



Identification of Quarry Blasts Aided by Infrasound Data

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Abstract—We present our analysis of the detections from the Piskés-tető, Hungary infrasound array that has been operational since May 2017. We introduce an automatic search method to associate infrasound detections with a preliminary list of explosions detected by the seismic network. Once infrasound detections are associated with seismic events, we relocate the events using both the seismic arrival time and infrasound azimuth observations. We validate our methodology on ground truth events, i.e., explosions confirmed by the mine operators. We demonstrate that seismo-acoustic locations are able to identify the source of explosions even for closely spaced quarries. The discriminative power of the infrasound azimuth is strongest at near-field distances, where local and regional seismic discrimination methods have the most difficulties.

Keywords: Seismology, infrasound, discrimination, seismo-acoustic location.

1. Introduction

Separating natural seismicity from man-made events is necessary to study tectonic processes and to estimate seismic hazard and risk in a region. One of the major drivers behind seismic discrimination studies is the need to distinguish between earthquakes and nuclear explosions in order to provide a reliable verification regime for the Comprehensive Nuclear-Test-Ban Treaty (Blandford, 1977; Bowers & Selby, 2009; Richards & Zavales, 1990). Studies that combine seismic and infrasound signals significantly improve source identification and constrain propagation path effects (Che et al., 2011, 2019; Ford &

Walter, 2015; Gibbons et al., 2007, 2019; Sorrells et al., 1997; Stump et al., 2002). The association of infrasound signals with seismic signals not only can provide additional constraints on the source type, but can further complement seismic data by providing a more precise back-azimuth estimate and thus give reliable event direction for purposes of location.

The first infrasound array in Hungary (PSZI) began operations on 25 May 2017. One of the main motivations for the new station is to aid in the discrimination of natural and anthropogenic seismicity. Explosions occurring at or near the surface not only generate seismic waves, but the energy propagates large distances in the atmosphere in the form of infrasonic waves. The infrasound array in Piskés-tető was intentionally designed so that it is co-located with a seismic station. Hence, the infrasound array and the seismic station together can serve as a seismo-acoustic receiver. Combined with well-established seismic discrimination techniques, the infrasound records will help us to routinely distinguish earthquakes from explosions.

The Hungarian National Seismological Network operated by the Kövesligethy Radó Seismological Observatory (KRSZO), Geodetic and Geophysical Institute of the Research Centre for Astronomy and Earth Sciences, consists of 15 permanent and 13 temporary broadband seismological stations (Fig. 1). The events are published annually in the Hungarian National Seismological Bulletins (Grácz et al. 2018, 2019). Hungary is characterized by low-to-moderate seismicity. However, approximately two thirds of the seismically recorded events are anthropogenic events, such as quarry blasts and mine explosions. Hence, to study the natural seismicity of the country and produce reliable seismic hazard estimates, it is important to identify and separate natural events from anthropogenic ones.

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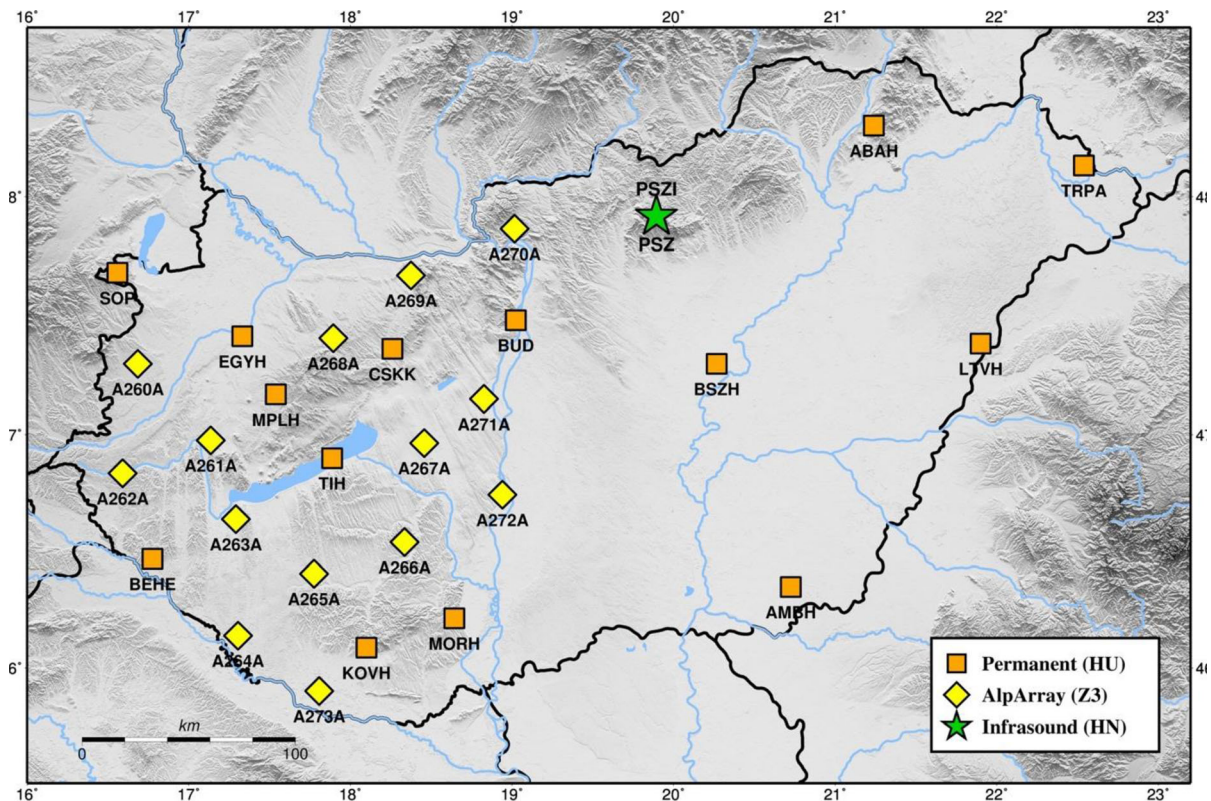


Figure 1

Permanent (orange) and temporary (yellow) seismic networks operated by the Kövesligethy Radó Seismological Observatory between 2017 and 2019. Green star denotes the location of the PSZI infrasound array co-located with PSZ permanent seismic station

Discrimination between natural earthquakes and mine explosions is performed manually by an experienced analyst based on seismological data as well as reports by the mining agencies.

