T2.3-P3

Analysis and modeling of the infrasound signals from the 2017 DPRK nuclear explosion at IMS station IS45

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Abstract

Strong infrasound signals from the Democratic People's Republic of Korea (DPRK) underground nuclear test on 3 September 2017 were observed at IMS infrasound station IS45 in Russia around 25 minutes after the explosion, consisting of 2 distinct high-amplitude peaks about 1 min apart. From Progressive Multi-Channel Correlation (PMCC) processing and frequency wave-number (FK) analysis these arrivals yield distinctly different estimates for back azimuth and apparent (trace) velocity indicating different propagation paths. Furthermore, we were able to identify some weaker precursory arrivals as well as an infrasound arrival about 8 minutes later, thus presumed to be associated with the explosion's aftershock, i.e. collapse event.

For the numerical modeling of the identified infrasonic phases we applied two-dimensional (2D) ray-tracing and 1-D parabolic equation methods with atmospheric velocity profiles derived from an ECMWF forecast model augmented by empirically deduced velocity variations. These propagation calculations indicate for epicentral seismic-acoustic wave conversion that both stratospheric and thermospheric ducting has occurred explaining well the major peaks and the aftershock signal. For the precursory signals we applied grid search calculations for backtracking the likely source regions where additional conversions of seismic waves into acoustic energy occurred.

Infrasound from DPRK's nuclear tests

Infrasound signals from the announced underground nuclear explosions at the North Korean test site were identified at regional infrasound stations in South Korea. For the nuclear test in 2013, corresponding arrivals were also detected at the two closest IMS stations in Russia (IS45) and Japan (IS30), see figure 1a. Additional infrasound signals related to the other announced DPRK tests were successfully identified during a comprehensive study (*Koch and Pilger, GJI 2018, doi: 10.1093/gji/ggy381*). They correspond to arrival times modeled by ray-tracing (figure 1b) but can only be fully explained when taking into account small-scale atmospheric variations like gravity waves (figure 1c), which is also relevant for the 2017 test.

a)

