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

universität wien

Florian Fuchs | Felix Schneider | Petr Kolinsky | Götz Bokelmann | AlpArray Working Group

Abstract

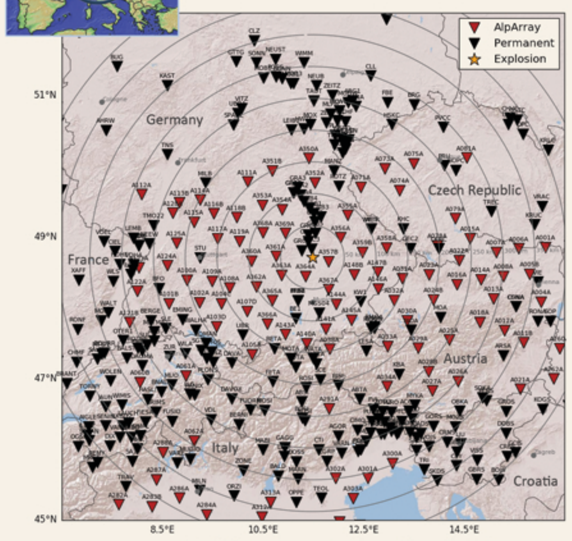
On the first of September 2018, a devastating explosion occurred on the facility of an oil refinery near Ingolstadt, Germany. We analyzed data of 400 permanent and temporary seismic stations within 400 km radius from the explosion site and find strong seismo-acoustic signals on more than 80 seismic stations. Thanks to the dense spatial coverage of the AlpArray seismic network, the infrasound signal generated by the explosion is detectable within 10 - 400 km from the source, with high spatial resolution.

The high spatial sampling reveals a pronounced spatial pattern. The event can be localized both by seismic and seismo-acoustic picks, yet the seismo-acoustic location results are significantly more precise. Seismo-acoustic amplitudes are strongly station-dependent, and are affected by the type of installation. Still, the uniform spatial coverage allows us to study the regional infrasound attenuation. We identified three separate acoustic phases with celerities of 332, 292 and 250 m/s, respectively; they probably represent tropospheric, stratospheric, and thermospheric phases, with each of them having its particular propagation direction.

Our findings highlight that regional infrasound propagation can be strongly anisotropic due to winds, and that the detection of such events strongly depends on station density and geometry.

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**.

