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Detection and properties of local artillery infrasound

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Background

Explosions excite infrasound , i.e., low-frequency sound (<20 Hz) that can be recorded at large distances from the source

Identifying explosive source characteristics from infrasound recordings would provide valuable data for defense and civilian purposes

However, the detectability of infrasound (i.e, acoustic amplitudes and spectral characteristics) is highly dependent on atmospheric models. Correlations between source type, source-receiver distance, and wind anisotropy are not well constrained

Is there any invariance in waveform characteristics with specific explosive sources and weather properties?

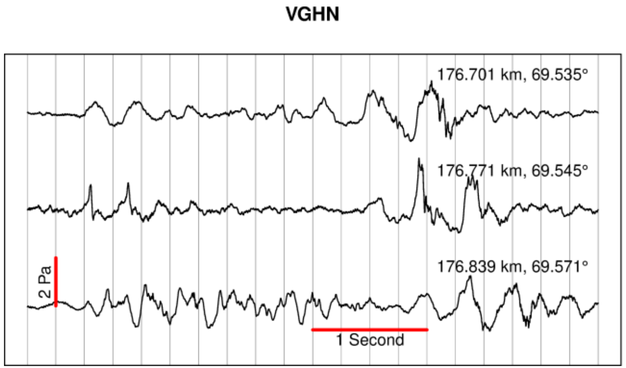


Fig: Recorded infrasound from identical ground chemical explosions occurring tens of seconds apart. From Bowman, et al, AGU 2020

Infrasound propagation

Infrasound can be excited by a variety of natural (e.g., volcano, earthquakes) and man-made sources (e.g, explosions, aircrafts)

Because of its low frequency content, infrasound can propagate over large distances without being attenuated and then be recorded at the ground

Infrasound ray paths in the atmosphere are dependent primarily on wind variations with altitude (see Fig 1)

Three types of infrasound phases (as well as infrasound converted to seismic phases) can be excited by artillery shots (see Fig 2): muzzle, projectile, and impact

Can we use these phases to better constrain the source?

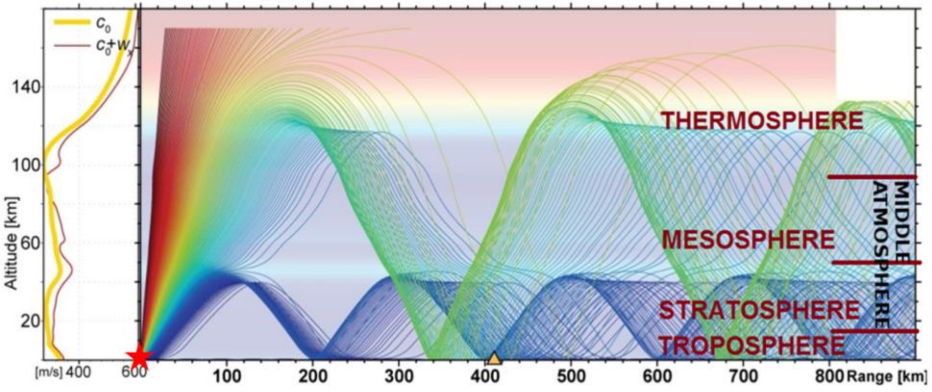


Fig 1: Right, infrasound ray paths from the source (red star). Acoustic refractions occur for positive effective velocity gradients. Left, sound velocity (c_0) and effective sound velocity (c_0+w_x) profiles, with w_x = wind.