Figure 2 shows the percentage of earthquakes and explosions in the earthquake catalog of Hungary for each year. Since the PSZI array has started its operation increased interest turned towards identifying mining explosions in the KRSZO, and as a result of careful analysis of seismic data completed with infrasound detections, the ratio of identified explosions among the seismically recorded events has significantly increased.

In this paper we show that infrasound detections play an important role in identifying quarry blasts, especially at local distances where there are no reliable established seismic discrimination methods.

2. The PSZI Infrasound Array

The first Hungarian infrasound array, PSZI was installed in May 2017 as the first station of the Hungarian National Infrasound Network (HNIN, <https://doi.org/10.14470/UA114590>). It is located in North Hungary, on Piskés-tető peak in the Mátra mountains, at 930-m elevation. The array consists of four elements and has an aperture of approximately 250 m. All elements are equipped with SeismoWave MB3d microbarometers. The central element of the array is co-located with a broadband three-component seismological station (PSZ) jointly operated by GEOFON and KRSZO. The site is located in temperate mixed forest with relatively dense undergrowth that helps to further reduce environmental noise.

All infrasound data are acquired in real time in miniSEED format by the HNIN data center located at

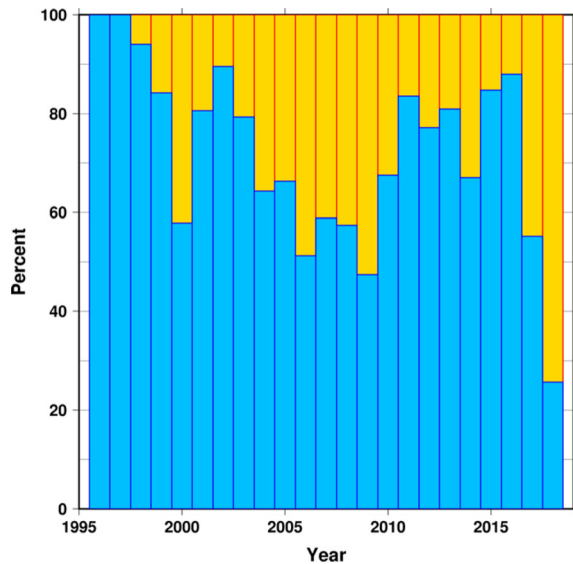


Figure 2

Relative occurrence of natural (blue) and anthropogenic (yellow) events in the Hungarian event catalog between 1996 and 2019. The number of events identified as explosion has been increased since the operation of the PSZI infrasound array has begun

the Kövesligethy Radó Seismological Observatory, Budapest, Hungary. The sampling rate for the infrasound BDF channels is set to 100 Hz. The array is registered at the International Registry of Seismographic Stations with the FDSN network code HN. For data acquisition we use SeisComp3 (<http://www.seiscomp3.org>) and for data processing we use DTK-PMCC, based on the progressive multichannel correlation method (PMCC, Cansi, 1995), both software being part of the CTBTO NDC-in-a-box software package.

The array detects signals from various sources including microbaroms from the Northern Atlantic Ocean and the Black Sea, regional thunderstorms (Pásztor et al., 2020), sonic booms, volcanic eruptions, aircraft passing above the array, bolides (Kereszturi et al., 2020), industrial and accidental explosions (Koch et al., 2020). Seismo-acoustic and acoustic-only events detected by the array are published annually in the Hungarian Seismo-Acoustic Bulletin (Bondár et al., 2019, 2020).

3. Mining Explosions

There are a number of mines and quarries in Hungary and neighboring countries that blast regularly. Many of these explosions are detected by the seismic network, and some also by the PSZI infrasound array. We will use these events to develop and test a method for improving the discrimination of explosions from earthquakes. First we study the array's ability to detect explosions from the mines around the country.

The events detected by the seismic network are classified as explosions by an experienced analyst who also associates them with individual mines. Note that some of the mine operators report their explosions, so these are regarded as ground truth events.

For the infrasound analysis we use the preliminary list of explosions from the seismic analysis. The list typically contains many more events than those published in the Hungarian National Seismological Bulletin (HNSB) as many of these explosions are detected by only two seismic stations, or due to large uncertainties they are screened out from the HNSB. However, the seismic signals show evidence of an explosion, and this information can still be used for testing the infrasound detections.

We consider the mines from which at least five explosions have been recorded at PSZI between 2017 May and 2019 December. Altogether 1500 explosions have been recorded from these mines by the seismological network, with magnitudes between 0.5 and 2.5.

Based on the seismic event list, we search for infrasound arrivals in the expected arrival time and back-azimuth ranges. The infrasound data is uniformly processed with the PMCC method (Cansi, 1995) for the entire period to determine the horizontal trace velocity and back-azimuth of the signals. The processing parameters are optimized for broadband observation, i.e., for detecting signals from various sources in a broad frequency range. Parameters used for PMCC processing of the data are shown in Table 1.

For each event in the seismic event list, we compute the expected arrival time of the signal based on the seismic location and origin time, using a nominal $c = 300$ m/s propagation velocity. The

Table 1

Parameters used for PMCC processing of PSZI data

Detection range	0.09–7.1 Hz
Window length	60–12.35
Window overlap	95%
Consistency	0.02
Filter	Chebyshev
Azimuth tolerance	3°
Family size	100–2000 pixels

detections for each event are searched in a 6-min-long time window around the expected arrival time.

