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The Baumgarten and Ingolstadt explosions: infrasound observations from ground truth sources in Eastern Austria and Southern Germany

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1 The Dec. 12, 2017 (07:44 UTC) Baumgarten explosion

Seismo-acoustic signals from the explosion were widely recorded at the AlpArray seismic network (Schneider et al., 2018). An infrasound signal was also identified at the Hungarian array PSZI about 230 km to the east. F-K (Stammler, 1993) and PMCC (Cansi, 1995) analyses of this signal point towards this source, but exhibit large azimuth residuals. Applying a corrrection for elevation of array elements reduced this residual by half. And 3D ray tracing can provide an explanation for the remainder, as well as for the high trace velocities observed.

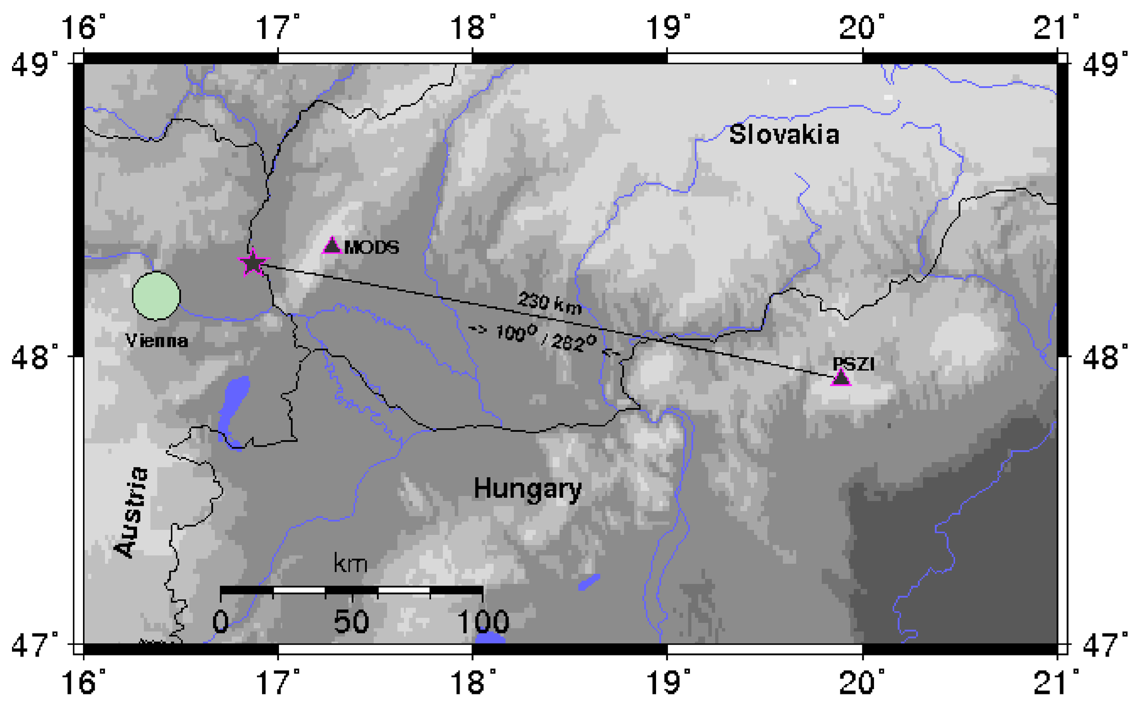


Fig.1: Map of the region east of Vienna showing the location of the explosion site and the Hungarian infrasound array PSZI. Also shown is the seismic station MODS in Slovakia used for magnitude estimation.