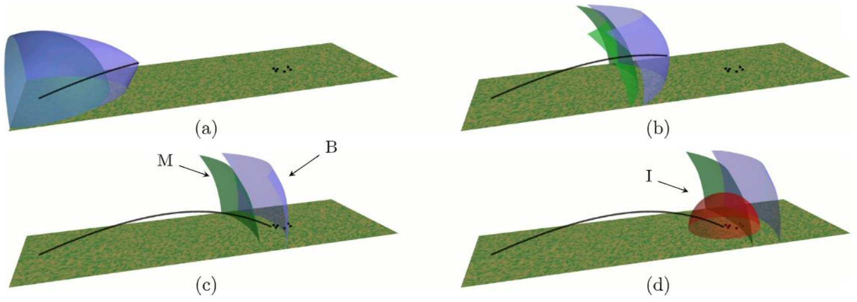


Fig 2: Sketch of artillery shot. The muzzle blast, ballistic shockwave and impact signal (M, B, and I, respectively) are displayed at different times. The projectile trajectory is the black line. From Dagallier, 2019

Ray path sensitivity to wind conditions

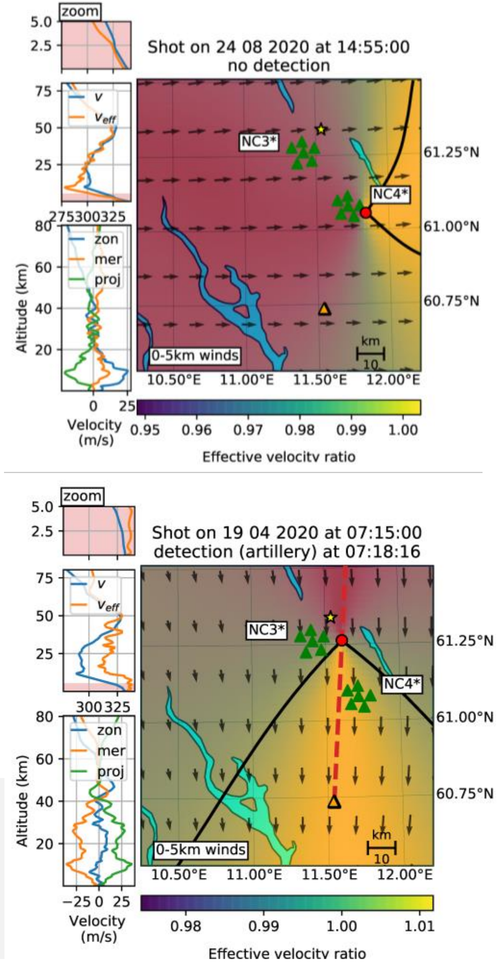
The strength of the wind blowing in the direction of a receiver from a given source primarily controls the detection likelihood.

Wind strength along the source-receiver path is characterized by the effective velocity, i.e., sound velocity + wind along source-receiver path

Effective velocity ratio map provide a qualitative metric to assess the likelihood of a refraction in a given altitude range between a source and a receiver

$$\frac{Average\ effective\ velocity\ in\ a\ given\ altitude\ \mathrm{range}}{Effective\ velocity\ at\ ground\ level}\ \begin{cases} < 1 & \text{Unlikely refraction} \\ > 1 & \text{Likely refraction} \end{cases}$$

In this study, we extract wind properties from the atmospheric model ERA5 reanalysis at the ECMWF



Figs: Effective velocity ratio maps for artillery shots on two different days. An arrival was detected on April 19 but none on August 24. On the left we show the wind and effective velocity profiles.

Dataset

The Norwegian armed forces provided ground-truth data about a large number of live fire exercises in Southern Norway in 2019-2020 (see video)

Multiple artillery ammunition types (3 explosive and 1 non-explosive), muzzle velocities, and target ranges were tested

NORSAR runs three permanent seismic arrays and one infrasound array at close proximity of the area of the military exercises

This unique dataset enables us to study dependences between waveform characteristics and source or environmental factors