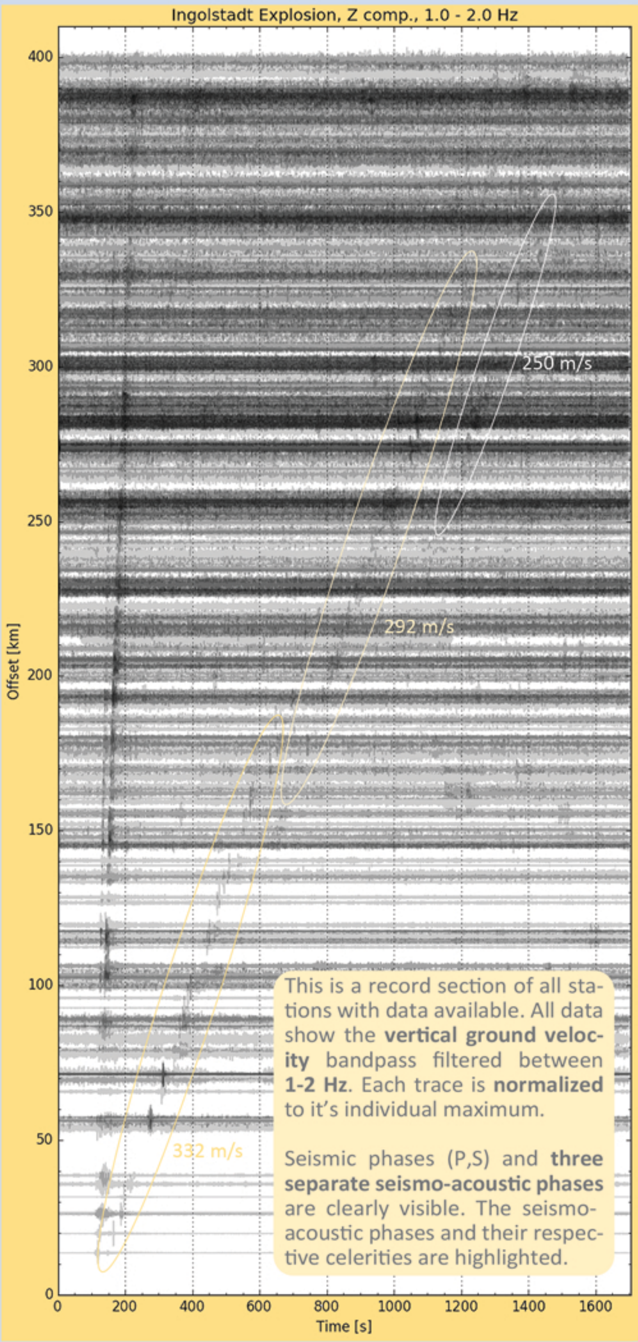


We acquired data from **400** broadband stations (100 sps continuous data, vertical component)

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**. 10 people were injured and 2000 people were evacuated from their homes in the vicinity of the refinery.