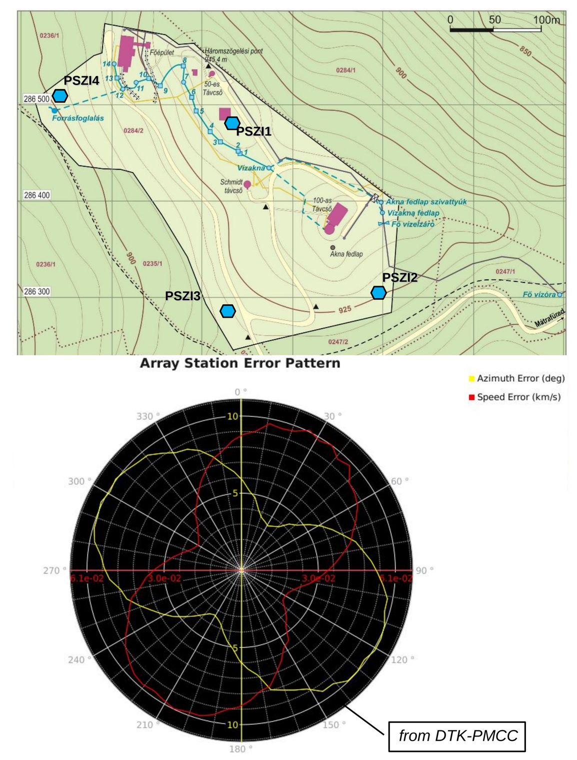
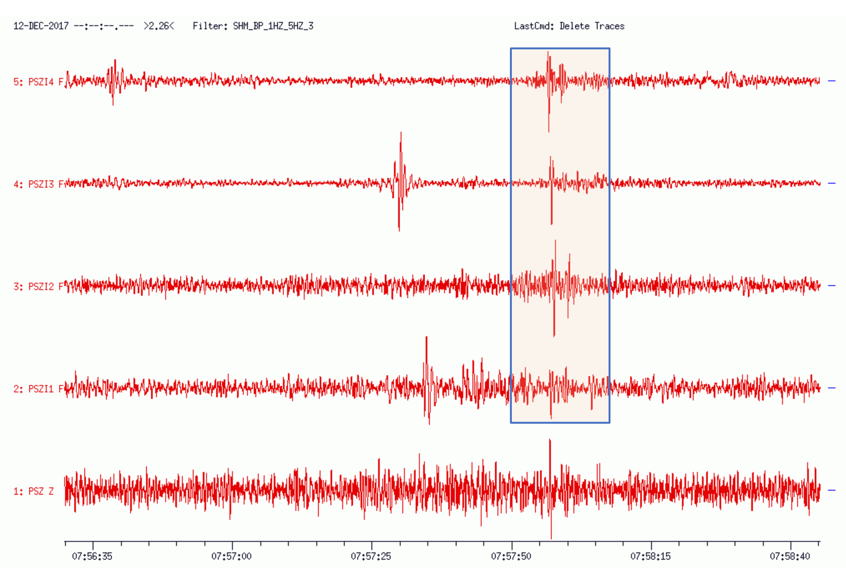


Fig.2: Array geometry and topography of PSZI (upper part) and uncertainty estimates for backazimuth and slowness determination from PMCC (lower part).



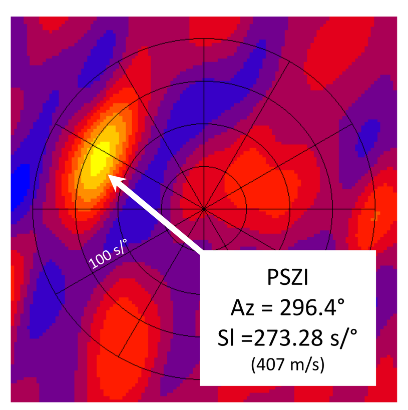


Fig.3: Waveforms recorded at PSZI on 12 Dec. 2017 from 07:56:30 to 07:58:45 UTC and bandpass-filtered between 1 and 5 Hz. The result of FK analysis of an 18 s window suggests a backazimuth of 296° (azimuth residual of 14°) and a slowness of 273 s/deg (i.e. trace velocity of 407 m/s)