The expected back-azimuth is also computed based on the seismic location. Seismic location uncertainties are typically not greater than 10 km in the HNSB. However, in some cases in the preliminary event list used for this work, location errors can be larger than 20 km, due to poor station coverage and suboptimal network geometry. At small distances from PSZI, such location errors can cause large back-azimuth deviations, so it is important to correctly set the azimuth window for automatic search for detections. For instance, 20 km location error at a distance of 10 km from the station (which is the distance of the nearest quarry, Gyöngyösolymos) can result in a back-azimuth deviation up to 75°, while the same location error at 60 km distance causes only a 10° deviation. Azimuth windows for matching detections with the seismic events are adapted to the distance between seismic epicenter and PSZI station. The azimuth range for the search is defined as

$$\text{BAZ}_{\text{err}} = 2\arcsin(d\Delta/2\Delta),$$

where Δ is the epicentral distance and $d\Delta$ is the estimated location uncertainty. When this value is lower than 15° for $\Delta > 40$ km, $\text{BAZ}_{\text{err}} = 15^\circ$ value is used uniformly. In the extreme case when the location uncertainty is larger than twice the epicentral distance, the azimuth window is set to 180°, and the time window is checked for detections regardless of the back-azimuth values. Time and back-azimuth windows for automatic search are intentionally chosen large enough to have false detections rather than missed events. For this reason, 20 km location error is used for calculating back-azimuth windows, even if it is much more than the typical location errors for

most events. Minimum back-azimuth window and time window are set based on experiments to obtain the best result. The matching detections are always manually checked again by an experienced analyst to confirm that they are really a signal from a quarry blast.

Sometimes signals from other sources (e.g. microbaroms) match the search criteria, but they can be easily screened out by the analyst by the shape of waveforms and PMCC detections. An example is shown on Fig. 3 for a typical signal of an explosion in a nearby mine, and microbarom signal from similar direction.

The search method was applied for the data set of 1500 seismically detected explosions. Out of the 1500 events, 319 were detected by the PSZI infrasound array. Figure 4 shows the location of the quarries where the radius of the circles is proportional to the number of explosions detected seismically, and the color shows the percentage of explosions recorded by the infrasound array. The geographical distribution of the mines and the number of explosions at each mine is uneven, which makes it difficult to conduct comprehensive analysis of detectability based on location. However, there are some trends as a function of distance from PSZI.

Figure 5a shows the detection rates as a function of distance from PSZI regardless of the azimuths, in 10 km-wide zones, defined as the total number of explosions detected by the infrasound array in the zone divided by the total number of seismically detected explosions in each zone. A more detailed table with event numbers and detection rates for each mine are listed in the Appendix. In the vicinity of the array, detection rates are the highest; up to 40 km the detection rate is above 60%. Between 40 and 90 km the detection rates decrease, varying between 20 and 55%. In the range between 90 and 190 km, the detection rates are very low, well below 20%, and beyond 190 km the rates are higher again. These trends can be explained by the propagation patterns of the infrasound waves.

Infrasound propagation is controlled by wind speed and direction and by temperature along the path it travels from source to receiver. These factors vary in time and space and cause the infrasound waves to refract at different altitudes (Drob et al.,

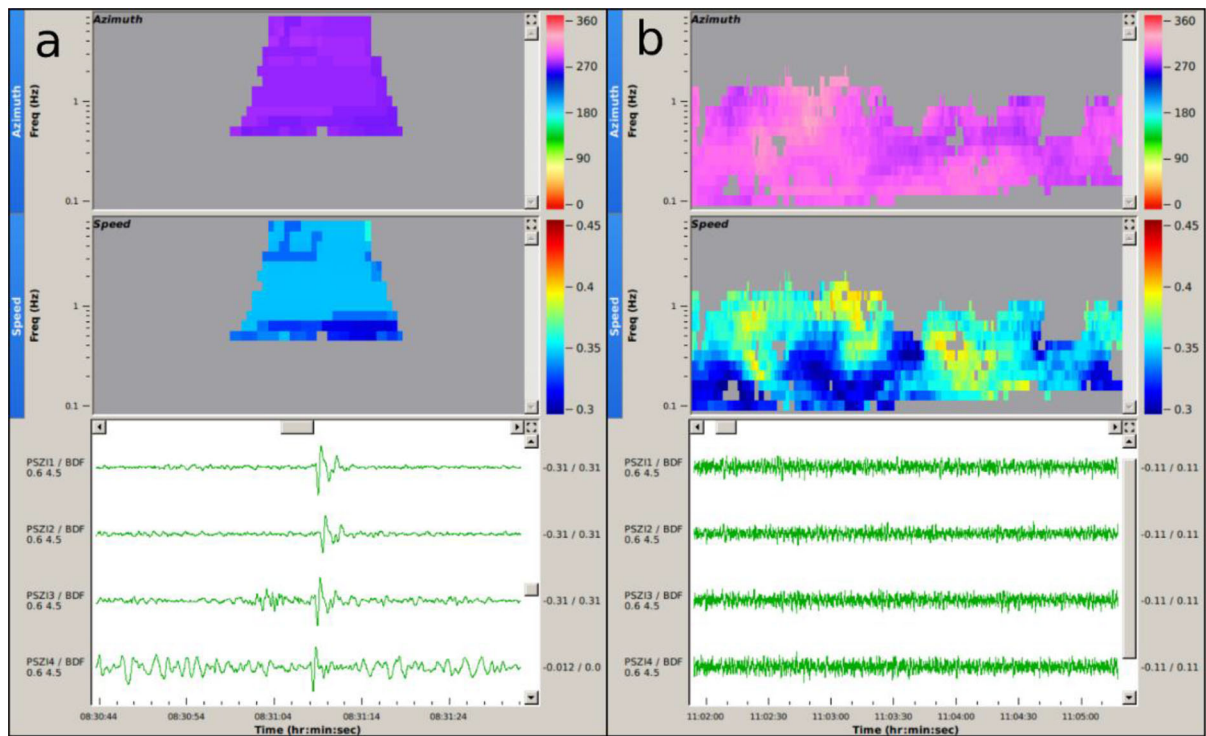


Figure 3

The lower blocks show infrasound waveforms recorded by the four elements of PSZI, filtered with a 0.6–4.5 Hz bandpass filter; the top and middle blocks show the corresponding PMCC detections, colored by azimuth and apparent velocity, respectively. **a** is an example for a real signal of an explosion at Szanda mine located 35 km from the PSZI array in the north-western direction (269° back-azimuth), which is the typical direction of microbaroms from the North Atlantic Ocean. **b** Shows microbarom signals from a similar direction (287–290°), thus matching the search criteria and marked as detection by the automatic search. The two signals can be easily distinguished by the analyst

2003). In our distance range of interest (up to 300 km) we can expect phases reflected in the troposphere and the stratosphere, as seen in previous studies (e.g. Fuchs et al., 2019; Koch & Pilger, 2020; Schneider et al., 2018). Observed infrasound phases coming from different paths in the atmosphere can be distinguished based on their celerities (Kulichkov, 2000; Negraru et al., 2010), defined by the travel time of the signal divided by the horizontal distance of the source and the receiver.

