Regional infrasound propagation following the Ingolstadt explosion (September 1, 2018) recorded by the AlpArray seismic network with high (40km) spatial resolution

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Abstract

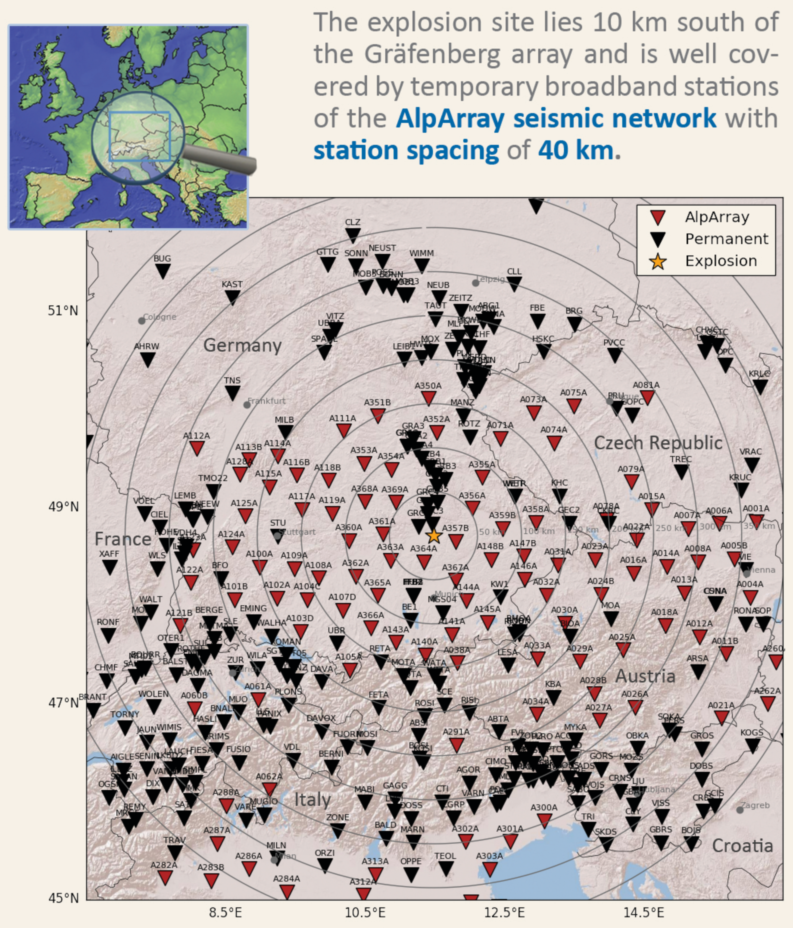
On September 1st, 2018 a devastating explosion occurred on the facility of an oil refinery near Ingolstadt, Germany. We analyzed data of 400 permanent and temporary seismic stations and find strong seismo-acoustic signals on more than 80 seismic stations. The infrasound signal is detectable on seismic stations within 10–350 km from the source, with 40 km spatial resolution.

We confirm the explosion site both by the seismic and seismo-acoustic arrivals. Apart from seismic P- and S waves, we identified three separate acoustic phases with celerities of 332, 292, and 250 m/s, respectively, each of which has a particular spatial pattern of positive detections at the ground. Seismo-acoustic amplitudes are strongly affected by the type of seismic installation but still allow potential insight into regional infrasound attenuation.

Our observations likely represent tropospheric, stratospheric, and thermospheric infrasonic phases. We performed 3D acoustic ray tracing to validate our findings, using atmospheric data from ECMWF weather forecast models. Tropospheric and thermospheric arrivals are to some extent reproduced by the atmospheric model. However, ray tracing does not at all predict the observed acoustic stratospheric ducts. Our findings suggest that small-scale variations had considerable impact on the propagation of infrasound generated by the explosion.

Seismic stations

The explosion site lies 10 km south of the Gräfenberg array and is well covered by temporary broadband stations of the **AlpArray seismic network** with **station spacing** of **40 km**.