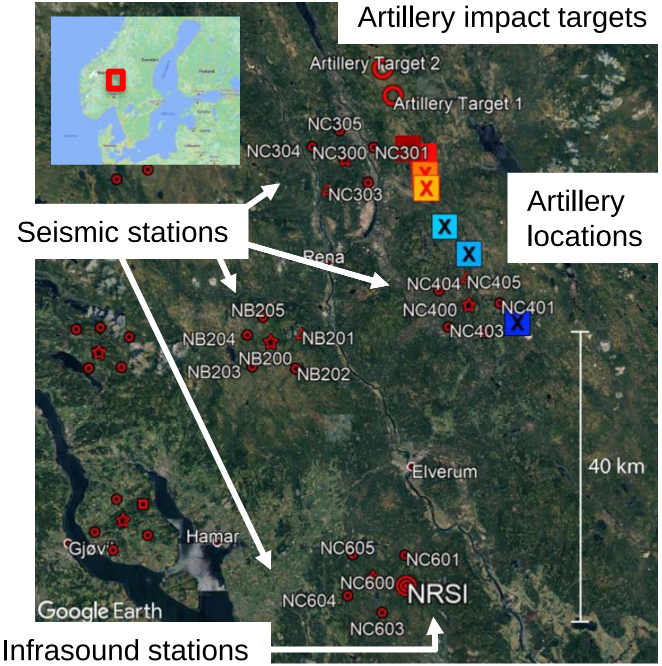


Fig: Map showing artillery targets (red circles), artillery locations (square with cross), seismic stations (NC and NB arrays), and infrasound stations (NRSI)

Identifying artillery infrasound and seismic phases

We used a Capon FK analysis to detect acoustic and seismic phases from the artillery and impacts

With a known shot time, we can identify the source mechanism behind each detected phase by comparing their velocity across all stations

Below, we highlight the variations in detected phases by showing recordings from shots on different days and using different types of ammunition

