Broadband seismic effects from train vibrations

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Abstract

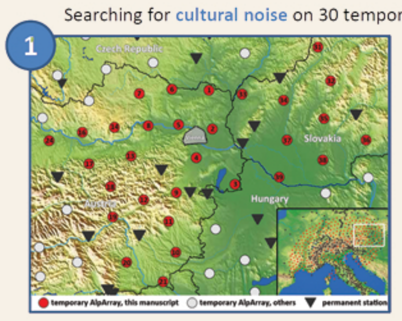
We analyze in detail the seismic vibrations generated by trains and measured at distance from the track with high sensitivity broadband sensors. We show and analyze various train vibration signals obtained from a set of seismic broadband stations temporarily installed for the AlpArray project.

The geometrical restrictions of the network resulted in a number of instruments deployed in the vicinity of railway lines. On seismic stations within 1.5 km of a railway we observe characteristic seismic signals which we can relate to the passage of trains. All train signal share a characteristic feature of sharp equidistant spectral lines in the entire 2--40 Hz frequency range. For a site located 300 m from a busy track we study the train records in detail. Here, frequency spacing is between 1 and 2 Hz and relates to train speed. From the spectrograms of individual trains we can identify acceleration and deceleration phases which match well with the expected driving profile for different types of trains.

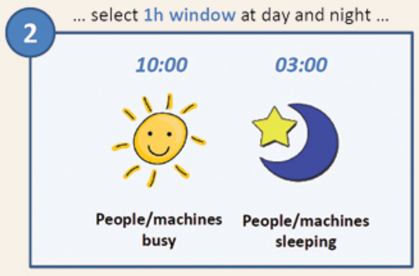
We discuss possible mechanisms which could be responsible for the strikingly equidistant spectral lines. We search for Doppler effects and compare the observations with theoretically expected values. Based on a cepstrum analysis we finally suggest quasi-static axle load by consecutive bogies as the dominant mechanism behind the 1--2 Hz line spacing. The striking feature of the equidistant spectral lines within the train vibrations renders them quite outstanding seismic sources which may have potential for seismic imaging.

Workflow

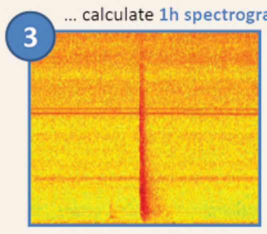
1 Searching for cultural noise on 30 temporary broadband stations ...



2 ... select 1h window at day and night ...



3 ... calculate 1h spectrograms for each day

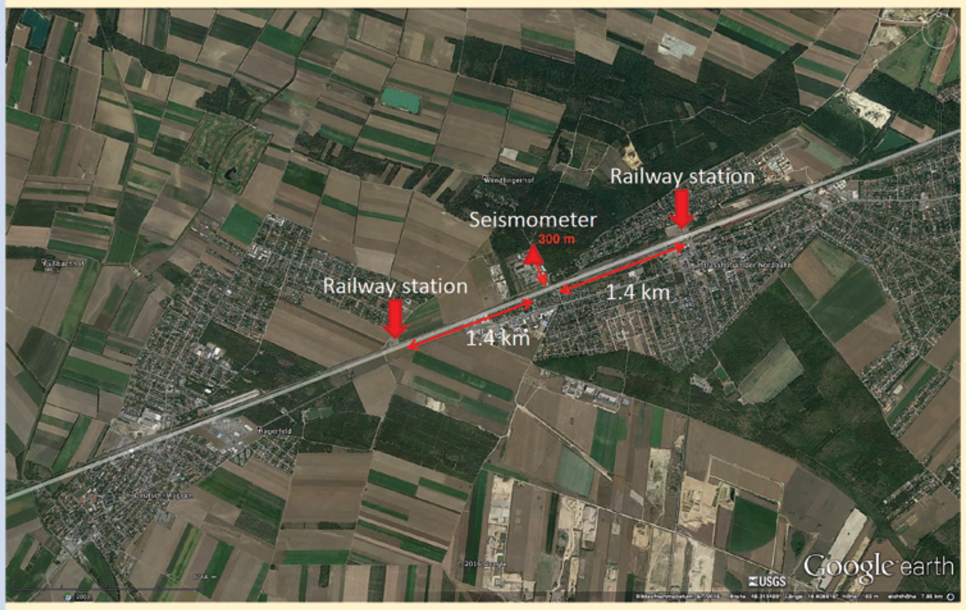


5s window length
90 % overlap
Logarithmic color scale

Many stations show marked, repeating peaks at day times which we could relate to passing trains. All of such train signals show pronounced spectral lines with constant spacing over a wide frequency range. Here we present measurements from a well documented stations near Vienna.