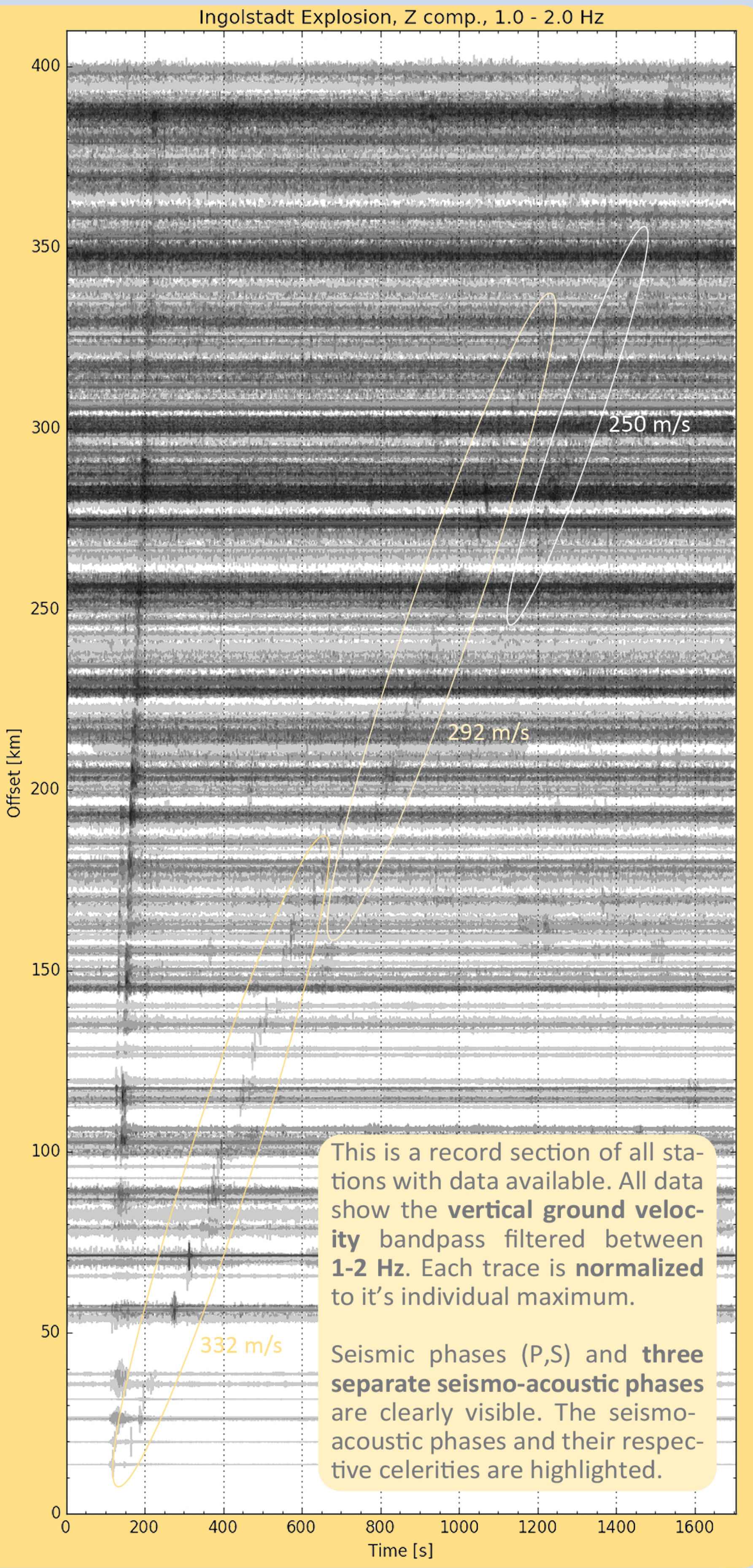


We acquired data from **400** broadband stations (100 sps continuous data, vertical component)

The incident: Refinery explosion near Ingolstadt (Germany)

On September 1st, 2018 a devastating **explosion** hit the facilities of a **refinery** of BayernOil in the town of Vohburg, near Ingolstadt in Bavaria, Germany. Local newspapers reported the **origin time** of the explosion between **03:00 and 03:15 UTC**. 2000 people were evacuated from their homes in the vicinity of the refinery. The explosion was audible in several kilometers distance and caused severe damage to buildings in neighboring villages.

