EGU General Assembly 2023

Analysis of infrasound and seismic signals recorded from repetitive explosion sources at near-regional distance

Daniela Ghica[1], Constantin Ionescu[1]

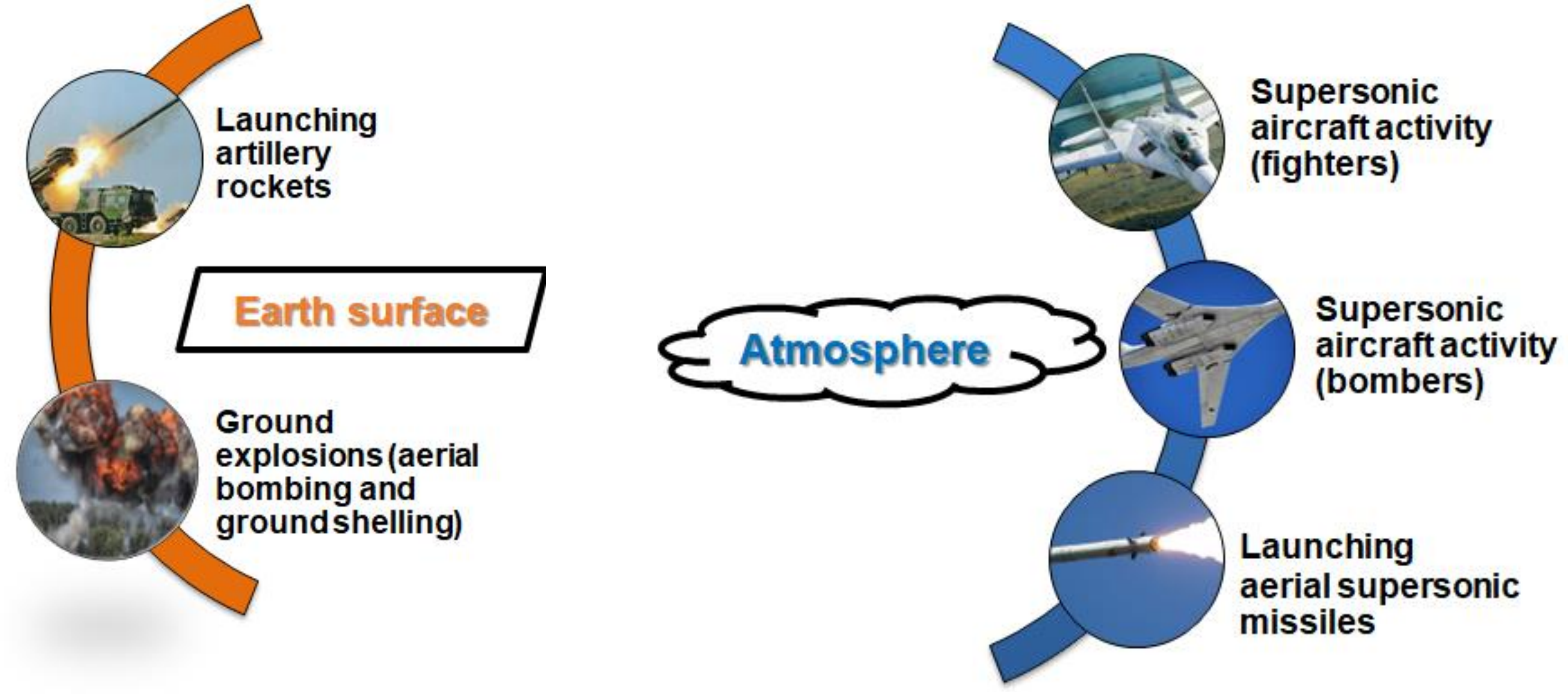
[1] National Institute for Earth Physics, Magurele, Romania

EGU23-5764

EGU General Assembly, Vienna, Austria, 23-28 April 2023

Probable seismo-acoustic sources

- Since 24 February 2022 when the Russian military began attacks on targets in Ukraine, numerous missile strikes and explosions in major cities, including the capital Kiev, was reported by mass media sources
- These repetitive explosion sources at near-regional distance generated a plethora of impulsive signals which could be observed into the data recorded with Romanian seismic and infrasound arrays



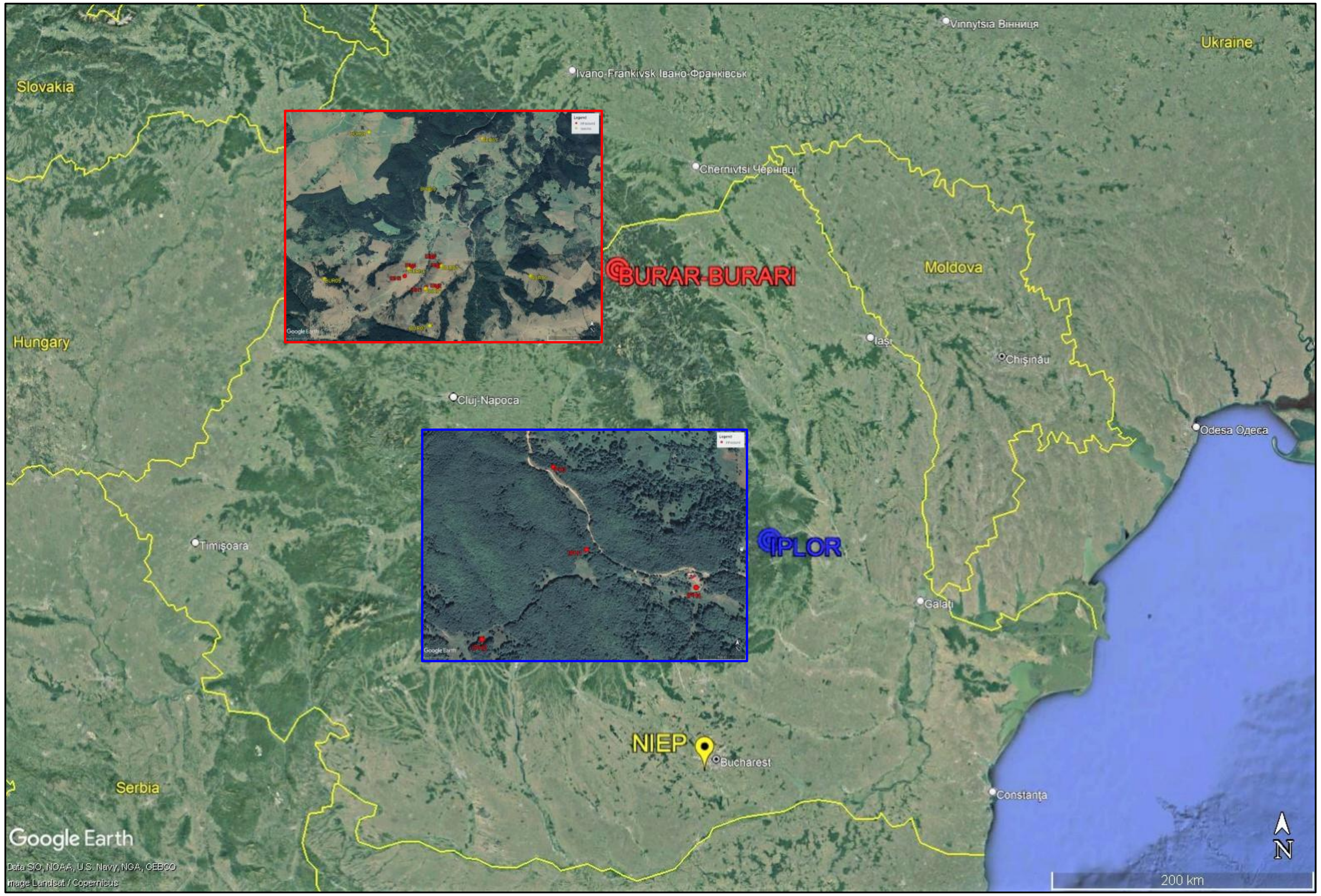
Purpose & Method

- To understand what kind of seismic and acoustic information may be most useful for event characterization, it is essential to know the type of the potential sources of interest, i.e. to identify the regions of repetitive explosions
- Analysis of the types of near-regional sources observed during the war in Ukraine aims to:

  - identify their seismo-acoustic signature (signal shape and amplitude, frequency content, energy spectrum)
  - investigate the propagation path of infrasonic signals
- Directions of IPLOR and BURARI infrasonic detections are used to estimate locations by cross-bearing the derived back azimuths
- Seismic and acoustic signals observed with BURAR seismic array are added to better characterize type of events
- CEA/DASE PMCC detector (*Cansi 1995; Cansi and Le Pichon, 2008*) embedded in DTK-GPMCC (CTBTO/NDC-in-a-box) has been applied for seismo-acoustic data processing and signal characterization
- Seismo-acoustic detections are analyzed by using processing capabilities of the DTK-GPMCC and DTK-DIVA software (CTBTO/NDC-in-a-box)
- Propagation of acoustic energy over the distances of interest (hundreds km) depends on atmospheric conditions, i.e., the wind and temperature profiles of the atmosphere along the path from the source to the station
- Propagation path of acoustic signals is analyzed by applying infraGA 2D ray tracer through NRL-G2S atmospheric model