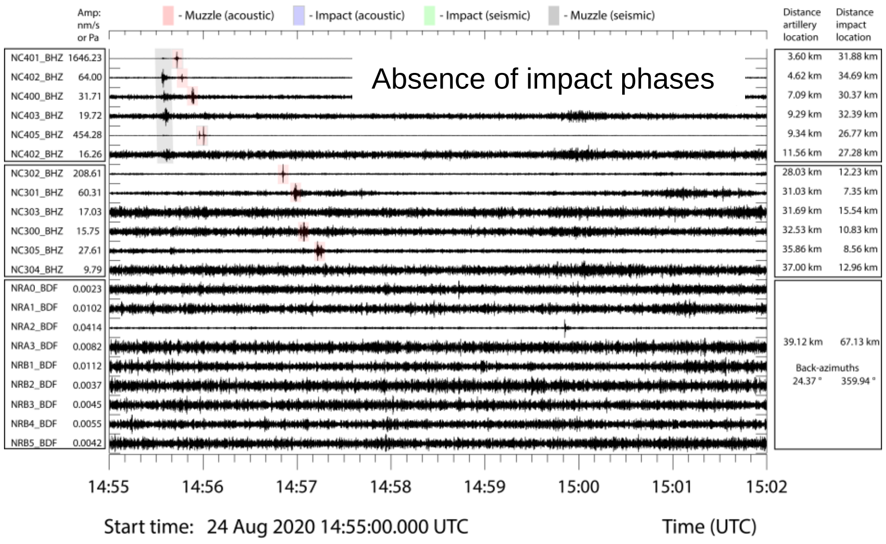


Fig 1: Seismic (NC3-4) and infra. (NR) timeseries after shot on Aug. 24

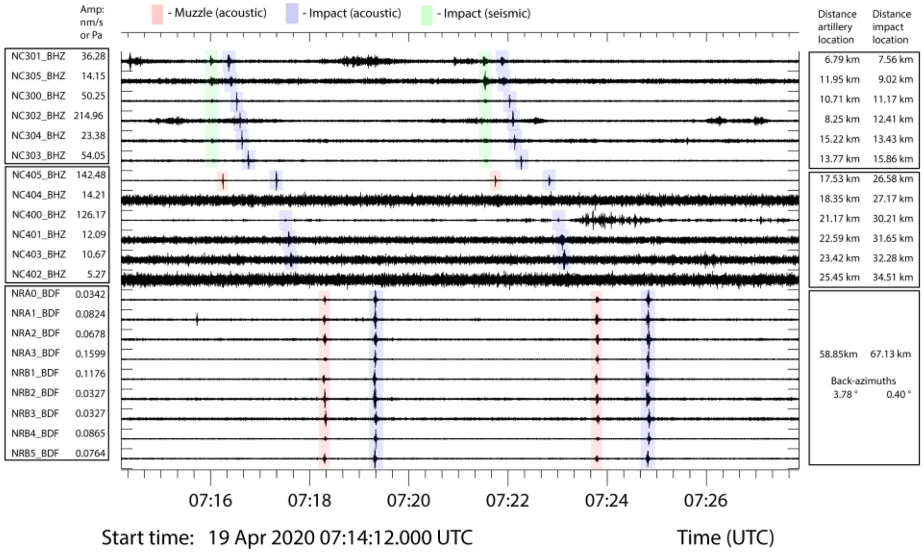


Fig 2: Seismic (NC3-4) and infra. (NR) timeseries after shot on Apr. 19

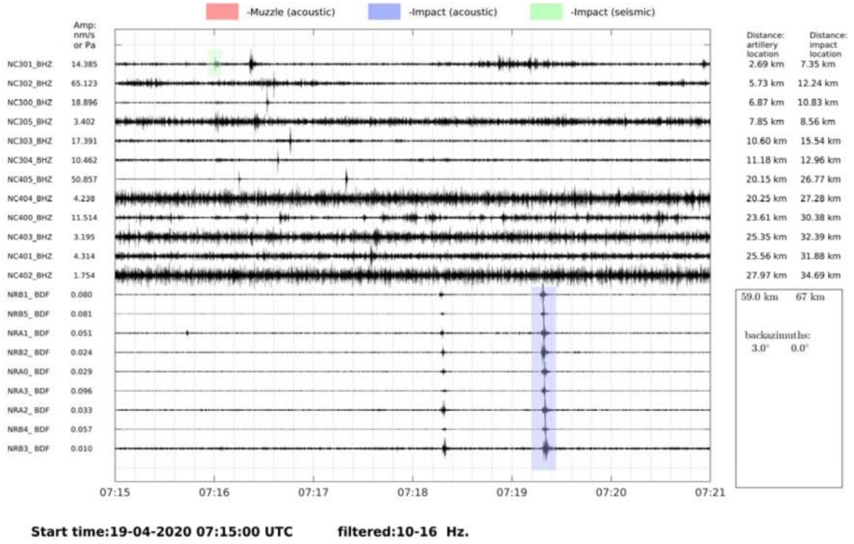
Locating the source

Using both artillery acoustic and seismic arrival times, we can iteratively optimize the source location for a given seismic velocity model (e.g., HYPOSAT, Schweitzer, 2001). For this preliminary inversion, we considered a fixed infrasound celerity

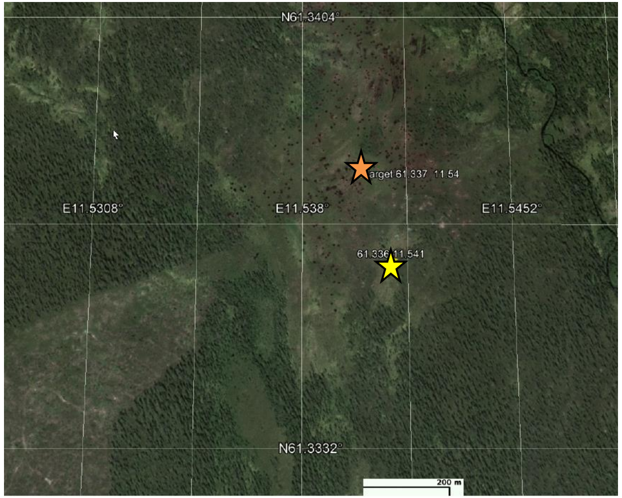
When both converted seismic phases are observed near the impact or the muzzle (< 5km), accurate location can be extracted (see Figs)

Without converted seismic phases, the inversion is subject to larger uncertainties owing to the assumption of fixed celerity

With additional infrasound stations, and by including uncertainties in wind models, source at larger distance from the receivers could be efficiently inverted for (e.g., Blom, 2015)



Figs: Top, Seismic (NC3-4) and infra. (NR) timeseries after shot on Apr. 19. Bottom, inverted (orange) and true (yellow) impact locations on Apr 19.