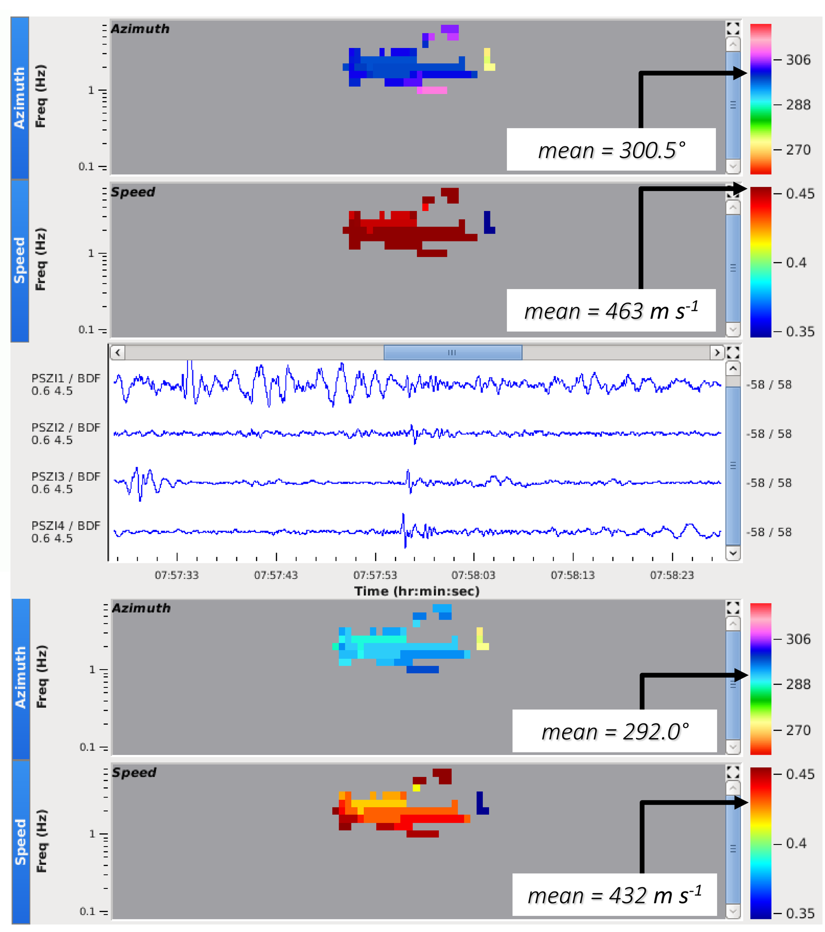


Fig.4: Results of PMCC processing for PSZI waveforms shown in Fig.3 with assumed planar array geometry (upper plot) and when taking elevation differences of array elements into account (lower plot). In the centre the analyzed waveform segment is displayed.

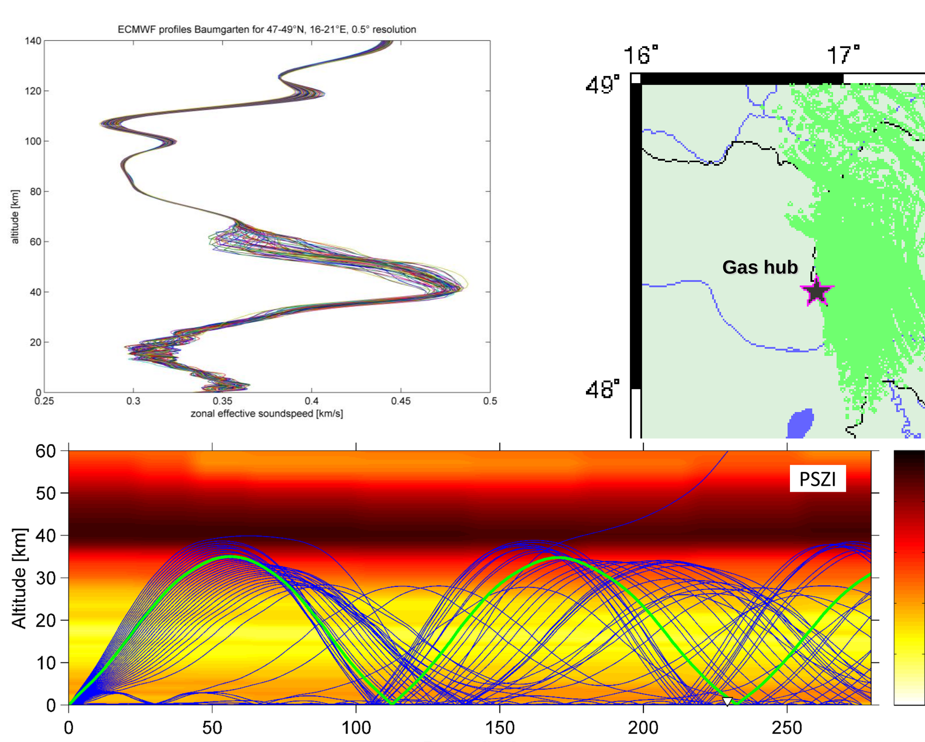


Fig.5: Effective sound speed profiles (top) towards the east for the region between 45° and 49° N and 16° and 21° E on a 0.5° x 0.5° grid showing a strong stratospheric duct at relatively low altitudes (~35 km). 2-D ray tracing along the Baumgarten-PSZI path shows an eigenray for PSZI on the second bounce (bottom).

