., 2005). The sensitivity to both seismic and acoustic waves has been discussed in previous seismo-acoustic analyses of larger earthquakes (e.g., Le Pichon et al., 2003; Shani-Kadmiel et al., 2018).

We use time-domain (Melton and Bailey, 1957) and frequency-domain (Smart and Flinn, 1971) beamforming techniques for the detection of coherent infrasound and the estimation of plane-wave parameters, that is, back azimuth and apparent velocity. The detection of a signal is based on the evaluation of a Fisher ratio. The probability of detection can be estimated through the statistical framework of Fisher statistics. Moreover, a single-channel signal-to-noise ratio (SNR) value can be estimated from the Fisher ratio. A detailed description of these algorithms can be found in Evers (2008).

The waveform data are detrended and band-pass filtered before time-domain beamforming. A second-order Butterworth band-pass filter between 0.35 and 4 Hz appears to be a good trade-off between the coherency of the signals of interest and interference from low-frequency noise, such as coherent noise in the microbarom band. In addition, a 1.0–3.0 Hz frequency band is considered to detect smaller-amplitude arrivals that would otherwise be masked. The waveforms are oversampled to 100 Hz using Fourier interpolation for an enhanced time resolution because smaller time shifts may be used. This enhanced time resolution benefits the beamforming of the seismic arrivals.

The frequency-domain algorithm carries out the analysis in discrete frequency bands. The window size is 20 and 40 s for the time-domain and frequency-domain processing, respectively. In all cases, we consider 90% overlap between successive windows. The samples are delayed and summed over a horizontal slowness grid. The grid is designed to include back-azimuth and apparent velocity values of interest. The back-azimuth values range between 155° and 270° and are spaced by 1°. The lower limit of 155° is selected to avoid detection of microbarom sources in the Pacific. The apparent velocity values range between 300 m/s and 10 km/s. Between 300 and 450 m/s, the values are separated by 5 m/s (the infrasonic signal range), and between 450 m/s and 10 km/s the values are logarithmically spaced (the seismic signal range).

ARRAY-PROCESSING AND WAVEFORM ANALYSIS

Figure 2 shows array-processing results for I45RU between 03:30:00 and 04:05:00. From top to bottom, the frames show as a function of time: apparent velocity, back azimuth, best beam, and coherency as a function of frequency. Detections with an SNR above 0.6 are colored conforming to the color map. Travel time and celerity (defined as the epicentral distance divided by the travel time) are indicated on the lowest frame and are relative to the origin time. A first interpretation of the arrival structure follows from these celerity values.

Figure 2a shows the arrival of various coherent arrivals in the 0.35–4.0 Hz frequency band from the direction of the test site, indicated by the dashed horizontal line. The wavetrain between 57 and ∼300 s corresponds to the seismic arrivals. The first P-wave arrives after 57 s, which is in agreement with the iasp91 seismic travel-time tables (Kennett et al., 1995). After the high-frequency P-wave, a dispersive Lg-wave group is detected that represents a guided waveform with predominantly transverse particle motion. The measured apparent velocities are consistent with seismic propagation velocities. The seismic waves radiate infrasound vertically into the atmosphere, which is measured by the microbarometer (e.g., Cook, 1971). However, part of this measurement is a contribution from the mechanical sensitivity of the MB2000 (Alcoverro et al., 2005) for the larger accelerations between 57 and ∼130 s.

The second set of arrivals from the direction of the test site corresponds to infrasound waves that have propagated through the atmosphere, having typical celerity values between 0.23 and 0.34 km/s and apparent velocities around 340 m/s. These infrasonic arrivals are interpreted to be epicentral infrasound. The resolved back-azimuth and apparent velocity values show significant variations along the mostly emergent wavetrain. Most of the energy is coherent in a frequency range between 0.35 and 1.5 Hz.

Within this wavetrain, two phases that are detailed in Figure 3 stand out: (1) an oscillatory wave package with a duration of ∼20 s, arriving after 1440 s with a dominant frequency around 0.4 Hz and a peak-to-peak (ptp) amplitude of 0.3 Pa; (2) A broadband signal arriving after 1510 s, coherent between 0.05 and 4 Hz, and a ptp amplitude of 0.75 Pa. The broadband signal consists of higher frequencies that are superimposed on a low-frequency (∼0.1 Hz) U′ wave. The shape of this signal matches the classical shape of thermospheric return signals as described in many cases in the scientific literature (Whitaker and Mutschlechner, 2008; Assink, 2012; Lonzaga et al., 2014).

Another arrival, labeled 3 in Figure 3, is observed around 2025 s after the main event, with a dominant frequency around 0.25 Hz and a ptp amplitude of 0.15 Pa. The back azimuth is consistent with the direction of the test site, and apparent velocities are consistent with an acoustic signal. When associated with the nontectonic aftershock, this late arrival has a similar travel time (indicated by horizontally spanning arrows in Fig. 2a) as arrival 2 does with respect to the main event, suggesting it has propagated along a similar path.