Investigating wind, source, and waveform correlations

By detecting and identifying phases across the full dataset, we can observe some specific correlations:

Detectability of high-frequency artillery shots within 70 km is tied to high effective velocity ratio for lower tropospheric wind conditions (< 5 km altitude)

Ammunitions with impact explosions increase the detectability likelihood. However, muzzle blasts excite strong infrasound and can provide important constraints on the source even at source-receiver distances up to 70 km

Correlations with muzzle velocity can not be resolved since muzzle velocities were strongly correlated to the distance to the artillery

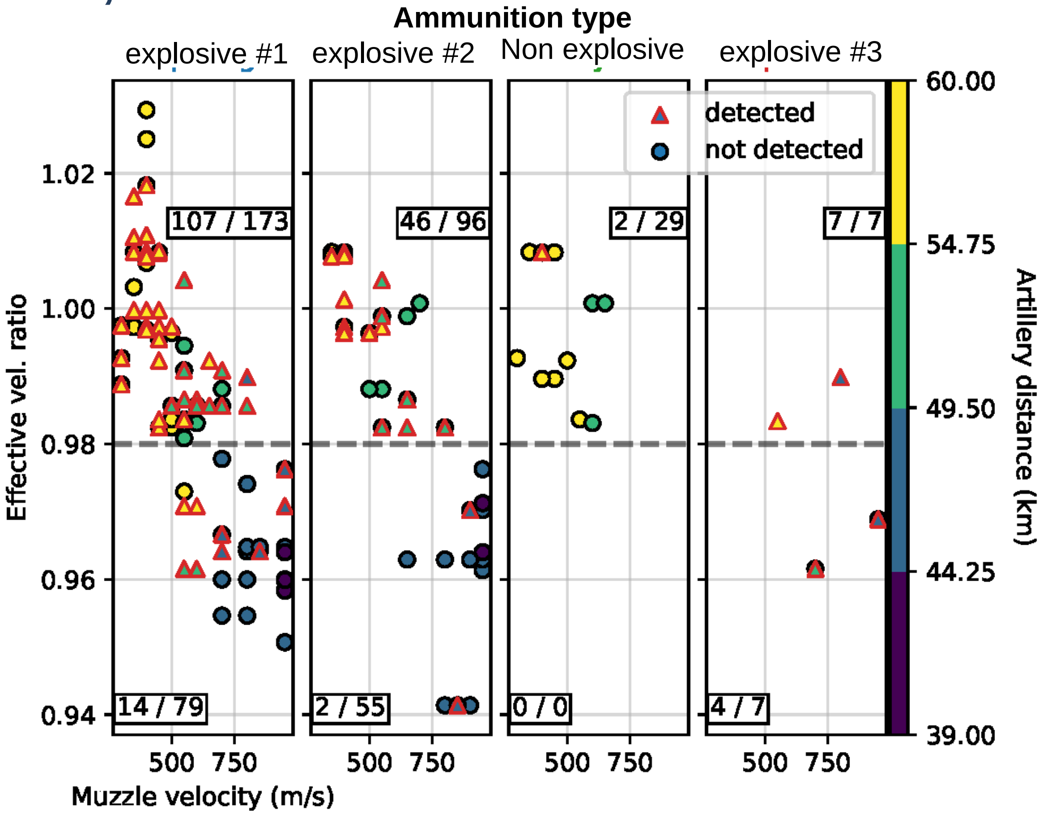


Fig: Detection of at least one artillery phase and non detection for each shot vs muzzle velocity and effective velocity ratio in the 0-5km altitude range. Results shown for 4 different ammunition types. Points are color-coded with the source-infrasound station distance.