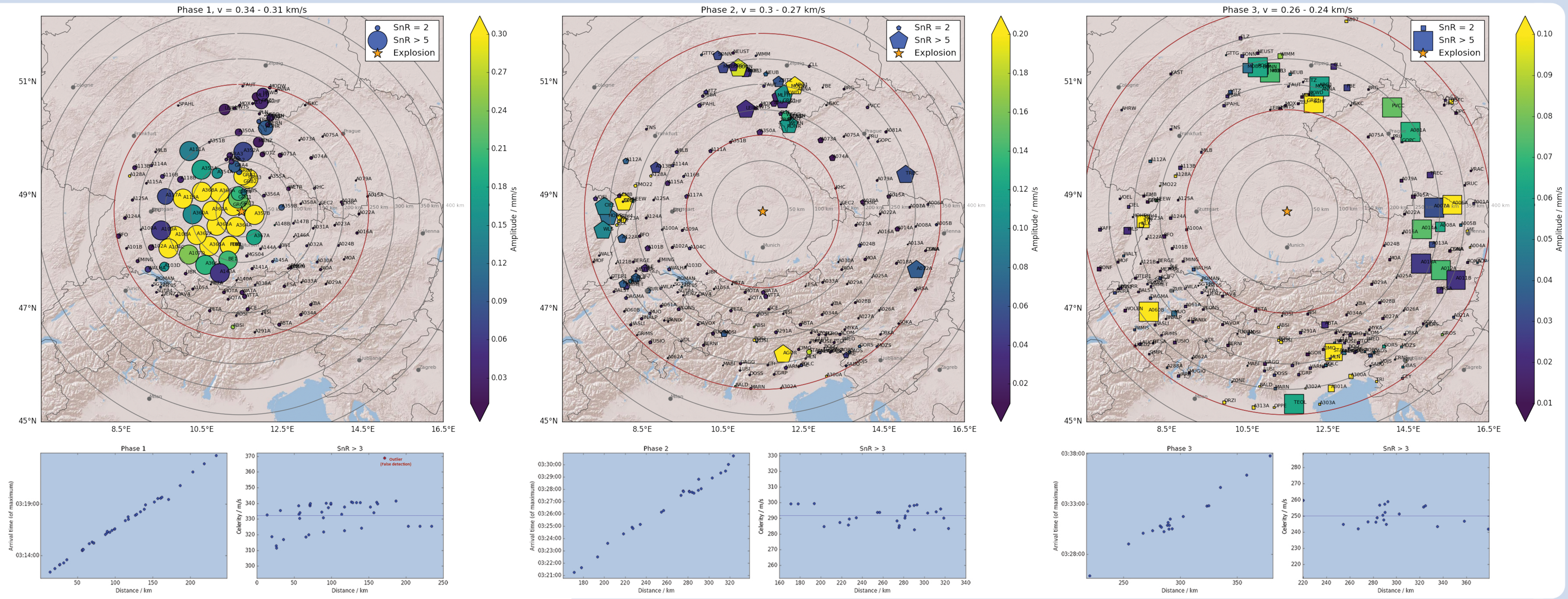
Seismic record section



This is a record section of all stations with data available. All data show the **vertical ground velocity** bandpass filtered between **1-2 Hz**. Each trace is **normalized** to it's individual maximum.

Seismic phases (P,S) and **three separate seismo-acoustic phases** are clearly visible. The seismo-acoustic phases and their respective celerities are highlighted.

Seismo-acoustic detections

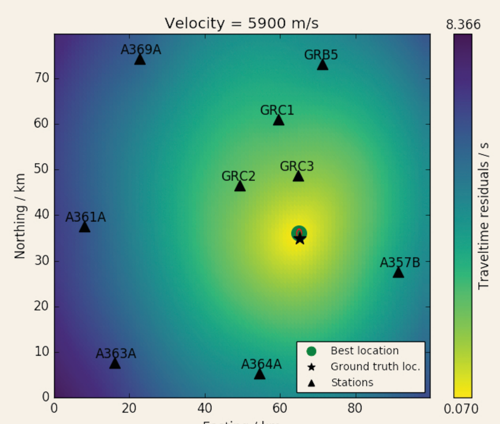


For each seismo-acoustic phase we evaluate the **vertical peak ground velocity (PGV)** in the **1–2 Hz frequency band**. In the maps above **colors indicate the PGV**. Note that color scales are truncated at different levels for each of the phases. The signal-to-noise ratio (SnR) is calculated as (PGV / 3σ) from the standard deviation before the explosion. All symbol sized are **scaled by the SnR**. We observe a SnR > 3 on in total **84** different **seismic stations within 350 km** from the explosion site, 35 of which are temporary AlpArray installations.