Figure 2b shows the array-processing results in the 1.0–3.0 Hz band. In between 600 and 1300 s, coherent infrasound is detected that is predominantly coherent between 1.0 and 2.0 Hz. As such, these arrivals have celerity values between 0.6 and 0.34 km/s and appear before the epicentral infrasound.
Compared to the epicentral infrasound, these arrivals have much smaller amplitudes and arrive from different back azimuths. The resolved back azimuth is 208°, whereas the test site is at 218°. Similar signals have been identified in previous studies on infrasound from large earthquakes as secondary infrasound (Le Pichon et al., 2003; Marchetti et al., 2016; Shani-Kadmiel et al., 2018). To understand where seismo-acoustic coupling occurs, array-processing results are backprojected following the method described in Shani-Kadmiel et al. (2018).

**BACKPROJECTIONS**

Detections shown in Figure 2 are backprojected assuming a constant seismic and infrasonic propagation velocities. Because of the order of magnitude difference between seismic and infrasonic propagation velocities, this procedure is much more sensitive to the latter than the former. It is therefore fairly safe to approximate the seismic propagation velocity by fixing it around the celerity value of the peak-amplitude arrival of the seismic wavetrain and to test a range of infrasonic propagation velocities. For the purpose of this study, we fixed the seismic propagation velocity to 6 km/s. In contrast to seismic propagation velocities, infrasonic propagation velocities are constrained to a relatively small range between 0.22 and 0.34 km/s. In this range, 0.28 km/s was found to provide the best overlap with respect to epicentral location, topographic features, and potential sources of evanescent wave coupling (Fig. 4). It also matches the celerity value for the peak amplitude arrival of the infrasonic signal and is in agreement with expected celerities of thermospheric returns.

A grid of theoretical source-to-receiver travel times (seismic plus infrasonic) and back azimuths is constructed with

**Figure 2.** Array-processing results (a) 0.35–4.0 Hz wideband, and (b) 1.0–3.0 Hz narrowband of I45RU between 03:30:00 and 04:05:00 on 3 September 2017. The frames show the following wavefront parameters as a function of time: apparent velocity, back azimuth, best beam, and coherency as a function of frequency. The color scale indicates the signal-to-noise ratio (SNR) of the detection. Travel time in seconds and celerity (in km/s) are indicated on the lowest frame and are relative to the origin time. The color version of this figure is available only in the electronic edition.
The time of arrival and back azimuth associated with each detection point, arriving more than 600 s after origin time with SNR > 0.7 and apparent velocity in the 280–450 m/s range, are used to locate the grid cell from which it most likely originated. The contribution of each detection to the count of detections originating in each cell is the associated SNR value; for example, two detections originating from the same grid cell, one with SNR = 0.0136 and another with SNR = 0.8, will result in a count of 1.8. This approach does not account for any horizontal advection due to crosswind and along-track wind, which may result in inaccurate locations. However, as described in the Infrasound Propagation During a Weak Stratospheric Vortex section, during low wind conditions such as in this case, infrasound propagation is predominantly controlled by the temperature structure. Thus, we expect errors related to horizontal advection to be negligible.

Figure 4 shows backprojection results from both frequency bands shown in Figure 2. The wideband backprojection (Fig. 4a) illuminates an elongated infrasound radiation patch along the trend of the Hamgyong mountain range (see Fig. 1 for location) with its maximum surrounding the
test site. In the narrowband backprojections, smaller patches of increased infrasound radiation within the mountain range suggest that areas of more efficient radiation to station I45RU exist at this time (Fig. 4b). Additionally, infrasound is detected from the Tumen River delta (see Fig. 1 for location), about half-way between the test site and I45RU. Marchetti et al. (2016) and Shani-Kadmiel et al. (2018) made similar observations of anomalous infrasonic radiation atop alluvial basins due to the interaction of seismic waves with the unconsolidated sediments. Interestingly, this area is not illuminated in the wideband backprojections, presumably because seismic-wave interaction with the shallow unconsolidated sediments of the Tumen River delta is likely to generate higher frequencies and in turn radiate infrasound in the higher-frequency band. Infrasound is also detected from over the Japan basin east of the test site. This basin is within one hydroacoustical wavelength of the water–air interface, suggesting evanescent wave coupling. Seismic-wave interaction with seamounts protruding from the Japan basin generates higher frequencies. However, evanescent wave coupling may still occur because these are closer to the water–air interface. These effects are illustrated by our backprojection results in Figure 4. Contour lines in Figure 4 correspond to a depth of one acoustical wavelength at a range of frequencies calculated as $d_i = c_{II}/f_s$, with $c_{II}$ the hydroacoustic speed of sound taken to be 1550 m/s.

INFRASOUND PROPAGATION DURING A WEAK STRATOSPHERIC VORTEX

For the analysis of infrasonic propagation conditions, we compared the European Centre for Medium-Range Weather Forecasts (ECMWF) operational high-resolution ensemble data assimilation (HRES EDA) (Smet et al., 2015) with the MSIS-00 (Picone et al., 2002) and HWM14 (Drob et al., 2015) empirical models (Fig. 5). The vertical structure of the atmosphere in the region of interest is characterized by a typical eastward jetstream (maximum wind velocity of 16.5 m/s at 11 km) and a weak westward stratospheric vortex (average wind velocity of 5.8 ± 0.5 m/s between 17 and 50 km), with a maximum in the stratosphere (21.6 m/s at 55 km). Above 65 km, no synoptic state is represented by the climatologies: vertically narrow mesospheric inversion layers (MILs), intense wind shears, and sporadic layers are not present.