Investigating wind, source, and waveform correlations

By plotting the waveform characteristics of detected artillery and impact phases, we can note a few additional points:

No obvious correlations between the phase type and the signal dominant frequency

No obvious correlations between the effective velocity ratio and the dominant frequency

No obvious correlations between the muzzle velocity and the dominant frequency

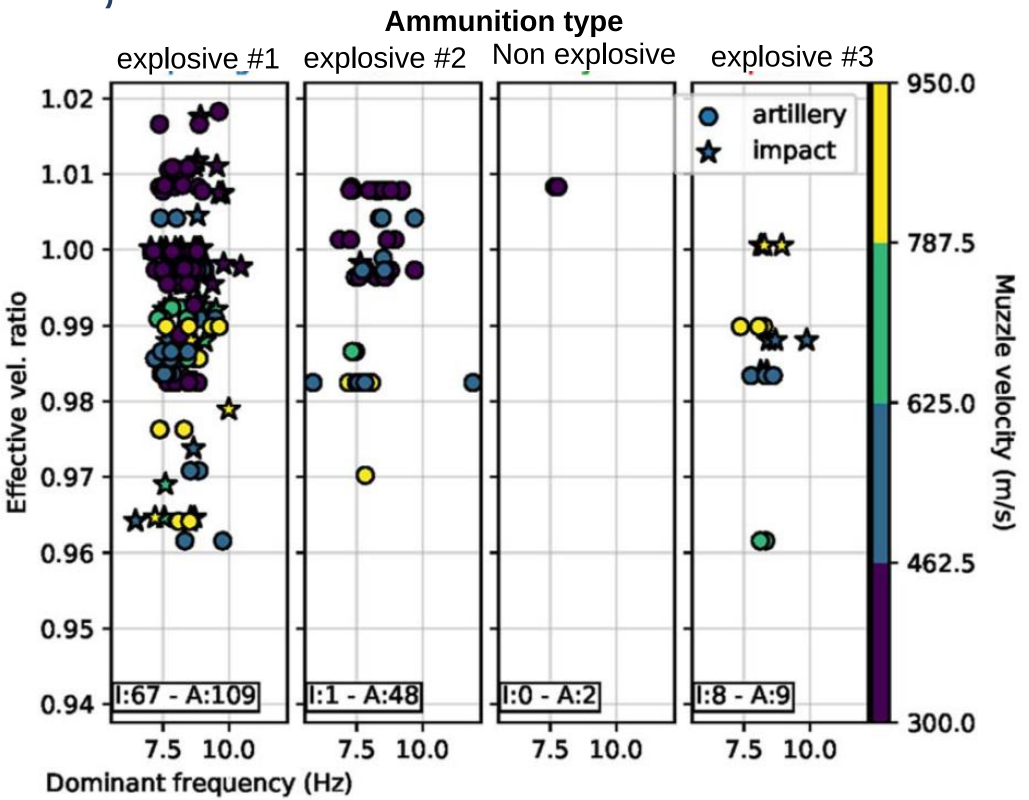


Fig: Detected artillery and impact phases vs signal dominant frequency and effective velocity ratio in the 0-5km altitude range. Results shown for 4 different ammunition types. Points are color-coded with the muzzle velocity.

Investigating wind, source, and waveform correlations

While dominant frequencies do not show strong correlations with other source or wind inputs, energy ratio between high (> 15 Hz) and low (< 15 Hz) frequencies show a dependency on the phase type. Impact phases seem to show more high frequencies.

We also observe a correlation between this ratio and the effective velocity ratio. The larger the ratio, the more energy at high frequency