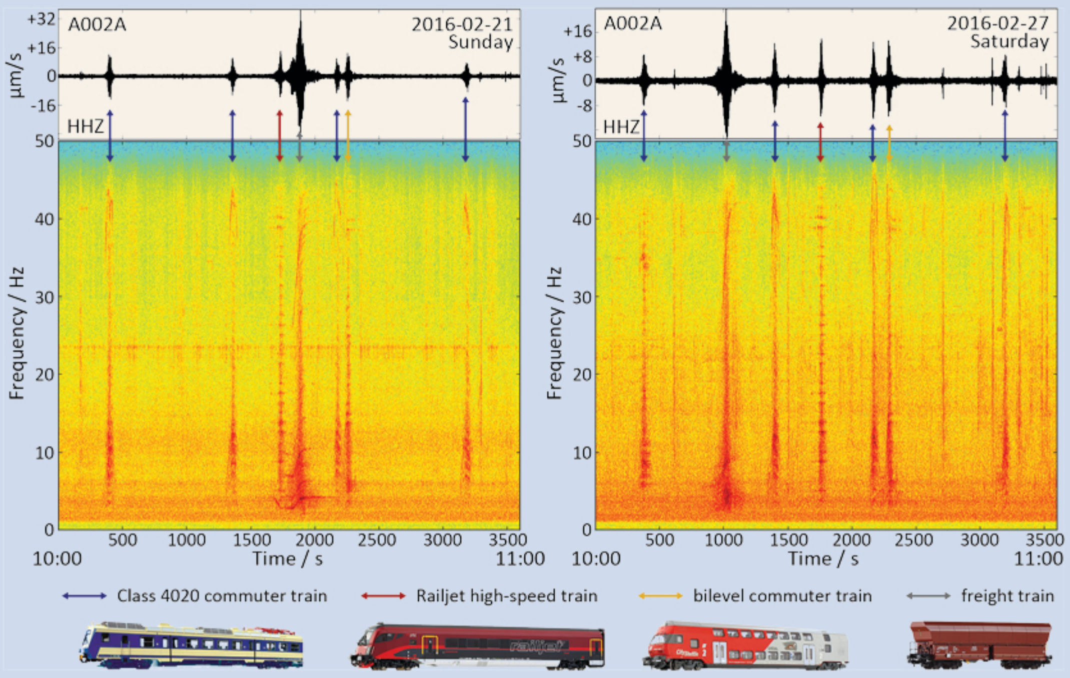
Map and geometrical setting

A002A Strasshof a.d. Nordbahn, Austria (25 km NE of Vienna)



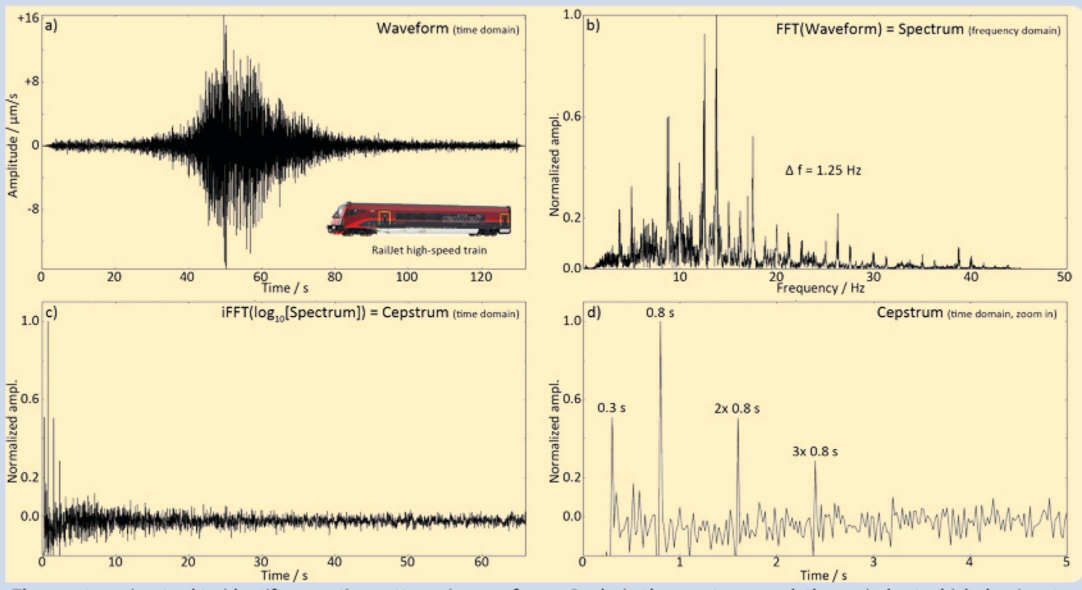
300 m from main railway to NE Austria & Czech Republic (Gänserndorf, Breclav, Brno, Prague, ...)