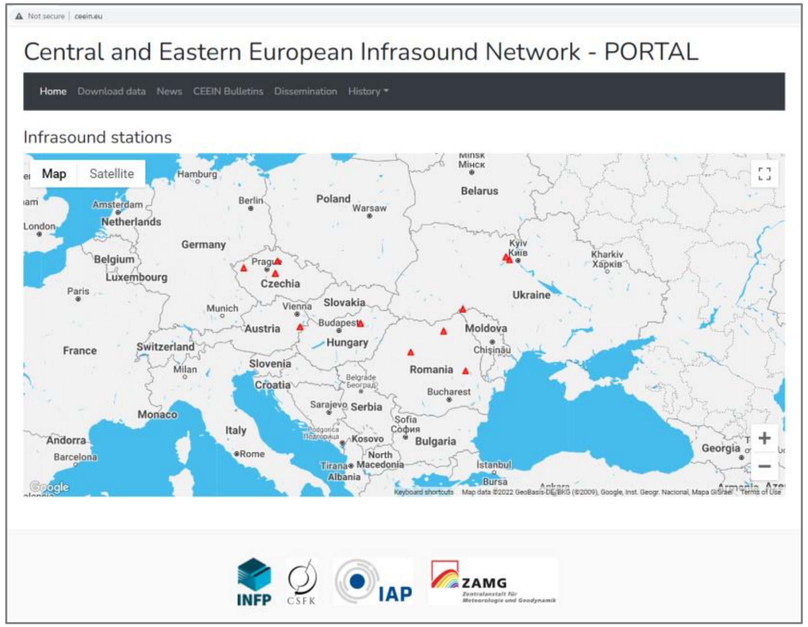
- *Cansi, Y., 1995. An automatic seismic event processing for detection and location: the P.M.C.C. Method, Geophys. Res. Lett., 22, 1021–1024*
- *Cansi, Y. & Le Pichon, A., 2008. Infrasound event detection using the progressive Multi-Channel correlation algorithm, in Handbook of Signal Processing in Acoustics, eds. Havelock, D., Kuwano, S. & Vorlnder, M., Springer, New York, NY.*

Romanian seismic and infrasound arrays



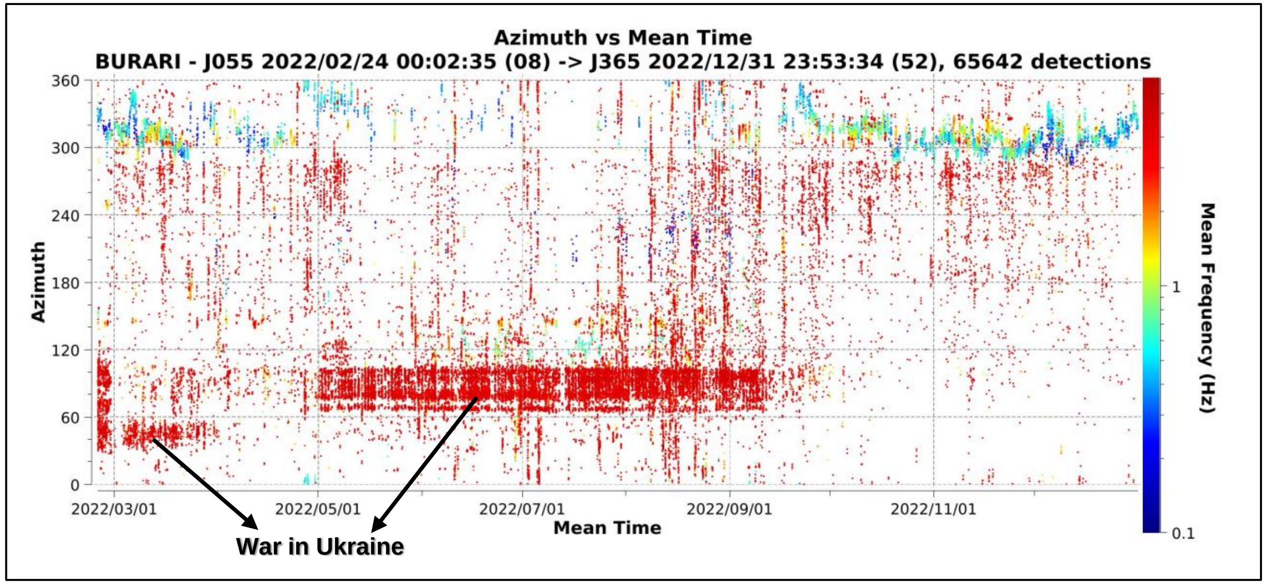
Station	Type	Location	No of elements	Type of sensors	Aperture (km)
BURAR	seismic	Benea, Suceava County	9	GS-21, SP vertical	4.5
BURARI	infrasonic	Benea, Suceava County	6	Hyperion IFS-5113	0.7
IPLOR	infrasonic	Ploştina, Vrancea County	4	Chaparral Physics Model 25	0.5

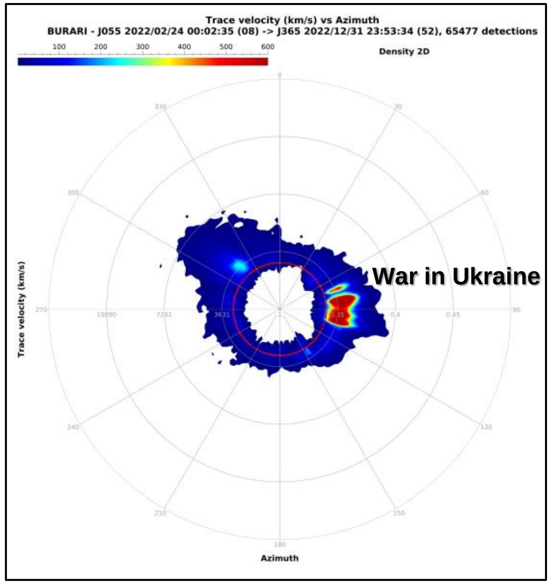
- Seismic waveforms are available at NIEP & NIEP EIDA node
- Infrasonic arrays BURARI and IPLOR are part of the Central and Eastern European Infrasound Network (CEEIN)
- Infrasound data and additional information, e.g. CEEIN seismo-acoustic bulletin for 2017-2020, can be found at the www.ceein.eu

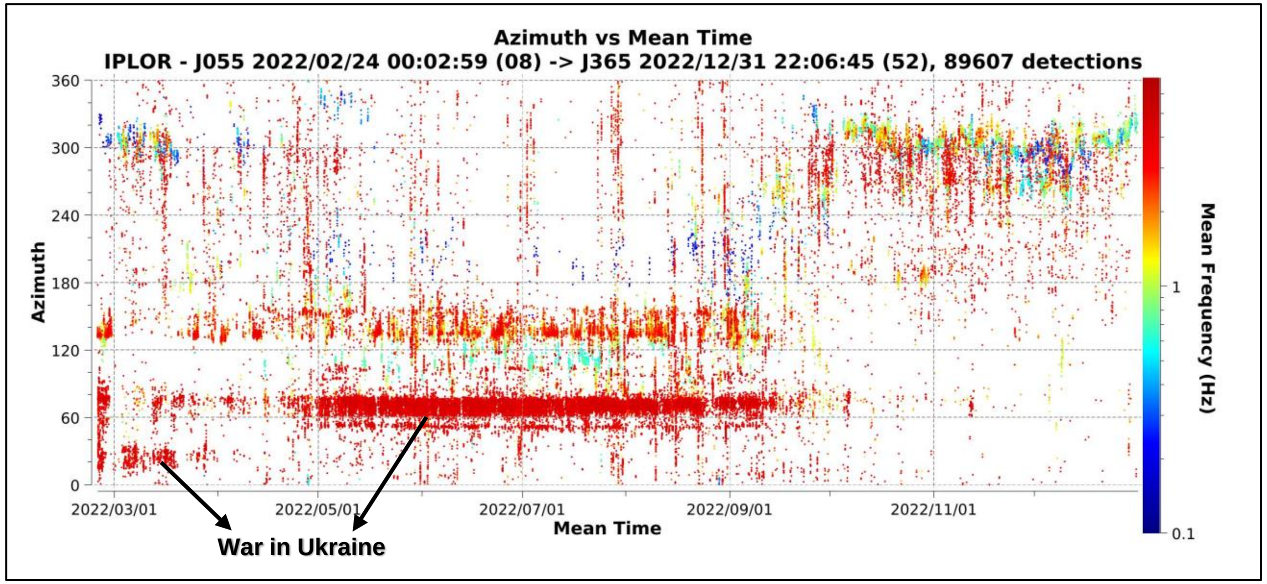


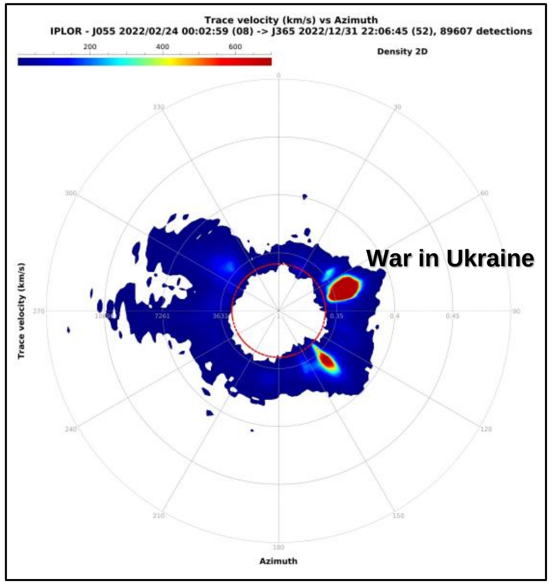
Infrasonic arrays performance (PMCC detections)