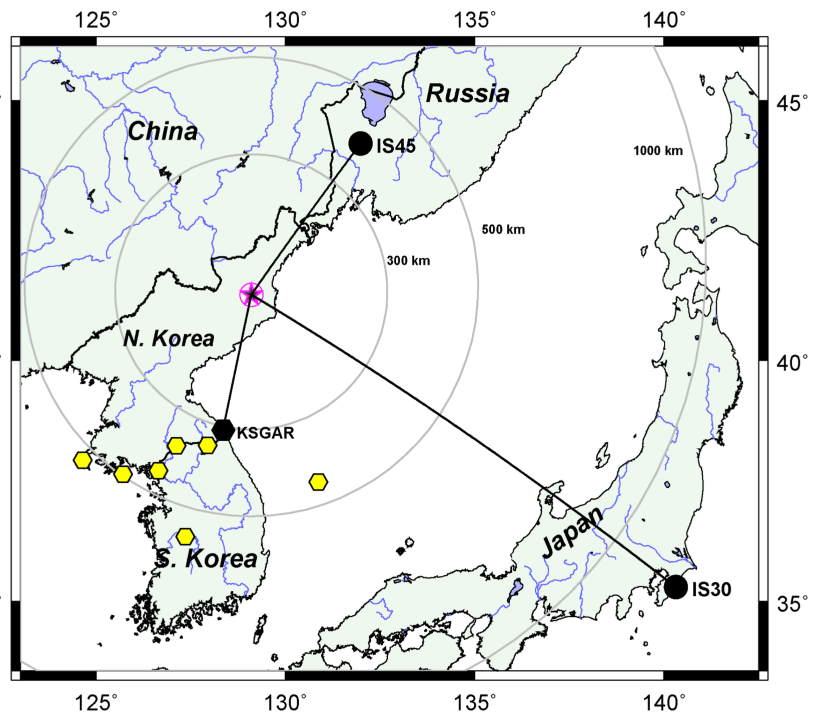
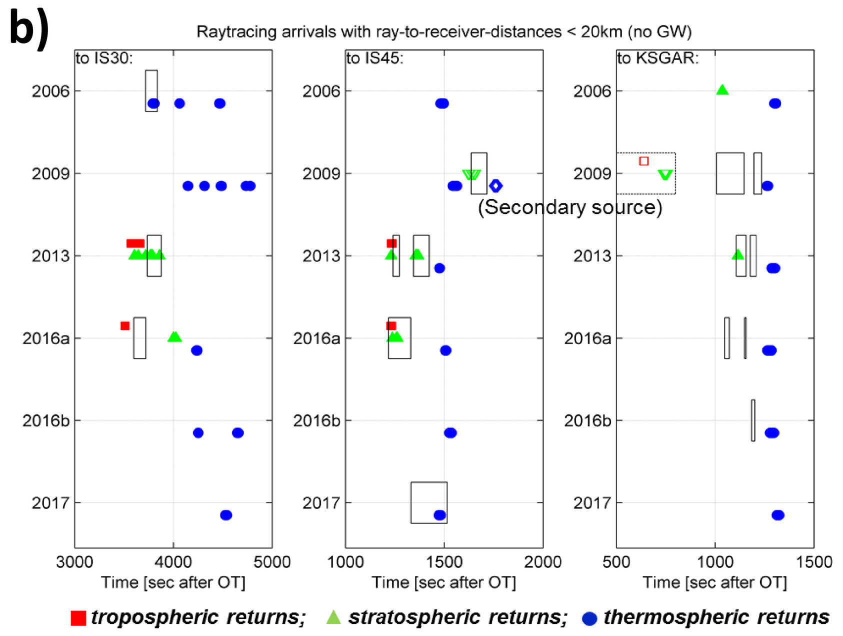
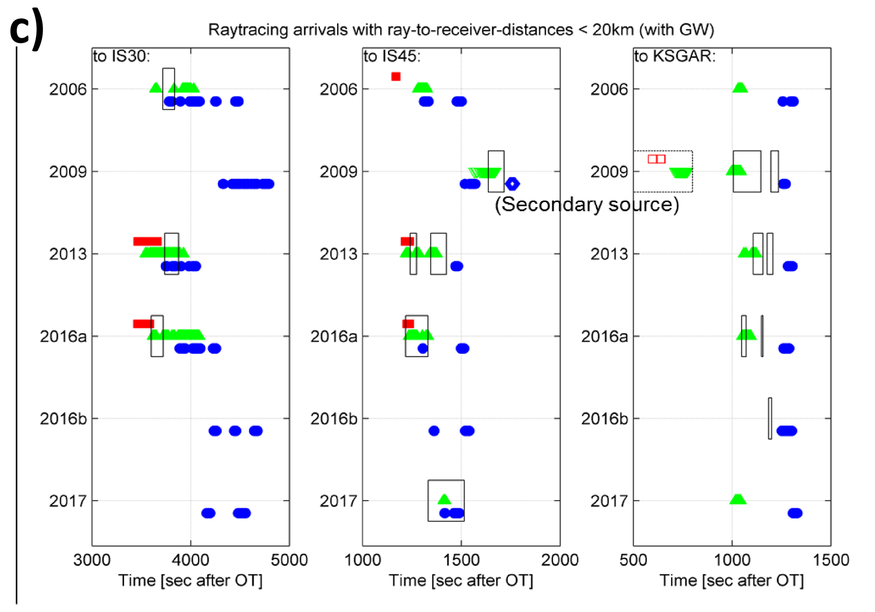


Fig. 1: a) Map of the greater region around the North Korean nuclear test site (magenta asterisk) with the stations of the IMS marked by closed circles, while hexagons represent the stations of the Korean Infrasound Network (KIN).
b) Traveltime analysis for infrasound signals at IS30, IS45 and KSGAR of all North Korean nuclear tests. The symbols mark the arrival times of tropospheric (red), stratospheric (green) and thermospheric (blue) phases. Open symbols (2009) are related to a secondary source. Boxes are representations of the signal windows found in corresponding F–K analyses or are estimated from published results.
c) Same as figure 1b, but with the implementation of gravity wave disturbances in the raytracing.

b)



c)



DRPK 2017 test – Infrasound observations

Epicentral infrasound is recorded at IS45 around 25 minutes after the test (see figure 2), arriving as two distinct waveform peaks from mean back-azimuth directions of 211° and 215°/217° (test site direction: 218°) as well as acoustic celerities of 290 m/s and 270 m/s and some forerunning wave activity. The different signal characteristics indicate separated stratospheric and thermospheric ducting, where the back-azimuth and amplitude are lower for the main stratospheric arrival (Is_2) due to crosswinds and only partial reflection conditions.

a) b)