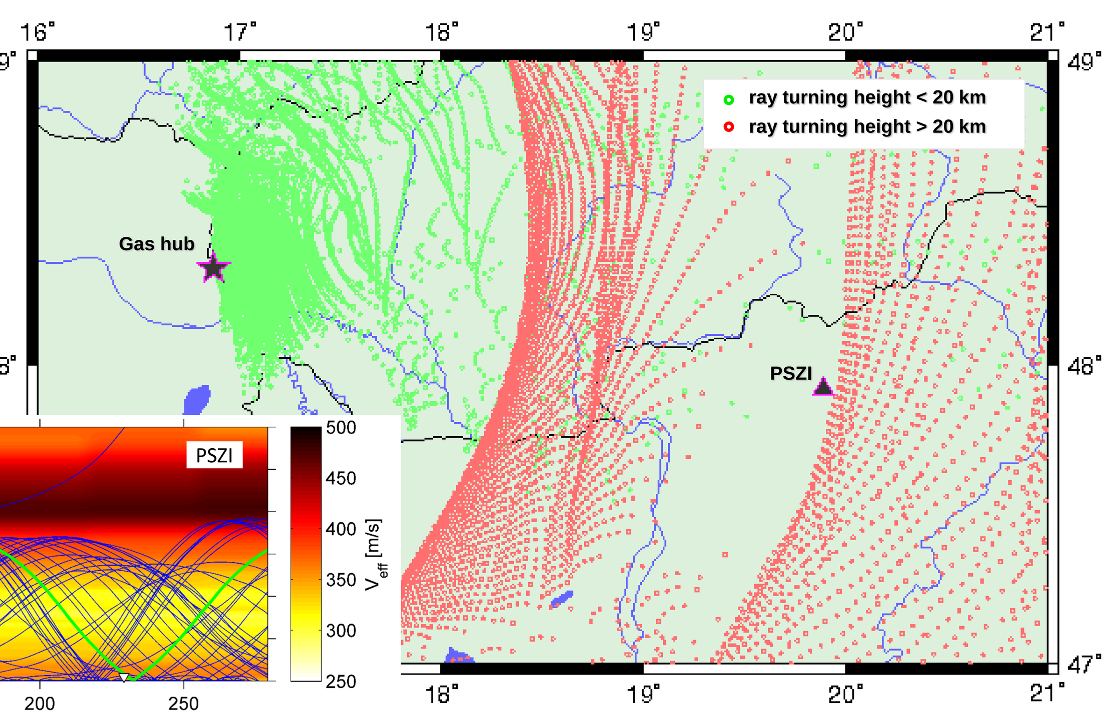


Fig.6: Bounce point pattern from full 3D ray tracing (GeoAc; Blom & Waxler, 2012) for tropospheric (green) and stratospheric (red) propagation from the Baumgarten explosion site to PSZI. Atmospheric profiles are given on a 0.5° x 0.5° grid in the region shown. The azimuth deviation from 3D modelling exceeds 6°, so that the backazimuth of the PSZI observation moves within 4° of the source azimuth.

2 The Sep. 1, 2018 (03:11 UTC) Ingolstadt explosion

Seismo-acoustic signals from the explosion were observed again at the AlpArray seismic network (Fuchs et al., 2018) to distances of more than 300 km. Here we studied infrasound signals from various acoustic sensors in Central and Eastern Europe (for the latter, see also Czanik et al, 2018). F-K and PMCC analyses of the signals were carried out to estimate backazimuth and slowness (resp. trace velocity) in order to associate them to tropospheric, stratospheric or thermospheric arrivals.