However, muzzle velocity does not show any correlation with the energy ratio

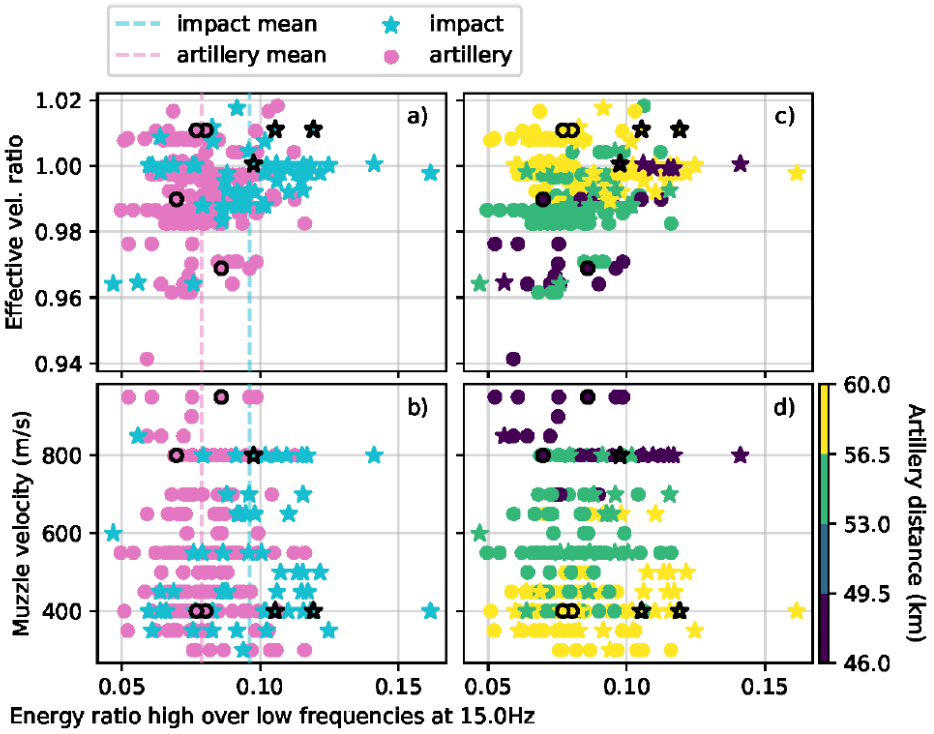


Fig: Detected artillery and impact phases vs energy ratio and effective velocity ratio in the 0-5km altitude range. Points are color-coded with the artillery distance.

Conclusion / future directions

Conclusion

Four different artillery phase types were observed from the military exercises studied: Seismic and acoustic artillery phases, and seismic and acoustic impact phases.

Lower tropospheric winds (< 5 km, extracted from the ERA5 reanalysis) primarily control the detectability of impact and artillery phases within 70km from both sources

The phase types (from the artillery muzzle or the impact) show differences in spectral energy distribution which can be used to discriminate between these two signal types.

The accuracy of estimated artillery and impact locations can be improved by including seismic phase observations at stations in the vicinity of the source (e.g., within 15 km).

Future directions

Only a few waveform, winds, and source parameters were compared to study correlations. An investigation of additional parameters (e.g., horizontal wind variations, spectrogram features, signal duration) should be carried out.

For future military exercises we propose to improve the spatial coverage of the signal observations by deploying additional infrasound and seismic stations

References

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Dagallier, A., Cheinet, S., Cosnefroy, M., Rickert, W., Weßling, T., Wey, P., & Juvé, D. (2019). Long-range acoustic localization of artillery shots using distributed synchronous acoustic sensors. The Journal of the Acoustical Society of America, 146(6), 4860-4872.

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Abstract

Acoustic-wave detection from man-made sources like explosions and artillery is of interest both for civilian and military purposes. Infrasound propagation from surface sources is controlled by a complex interplay between source location, winds, atmospheric attenuation, and topography. The seasonal and stochastic variability of stratospheric and tropospheric winds is known to play an important role in the detectability of infrasound on the ground. In particular, large wind-intensity variations occur between summer and winter months. However, the lack of high-quality observational datasets with good temporal coverage throughout the year limits our understanding of the correlations between source characteristics, range-dependent atmospheric properties, and topography. Here, we take advantage of an extensive set of artillery exercises, conducted by the Norwegian Armed Forces in southern Norway throughout 2020, to constrain the detectability and wave properties at local distances. Up to 70 km distance, signals are generally observed when the atmospheric models include stronger lower-tropospheric winds (1-5km altitude) blowing in the direction of propagation. When cross winds dominate the wind field, low-amplitude infrasound arrivals are still observed in the acoustic shadow zone while not predicted by ray-tracing simulations, highlighting both model and propagation uncertainties introduced by small-scale wind heterogeneities and diffraction effects.