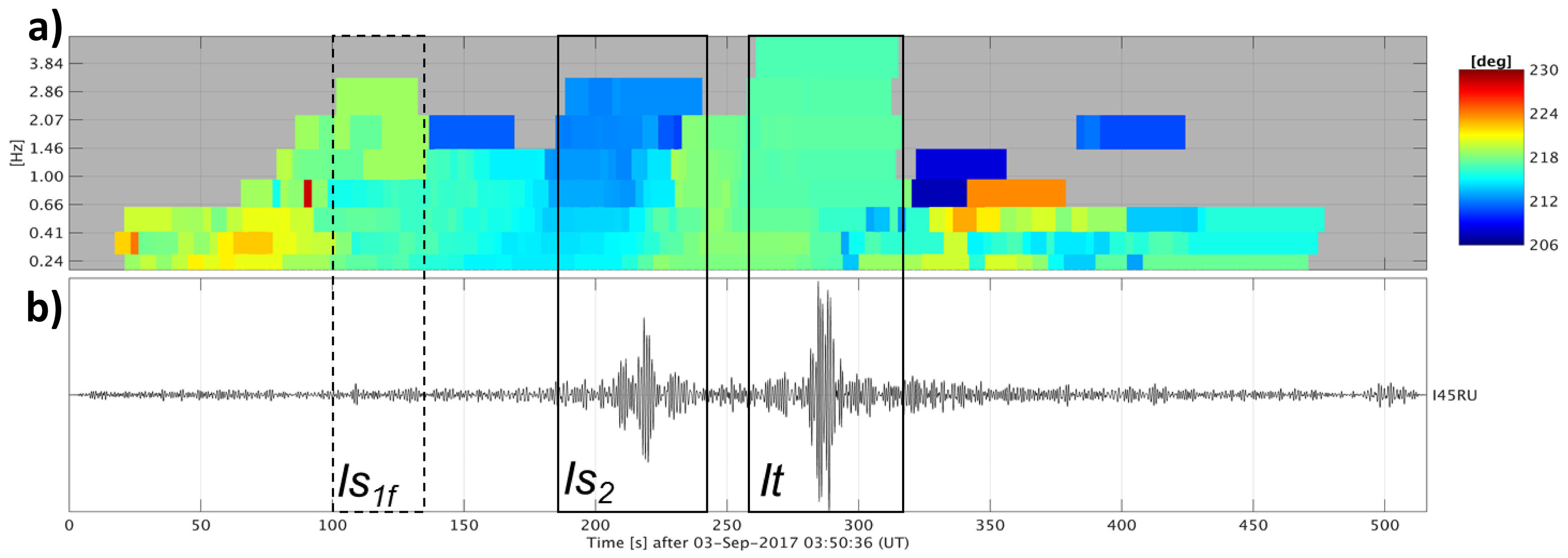
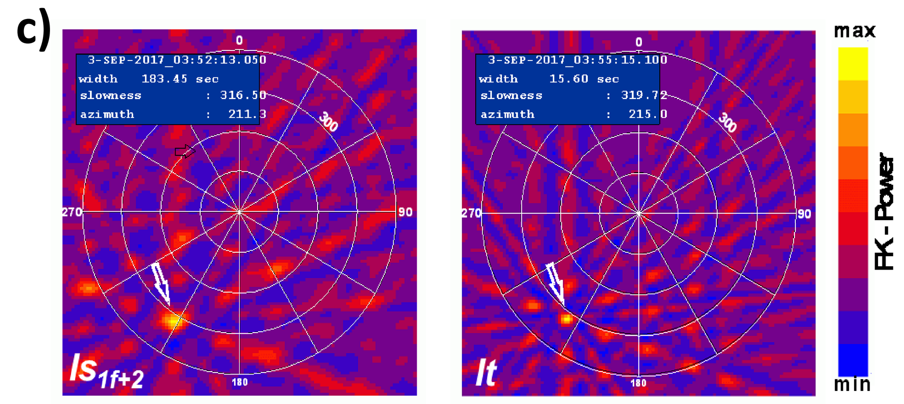


Fig. 2: PMCC analysis (**a**), waveform beam (**b**) and FK analysis (**c**) of the four-element infrasound array IS45 for the DPRK 2017 test. Information on back-azimuth direction is color coded. Is2 and It denote the corresponding stratospheric and thermospheric arrivals after 1450 and 1520 s, respectively, which are also covered in the corresponding FK time windows. Is1f shows an early (forerunner) detection.

