Discrimination of natural and anthropogenic events by the joint analysis of seismic and infrasound data

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Final report

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Motivation

The primary motivation for the project was the introduction of infrasound research to Hungary. Infrasound research, driven by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) that operates a global network of infrasound arrays to monitor atmospheric nuclear explosions, is a relatively new discipline with huge potentials not only in seismology but also in atmospheric research and climatology studies. Infrasonic waves are generated by both natural and anthropogenic sources. They propagate in the atmosphere with little attenuation over long distances with the speed of sound at frequencies below 20 Hz. Our research objective was to discriminate between natural (earthquakes, bolides, volcanoes, storms) and anthropogenic (explosions, quarry blasts, supersonic flights) sources by using both seismic and infrasound data. In a moderately active seismic region such as the Pannonian Basin, considerable amount of recorded seismicity may come from mining activities, and to perform reliable seismic hazard studies these need to be removed from the seismic event catalogues.

The Hungarian Academy of Sciences awarded 88 MHUF to the PI's proposal to establish the first infrasound array in Hungary in 2016. The Research Center for Astronomy and Earth Sciences (CSFK) deployed the infrasound array PSZI at Piszkés-tető that began operations in 2017. The waveforms are freely available at the GEOFON data center (https://geofon.gfz-potsdam.de/doi/network/HN). The array is co-located with a seismological station and thus allows the joint processing of seismic and infrasound data. The PSZI infrasound array regularly records quarry blasts, accidental explosions, as well as volcanic eruptions, bolides, storms, and lightning. The project webpage, www.infrasound.hu is regularly updated.

The Geodetic and Geophysical Institute, to which the Kövesligethy Radó Seismological Observatory (KRSO) belongs, exited the CSFK on April 1st, 2021. The new institute kept the ownership and the operation and maintenance responsibilities of the infrasound array at Piszkés-tető. However, the PI, and consequently the project, remained at the CSFK. The PI and some team members have joined the Institute for Geological and Geochemical Research (FGI). To increase redundancy, we established a data collection and processing system at the FGI, similar to the existing processing system at the KRSO.

International cooperation

Having awarded the grant to deploy the first infrasound array in Hungary, the CSFK joined the Atmospheric dynamics Research Infrastructure in Europe (ARISE)[1], a collaborative infrastructure

[1] Blanc E, Ceranna L, Hauchecorne A, Charlton Perez A, Marchetti E, Evers L, Kvaerna T, Lastovicka J, Eliasson L, Crosby N, Blanc Benon P, Le Pichon A, Brachet N, Pilger C, Keckhut P. AssinkJ, Smets P, Lee C, Kero J, Sindelarova T, Kämpfer N, Rüfenacht R, Farges T, Millet C, Näsholm P, Gibbons S, Espy P, Hibbins R, Heinrich P, Ripepe M, Khaykin S, Mze N, Chum J, Toward an improved representation of the middle atmospheric dynamics thanks to the ARISE project, *Surveys in Geophysics*, **39**, 171–225, https://doi.org/10.1007/s10712-017-9444-0, 2018.

Design Study project funded by the H2020 European Commission. To answer the H2020-INFRAIA-2020-1 call, the PI acted as one of the Work Package leaders in preparing the ARISE – Integrated Activity proposal (ARISE-IA-101008112) and participated several ARISE meetings in 2019 and 2020.

The PI initiated the establishment of the Central and Eastern European Infrasound Network (CEEIN, www.ceein.eu) as part of the ARISE network extension program (http://arise-project.eu) in 2018. The CEEIN is a collaboration between the CSFK (https://doi.org/10.14470/UA114590), the Zentralanstalt für Meteorologie and Geodynamik (now GeoSpheres Austria), Vienna, Austria (https://doi.org/10.7914/SN/OE), the Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czech Republic (https://doi.org/10.7914/SN/C9), and the National Institute for Earth Physics, Magurele, Romania (https://doi.org/10.7914/SN/R1). The Main Centre of Special Monitoring National Center for Control and Testing of Space Facilities, State Agency of Ukraine (https://doi.org/10.7914/SN/UD), joined CEEIN in 2019. Members of the CEEIN exchange data real time and collaborate in scientific infrasound research.

Besides the CEEIN, we also established a bilateral mobility program between the CSFK and the Institute of Atmospheric Physics of the Czech Academy of Sciences, sponsored by the Hungarian and Czech Academy of Sciences. This cooperation played a significant role in the success and international acceptance of the CEEIN effort.

For processing infrasound waveforms, we use the CTBTO NDC-in-a-Box software. Note that the infrasound package is developed by French Alternative Energies and Atomic Energy Commission (CEA) with whom we also maintain close cooperation. Two of our PhD students received training in infrasound processing at the CEA.

The CEEIN stations have significantly improved the detection capability of the European infrasound network (Bondár et al., 2022). Figure 1 shows the difference in detection threshold with and without the CEEIN stations around the spring and autumn equinoxes and the summer and solstices. Because of the seasonal regime of zonal stratospheric winds, infrasound detection capabilities show seasonal variations. The improvements due to CEEIN are most significant in summer when the stratospheric waveguide is driven by easterly stratospheric winds. During summer months better coverage of Eastern Europe, the Eastern Mediterranean and of the Black Sea is provided by CEEIN. In winter, when the stratospheric waveguide is driven by westerly stratospheric winds, sources located west of infrasound arrays are detected. CEEIN stations in Eastern Europe fill in the spatial gap and enable observations of sources in Central Europe. Near equinoxes when the stratospheric waveguide gets weak due to the seasonal reversal of zonal stratospheric winds and the remote monitoring of the events is reduced, observations by local stations become increasingly important.