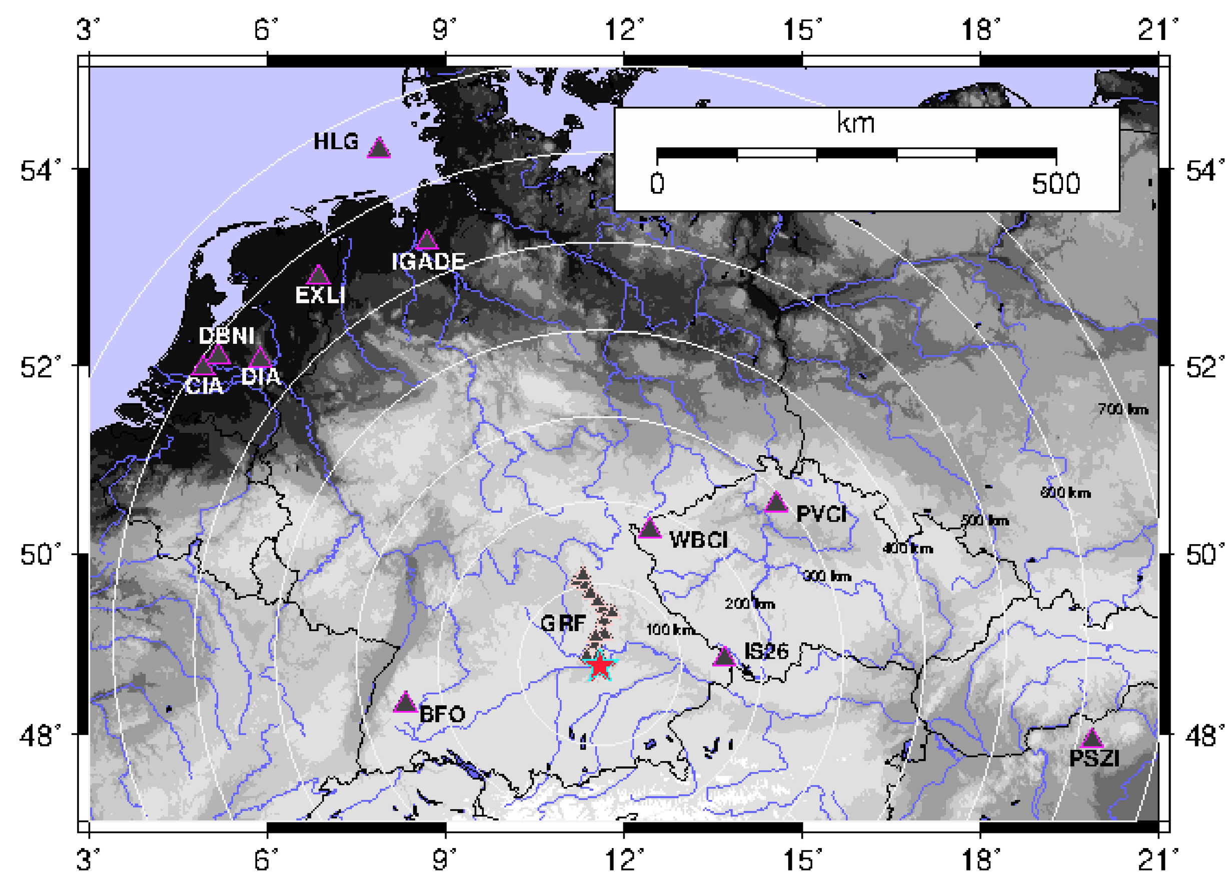


Fig.7: Map of Central Europe showing the locations of the Ingolstadt explosion site and the infrasound stations considered in this study. Also shown are the locations of the seismic GRF array elements, which are located north of the