Spectrogram examples



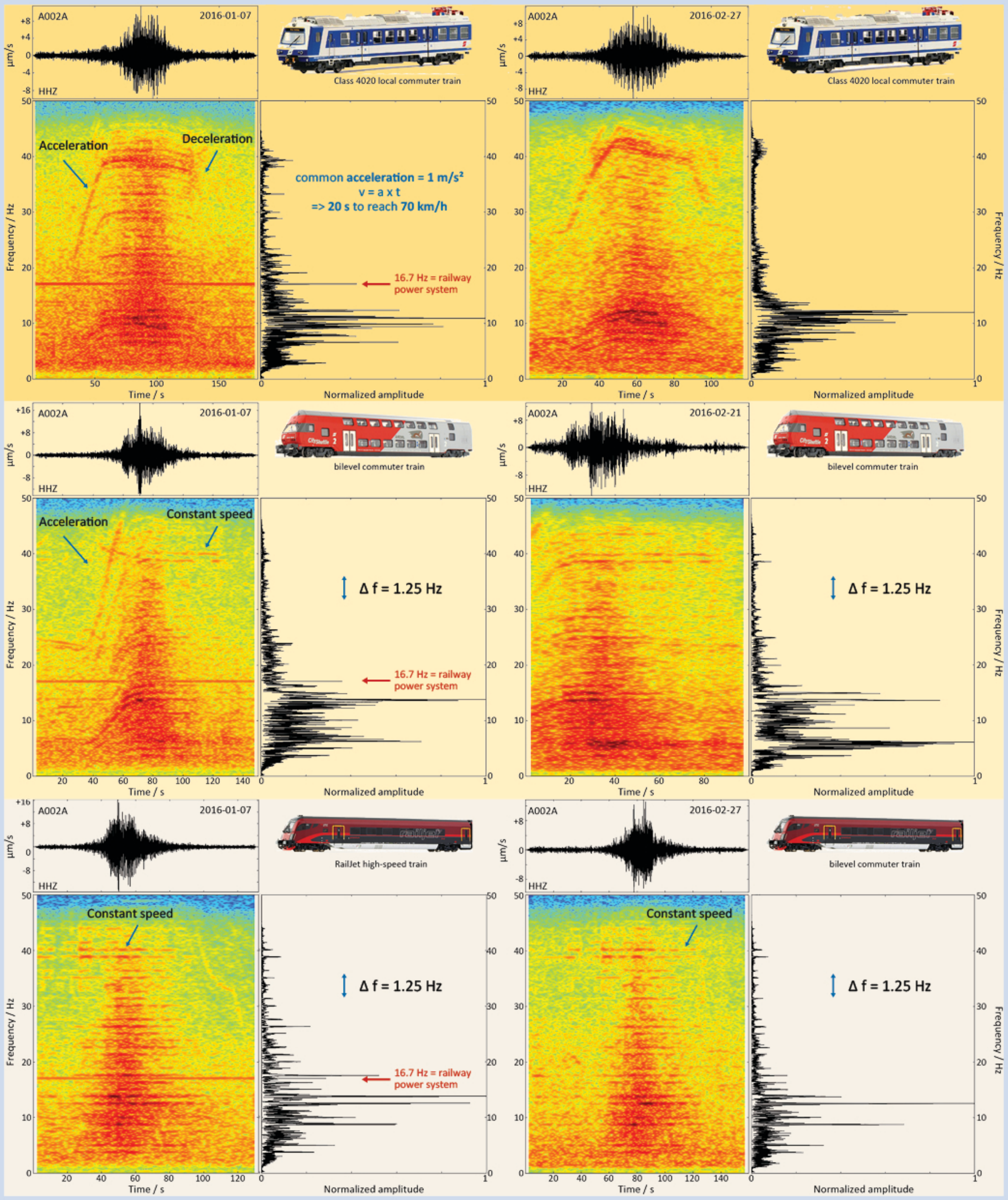
Ground velocity waveforms (upper panels) and spectrograms (lower panels) at station A002A. Left and right panel show the same 1 h time window starting at 10 AM local time on a Sunday and Saturday, respectively, when there is little cultural noise other than the train signals. Colored vertical arrows mark the train signals with the color indicating the type of train). Spectrograms were calculated with time windows of 5 s and 90% overlap, and the color scale is logarithmic. Note the frequency cut-offs towards 50 Hz (due to 100 Hz data sampling rate) and below 2 Hz (high pass filtering to enhance visual signal-to-noise ratio).