Among others, CEEIN stations recorded several bolides (Keresztury et al., 2020, 2021), including the Chelyabinsk meteor; the Hunga Tonga – Hunga Ha'apai underwater volcanic eruption on 20 December 2021, accidental explosions at the Baumgarten gas hub (Koch et al, 2020), the Beirut port, and the Ingolstadt oil storage; large North Atlantic storm systems (Šindelářová et al., 2021) as well as the Russian shelling on 24 February 2022 that marked the beginning of the Russian invasion of Ukraine.

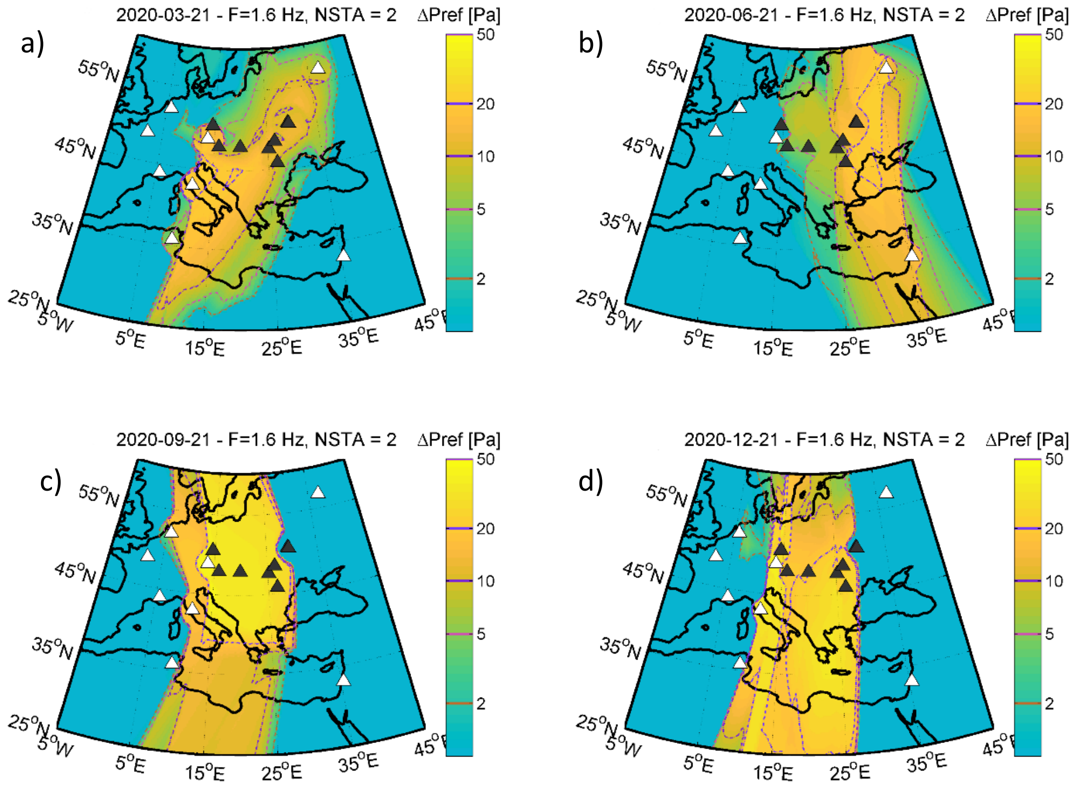

Figure 1. Difference between the detection thresholds of the infrasound network in Europe with and without the CEEIN stations where at least two stations were required to detect a signal arriving from any given locations. On the colour scale yellow indicates large improvement in detection capability. The CEEIN stations are shown as grey triangles; other infrasound stations (IMS and national arrays) are indicated as white triangles. a) 21 March 2020, b) 21 June 2020, c) 21 September 2020 and d) 21 December 2020.

Event location and Earth structure

Accurate event locations are a prerequisite for successful event discrimination. Event location requires a velocity model of the Earth. Due to the tectonic complexity of the Pannonian Basin and its surroundings a simple 1D velocity model is insufficient to obtain reliable locations. Therefore, we use the state-of-the-art iLoc location algorithm[2], that allows the use of seismic, infrasound and hydroacoustic observations and applies the 3D global upper mantle RSTT model travel-time predictions in the location[3].

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[2] Bondár, I. and K. McLaughlin, Seismic location bias and uncertainty in the presence of correlated and non-Gaussian travel-time errors, *Bull. Seism. Soc. Am.*, **99**, 172-193, https://doi.org/10.1785/0120080922, 2009.
Bondár, I., and D. Storchak, Improved location procedures at the International Seismological Centre, *Geophys. J. Int.*, **186**, 1220-1244, https://doi.org/10.1111/j.1365-246X.2011.05107.x, 2011.

[3] Myers, S.C. M.L. Begnaud, S. Ballard, M.E. Pasyanos, W.S. Phillips, A.L. Ramirez, M.S. Antolik, K.D. Hutchenson, J.J. Dwyer, C.A. Rowe and G.S. Wagner, A crust and upper-mantle model for Eurasia and North Africa for Pn travel-time calculation, *Bull. Seism. Soc. Am.*, **100**, 640-656, 2010.
Begnaud, M.L., S.C. Myers, B. Young, J.R. Hipp, D. Dodge. W.S. Phillips, Updates to the Regional Seismic Travel Time (RSTT) Model: 1. Tomography, *Pure Appl. Geophys.*, **178**, 2475–2498, https://doi.org/10.1007/s00024-020-02619-5, 2021.
Begnaud, M.l., D.N. Anderson, S.C. Myers, B. Young, J.R. Hipp, W.S. Phillips, Updates to the Regional Seismic Travel Time (RSTT) Model: 2. Path-dependent travel-time uncertainty, *Pure Appl. Geophys.*, **178**, 313-339, https://doi.org/10.1007/s00024-021-02657-7, 2021.