explosion site. Elements GRC2 and GRC3 are within 15-20km of the source and recorded very strong seismic and acoustic phases. Seismic phases were used for location and magnitude estimation.

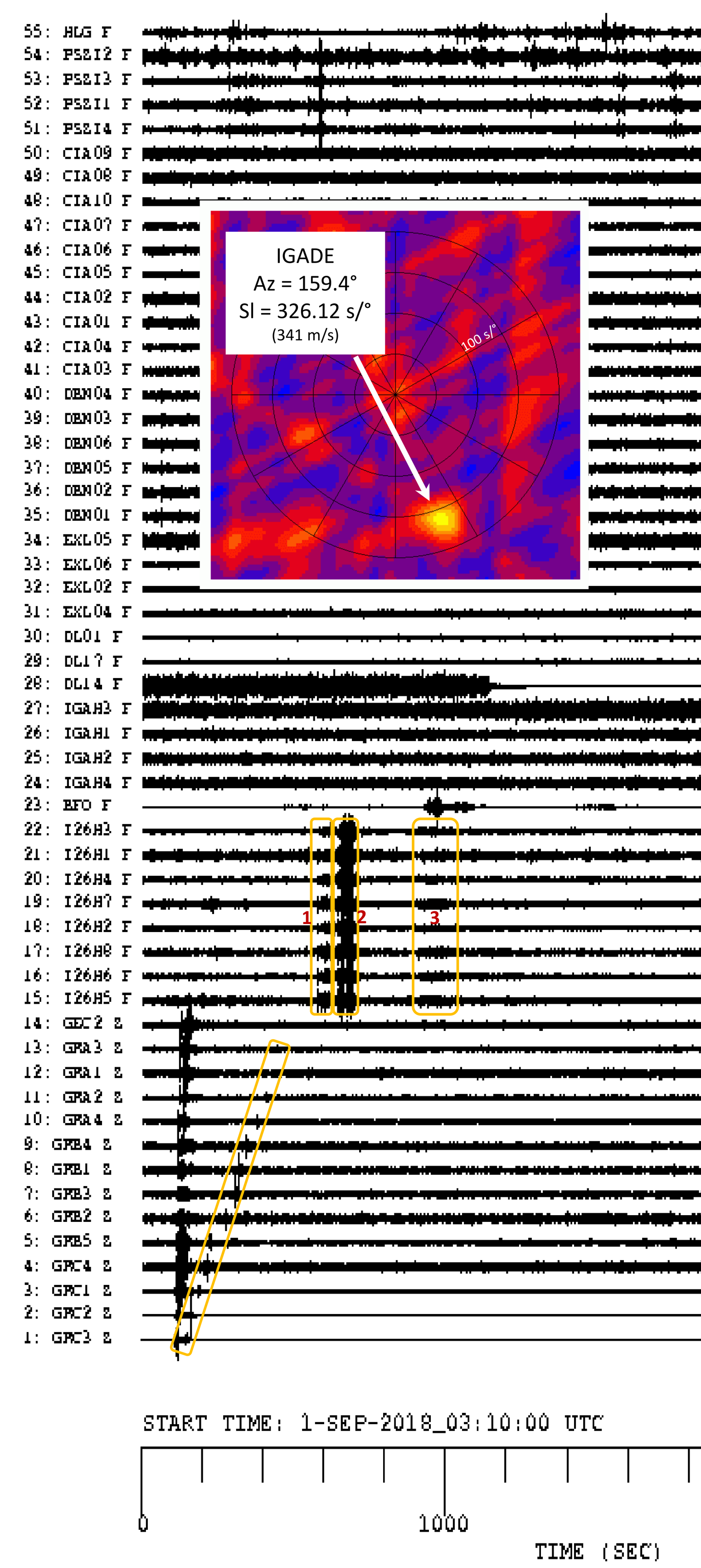
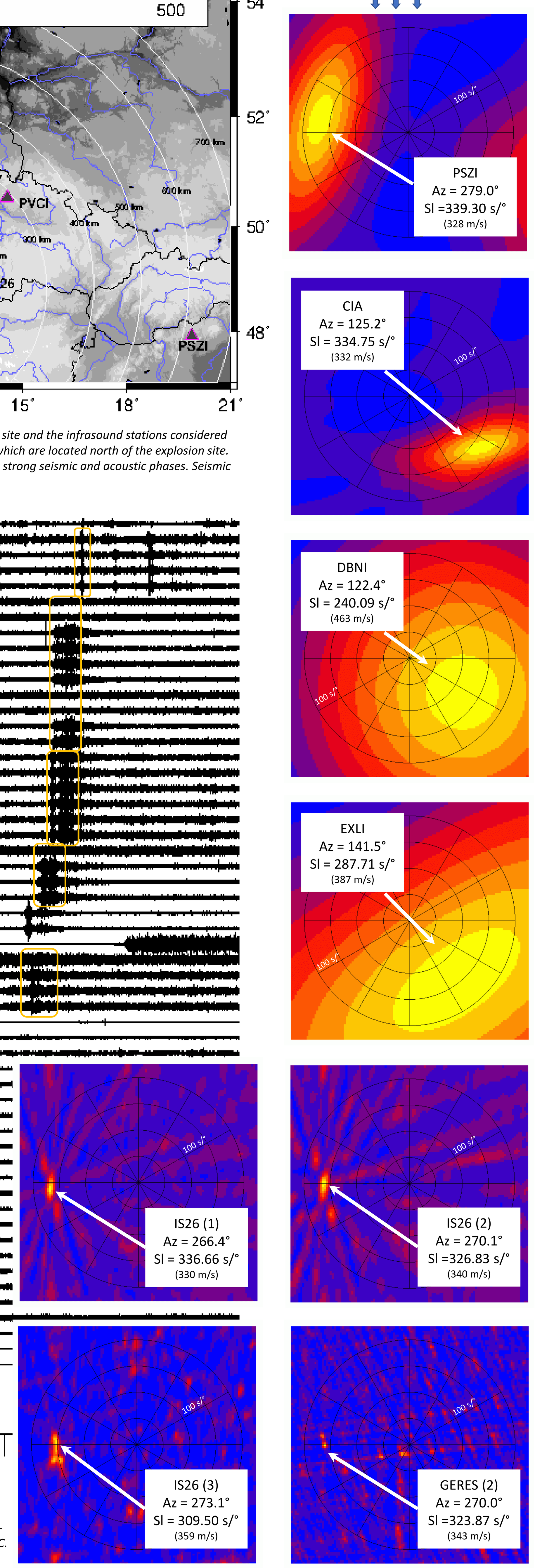