Figure 5b shows the celerity of each detected explosion as a function of its distance from PSZI. The plot shows a nice grouping of the events that can be associated with different phases. In the 0–40 km range the events have high celerities, mostly above 330 m/s, which according to Negraru et al. (2010) can be associated with phases reflected at heights up to 1 km. Note that in this short range the location

errors can cause large errors in the calculation of celerity, which explains the significant scatter in the celerity values.

In the 40–90 km zone the celerity values are less scattered and are all between 310 and 360 m/s, which suggests that these are detections from tropospheric and lower-altitude turning points. In the range beyond 190 km, most of the events have celerities between 280 and 310 m/s which is the typical celerity range for stratospheric arrivals.

In the zone between 90 and 190 km, where detection rates are very low, celerity values show high variability. While there is a group of events in the typical celerity range of tropospheric phases (310–330 m/s), another group is also present with much lower celerities and large scatter; these arrivals can be associated with stratospheric phases according to Nippress et al. (2014). The low detection rates

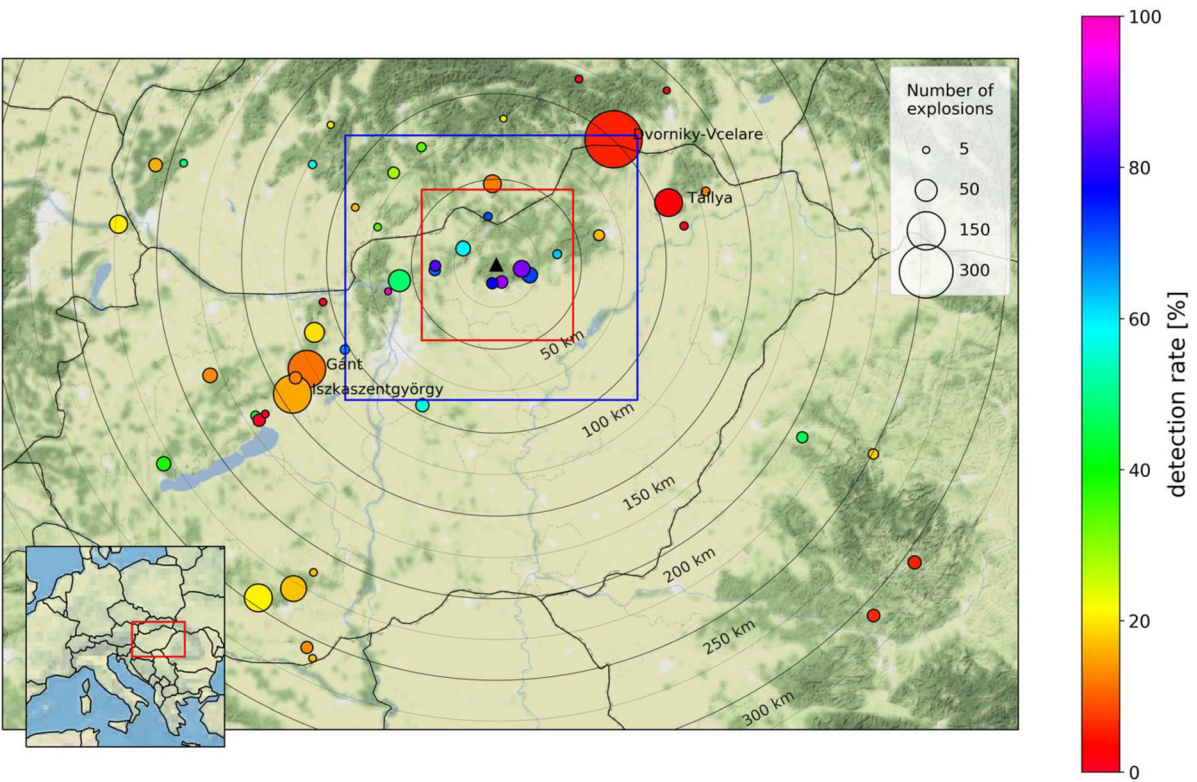


Figure 4

Surface explosions from quarries and mines detected by the PSZI infrasound array (triangle). The size of the circles at the mine locations is proportional to the total number of events color-coded by the detection rate at PSZI. Blue and red squares mark the areas shown on Figs. 6 and 7, respectively

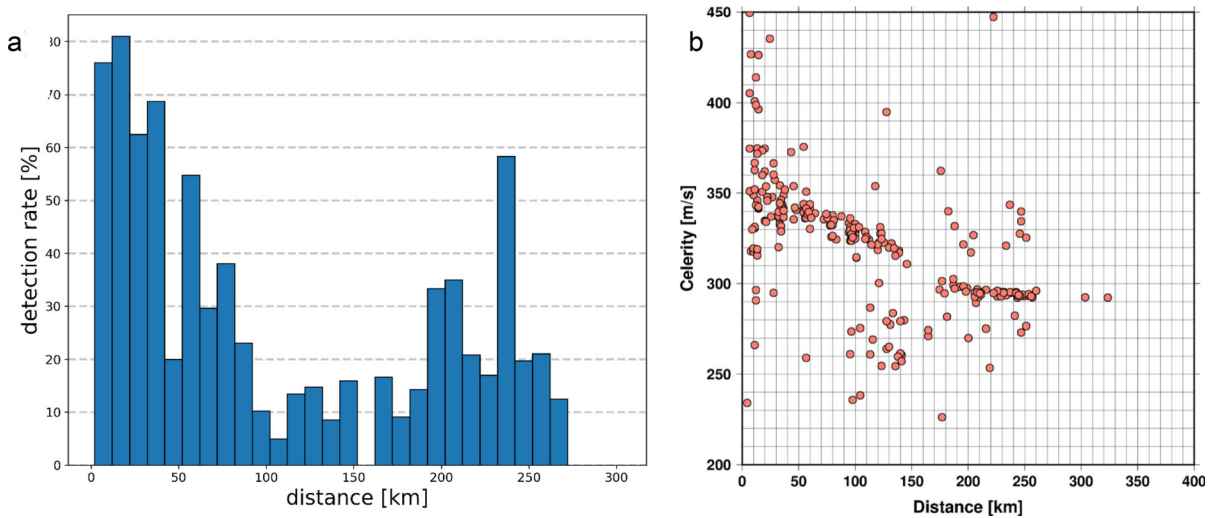


Figure 5

a Detection rates and **b** celerity of the detected event as a function of distance from PSZI