24 February - 31 December 2022





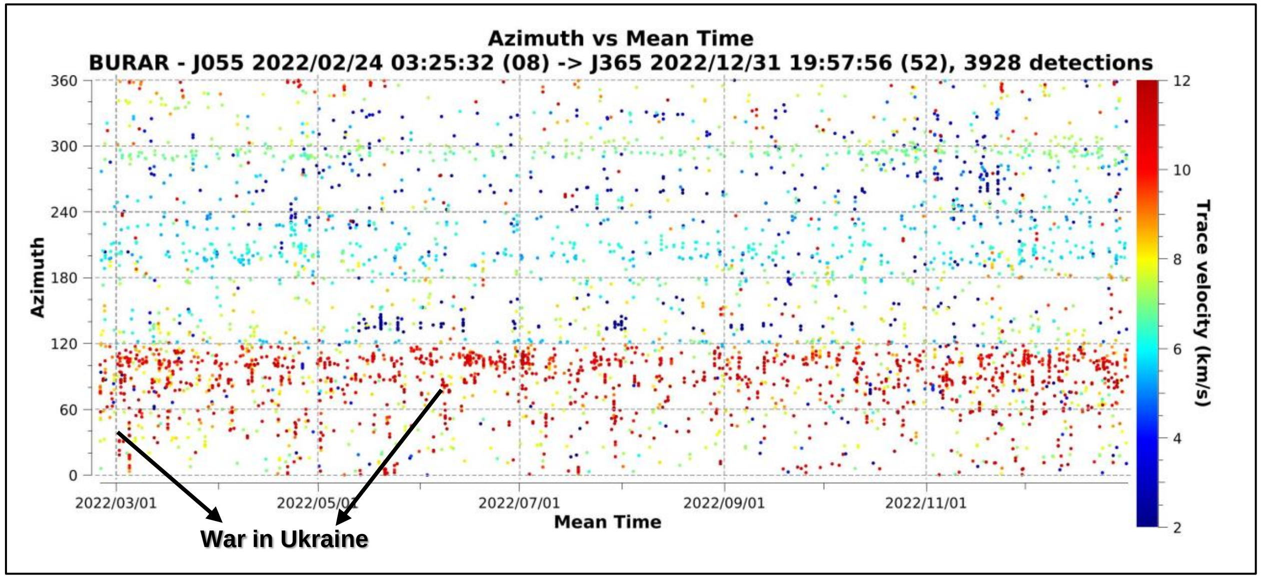


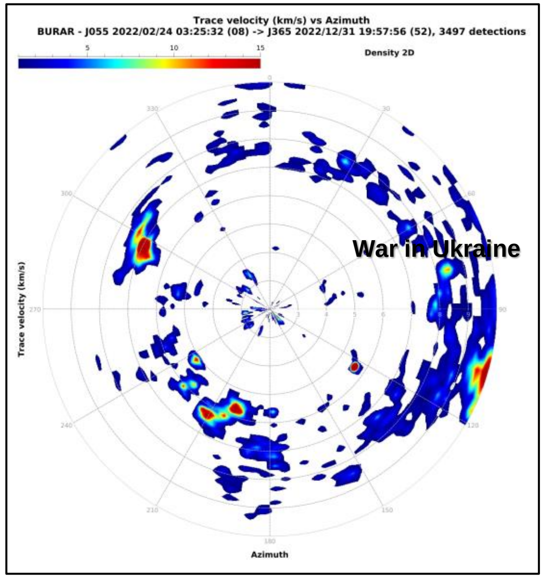


Seismic array performance (PMCC detections)