The positive detections of the seismo-acoustic explosion signal show **pronounced spatial patterns** that are significantly different among the three separate phases. Notably, seismo-acoustic phase 1 is almost exclusively recorded north-west to south-west of the explosion site. A branch of weak signals also potentially propagates northwards past the Gräfenberg array. Phase 2 is especially recorded in narrow bands towards North and West and absent elsewhere. Phase 3 is recorded in a broad azimuth range from North to South-East of the explosion site.

Note, that within the distance ranges of phases 2 and 3 (past 150 km distance) the spatial station coverage is greatly reduced into north-western (beyond the extent of the AlpArray stations existing, but no real-time data available) directions.

Localisation & origin time



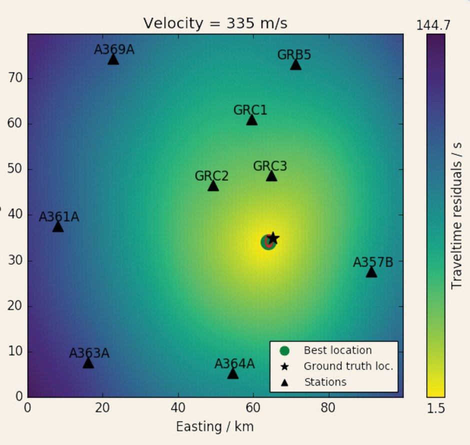
Seismic picks locate the source 1 km (i.e.one grid point) north of the true origin.

Remaining residuals compared to total travel time: 0.07 s / 7.6 s = 0.9% (comparable to acoustic)

In order to **independently locate and time** the source of the detected signals we identified the 9 stations that show the earliest arrivals of both the seismic and the seismo-acoustic phase. We **manually picked** the **first onset** of the seismic **P-arrival** and the first onset of the **seismo-acoustic arrival**. Both picks were independently used for a simple **grid search** routine that determines the epicenter and origin time. The grid search assumes a **constant propagation velocity** (5.9 km/s for seismic waves; 0.35 km/s for acoustic waves) and determines the grid point that minimizes the root-mean-squared residuals (between observed and theoretical arrival times) of all stations simultaneously.

(Grid spacing: 1km, 1s acoustic, 0.1s seismic)

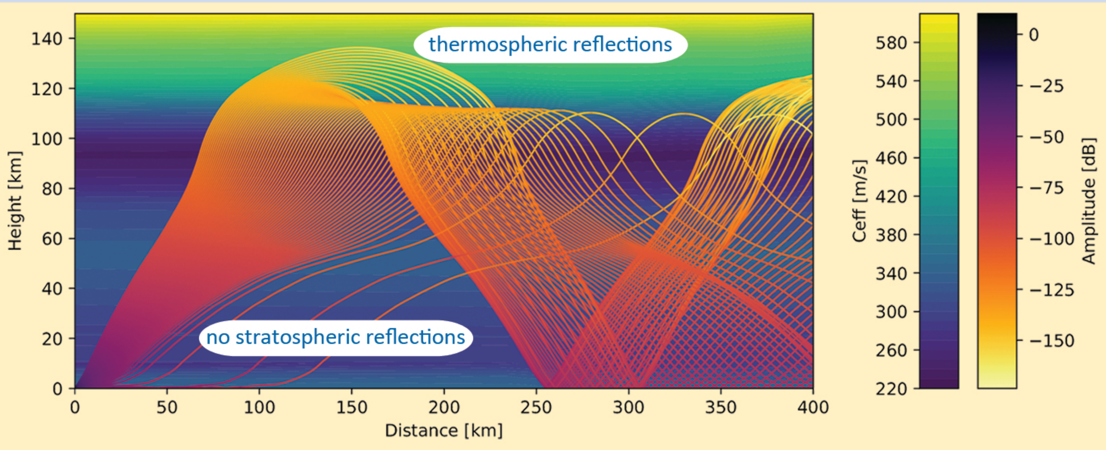
Origin time = 03:11:45 UTC +/- 1s
(in agreement with video footage)