suggest that most of the time, the 90–190 km range is in a geometrical shadow zone for PSZI between tropospheric and stratospheric phases; however, the temporally varying atmospheric conditions sometimes still allow some signals to reach PSZI from this zone, through different ducts. Note that the most active mines are located in this zone, namely Iszkaszentgyörgy, Gánt, Tállya and Dvorniky-Vcelare. Explosions from these four mines constitute 28% of all the events (419 explosions), which explains the relatively low overall detection rate. There are not enough events in our data set for more detailed analysis of the detection patterns, and this will be the focus of further studies when more events will be accumulated.

4. Near-Field Events

In order to use the automated search as a base for selecting anthropogenic events from natural ones, we first apply it to a set of events that contain both explosions and earthquakes. To test the efficiency of the method, we use a smaller amount of data and check every single event manually, and determine whether the automatic search result was correct. In other words, in the entire data set, only those events were checked manually where the automated search found a matching signal. Events without a matching signal were screened out immediately, although a few detections might have been lost this way.

For this test we chose the area with the highest detection rates: the 60 km-radius circle around the array where 60% of the events were detected. This region also included natural seismic events detected by the seismic network in the same time period (May 2017–December 2019), which allowed us to test and validate the automated search.

We use the events from the Hungarian National Seismological Bulletin for 2017 and 2018 (HNSB, Grácz et al., 2018, 2019), completed with the preliminary event list for 2019, which was not published at the time of writing. Note that the preliminary seismic locations in 2019 rely on picks from the permanent network, as the picks from the much denser temporary deployments will only be added during the final review. Hence, the quality of the

2019 seismic locations is somewhat lower than those from 2017 to 2018.

Figure 6 shows the data set for 267 events within a distance of 60 km from the PSZI array between 1 July 2017 and 31 December 2019. Of these, 227 events are classified as known or suspected explosions and 44 events are identified as earthquakes, mostly from a sequence of small earthquakes that occurred 45 km south-east of PSZI in August 2019 with magnitudes of 0.5–2.5.

The automatic search results are summarized below.

- One hundred and twenty-two explosions were detected by the infrasound array and also correctly found by the automatic search.
- Ten events were detected by the infrasound array but missed by the automatic search. It was in most cases due to large seismic location errors, even larger than 20 km in the case of events detected by only two seismic stations.
- Twenty false detections for explosions: detections found in the time-azimuth window that did not originate from the actual explosion. Many of them are from the Vác and Nagylóc mines, located at 261 and 296 azimuths from PSZI, respectively, i.e., in the direction from where North Atlantic microbaroms are detected throughout the winter period. Microbarom detections may satisfy the automatic search criteria, while the real signal from the explosion is hidden in the microbarom signals or lost due to atmospheric conditions. In other cases, detections made from some unknown source of continuous noise or detections from aircraft passing above the station fit the search criteria.
- Sixty-eight explosions were not detected by the infrasound station and no matching detection was found.
- One explosion was found in the published bulletins previously classified as earthquake: a blast from the Szanda mine, with magnitude 1.6. In other words, the approach worked for separating an explosion from an earthquake.
- Seven natural earthquakes had a matching detection. All of them were events from the earthquake series that occurred in August 2019 near the town of Tenk, approximately 133°–135° from PSZI,