c)



DRPK 2017 test – Infrasound propagation

Atmospheric propagation modeling is applied in figure 3 to estimate ducting conditions and signal amplitudes for the DPRK 2017 test case. Atmospheric backgrounds suggest no or only weak stratospheric ducting conditions (figure 3a, effective sound speed ratios around 0.95). Adding gravity wave variations to the model backgrounds (of figures 3c and 3d) confirms partial stratospheric reflections. Ratios during ±1 week around the test predominantly show these same conditions (see figure 3e). Amplitudes are ~5 dB weaker in the stratosphere compared to the thermosphere (figure 3d) since only a small portion of signal energy is ducted this way.

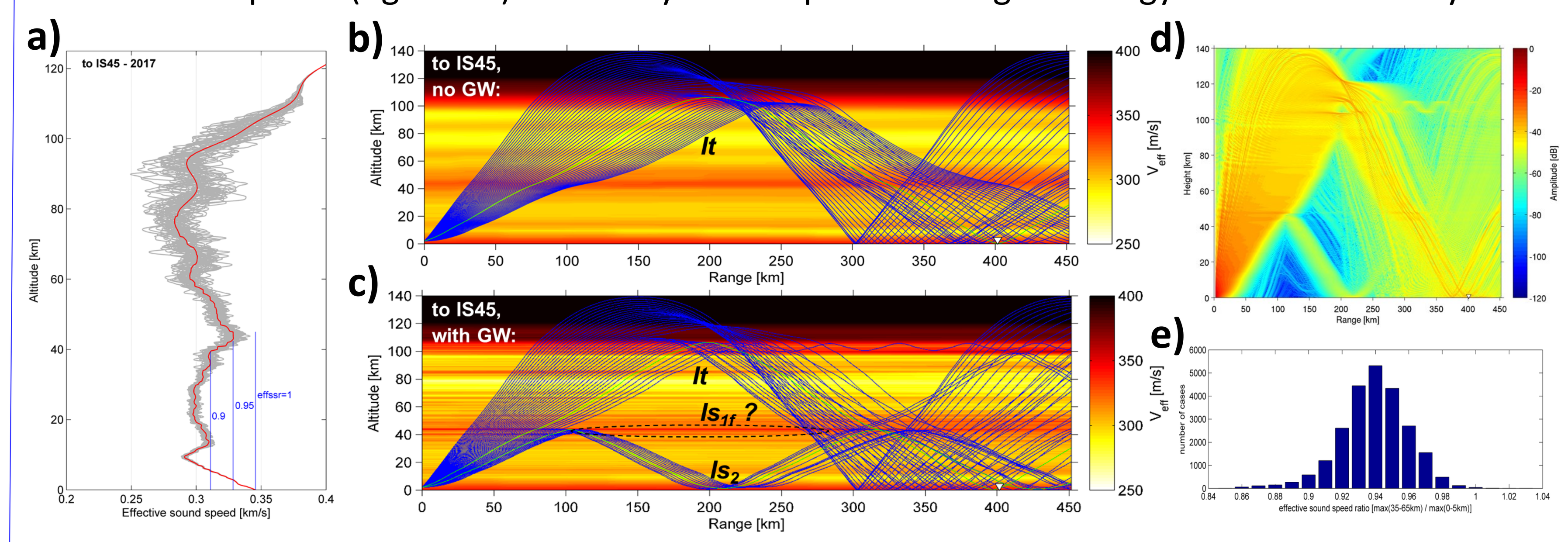


Fig 3: a) Atmospheric background profile derived from ECMWF and HWM/MSIS climatologies, showing the effective sound speed (in red), the variations by adding gravity wave profiles (in gray), and the effective sound speed ratios between ground and stratosphere (in blue). **b)** Propagation modeling using two-dimensional finite differences ray tracing from the test site to the station IS45, the effective sound speed background is color coded. **c)** Same propagation modeling, but with gravity wave variations added to the background. **d)** Propagation modeling using one-dimensional parabolic equation modeling and gravity wave perturbed backgrounds. **e)** Statistics of the stratosphere-to-ground effective sound speed ratios over 24,000 modeling cases (15 days around the event, 4 times per day, 10 profile along the path, 40 gravity wave cases).