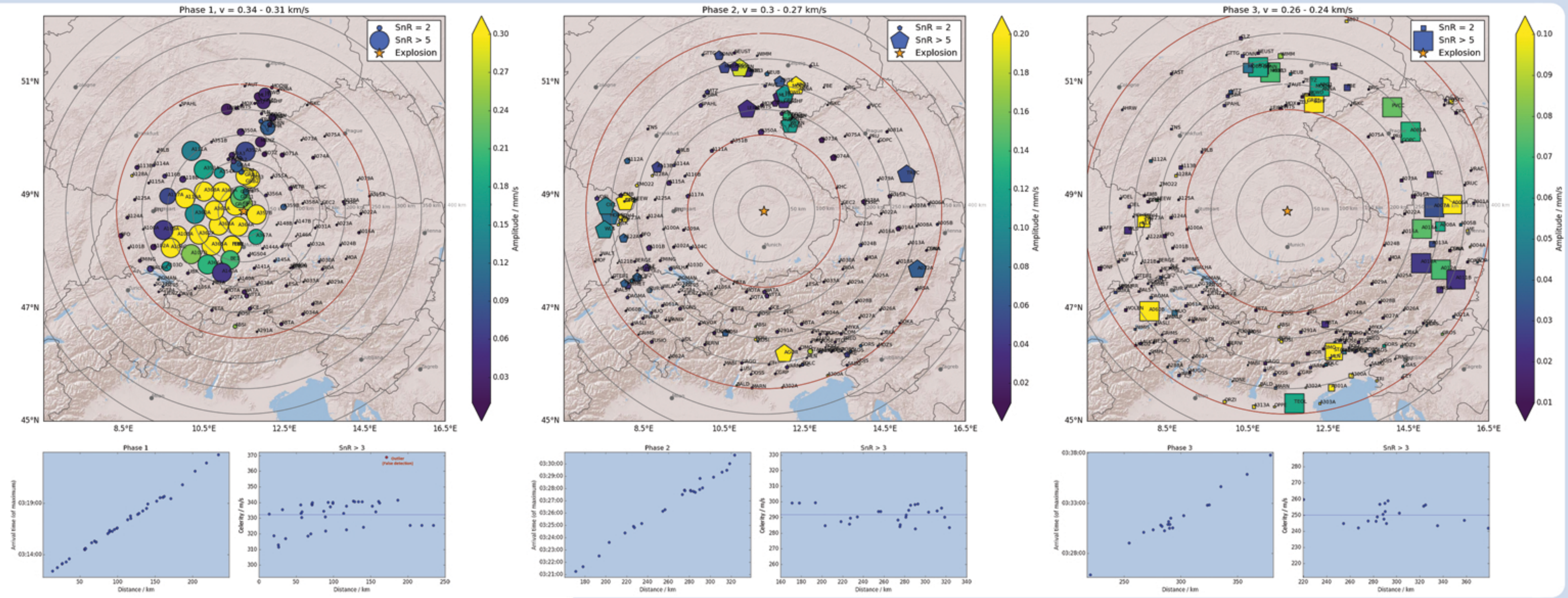
Seismic record section



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

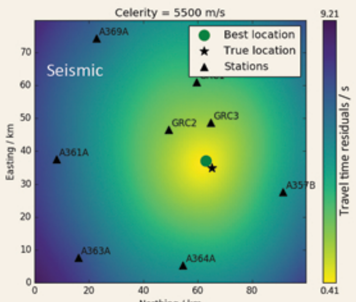


For each seismo-acoustic phase we evaluate the **vertical peak ground velocity (PGV)** in the **1–2 Hz frequency band**. In the maps above **colors indicate the PGV**. Note that color scales are truncated at different levels for each of the phases. The signal-to-noise ratio (SnR) is calculated as (PGV / 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 elswhere. 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 seismic network) and north-eastern (AlpArray stations existing, but no real-time data available) directions.

Localisation & origin time



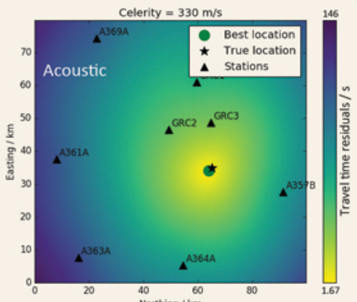
Seismic picks locate the source 3 km (i.e.two grid points along diagonal) north-west of the true origin,

Remaining residuals compared to total travel time: 0.41 s / 9.7 s = 4.2% (three times higher than 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 independetly used for a simple **grid search** routine that determines the epicenter and origin time. The grid search assumes a **constant propagation velocity** (5.5 km/s for seismic waves; 0.33 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)

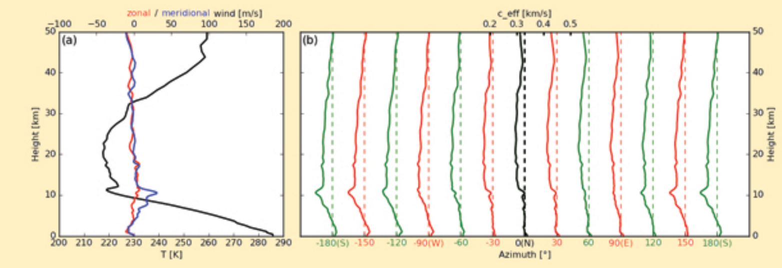
Origin time = 03:11:43 UTC
(based on acoustic picks)