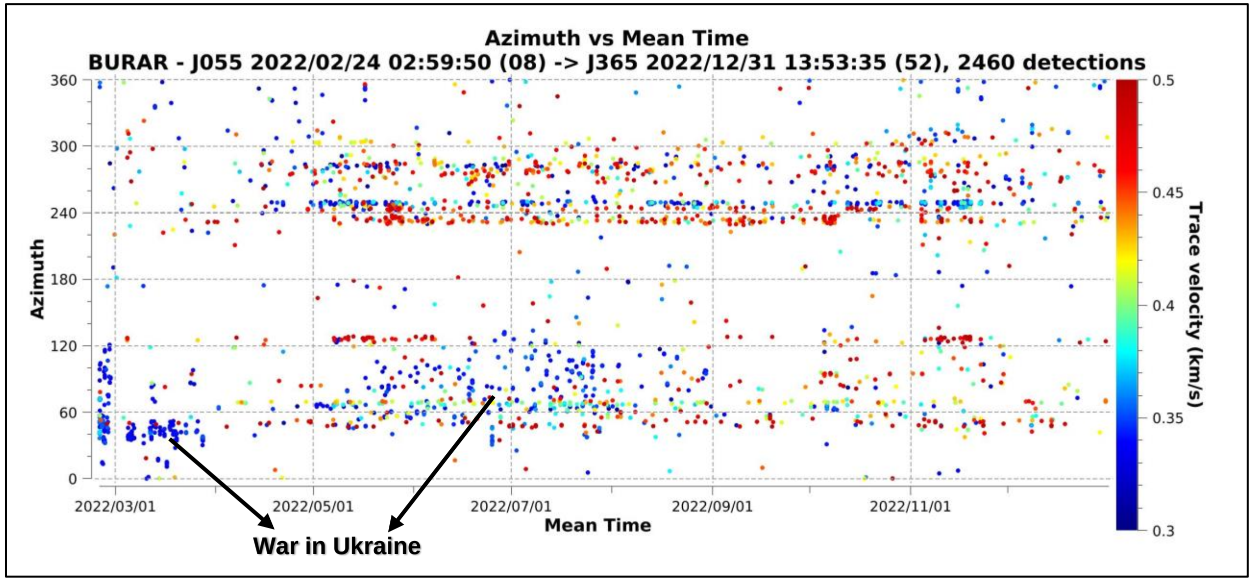
24 February - 31 December 2022

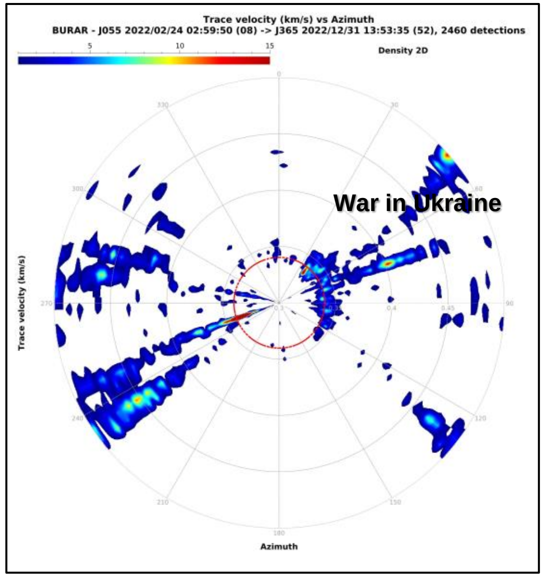
seismic phases





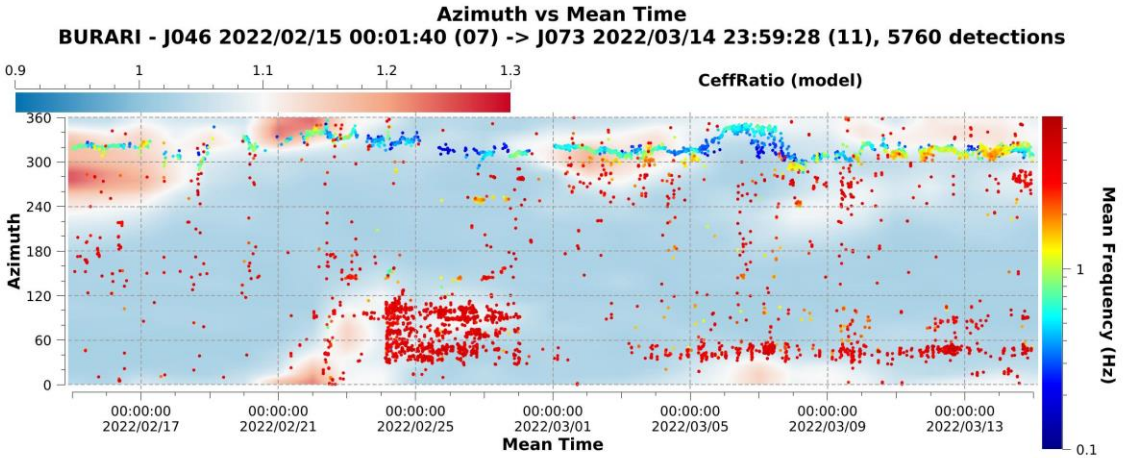
infrasonic phases

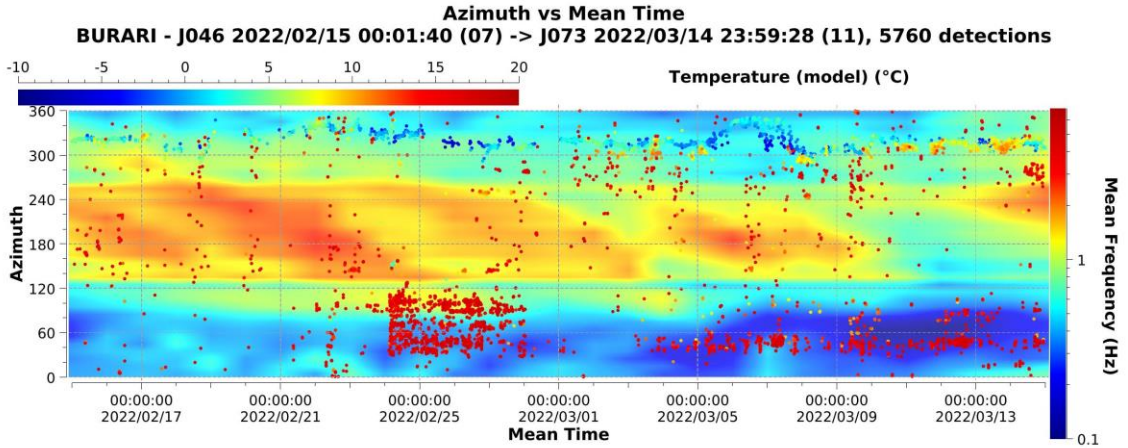


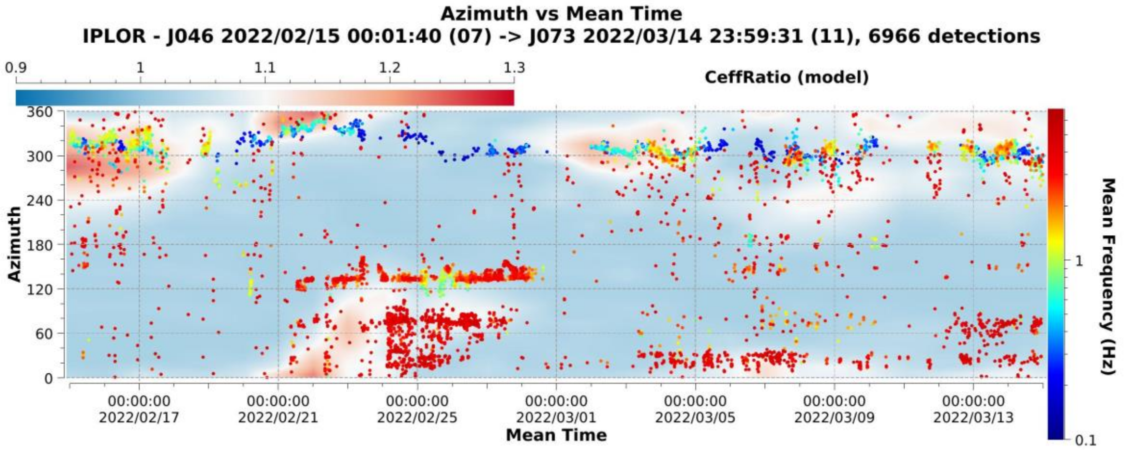


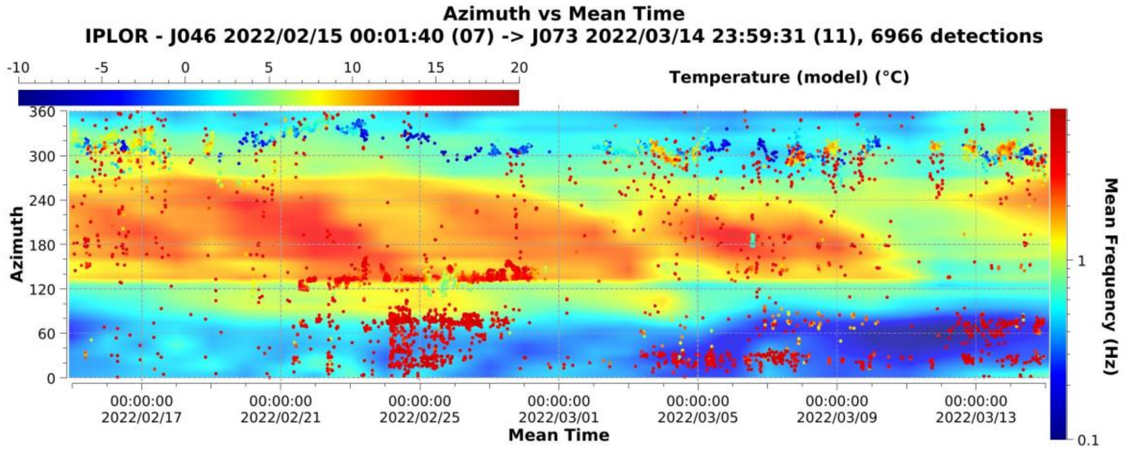
SSW occurred from 20 to 28 February 2023

- Between 20 and 28 February the inversion in the stratospheric winds developed a favourable propagation duct that allowed a particularly good detection performance of infrasound stations for the repetitive explosion sources in Ukraine region, i.e. backazimuth between 30 and 110 degrees for BURARI, and between 10 and 90 degrees for IPLOR