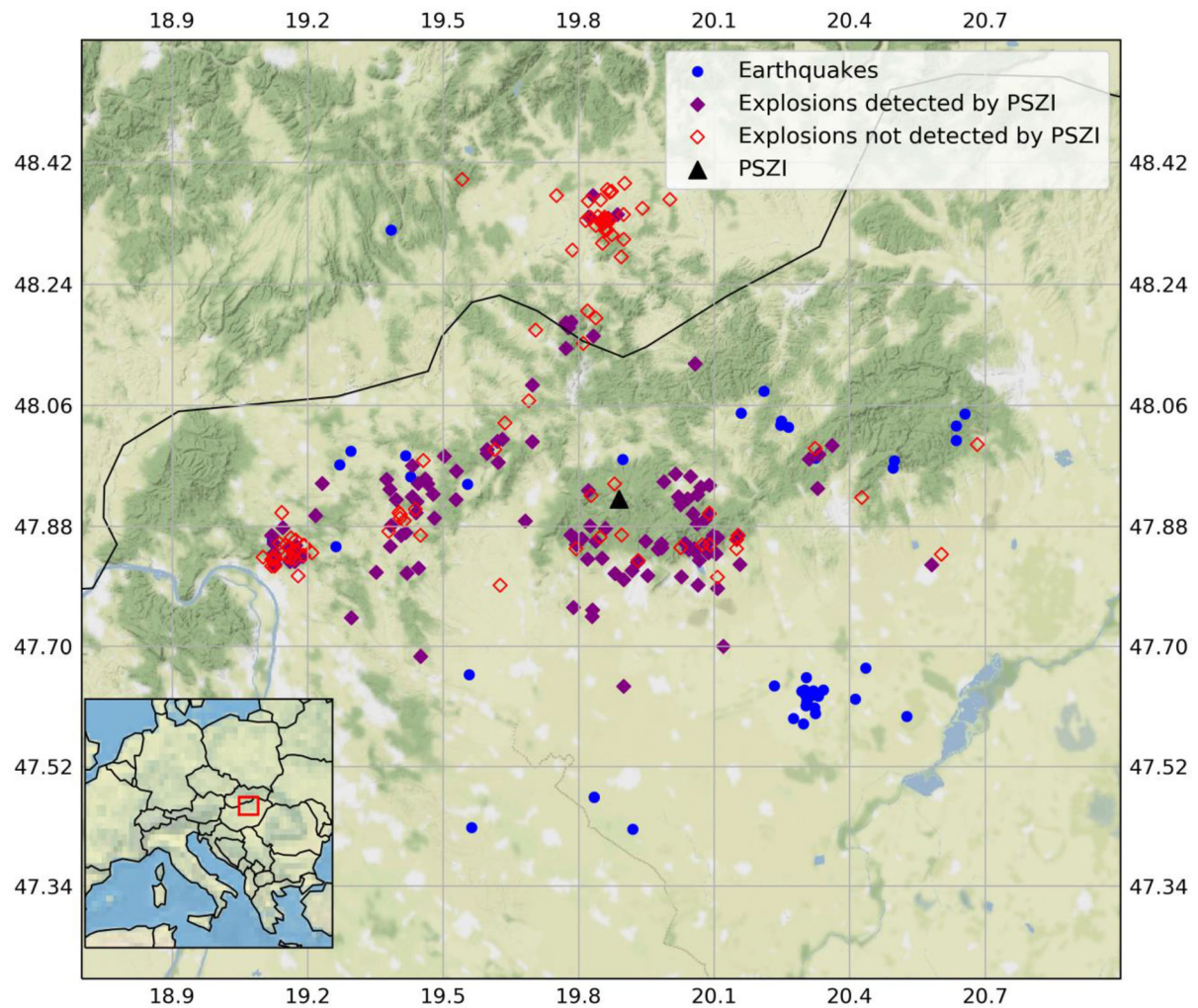


Figure 6

Near-field events around PSZI (triangle) between 1 July 2017 and 31 December 2019. Circles indicate the locations of earthquakes, filled diamonds are explosions detected by PSZI, and empty diamonds denote explosions that were not detected by PSZI

which is almost exactly the direction of the Mátra Power Plant, located 20 km from PSZI at 137°, that continuously produces detections throughout the summer period, thus satisfying the search criteria for the Tenk earthquakes. Manual analysis confirmed that the detections are indeed industrial noise from the Mátra Power Plant and thus can be considered false alarms.

- Thirty-six natural earthquakes did not have any matching signal.
- At the time of two events, the infrasound array was not working, and no infrasound data are available.

Table 2

Confusion matrix of the automated search results

	Detected by PSZI	Not detected by PSZI
Found by auto-search	True detections: 122 explosions (46%)	False detections: 21 explosions/7 earthquakes (11%)
Not found by auto-search	Missed detections: 10 (4%)	No detectable infrasound: 68 explosions/36 earthquakes (39%)

Table 2 summarizes the results in a confusion matrix. Our automatic search correctly associated infrasound detections to seismic events in 46% of the cases, did not make an association when there was none in 39% of the cases, missed 4% of the events and made false associations in 11% of the cases. Hence, the true positives and true negatives make up 85% of the cases, while the false negative and positives constitute 15%. Note that the table does not include the event that was previously mistakenly identified as an earthquake and the two events where no infrasound data was available.

4.1. Seismo-acoustic Locations

The association of explosions with the origin mines is based primarily on seismic location, occasionally complemented with ground truth information from the mining authorities. However, the report from the mines may only arrive several months after real time; therefore, the association to the mines strongly depends on our experienced analyst. Our objective is to develop a method for the automatic association of events to mines.

We focus on the close vicinity of the PSZI array, where just a few kilometers of location errors may result in large deviations in back-azimuths. In this region there are several mines that are separated from each other within the uncertainty of seismic location. Hence, it is difficult to clearly identify exactly which mine was the source of the event. Seismic discrimination techniques have very limited use at very local distance ranges of a few tens of kilometers (Kintner et al., 2020; O'Rourke et al., 2016). However, in such a small distance, the resolving power of the infrasound azimuth measurements can have a significant effect on event locations. We relocate the events using both seismic and infrasound observations and show that the improved locations due to the contribution of infrasound data can be used to correctly identify the mine that carried out the blast. Finally, we validate the result using the available ground truth information.

To relocate the events, we use the location algorithm (Bondár & McLaughlin, 2009) originally implemented at the International Seismological Centre (Bondár & Storchak, 2011) and further developed

as iLoc (Bondár et al., 2018). iLoc is able to use arrival time, back-azimuth and slowness measurements from seismic, hydroacoustic and infrasound stations, and therefore it is a natural candidate to obtain seismo-acoustic locations. Infrasound azimuth measurements are typically very accurate (Che et al., 2019); therefore, iLoc assigns a much smaller a priori measurement error estimate of 1° to infrasound azimuth observations than to seismic azimuths, and a much larger a priori measurement error estimate to infrasound travel times. The a priori measurement error estimates in effect down-weight infrasound travel times so that they do not contribute to the location, while the infrasound azimuth measurements have a weight comparable to the first arriving P phases in the location.

Figure 7 shows the location of PSZI and eight selected mines (Gyöngyössolymos, Gyöngyöstarján, Recsk, Kiskő, Egerbakta, Bercel, Szanda, Nagylóc) to demonstrate the value of infrasound-aided relocation of seismic events for identifying the source mines. Squares indicate the location based on seismic data only. Circles show the seismo-acoustic locations using both seismic and infrasound data. Owing to the

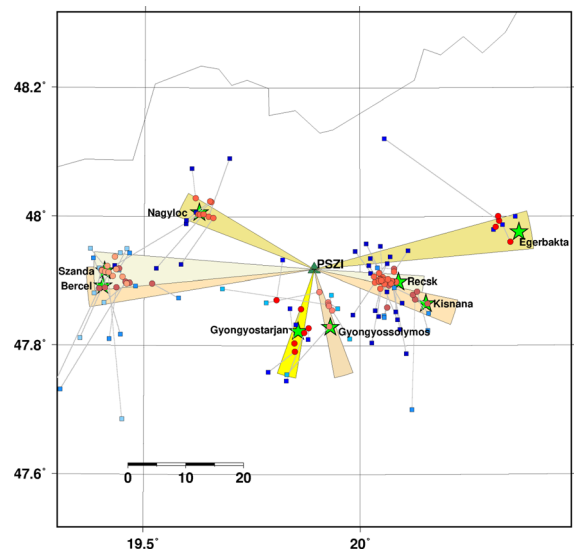


Figure 7

Seismic (squares) and seismo-acoustic (circles) locations of mine explosions. Besides the seismic arrival times, iLoc uses the infrasound azimuth measurements in the seismo-acoustic locations. Stars indicate the quarries; the search range in azimuth for each mine is indicated by wedges

use of infrasound azimuth in the location, the seismo-acoustic locations significantly reduce the mislocations.