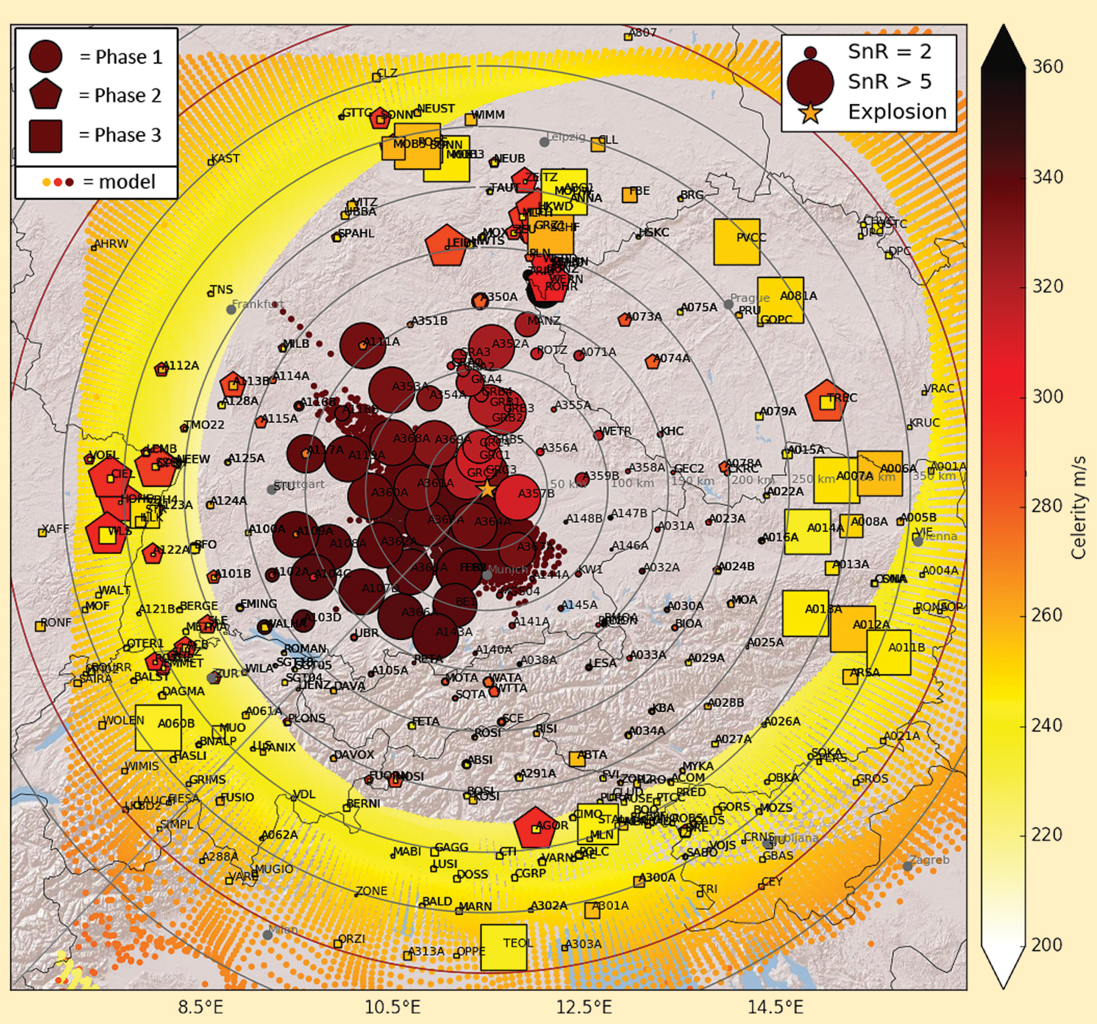


Acoustic picks locate the source 1.5 km (i.e. one grid point along diagonal) south-west of the true origin.

Remaining residuals compared to total travel time: 1.5 s / 108 s = 1.4% (comparable to seismic)

Infrasound raytracing





Similar to the approach by Schneider et al. (2018) we **modelled the propagation of infrasound rays** from the source up to 400 km distance. We used the **GeoAc raytracing suite** (Blom and Waxler (2012). We extracted the required 3D atmospheric parameters (**wind speed, wind direction, temperature**, etc.) from an hourly updated **forecast model** provided by the European Centre for Medium-Range Weather Forecasts (**ECMWF**). We retreived output from the ECMWF model for **03:00 UTC** on a latitude–longitude grid with 0.125° resolution. As within 400 km from the source thermospheric arrivals are expected, we extended the ECMWF model to higher altitudes with the MSISE-00 and HWM14 empirical models for the thermosphere.

The upper panel on the left shows calculated rays into SW direction. The acoustic velocity profile in the atmosphere **predicts thermospheric reflections, but no stratospheric reflections**. The lower panel on the left displays predicted **surface bounce points** (small symbols) for all expected rays up to 400 km form the source. Bounce points are colored by the celerity (= lateral distance / travel time) and compared to the measured celerities (large symbols).