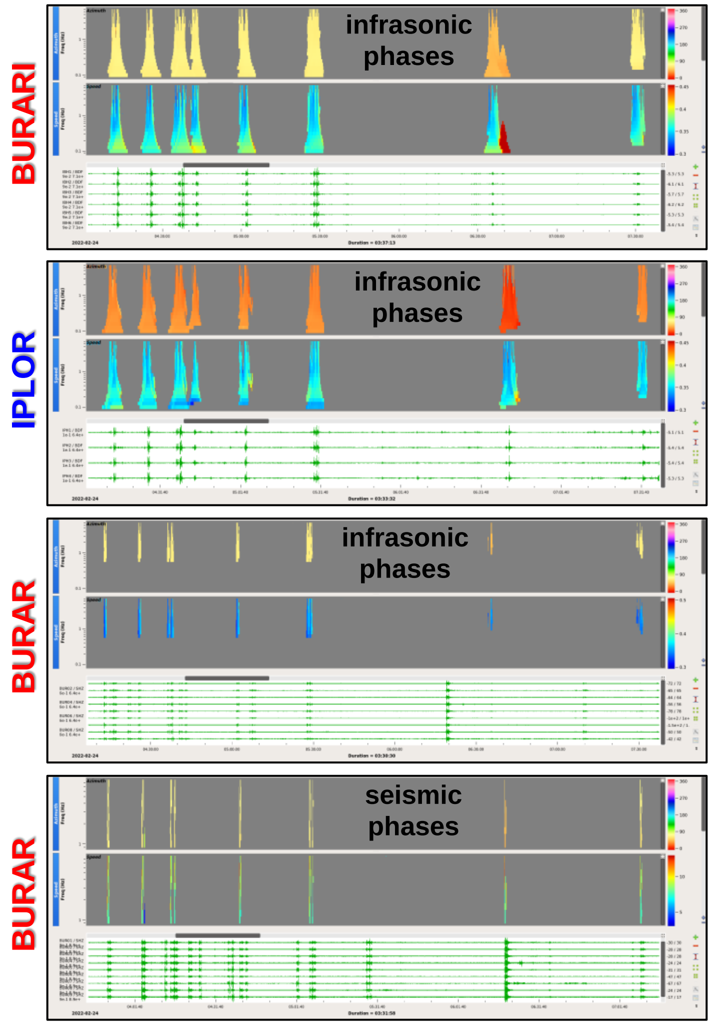


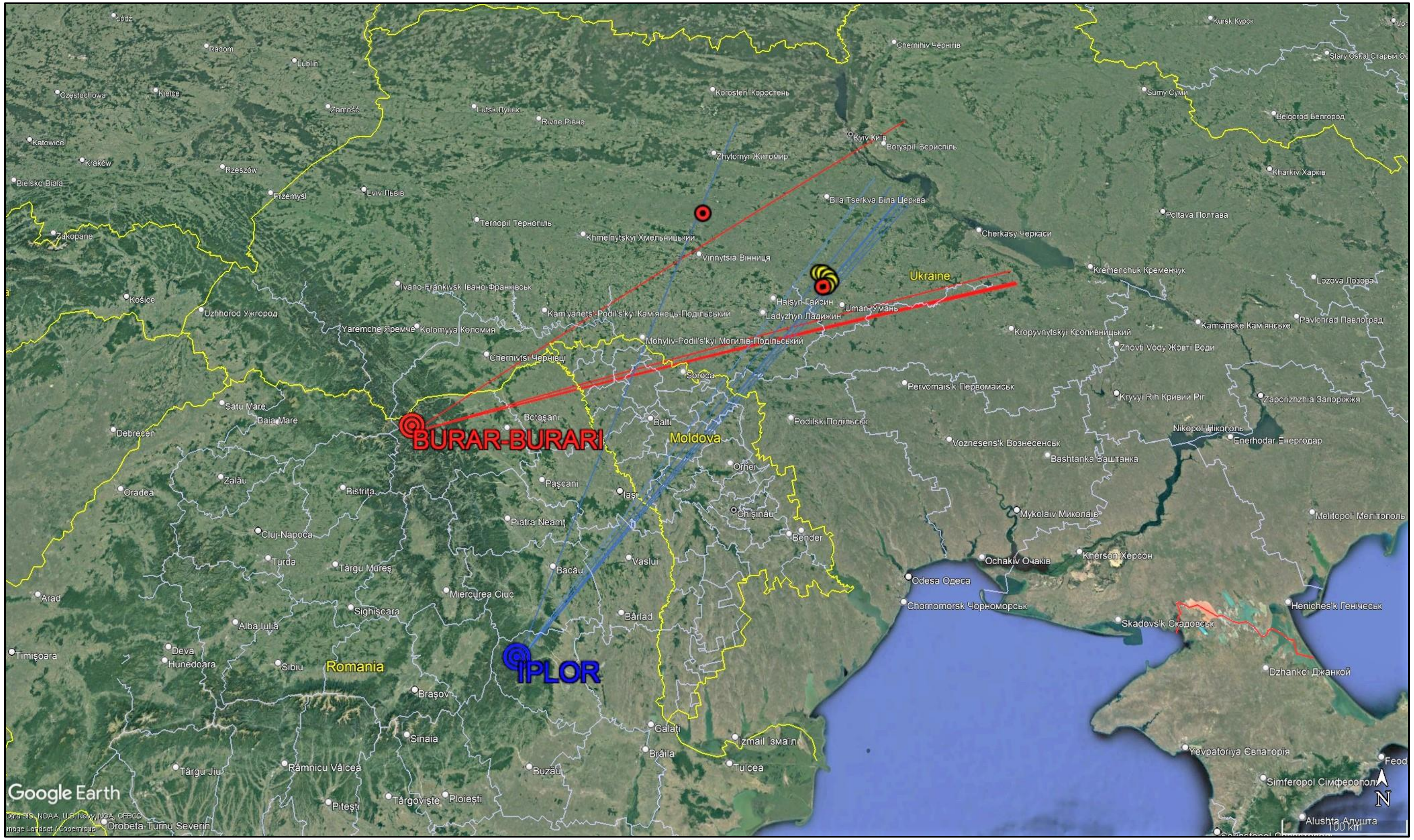


ECMWF - GRIB files kindly provided by Julien Vergoz

Infrasound and seismic signals

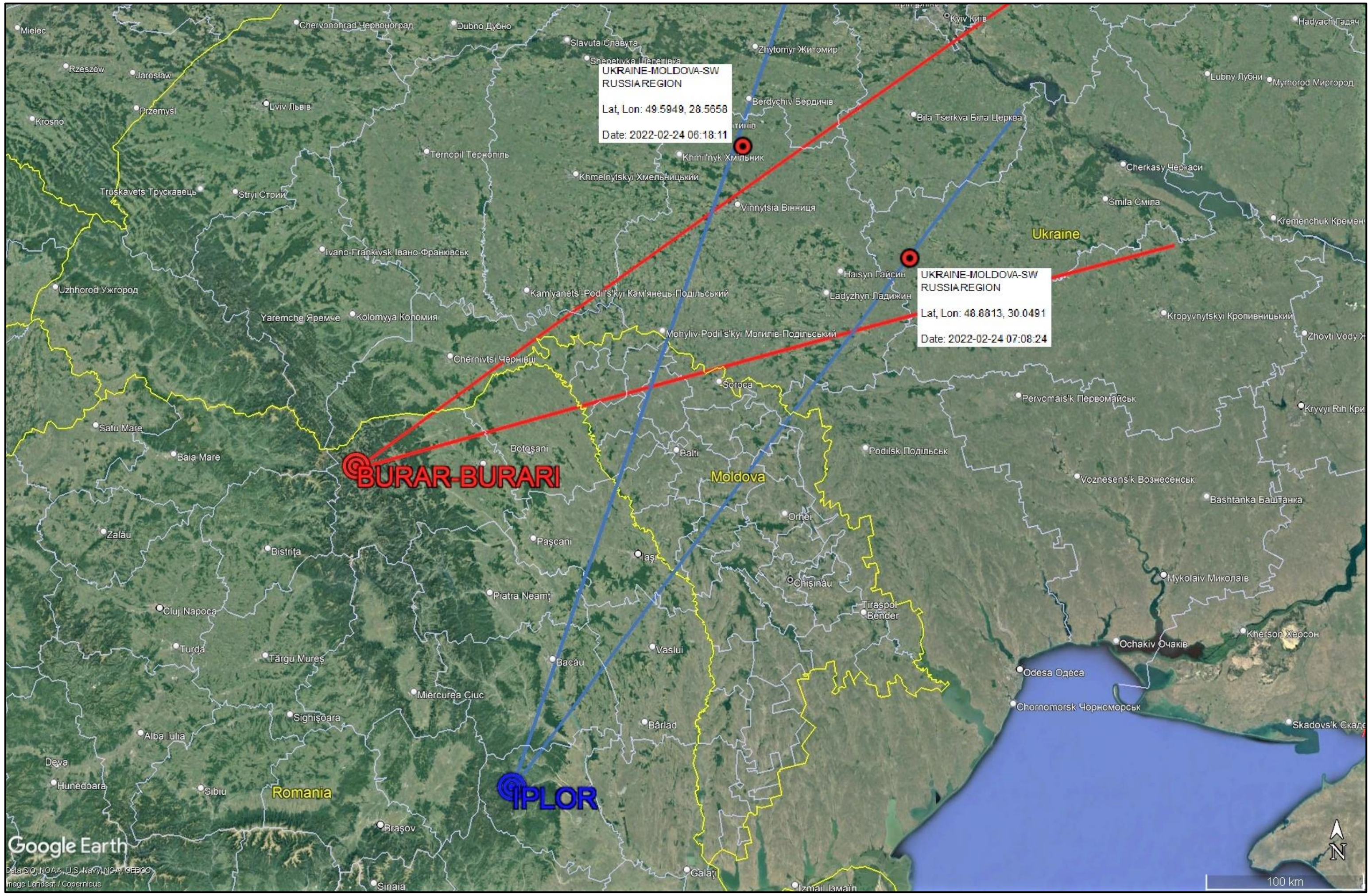
- On 24 February 2022, shortly after 03:00 UTC, explosions were reported in mass media in Kyiv, Kharkiv, Odessa, and Donbas region ➔ Romanian seismic array (BURAR) and infrasonic arrays (BURARI, IPLOR) detected numerous sharp-onset signals with high frequency content and rather large peak-to-peak amplitude (up to 9 Pa at BURARI and up to 7 Pa at IPLOR)
- 6 events located into LEBs (with yellow and red dots) on 24 February, and detected with Romanian arrays are showed ➔ backazimuth cross-bearing of BURARI and IPLOR arrays is biased by deviating effects of zonal cross-winds along the propagation path through the atmosphere





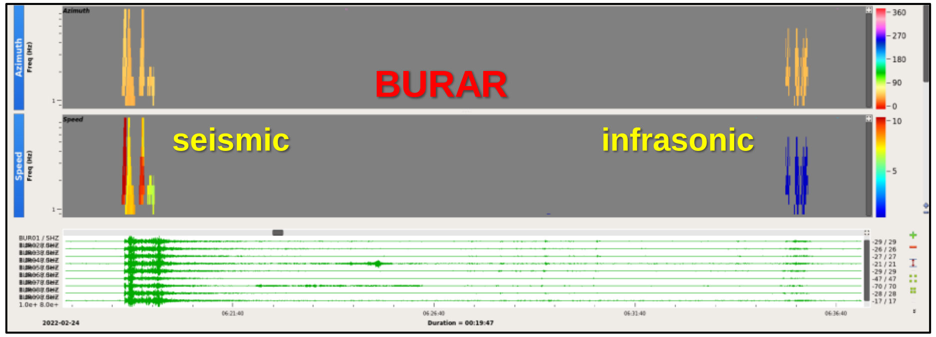
Seismo-acoustic events on 24 February 2022 (explosions)

- Two events located on 24 February 2022 in CTBTO/REB bulletins were analyzed
- Generation of both seismic and infrasound signals ➔ near-surface explosions



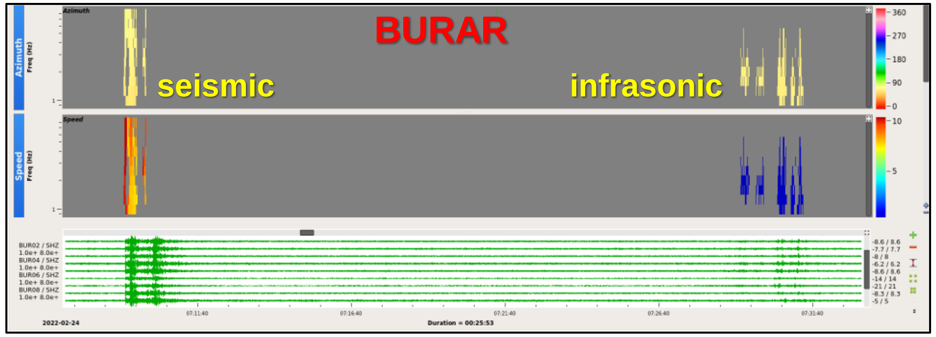
(1) 06:18:11 UTC (ML = 2.8, mb = 3.3)