The two closest mines to PSZI are Gyöngyössoly-
mos and Gyöngyöstarján, both located approximately
10 km from PSZI and 5 km from each other.
Gyöngyössoly-
mos is at 163°; Gyöngyöstarján is at 197° from PSZI. The back-azimuth of the detected
infrasound signal can easily discriminate between
these two mines.

Szanda and Bercel are located about 35 km to the
NW from PSZI, at 269° and 265°, respectively, and
separated by 2.5 km. Nagylóc is located 22 km and
296° from PSZI, roughly 19 km from Bercel and
Szanda. Events from these mines are often detected
only by three seismic stations, and due to the large
azimuthal gap, the seismic location errors often
exceed 20 km. Due to the large location errors
explosions from Nagylóc are also often associated
with Szanda or Bercel and vice versa. Although the
difference of back-azimuths is very small for these
mines, infrasound data can help to reduce uncertainty
of locations and determine the source of the
explosion.

Recsk and Kisnána are also two mines with a
relatively small separation of 6 km from each other
and overlapping back-azimuth windows. Being well
within the typical seismic location uncertainties, the
explosions are often wrongly associated with one of
these mines. Improved locations due to the infra-
sound back-azimuth helps in correcting the
misassociations.

To validate our method, we tested the event—
mine association process with the available ground-
truth information. First, we associated the mine
located nearest to the seismic-only location of the
event. After relocating the events by adding the
azimuth from the infrasound detection, we associated
again the nearest mine with the new, seismo-acoustic
location, and compared with the ground truth infor-
mation reported by the mines.

Of the 67 events in Fig. 7, 49 ground-truth events
were reported by the mine operators. Out of the 49
events, 33 had been already associated with the
correct mine based on the seismic-only location, 32
of them remained correctly associated with the
seismo-acoustic location (however, location errors

significantly decreased), and one event was reassoc-
iated from the right mine (Bercel) to a wrong one
(Szanda). Sixteen events were originally associated
with wrong mines by the seismic locations. Fourteen
of them were correctly reassociated by the seismo-
acoustic location, and two events were still reassoc-
iated with the wrong mine. Altogether, based on the
seismo-acoustic location, out of 49 events, 46 were
correctly associated with their real source, and only
three were associated with wrong mines.

Figure 8 shows the cumulative distribution of
mislocations of the seismic and seismo-acoustic
locations of GT events. The median mislocation is
reduced from 6.1 to 2.6 km, and at the 90% percentile
level it is reduced from 13.4 to 4.3 km.

5. Discussion

Our results show that infrasonic data is a very
effective tool to complement seismic data for dis-
crimination of natural earthquakes from surface
explosions. The method is the most effective in the

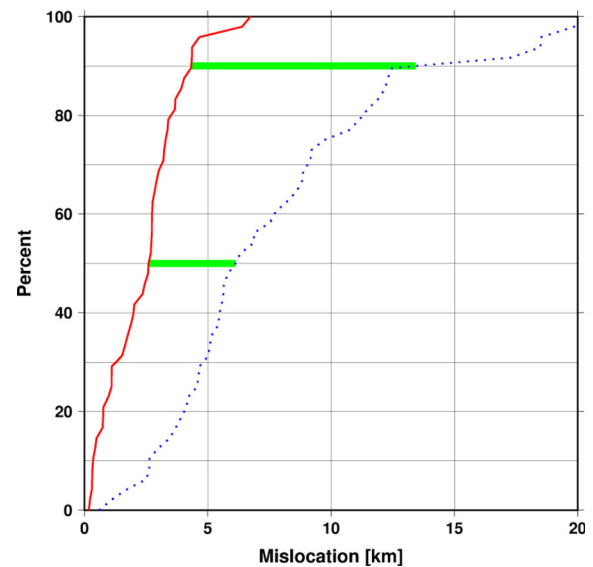


Figure 8
Cumulative distribution of mislocation of GT mine explosions of
seismic (dotted line) and seismo-acoustic (solid line) locations with
iLoc. The seismo-acoustic locations use the seismic arrival times
together with the infrasound azimuth measurements. The thick
horizontal lines emphasize the location improvements at the
median and the 90th percentile levels

distance range of direct arrivals, within a few tens of kilometers of the infrasound array, but it can still contribute to the analysis of more distant events as well, depending on atmospheric conditions.

Mining explosions are typically low-magnitude seismic events, detected by only a few seismic stations, and the low number of phases used in the location often result in poor location quality. Combining seismic arrival times with infrasound back-azimuth measurements can significantly improve locations, especially at local distances. Better locations also help associating seismo-acoustic events to mines and quarries. These explosions produce more than a hundred seismo-acoustic events with accurate locations and they are published annually in the Hungarian Seismo-Acoustic Bulletin (Bondár et al., 2019, 2020), including the ground-truth events confirmed by the mines. Our bulletin will contribute to the European Infrasound Bulletin (Pilger et al. 2018).

Our procedures can be further improved by fine-tuning the PMCC processing parameters so that they are optimized for detecting explosions, instead of using our general-purpose parameters for PMCC. As data accumulate in time, we will be able to analyze seasonal trends in the detection of stratospheric phases from events that occur far (beyond 200 km) from the infrasound array. Ground truth events will also allow us studying regional propagation conditions (Gibbons et al., 2019; Smets et al., 2015).