Because the nuclear test occurred near the autumnal equinox, planetary waves can reach a zero-wind condition in the middle atmosphere (stratosphere–mesosphere, Fig. 5a), enhancing turbulence and small-scale wave activity. MILs typically form near the mesopause throughout the year and near the middle mesosphere during equinox and winter-solstice periods (Brown et al., 2004). Small-scale structure and wind shear layers can occur, for example, due to the breaking of gravity waves (Yue et al., 2010).

From the effective sound speed profile (Fig. 5b), it follows that only a thermospherically ducted arrival is supported (Fig. 5c). The effective sound speed is defined as the sum of the adiabatic sound speed and the wind speed in the direction of propagation. Estimates of travel time (1507 s, indicated by a vertical blue line in Fig. 3), back azimuth, and apparent velocity from ray tracing are in first-order agreement with the observed low-frequency arrival at 1510 s after the explosion. This arrival propagated through the mesosphere and lower thermosphere where nonlinear propagation effects are significant. This nonlinearity distorts the frequency content of the signal through signal lengthening and wavefront steepening.

There is an interplay between these nonlinear effects and attenuation because lengthening mitigates against signal attenuation whereas attenuation limits shock formation (Lonzaga et al., 2014). Indeed, this particular arrival is coherent down to 0.05 Hz.

However, this propagation path does not explain all the observed infrasound at I45RU, because infrasonic arrivals with high celerities, higher frequency content, and other azimuths are also observed. These arrivals could be explained by a combination of various mechanisms (Fig. 5c), including:

- scattering and (partial) reflections off small-scale structure and wind-shear layers (e.g., Kulichkov, 2010; Chunchuzov et al., 2015). Higher frequencies are more likely to reflect off such structures.
- propagation along the Earth surface by coupled seismo-acoustic modes. This could be reflected by the similarity in the frequency spectrum between the $L_g$ phase and the bulk of the infrasonic arrivals.
- evanescent wave coupling from a shallow, low-frequency source. Interaction of radiated energy, from both evanescent and surface waves can keep the energy trapped near the surface and propagate over long distances.
- uncertainties in atmospheric models or assimilation of data below the mesosphere is possible (e.g., Smet et al., 2016). However, simultaneous observations of Pacific microbaroms at the time of the nuclear tests indicates that the stratospheric vortex was indeed weak, yielding thermospheric ducting (see the electronic supplement to this article).

Finally, the mathematical and physical approximations that are made in the derivation of the propagation modeling techniques should be considered.

DISCUSSION AND CONCLUSIONS

Array-processing of recorded pressure fluctuations at IMS array I45RU, 401 km northeast of the Punggye-ri nuclear test site, show seismic and infrasonic signals related to the nuclear test. Seismic arrivals are detected with a back azimuth that corresponds to the direction of the test site. Epicentral infrasound with acoustic apparent velocities and celerities in the 0.23–0.34 km/s range are also detected as a result of the nuclear test.

Backprojections using the above detections in two frequency (wide and narrow) bands reveal sources of infrasound radiation. Four infrasound sources are identified: (1) the epicentral region, (2) the Hamgyong mountain range, (3) the Tumen River delta, and (4) the Japan basin and the seamounts protruding from it. The narrowband backprojections illuminate different regions. This perhaps has the potential to
discriminate between sources of infrasound. We defer this investigation to future studies.

A weak stratospheric vortex occurs twice a year during the vernal and autumnal equinox as well as at the onset and recovery of sudden stratospheric warming events. During this time, the paradigm of classical infrasound propagation paths in the middle atmosphere is challenged. During the 2017 test, the structure of the speed of sound in the atmosphere is mostly attributed to the temperature structure, with little direct contribution from wind. However, turbulence and small-scale wave activity enhance during these low-wind conditions, increasing the importance of scattering and (partial) reflections and the need for synoptic upper atmospheric specifications.

Although the use of infrasound in the estimation of source depth has been previously discussed, a depth analysis has not been considered here due to the unexpected propagation paths.

DATA AND RESOURCES

The Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and European Centre for Medium-Range Weather Forecasts (ECMWF) data used for this article are available to member states but can be requested for academic purposes. The CTBTO and International Monitoring System (IMS) station operators are thanked for the high-quality data and products. Infrasound data can be requested at the CTBTO International Data Center (IDC) in Vienna, via the virtual Data Exploration Center. Atmospheric data can be requested at the ECMWF via the Meteorological Archival and Retrieval System (MARS). The yield estimates are published at NORSAR’s website: https://www.norsar.no/press/latest-press-release/archive/the-nuclear-explosion-in-north-korea-on-3-september-2017-a-revised-magnitude-assessment-article1548-984.html (last accessed April 2018).

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