Seismic event locations were further improved using multiple event location algorithms, such as the double difference algorithm[4] (Czecze and Bondár, 2019) and Bayesloc[5], a Bayesian nonlinear multiple event location algorithm (Czecze and Bondár, 2021). Figure 2 illustrates the location improvements on the border region between Hungary and Slovakia when using Bayesloc. The large cluster represents the Dvorniky-Vcelare quarry blasts. Bayesloc makes the event clusters tighter and brings them closer to the actual location of the quarries.

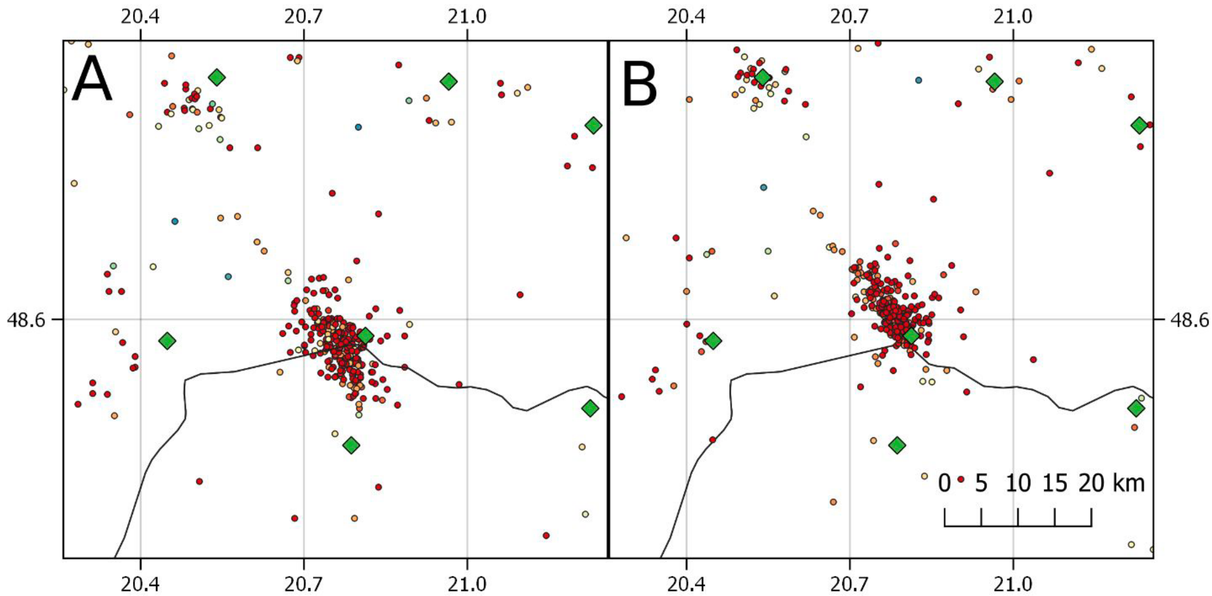

Figure 2. Location of quarry blasts in the Hungarian-Slovakian border region with a) iLoc using RSTT travel time predictions and b) Bayesloc. Bayesloc tightens the locations around the quarries (green diamonds).

We have discovered recent seismic activity in the Mór Graben, Hungary. To further study the phenomenon, we deployed a temporary seismic network of three stations that operated for twenty months. With the help of the temporary network stations as well as permanent stations from the KRSO and GeoRisk, Ltd. (www.georisk.hu) networks, we have identified six small-magnitude swarms. Note that the KRSO permanent seismological network alone cannot determine such small events. Figure 3 shows that using waveforms correlation detectors such as the subspace detector[6], we could detect swarm events that cannot be seen on the seismograms by the naked eye (Bondár et al., 2022; Czecze et al., 2023).

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[4] Waldhauser, F., WL Ellsworth, A double-difference earthquake location algorithm: method and application to the northern Hayward fault, California, *Bull. Seism. Soc. Am.*, **90**, 1353–1368, 2000.

[5] Myers, S.C., G. Johannesson and W. Hanley, A Bayesian hierarchical method for multiple-event seismic location, *Geophys. J. Int.*, **171**, 1049-1063, https://doi.org/10.1111/j.1365-246X.2007.03555.x, 2007.
Myers, S.C., G. Johannesson, and W. Hanley, Incorporation of probabilistic seismic phase labels into a Bayesian multiple-event seismic locator, *Geophys. J. Int.*, **177**, 193–204. https://doi.org/10.1111/j.1365-246X.2008.04070.x, 2009.

[6] Harris, D. Subspace Detectors: Theory, *Lawrence Livermore National Laboratory*, UCRL-TR-222758, 2006.
Harris, D.B. and D.A. Dodge, An Autonomous System for Grouping Events in a Developing Aftershock Sequence, *Bull. Seism. Soc. Am.*, **101**, 763–774, 2011.
Chamberlain, C.J., C.J. Hopp, C.M. Boese, E. Warren-Smith, D. Chambers, S.X. Chu, K. Michailos, J. Townend, EQcorrscan: Repeating and Near-Repeating Earthquake Detection and Analysis in Python, *Seismol. Res. Lett.,* **89**, 173-181, 2018.