Finally, the PSZI array is not only useful for detecting local events but also contributes to the European and global infrasound network. The Central and Eastern European region has been sparsely covered by infrasound stations for many years, before the deployment of PSZI and other stations in the Central and Eastern European Infrasound Network (CEEIN; Czanik et al., 2019). PSZI has a central location in the region, and therefore significantly improves the coverage of the European network in the region (Le Pichon et al., 2008, 2012).

6. Conclusions

We have demonstrated that infrasonic data can be a very useful addition to complement seismic data for discrimination between natural earthquakes and

surface explosions. Our automated search method that associates infrasound detections with seismic events gives reasonably robust results, being correct 85% of the time. The use of azimuth observations of an infrasound array together with travel times of seismic phases in a state-of-the-art location algorithm not only allows us to discriminate between earthquakes and explosions, but also helps to identify the source of the explosion with high confidence, even in the case of closely spaced mines. The power of the method is most effective in the distance range of direct infrasonic arrivals, i.e., within 50–100 km of the infrasound array, where local and regional seismic discrimination methods have the most difficulty in distinguishing between explosions and earthquakes.

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Code availability

We used the CTBTO NDC-in-a-box software (SeisComp3, PMCC, DTK-Diva) distributed by the Comprehensive Nuclear-Test-Ban Treaty Organization among the State Parties. iLoc is open-source and can be downloaded from <https://seiscode.iris.washington.edu/projects/iloc>.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Availability of data and material The Hungarian Seismo-Acoustic Bulletins are available for download at <http://www.infrasound.hu/index.php/en/hungarian-seismo-acoustic-bulletin>.

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Appendix

Summary of Detection Statistics of Quarry Blasts for the PSZI Infrasound Array. Mines are Ordered by their Distance from PSZI. Dabas is a Site Used to Detonate Spent Ammunition

Mine	Latitude	Longitude	Distance	baz	All	Detected	Rate%
Gyöngyössolymos, HU	47.83	19.93	10.64	162.94	16	14	88
Gyöngyöstarján, HU	47.82	19.86	11.15	192.73	13	10	77
Recsk, HU	47.90	20.09	15.09	98.96	29	25	86
Kisnána, HU	47.87	20.15	20.59	107.18	25	18	72
Nagylóc, HU	48.01	19.63	21.80	296.15	22	13	59
Siatorska-Bukovinka	48.17	19.82	28.67	350.14	7	5	71
Szanda, HU	47.92	19.41	35.97	269.31	12	10	83
Egerbakta, HU	47.98	20.37	36.34	79.96	8	5	63
Bercel, HU	47.89	19.40	36.40	265.27	13	9	69
Velke-Dravce, SK	48.35	19.86	47.49	357.23	33	4	12
Sejce-Vác, HU	47.84	19.13	57.84	260.93	50	24	48
Miskolc-Mexikóvölgy, HU	48.08	20.70	62.79	73.77	12	2	17
Dunabogdány, HU	47.78	19.04	65.72	256.53	5	5	100
Horne-Turovce, SK	48.12	18.96	73.14	287.87	6	2	33
Krupina, SK	48.40	19.08	80.74	312.11	14	4	29
Viglas, SK	48.54	19.30	81.60	327.73	9	3	33
Tisovec, Sk	48.69	19.95	85.49	2.76	5	1	20
Hontianske-Trstany, SK	48.22	18.78	89.37	292.47	6	1	17
Dabas, HU	47.17	19.31	94.13	208.01	18	10	56
Dvorníky-Vcelare, SK	48.58	20.81	100.43	42.70	342	19	6
Etyek, HU	47.47	18.70	102.69	241.14	9	6	67
Bersekbanya-I, HU	47.72	18.52	104.59	258.36	6	0	0
Tállya, HU	48.25	21.25	107.37	69.70	80	2	3
Tarcal, HU	48.12	21.37	112.55	77.82	7	0	0
Tatabánya, HU	47.56	18.46	114.66	250.10	41	8	20
Spisska-Nova-Ves, SK	48.89	20.54	118.41	23.74	6	0	0
Hostie, SK	48.45	18.44	122.64	299.14	7	4	57
Kamenec-pod-Vtacnikom, SK	48.66	18.58	126.77	310.66	5	1	20
Gánt, HU	47.36	18.40	128.06	241.67	147	17	12
Sárospatak, HU	48.31	21.54	130.14	70.12	8	1	13
Magyaralmás, HU	47.32	18.31	136.53	241.16	16	2	13
Trebejov, SK	48.84	21.23	142.25	43.84	5	0	0

continued

Mine	Latitude	Longitude	Distance	baz	All	Detected	Rate%
Iszkaszentgyörgy, HU	47.23	18.28	143.14	238.20	150	23	15
Vilonya, HU	47.12	18.07	163.15	237.82	6	0	0
Litér, HU	47.09	18.02	168.22	237.47	16	0	0
Királyszentistván, HU	47.11	17.99	168.63	238.63	9	4	44
Ugod, HU	47.33	17.64	181.74	249.68	22	3	14
Horne-Oresany, SK	48.46	17.43	192.54	288.91	6	3	50
Rohoznik, SK	48.45	17.21	207.94	287.30	19	3	16
Tetchea, RO	47.00	22.30	208.56	118.55	13	6	46
Nagymányok, HU	46.27	18.45	214.03	211.26	6	1	17
Hainburg, A	48.13	16.91	223.22	277.20	34	7	21
Komló, HU	46.18	18.29	228.69	212.64	69	12	17
Várvölgy, HU	46.85	17.27	230.55	240.06	21	8	38
Bükkösd, HU	46.13	18.02	245.17	216.23	81	17	21
Poieni, RO	46.91	22.86	250.72	115.57	11	2	18
Nagyharsány, HU	45.85	18.40	256.43	206.88	15	2	13
Beremend, HU	45.79	18.44	260.97	205.56	6	1	17
Rosia-Poieni, RO	46.32	23.18	306.73	124.22	18	1	6
Baita, RO	46.03	22.86	308.73	131.84	16	1	6
Sum					1500	319	21

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