Fig 8: Waveforms recorded at the GRF array (seismic/acoustic - Z) and at the available infrasound stations in Central Europe (acoustic- F) .All traces start at 03:10UTC. The GRF and F-K analyzed infrasound arrivals are marked by yellow boxes.

Fig.9: Results of F-K analyses of the signals as shown in Fig. 8 (see the marked signal windows) and annotated with the station code and the estimated azimuth and slowness (trace velocity) values.



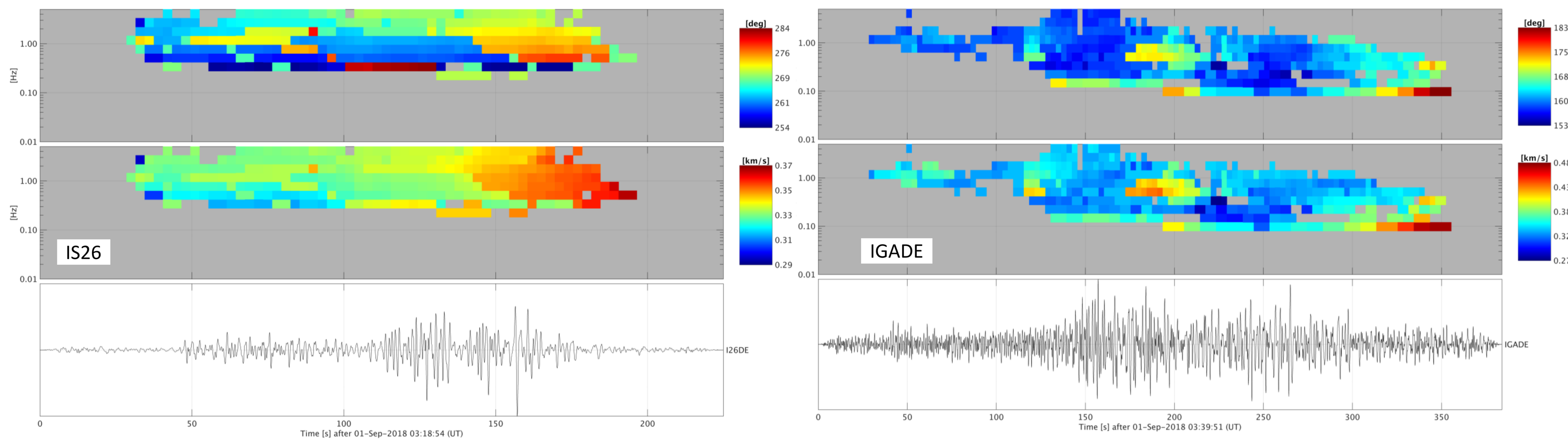


Fig.10: PMCC analyses of the infrasound signals recorded at IS26 (left) and IGADE (right) with results agreeing well with those obtained by F-K-analysis. The late third arrival about 5 minutes after the strong signal at IS26 could not be extracted with PMCC.

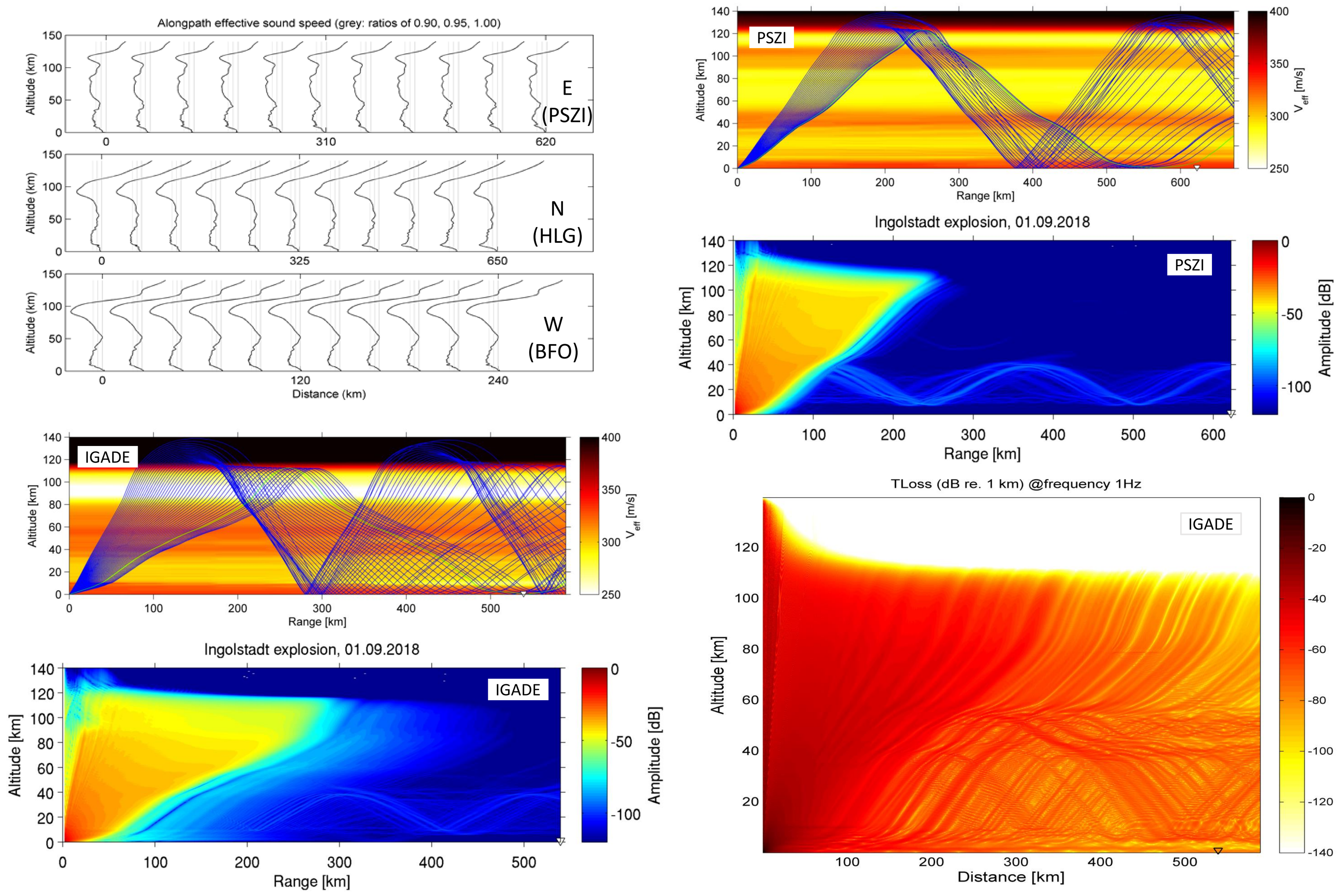


Fig.11: Propagation modelling for a path to the East (PSZI) and to the North (IGADE) - the effective sound speed profiles for directions approx. towards east (PSZI), north (HLG) and west (BFO) are given on the top left. For each station the result of 2D ray-tracing and 1D parabolic equation (PE) modelling is shown, for IGADE additionally the 2D PE results. While by ray-tracing we find only thermospheric paths, the PE modelling suggests some weak and elevated stratospheric ducting.