IMS stations: five seismic & three infrasonic



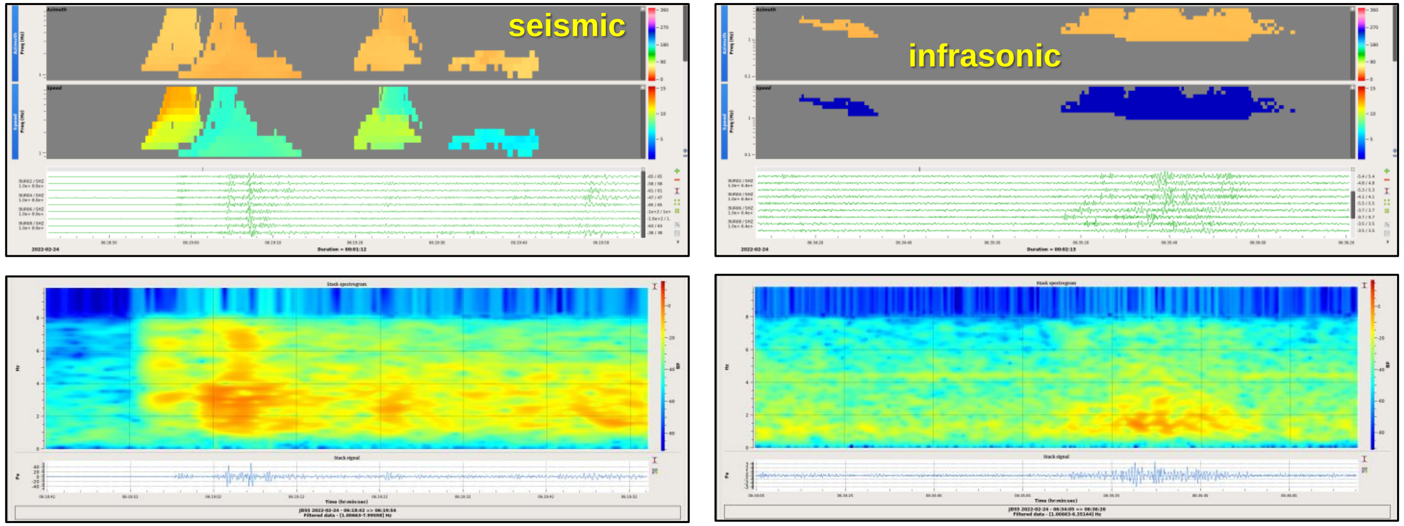
(2) 07:08:24 UTC

IMS stations: one seismic & three infrasonic



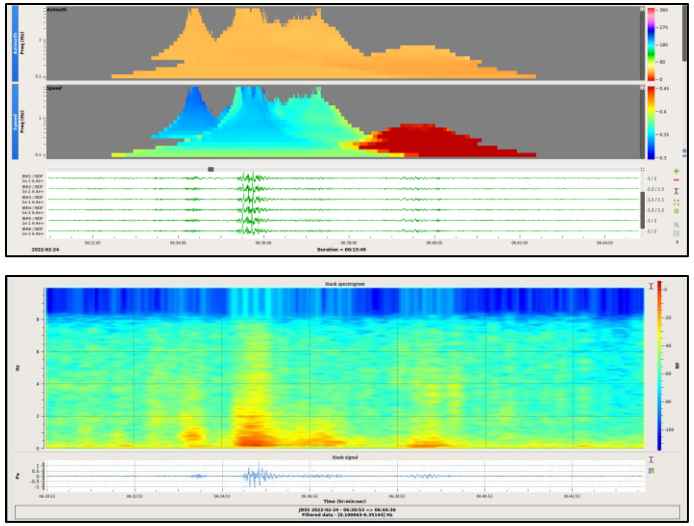
Seismo-acoustic event on 24 February 2022 at 06:18:11 UTC

Seismo-acoustic observations

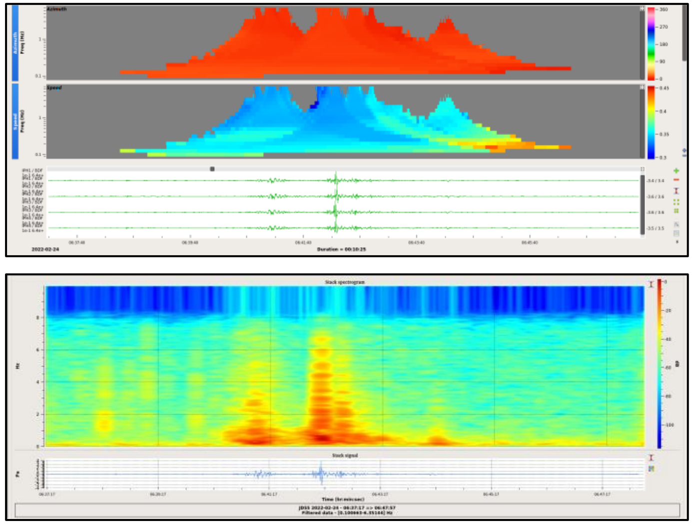


BURAR

Infrasonic observations



BURARI



IPLOR

		Infrasonic			Seismic	
		BURARI	IPLOR	BURAR		BURAR
Distance (km)		331.1	440.6	331.1		331.1
Theoretical back azimuth (deg)		47.0	18.4	47.0		47.0
Arrival time (UTC)		06:32:42	06:38:31	06:34:13		06:18:57
Apparent speed (km/s)		0.350	0.342	0.335	Pn	10.8
					Pg	8.2
Back azimuth (deg)		51.0	17.3	49.7		50.4
Mean frequency (Hz)		2.4	2.9	3.2		3.8
PP amplitude (Pa)		2.1	4.7	7.0		
Celerity (km/s)	Is	0.380	0.361			
	It	0.262	0.293			
Cross-wind $W_{c,T}$ (km/s)*		-0.027	0.007			

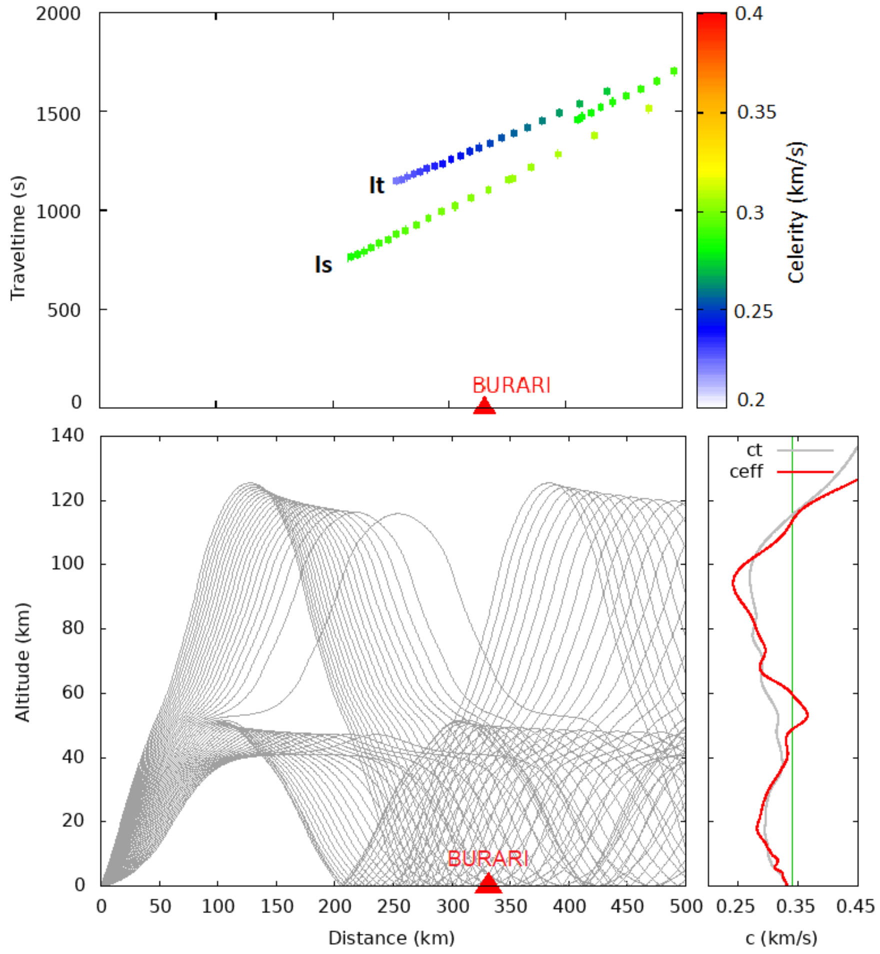
* Travel-time weighted mean cross-wind (*Blixt et al., 2019*)