DRPK 2017 test – Seismoacoustic observations

Further acoustic signals observed at IS45 arrive 12 minutes, 16.5 minutes and 33.5 minutes after the underground nuclear test (see figure 4). All signal families have back-azimuth values within ±12° of the test site and show acoustic trace velocities of ~350 m/s, but celerities inadequate for ducted infrasound (> 500 m/s for the precursors, <200 m/s for the late signal). Thus the precursory signals can be explained by seismic-to-acoustic conversions, and the late arrival by to the seismic aftershock and cavity collapse 8 minutes after the nuclear explosion.

a) b)

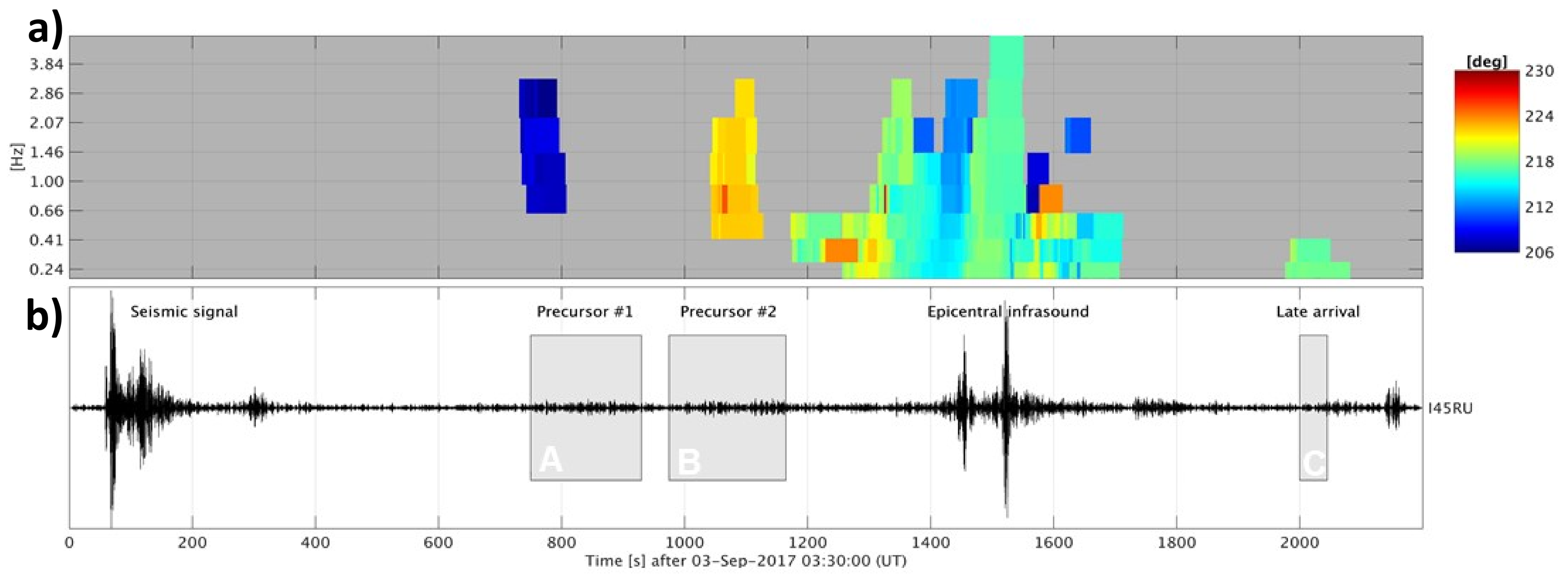
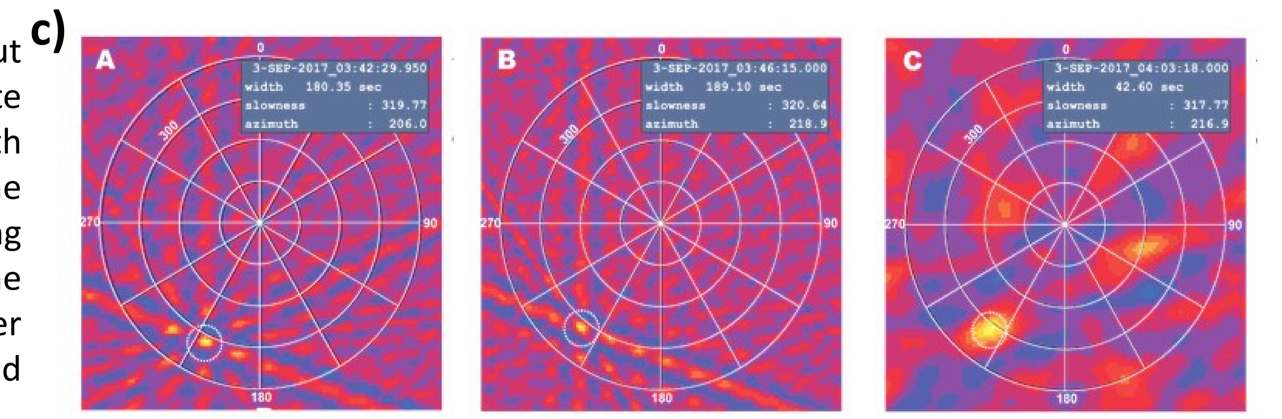