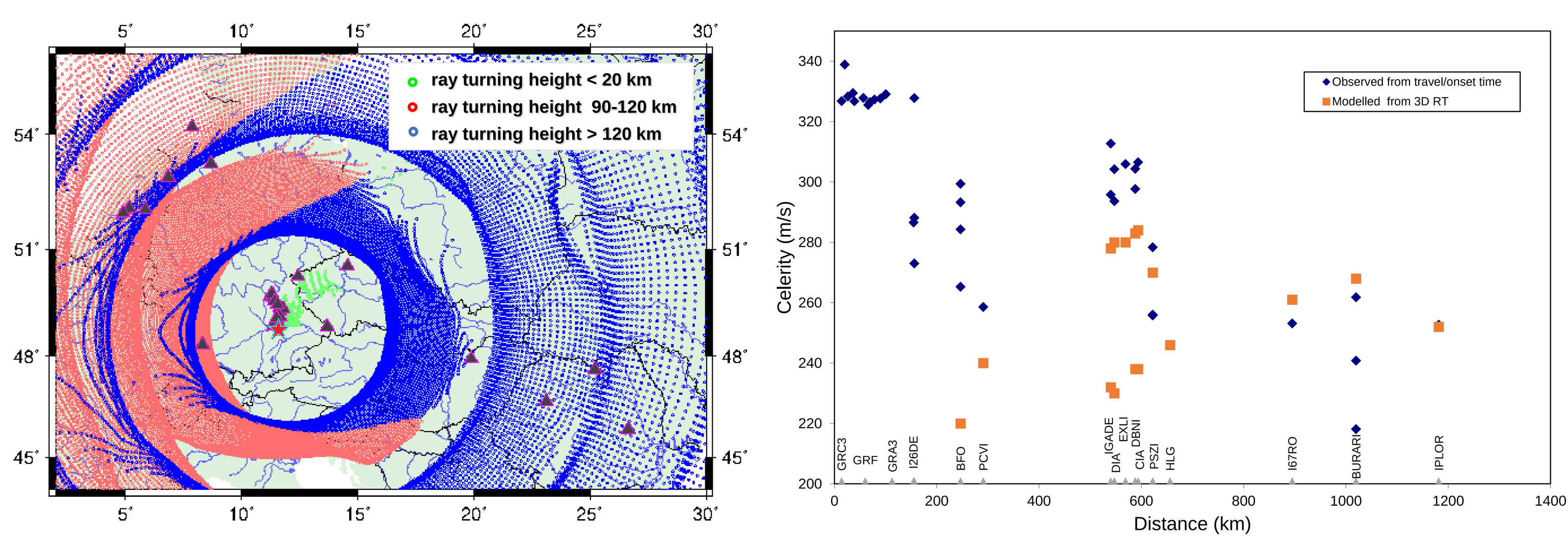


Fig.12: Bounce points of 3D ray-tracing from the Ingolstadt explosion towards the European infrasound stations. Except for short distance tropospheric ducts, ray tracing only predicts thermospheric propagation with returns from either about 110 km (red dots) or 125 km (blue dots) altitude (left); Comparison of celerity for the different signal onsets identified with the modelling results (right). The short distance GRF arrivals indicate tropospheric ducting, while all other stations stratospheric or thermospheric ducting. Only for the largest distances, the thermospheric returns agree well with the observations, while for distances between 160 and 600 km stratospheric ducting better explains the observations.

3 Summary & conclusions

- The Baumgarten explosion produced an acoustic arrival at PSZI with large azimuth residual and very high trace velocity. Elevation correction and 3D ray-tracing modelling, however, can explain these extreme values by the stratospheric duct.
- The Ingolstadt explosion was observed at infrasound stations throughout Central and Eastern Europe to distances of 1200 km. Backazimuths are within a few degrees of the theoretical values.
- 2D and 3D ray-tracing for stations beyond 150 km from the Ingolstadt source predicts only thermospheric ducting, while many station signals suggest stratospheric ducting. The several onsets at IS26 can not be explained well or at all.
- Some stratospheric ducting for the Ingolstadt explosion is suggested by the PE modelling in 1D and 2D.
- This study suggests that propagation modelling with the ECMWF atmospheric model is quite successful for the Baumgarten explosion, but this does not apply for the case of the Ingolstadt explosion.
- The seismic magnitudes for the Baumgarten and Ingolstadt explosions were estimated to ML=0.6 and ML=2.1, resp..

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