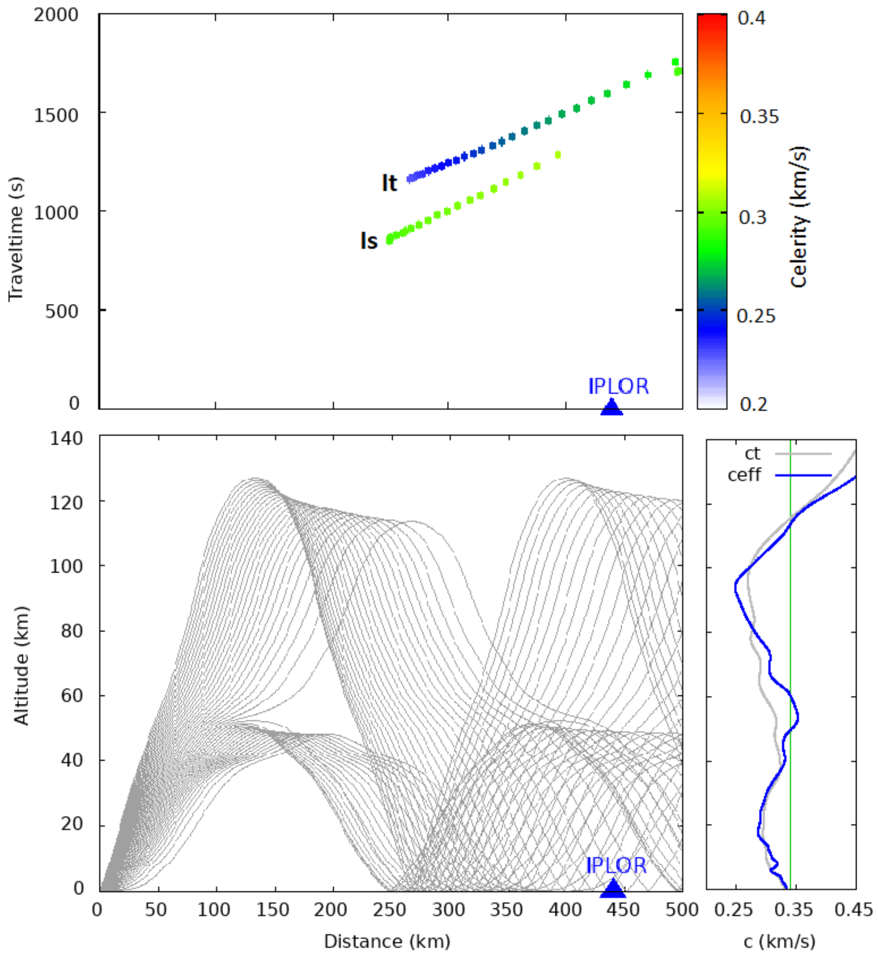
Blixt, E. M., Nasholm, S. P., Gibbons, S. J., Evers, L. G., Charlton-Perez, A. J., Orsolini, Y. J., & Kværna, T. (2019). Estimating tropospheric and stratospheric winds using infrasound from explosions. The Journal of the Acoustical Society of America, 146(2), 973–982, https://doi.org/10.1121/1.5120183

Seismo-acoustic event on 24 February 2022 at 06:18:11 UTC – cont.

Infrasound propagation analysis

- To predict the arrivals that can be recorded, the ducting conditions towards BURARI and IPLOR stations were described by using the infraGA 2D ray tracer (https://github.com/LANL-Seismoacoustics/infraGA) through NRL-G2S atmospheric model (*Drob et al., 2003*)



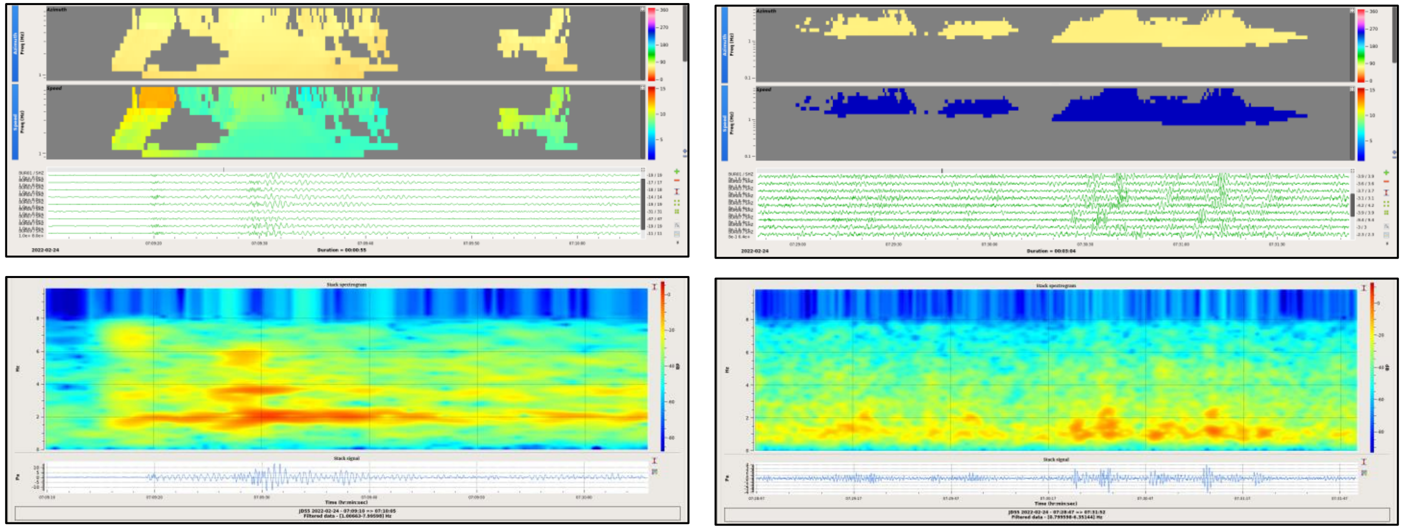


- Temperature dependent sound speed (*ct*) and effective sound speed (*ceff*) are showed; the green line represents the effective sound speed at the surface (*ceff,0* = 0.34 km/s)
- Rays propagating from the source in the direction of BURARI and IPLOR bend towards the earth's surface between 40 and 60 km altitude, i.e., the stratosphere and from 120 km upwards, i.e., the thermosphere (lower frame)
- Upper frame gives the traveltime for the rays: stratospheric (**Is**) and thermospheric (**It**) phases are predicted to reach the station, which is consistent with the infrasound phases detected (PMCC results)

- *Drob, D.P., Picone, J.M., Garcés, M. (2003). Global morphology of infrasound propagation. J Geophys Res 108(D21):4680. DOI 10.1029/2002JD003307*

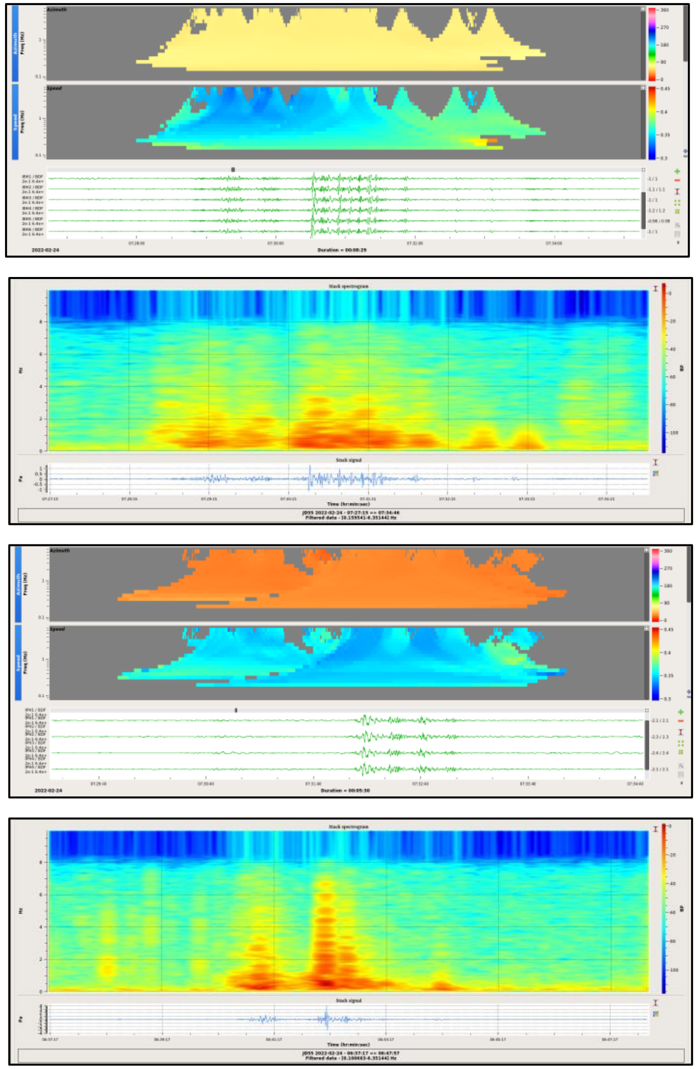
Seismo-acoustic event on 24 February 2022 at 07:08:24 UTC

Seismo-acoustic observations



BURAR

Infrasonic observations



BURARI

IPLOR

		Infrasonic			Seismic	
		BURARI	IPLOR	BURAR	BURAR	
Distance (km)		385.7	423.9	385.7		385.7
Theoretical back azimuth (deg)		66.8	18.4	66.8		66.8
Arrival time (UTC)		06:32:42	06:38:31	07:29:19		07:09:19
Apparent speed (km/s)		0.350	0.342	0.352	Pg	10.1
					Pn	8.1
Back azimuth (deg)		51.0	17.3	72.1		72.2
Mean frequency (Hz)		2.4	2.9	2.8		2.8
PP amplitude (Pa)		2.1	4.7	4.2		
Celerity (km/s)	Is	0.380	0.361			
	It	0.262	0.293			
Cross-wind $W_{c,T}$ (km/s)*		-0.028	0.003			