Cepstrum analysis

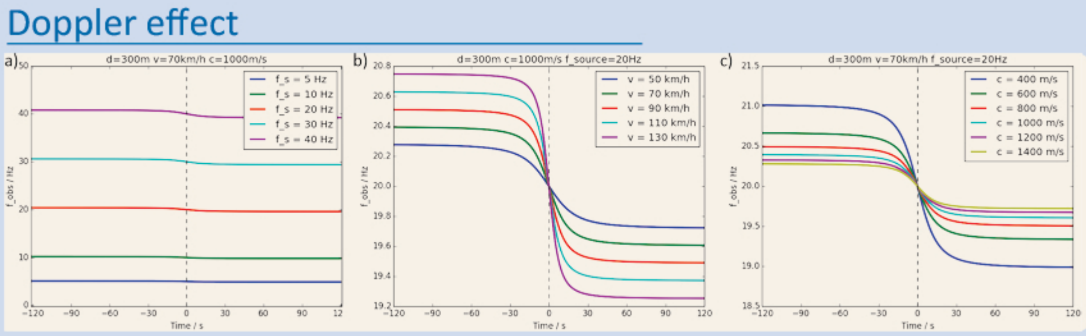


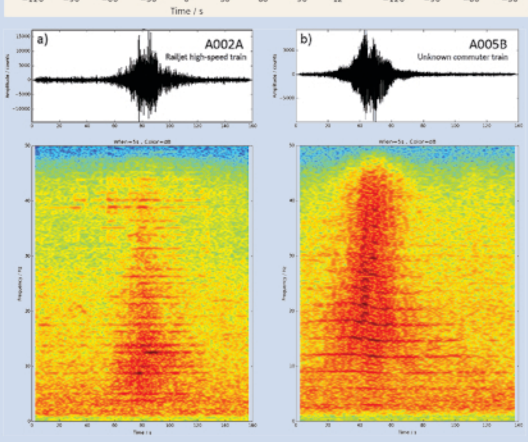
The cesptrum is a tool to identify repeating patterns in waveforms. Peaks in the cepstrum mark the periods at which dominant patterns in the waveforms repeat. This example is for the Railjet high-speed train. a) Raw waveform in units of velocity. b) Spectrum of the waveform. c) Cepstrum of the waveform. d) Zoom onto the main peaks in the cepstrum. The highest peak in the cepstrum (0.8 s) corresponds to a frequency spacing of Δf = 1/0.8 s= 1.25 Hz. The peaks at longer periods are higher orders of the main peak. A patch of signal repeating each 0.8 s is also visible in the waveforms when zooming in.

Individual trains in detail



Doppler effect





If the dominant source of vibrations is moving we expect to observe a Doppler effect. We calculated expected frequency shifts for the setting at A002A and compared it to the observations.

Top: Calculated Doppler effect with variable parameters. Frequency shifts of up to 2 Hz between approaching and departing train would be expected, depending on train speed and seismic wave propagation velocity. The distance of the seismometer to the track is fixed to 300 m. a) Variable source frequencies, b) Variable train speed, c) Variable propagation velocity. Note, that given the frequency scale of the spectrograms in this work (see panel a, 0 to 50 Hz) clear Doppler effects may only be directly observed for slow seismic velocities and higher source frequencies since Doppler effect is proportional to the source frequency.

Left: a) Example of a high-speed train showing no Doppler effect at all. b)) Example of an unknown train, potentially showing Doppler effect. Note the apparent transition to lower frequencies between approaching and departing part.

Possible mechanisms

Irregular surface of train track
(stationary)

Spacings in train track no longer exist

Bridges / Switches

Surface roughness of rail

No Doppler effect expected

Frequencies depend on train speed

Constant frequencies not expected over several kilometers of train track

→ no

Irregular surface of train wheels
(moving)

„Out of roundness" of wheels
Doppler effect expected
Frequency depends on wheel diameter and train speed

⌀ = 92 cm (for RailJet)
=> Circumference = 2.9 m

Rotation frequency:
⇒ 5 Hz @ 50 km/h
⇒ 7 Hz @ 70 km/h

too high to explain frequency spacing

no such peak in Cepstrum

→ no

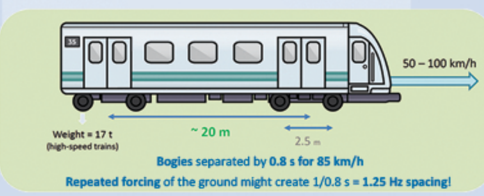
Quasi-static axle load
(stationary? moving?)

Axle load and response of ground

Doppler effect unclear

Only in near field?

Frequency depends on wagon length and train speed



→ yes

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