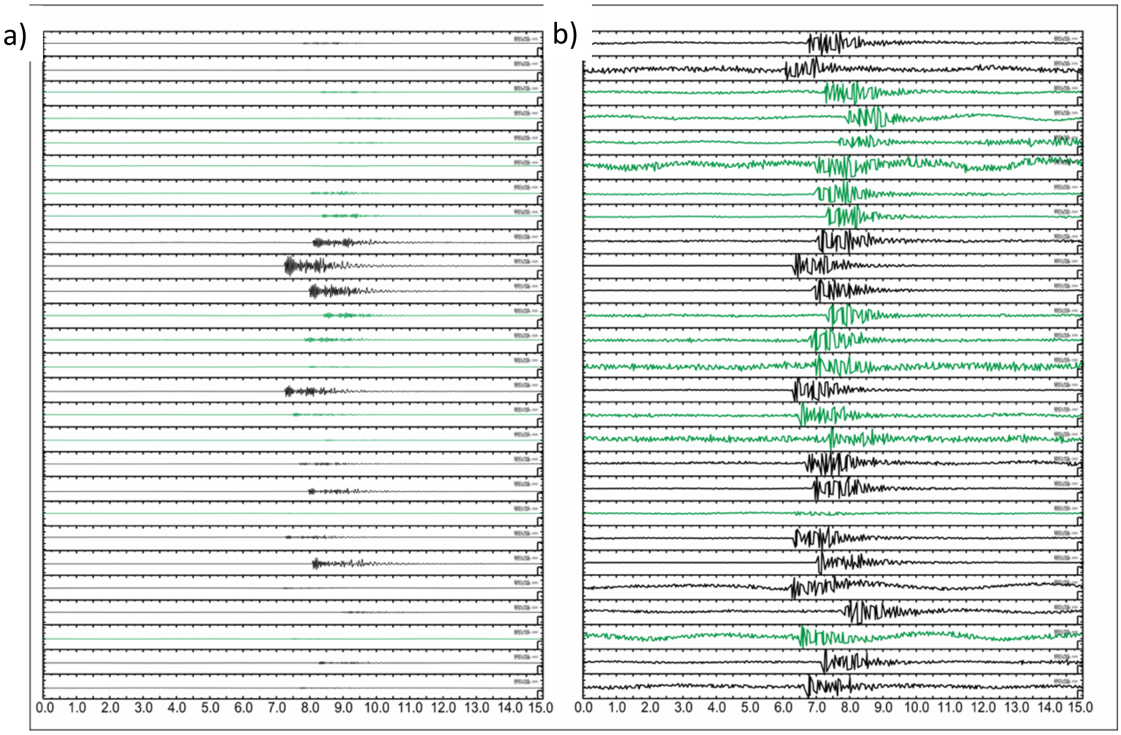

Figure 3. Manually identified events (black traces) and those identified only by the subspace detector (green traces) in the SW2 swarm at MSW1 a) normalized by the global maximum amplitude of the swarm and b) normalized at individual traces. The subspace detector is able to detect events that cannot be seen by the naked eye.

The Bayesloc location studies demonstrated that the 3D RSTT velocity model could be further improved in the region. Work toward obtaining a more accurate velocity model has begun in partial overlap with the K124241 OTKA project. Exploiting the unprecedented density of temporary seismic station deployments in the region, we performed P receiver function analysis for the Pannonian Basin and its surroundings (Kalmár et al., 2019), carried out the inversion of the receiver functions and developed a novel interpolation method that accounts for the azimuthal dependence of receiver functions (Kalmár et al., 2021). The results produced the most detailed maps of sediment thickness, Conrad and Moho discontinuities to date.

We also conducted a detailed magnetotelluric field survey with more than 20 measurement sites around Ciomadul, the youngest volcano of the Carpathian-Pannonian Region. In this area, results of seismic tomography modelling and other geophysical studies have already published, however, the interpretation of data is still controversial. We expect to gain a better knowledge about the crustal structure beneath a long-dormant volcano.

Coherent infrasound noise sources

All CEEIN stations record coherent noise sources coming from a specific back-azimuth. We have identified most of these sources as they help to focus on signals that we are interested in. At lower frequencies we see microbaroms from the North Atlantic, South Atlantic, and occasionally from the Mediterranean Sea and Black Sea. Microbaroms are the most prevalent source of infrasound background noise generated by marine storms by the nonlinear interaction of ocean surface waves and the atmosphere. At higher frequencies, above 1 Hz, coherent noise is generated by the eruptions of the Etna volcano and mostly by anthropogenic sources, such as oil refineries, power plants, mining activities as well as supersonic aircrafts. Figure 4 compares the coherent noise sources at PSZI between 2021 and 2022. The most striking feature is the appearance of the war in Ukraine since the Russian invasion on February 24, 2022.