Fig. 4: Same as figure 2, but for an extended 35 minute time duration starting with the seismic signals of the DPRK 2017 test and including the precursory as well as the late arrival before and after the epicentral infrasound shown in figure 2.

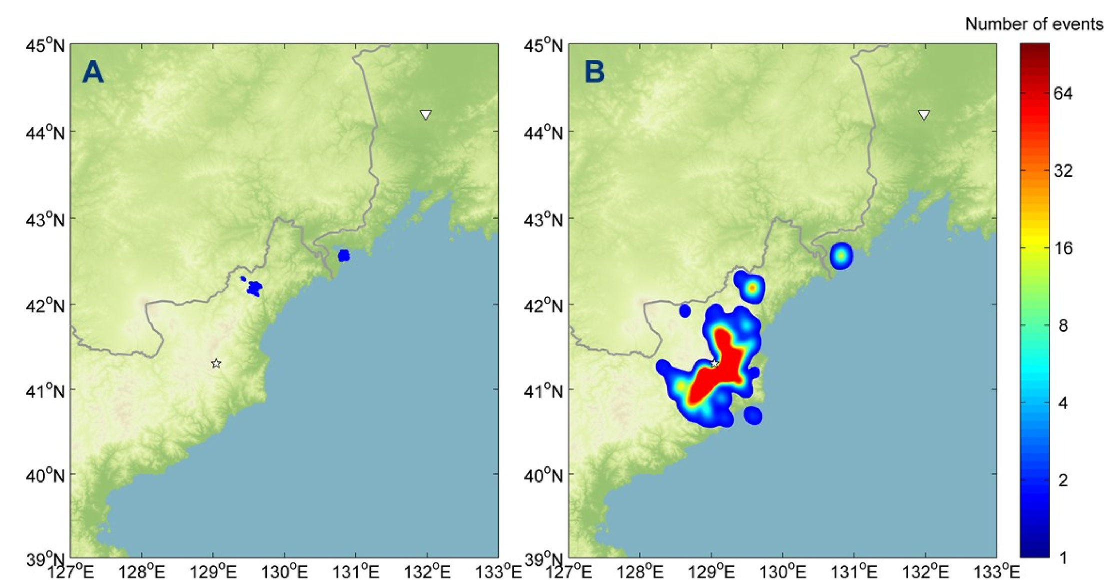
c)



DRPK 2017 test – Seismoacoustic backtracking

A crustal P phase of 6 km/s is combined with an infrasonic wave of 280 m/s (average celerity of the epicentral arrivals). This results in seismoacoustic conversion regions for the precursory arrivals (see figure 5a) in the border region of North Korea, China and Russia for the first, and a region in North Korea further to the south-west for the second signal.
Backtracking the epicentral infrasound arrivals (figure 5b) obtains a large area around the test site extending either to the northeast or the southwest as an expression of the two major signal groups corresponding to the stratospheric and thermospheric arrivals.

Fig. 5: Backtracking of the acoustic waveform energy on a 0.01° grid using the PMCC detection pixels shown in Fig. 4, identifying the seismoacoustic conversion areas from an initial P wave to a converted acoustic wave.
A) Results only using acoustic energy preceding the epicentral infrasound.
B) Conversion regions for all infrasound arrivals of figure 4 from contouring the spatial frequency distribution (see colorbar).



Conclusions

The infrasonic and seismoacoustic signals of the DPRK 2017 test are indicative of a strong, epicentral and remote surface movement and characterize the 2017 test as the strongest of all North Korean nuclear tests. Clear thermospheric infrasound is recorded in a distance of 400 km at the Russian infrasound array IS45 and stratospheric propagation, although suffering from disadvantageous ducting conditions, is nevertheless identified as well.