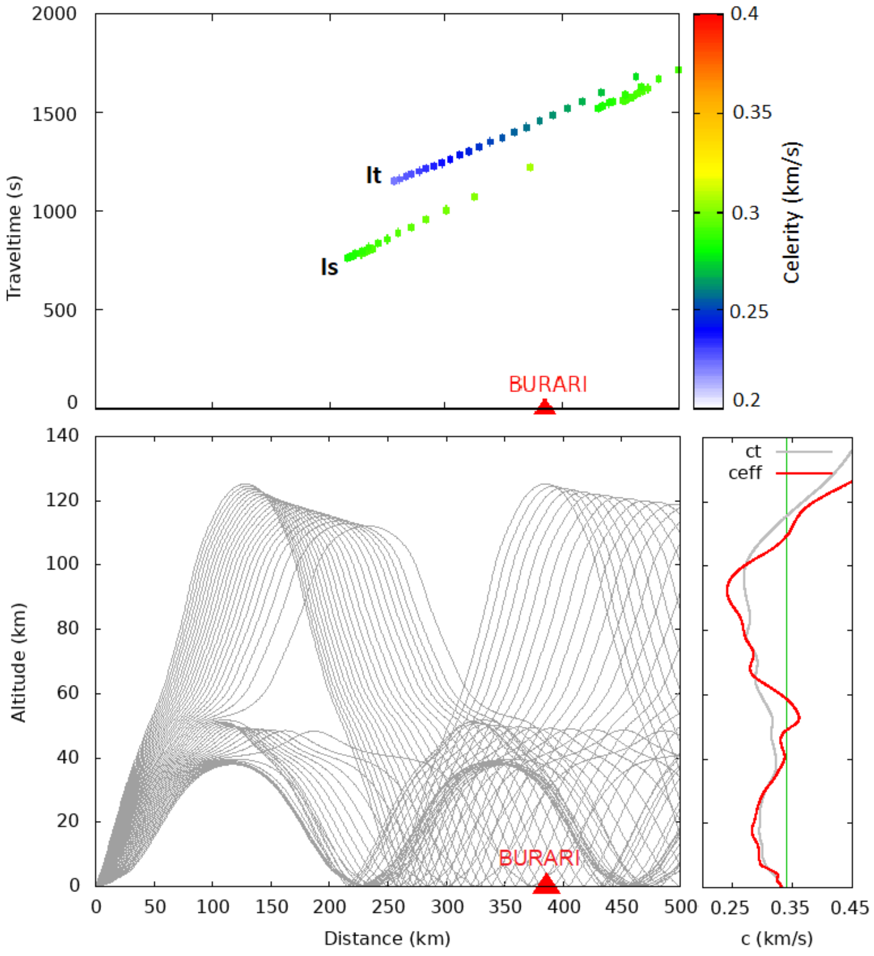
* Travel-time weighted mean cross-wind (*Blixt et al., 2019*)

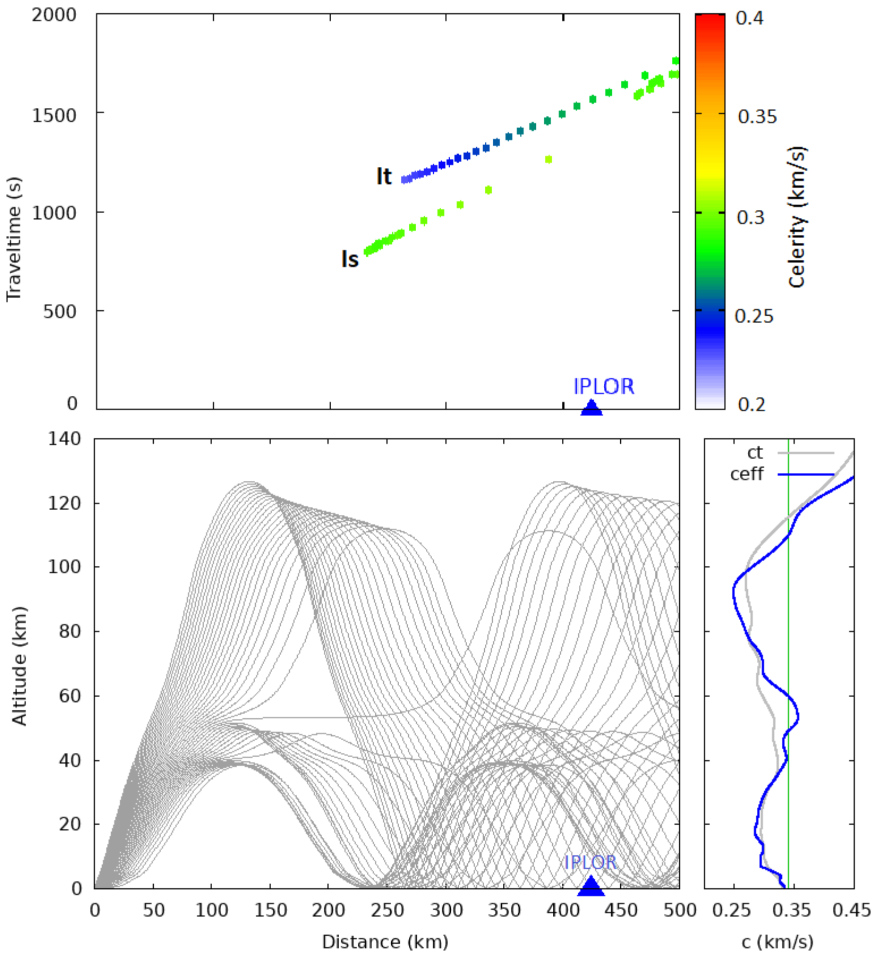
Blixt, E. M., Nasholm, S. P., Gibbons, S. J., Evers, L. G., Charlton-Perez, A. J., Orsolini, Y. J., & Kværna, T. (2019). Estimating tropospheric and stratospheric winds using infrasound from explosions. The Journal of the Acoustical Society of America, 146(2), 973–982, https://doi.org/10.1121/1.5120183

Seismo-acoustic event on 24 February 2022 at 07:08:24 UTC – cont.

Infrasound propagation analysis

- To predict the arrivals that can be recorded, the ducting conditions towards BURARI and IPLOR stations were described by using the infraGA 2D ray tracer (https://github.com/LANL-Seismoacoustics/infraGA) through NRL-G2S atmospheric model (*Drob et al., 2003*)





- Temperature dependent sound speed (*ct*) and effective sound speed (*ceff*) are showed; the green line represents the effective sound speed at the surface (*ceff,0* = 0.34 km/s)
- Rays propagating from the source in the direction of BURARI and IPLOR bend towards the earth's surface between 40 and 60 km altitude, i.e., the stratosphere and from 120 km upwards, i.e., the thermosphere (lower frame)
- Upper frame gives the traveltime for the rays: stratospheric (**Is**) and thermospheric (**It**) phases are predicted to reach the station, which is consistent with the infrasound phases detected (PMCC results)

- *Drob, D.P., Picone, J.M., Garcés, M. (2003). Global morphology of infrasound propagation. J Geophys Res 108(D21):4680. DOI 10.1029/2002JD003307*

Summary

- Simultaneous observations of infrasonic and seismic signals recorded with the Romanian seismo-acoustic arrays (BURAR, BURARI and IPLOR) are used to forensic tracking the repetitive explosion sources generated by bombing and shelling taking place in Ukraine since 24 February 2022
- Seismo-acoustic signature (signal shape and amplitude, frequency content, energy spectrum) analyzed indicates impulsive energetic signals
- Events reported in the bulletins provided by IDC/CTBTO are used as reference for associating infrasound and seismic detections of the Romanian arrays
- Infrasound signals observed with BURAR seismic array are added to better characterize the type of events
- Infrasonic detections are strongly influenced both by seasonally dependent stratospheric winds and local turbulence-induced pressure fluctuations, i.e., level of wind-generated background noise increases with station altitude
- Directions of IPLOR and BURARI infrasonic detections are estimated and the locations are obtained by cross-bearing the derived back azimuths. Deviating effects of zonal cross winds along the propagation path through the atmosphere affect the observed back azimuths: rays which arrive at BURARI are deflected towards the East with approx. 5^{o}, whilst at IPLOR, the azimuthal deviation is negligible (below 1^{o})
- Propagation path of infrasonic signals is analyzed by applying infraGA 2D ray tracer through NRL-G2S atmospheric model. Stratospheric and thermospheric infrasound phases are identified to be observed at BURARI and IPLOR stations

Acknowledgements

- The data processed in this paper are recorded by the Romanian infrasound and seismic stations and owned by National Institute for Earth Physics
- The work has been accomplished in the framework of National Core-Programme, SOL4RISC Project
- Part of the results obtained in this study will be included into the research carried out inside the project PN23360101: “Parametrization and evaluation of earthquakes and other natural and anthropogenic phenomena effects”
- We thank Julien Vergoz for advanced training to process infrasound data and helpful discussions