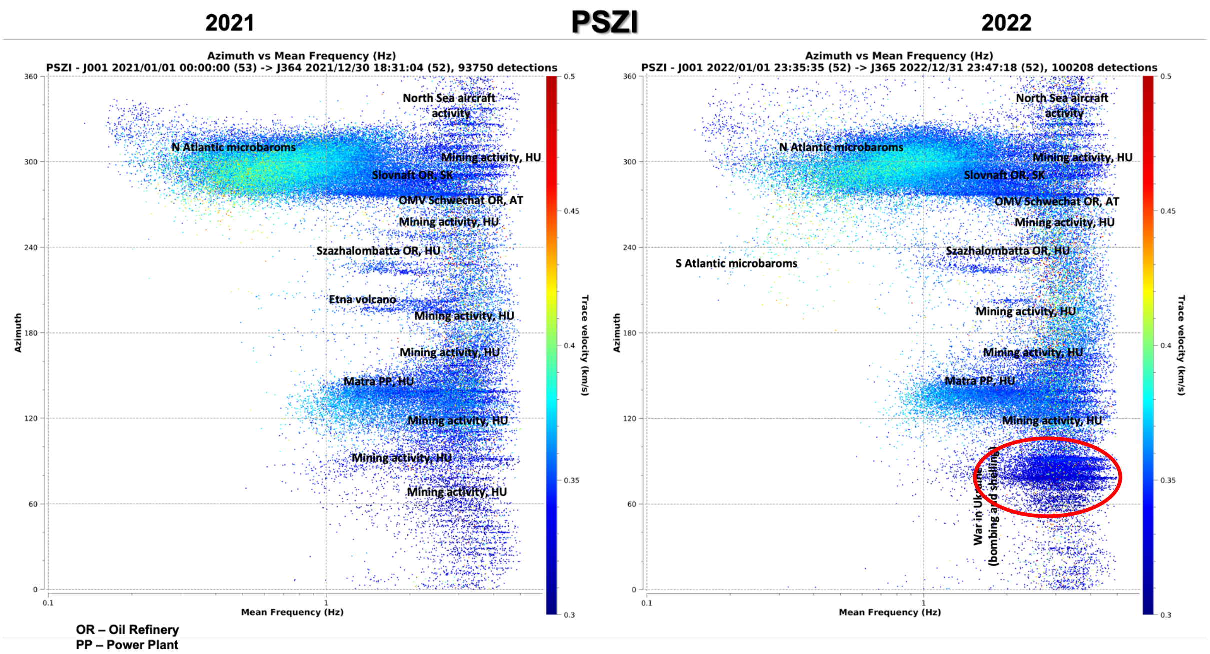

Figure 4. Coherent noise sources at PVCI, and PSZI in 2021 and 2022. Red circles highlight the detections from the war in Ukraine.

Seismic and seismo-acoustic event discrimination

Seismic discrimination is based on the different source physics of earthquakes (double couple mechanism) and explosions (point source or ripple fire mechanism). In theory, a point source does not generate shear forces, therefore the waveforms observed at larger distances show large, impulsive P waves but little S-wave and surface wave contents. This forms the base of the teleseismic mb:Ms discriminator that is successfully applied to distinguish between underground nuclear explosions and earthquakes recorded at distant seismic stations. However, this doesn't work at regional and local distances and smaller events. In that case the seismic discrimination relies on various measures of S/P spectral ratios measured at higher frequency bands.

Using earthquakes in the Mór Graben and the January 2011 Oroszlány aftershock sequence as well as quarry blasts (Gánt, Iszkaszentgyörgy and Magyaralmás) around the Csókakő (CSKK) station, we have developed single-station seismic discrimination criteria to distinguish between earthquakes and explosions at local distances (Kiszely et al., 2021). Figure 5 shows that the linear discrimination line separates earthquakes and explosions with 95% success rate. The misclassified earthquakes are all from the closest quarry at Magyaralmás, 6.5 km from CSKK, where it is not possible to measure spectral ratios at much higher frequencies due the high frequency background noise.

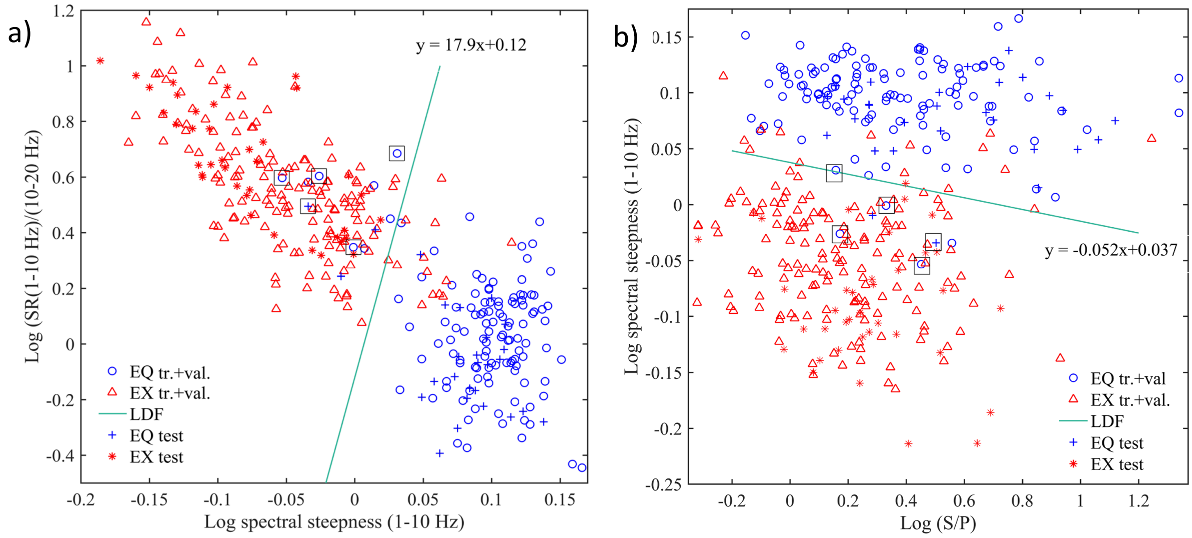

Figure 5 a) Spectral ratio versus steepness of power spectra. Spectral ratio values were calculated using the ratio of integrated spectral amplitudes in the selected lower (1–10 Hz) and higher frequency (10–20 Hz) bands. b) Steepness of power spectra plot versus peak amplitude ratio of S to P wave (filtered 6–8 Hz bands). Red triangles indicate the quarry blasts in the training and validation sets, red stars show the test data set. The earthquakes in the training and validation sets are indicated with blue circles. The earthquake test sets are indicated with blue crosses. The green line represents the linear discrimination line that separates earthquakes from explosions.