Modeling results and observations are **in agreement for the tropospheric reflections.** Yet, the raytracing approach is **not able to reproduce any of the stratospheric reflections observed in the data**. Likely, local small scale atmospheric variations that are not represented in the smooth ECMWF model are the cause of the stratospheric reflections. Such heterogeneities may have developed due to very weak stratospheric winds.

Unidirectional **thermosphere reflections** are predicted in all directions in **contrast** with our data that shows potential reflections exclusively in azimuths from 0° (North) to 110° (South-East). Still, the widespread detection of seismo-acoustic thermosphere signals is a novel observation.

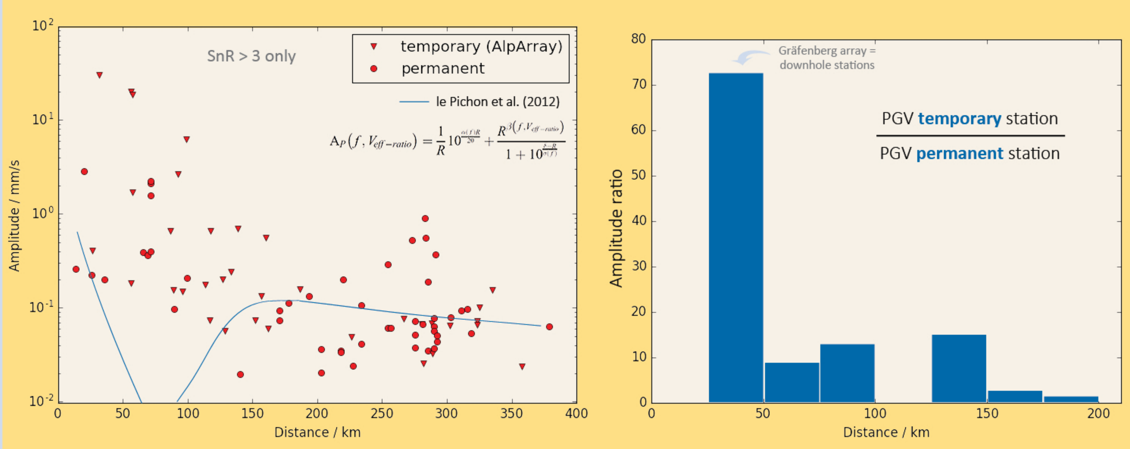
References

Blom P. and Waxler R. (2012): Impulse propagation in the nocturnal boundary layer: Analysis of the geometric component, Journal of the Acoustical Society of America, doi:10.1121/1.3699174

le Pichon A., Ceranna L. and Vergoz J. (2012): Incorporating numerical modeling into e timates of the detection capability of the IMS infrasound network, Journal of Geophysical Research, doi:10.1029/2011JD016670

Schneider F., Fuchs F., Kolinsky P. et al. (2018): Seismoacoustic signals of the Baumgarten (Austria) gas explosion detected by the AlpArray seismic network, Earth and Planetary Science Letters, doi:10.1016/j.epsl.2018.08.034

Seismo-acoustic attenuation



The dense spatial coverage allows us to analyze the **attenuation** of the seismo-acoustic signal with distance. The left panel shows the PGV of the seismo-acoustic signal with distance, compared to a numerical attenuation relation established by le Pichon et al. (2012). Data show large variations in amplitudes, but generally **within 200 km** from the source the seismo-acoustic amplitude **attenuates by approximately 1–2 orders of magnitude**. This is much less than predicted by geometric spreading. Notably, we observe that seismo-acoustic amplitudes are considerably larger on temporary installations compared to permanent seismic stations.

Conclusions

- **Seismo-acoustic signals** of a **refinery explosion** tracked over 400 km by purely seismic instruments with **40 km spatial sampling**.
- **Location accuracy of 1 km** using seismic and acoustic onset picks. Determination of origin time with 1s precision.
- Attenuation of seismo-acoustic signal similar to numerical simulations of le Pichon et al. (2012), but with low attenuation in additional tropospheric duct.
- **Pronounced spatial patterns** of surface detections, which can only partly be explained by simple acoustic raytracing.
- Observations indicate **presence of small scale structures and heterogeneities** in the atmosphere that **strongly affect acoustic wave propagation.**

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