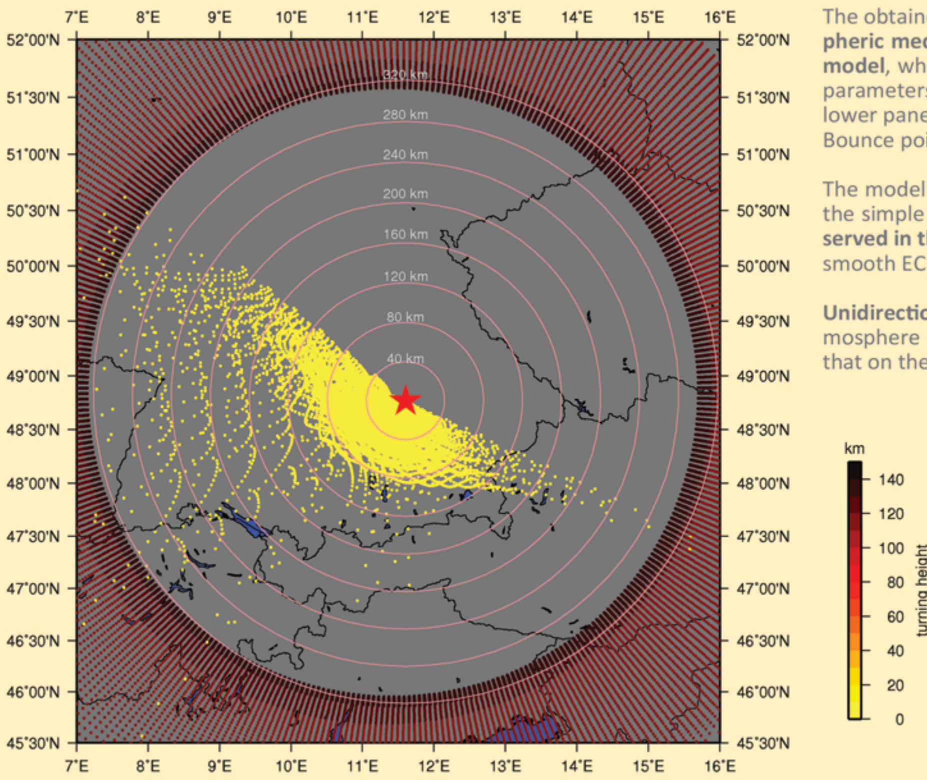


Acoustic picks locate the source 1.5 km (i.e. one grid point along diagonal) south-west of the true origin.

Remaining residuals compared to total travel time: 1.67 s / 110 s = 1.5% (three times lower than 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 andWaxler (2012). We extracted the required 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. **Vertical atmospheric profiles** for the 0–78 km altitude range were produced for the grid point closest to the explosion. As within 400 km from the source thermospheric arrivals are expected, we extended the ECMWF model to higher altitudes with a **generic thermosphere model**, that did not include any winds.

The obtained vertical atmospheric profiles were used to perform **raytracing in a stratified atmospheric medium**. From the final atmospheric parameters we derived a **1D effective sound speed model**, which is **anisotropic due to the wind direction**. The upper panel shows the atmospheric parameters and the effective sound speed model depending on the propagation azimuth. The lower panel displays **surface bouncing points** for all expected rays up to 350 km form the source. Bounce points are colored by the turning height of the respective wave. .

The modeling **results agree reasonable well** with our data for the **tropospheric reflections**. Yet, the simple modeling 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.

Unidirectional thermosphere reflections are in **contrast** with our data that shows potential thermosphere reflections exclusively in azimuths from 0° (North) to 110° (South-East). This suggests that on the day of the explosion north-easterly winds were present in the thermosphere.

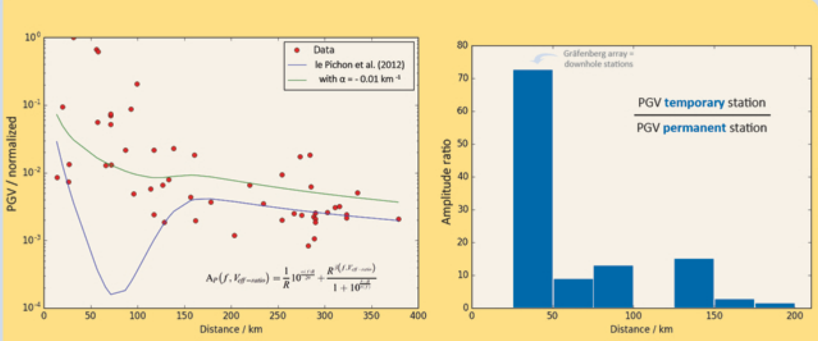
References

Blom, P. and Waxler, R.: Impulse propagation in the nocturnal boundary layer: Analysis of the geometric component, Journal of the Acoustical Society of America, 131, 3680–3690, doi:10.1121/1.3699174, 2012

le Pichon, A., Ceranna, L., and Vergoz, J.: Incorporating numerical modeling into estimates of the detection capability of the IMS infrasound network, Journal of Geophysical Research, 117, D05 121, doi:10.1029/2011JD016670, 2012

Schneider, F. M., Fuchs, F., Kolinsky, P., Caffagni, E., Serafin, S., Dorninger, M., Bokelmann, G., : Seismoacoustic signals of the Baumgarten (Austria) gas explosion detected by the AlpArray seismic network, Earth and Planetary and Science Letters, 502, 104–114, doi:10.1016/j.epsl.2018.08.034, 2018

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**. Notably, we observe that seismo-acoustic amplitudes are generally larger on the 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 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 **individual predominant wind directions** in **troposphere, stratosphere and thermosphere**.

Department of Meteorology and Geophysics | University of Vienna | Althanstraße 14 | 1090 Vienna | Austria

florian.fuchs@univie.ac.at