At infrasound arrays the back-azimuth (the direction where the signal comes from) can be measured very precisely and at local distances where the infrasound signal is a direct wave, deviations from the true back-azimuth due to atmospheric winds can be ignored owing to the relatively short ray path and travel time. Thus, including the infrasound back-azimuth measurements in the location can significantly improve locations. Figure 6 shows that adding the infrasound back-azimuth measurements to the seismic location problem significantly increases the location accuracy and at local distances it allows the distinction of explosion sources of quarries separated by less than 2 km (Czanik et al., 2021).

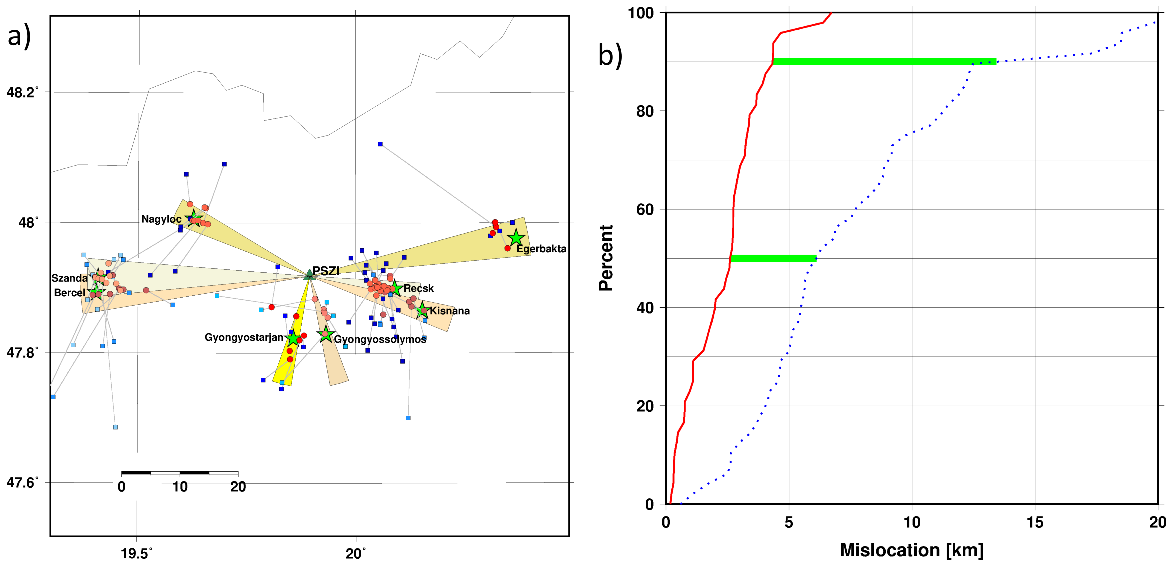

Figure 6. a) Seismic (blue squares) and seismo-acoustic (red circles) locations of mine explosions around PSZI. Stars indicate the quarry locations. The seismo-acoustic locations use both seismic arrival time and infrasound bac-azimuth measurements in the location. b) Cumulative distribution of mislocation of GT mine explosions of seismic (blue line) and seismo-acoustic (red line) locations with iLoc. The thick green lines emphasize the location improvements at the median and the 90th percentile levels.

The KRSO does not routinely use seismic or seismo-acoustic event discrimination methods to identify explosions. We have demonstrated that it would be possible to use our methodologies in routine operations with a high success rate.

Classification of infrasound signals using machine learning

We applied machine learning algorithms to identify infrasonic signals at the PSZI array (Pásztor et al., 2023). Our objective was to discriminate between quarry blasts, storms, and the noise from the Mátra power plant. We augmented the data to make them more evenly distributed and we trained and validated two different machine learning algorithms, Random Forest and Support Vector Machine (SVM) using 11 time and frequency domain features. We also defined 3 further PMCC-derived features and trained and validated the Random Forest and SVM algorithms again. We demonstrated that the performance of the two single-array machine learning algorithms is quite comparable, and when we include the PMCC-derived features in the feature vector, they perform even better.

Figure 7 shows the results on the test data set with the two algorithms and the two set of feature vectors. The confusion matrices show that the machine learning algorithms achieve a high true positive score (that is, storms, MPP and quarry blasts were correctly classified as storms, MPP and quarry blasts), while keeping the false positives and false negatives down. Another performance metric is the area under the receiver operating curve (AUC ROC). Here the 14-element feature vector clearly outperformed the 11-element feature vector in both the Random Forest and the SVM classifier.

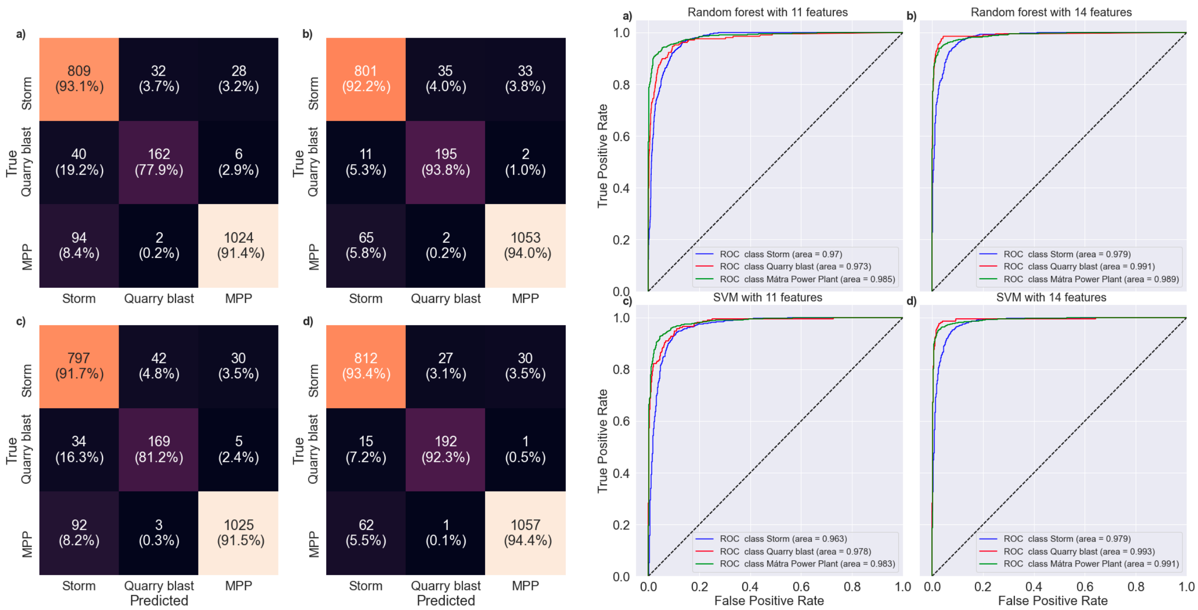

Figure 7. Left panel: Confusion matrices for the selected models generated on the test set. The upper row (a,b) contains the results of the random forest classifiers and the lower one (c,d) the ones of SVM. The left column (a,c) represents the case without the three PMCC-derived features and the right column (b,d) shows the confusion matrices with the PMCC-derived features. The percentages in each row sum up to 100%. Right panel: One-versus-all ROC curves for the random forest and SVM models generated on the test set. For each one-versus-all classifier, the ROC AUC scores are present in the legend. The black dashed line represents a random classifier. A line reaching the (0,1) point in the top left corner would mean a perfect classifier.

Seismo-acoustic bulletins

One of our major deliveries is the annual Hungarian Seismo-Acoustic Bulletin (Bondár et al., 2019, 2020, 2021, 2022, 2023) available at www.infrasound.hu. The Hungarian Seismo-Acoustic Bulletin contains events that are recorded by both seismic stations and the PSZI infrasound array and can be located by iLoc. Many, but not all, quarries in Hungary regularly send confirmation of their explosions to the KRSO. These events serve as ground truth and provide valuable information to validate travel-time predictions from 3D Earth velocity models. Most seismo-acoustic locations are within 5 km of the ground truth locations. Figure 8 shows that since the PSZI infrasound array is operational, the percentage of events identified as explosions in the Hungarian National Seismological Bulletin has dramatically increased, indicating that quarry blasts and mine explosions represent about 70% of the recorded seismicity in Hungary. Note that the KRSO publishes the Hungarian National Seismological Bulletin with one year delay or more, therefore their bulletin for 2022 is not yet available. Although the KRSO has not carried out a comprehensive probabilistic seismic hazard analysis for Hungary in the past 16 years, our result will help to remove anthropogenic events from the earthquake catalogue in the future when someone might do.

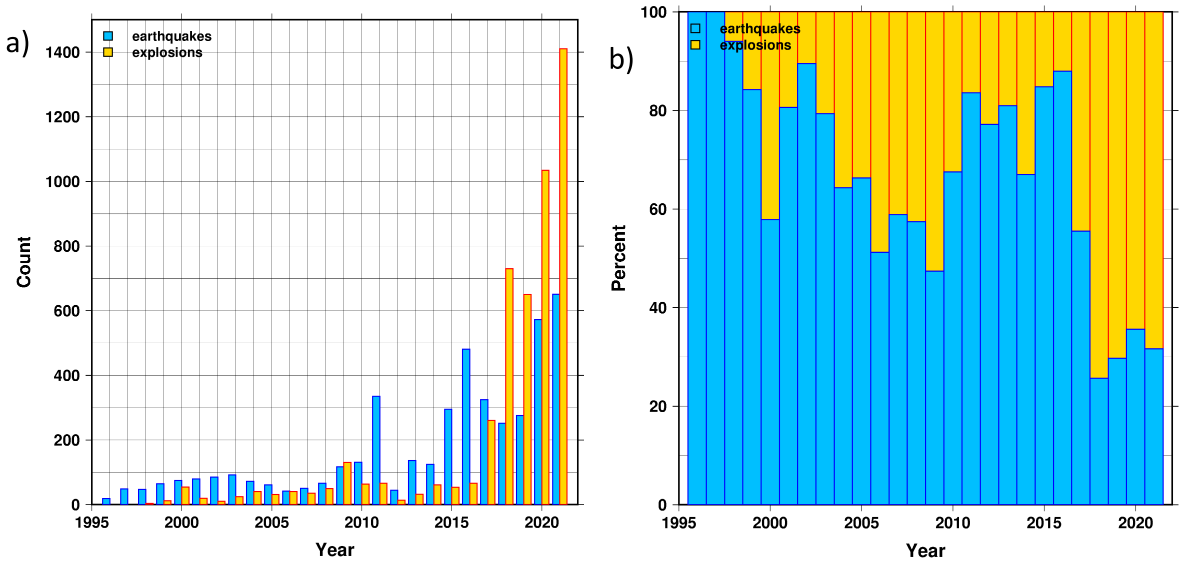

Figure 8. a) Number of earthquakes (blue) and quarry blasts (yellow) and b) relative percentage of earthquakes and quarry blasts in the Hungarian earthquake catalogue between 1996 and 2021. Ever increasing number of events are identified as anthropogenic origin since the deployment of the PSZI array in 2017/05/25.

Within the CEEIN cooperation we publish a seismo-acoustic bulletin every two years (Bondár et al., 2022). The bulletin contains infrasound and seismo-acoustic events that are recorded by at least two infrasound arrays and can be located by iLoc. The CEEIN bulletin is available at www.ceein.eu. Figure 9 shows the events in the CEEIN bulletin between 2017 and 2022. The bulletin includes bolides, earthquakes, sonic booms from supersonic fighter jets, quarry blasts, explosions, and since the Russian invasion of Ukraine, shelling, bombardments, and missile attacks. Note that the CEEIN bulletin is unique in a sense that apart from South Korea, nobody else in the world produces regular infrasound and seismo-acoustic bulletins.

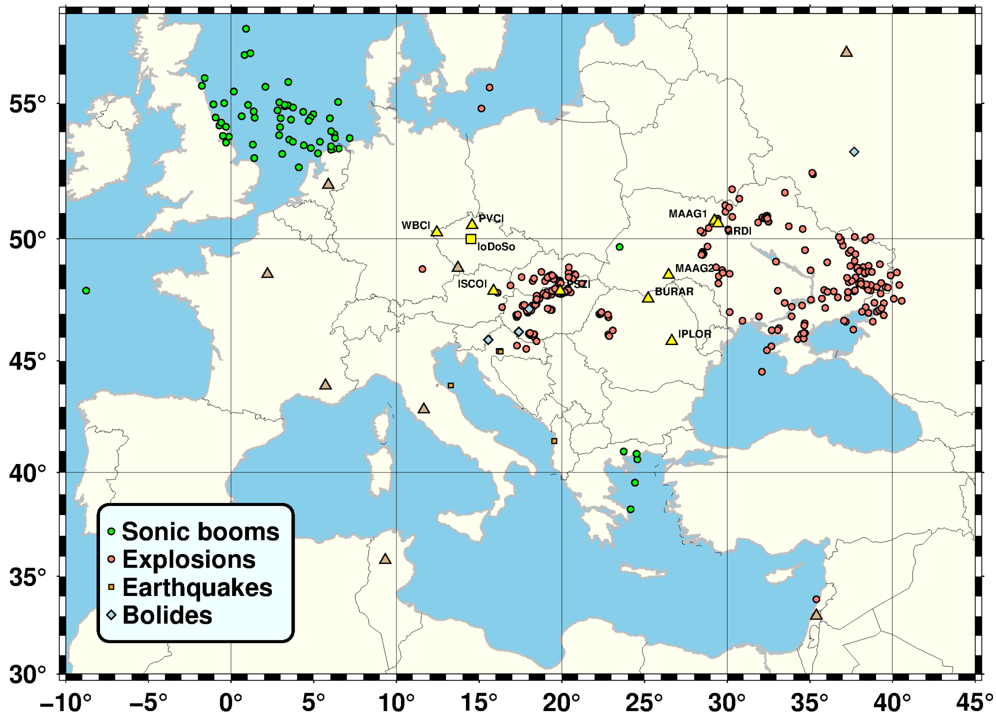

Figure 9. Events in the CEEIN bulletin, 2017-2022. Yellow triangles indicate CEEIN infrasound arrays, IMS and other infrasound arrays are shown as tan triangles. Green circles indicate sonic booms, red circles mark explosions and quarry blasts, red squares denote earthquakes and blue diamonds indicate bolides.

PhD students

Four PhD students participated the project under the supervision of István Bondár. Dániel Kalmár has obtained his PhD summa cum laude in 2022. Csenge Czanik and Barbara Czecze have finished their PhD studies and obtained their Absolutorium at the ELTE Doctoral School in 2022. Marcell Pásztor has joined the project in 2019 as an MSc student and began his PhD studies in 2021.

Dániel Kalmár participated in The Peter Bormann Young Seismologist Training Course in 2019. Csenge Czanik received a two-week training in infrasound processing at the French Alternative Energies and Atomic Energy Commission (CEA) and a one-week training on SeisComp3 waveform processing at the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO) in 2019. She went on maternity leave in 2020. Marcell Pásztor received a two-week training in infrasound processing at CEA in 2022. Both Csenge Czanik and Marcell Pásztor have completed the relevant on-line training courses at the CTBTO.

Papers

1. Czecze B. and I. Bondár, Hierarchical cluster analysis and multiple event relocation of seismic event clusters in Hungary between 2000 and 2016, *J. Seismology*, **23**, 1313-1326, https://doi.org/10.1007/s10950-019-09868-5, 2019. IF **1.494**
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Cumulative impact factor: **31.654**

Books

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