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Acoustic-Seismic Coupling of Broadband Signals - Analysis of Potential Disturbances during CTBT On-Site Inspection Measurements

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Disturbing Seismic Signals During CTBT On-Site Inspections caused by Acoustic-Seismic Coupling

For the verification of the Comprehensive Nuclear Test Ban Treaty (CTBT) the precise localisation of possible underground nuclear explosion sites is important. During an on-site inspection (OSI) sensitive seismic measurements of aftershocks can be performed, which, however, can be disturbed by other signals. To improve the quality and effectiveness of these measurements it is essential to understand those disturbances so that they can be reduced or prevented. In our work we focus on disturbing signals caused by airborne sources: When the sound of aircraft (as used by the inspectors themselves) hits the ground, it propagates through pores in the soil. Its energy is transferred to the ground and soil vibrations are created which can mask weak aftershock signals. The understanding of the coupling of acoustic waves to the ground is still incomplete. However, it is necessary to improve the performance of an OSI, e.g. to address potential consequences for the sensor placement, the helicopter trajectories etc. We present our recent advances in this field.

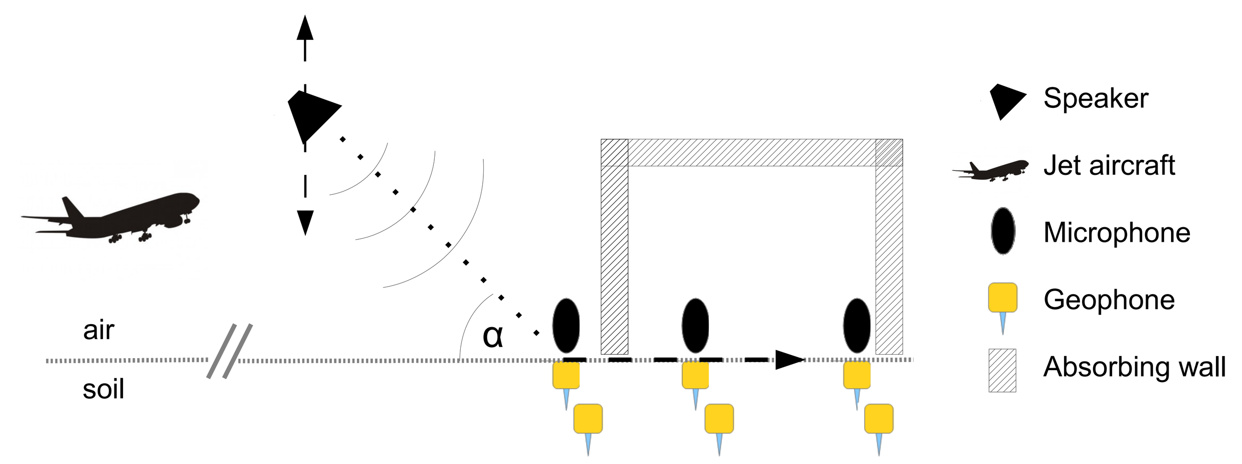
In this research we want to answer the following questions:

- Is the coupling of acoustic signals to the ground a local process or do acoustically induced propagating seismic waves contribute to the measured seismic response?
- Can seismic surface waves be excited by an acoustic plane wave incident on a large area of layered soil?
- What time is required for the transfer of acoustic energy to soil vibrations?

With a better understanding of the interaction of acoustic waves and the ground we aim to develop recommendations for sensitive seismic measurements during CTBTO on-site inspections to reduce disturbing vibrations caused by airborne sources.

Acoustic-Seismic Measurements

Several acoustic and seismic sensors were installed below the take-off trajectory of an airport (Münster-Osnabrück, Germany: FMO) at 4 km distance. Therefore taking off and landing jet aircraft passed nearly straightly above the setup. Microphones were placed close to the ground to record the sound pressure of incident acoustic signals and geophones were buried in different depths to measure the soil velocity. To separate local coupling from excitation further away from the sensors a wooden box (1 m * 1 m * 0.5 m) coated on the inside with acoustic damping foam was placed over some acoustic and seismic sensors to reduce the power of the incident acoustic signals and thus the locally created seismic vibrations.
Additionally, a speaker was used to provide known and reproducible broadband reference signal which, however, are not discussed here.



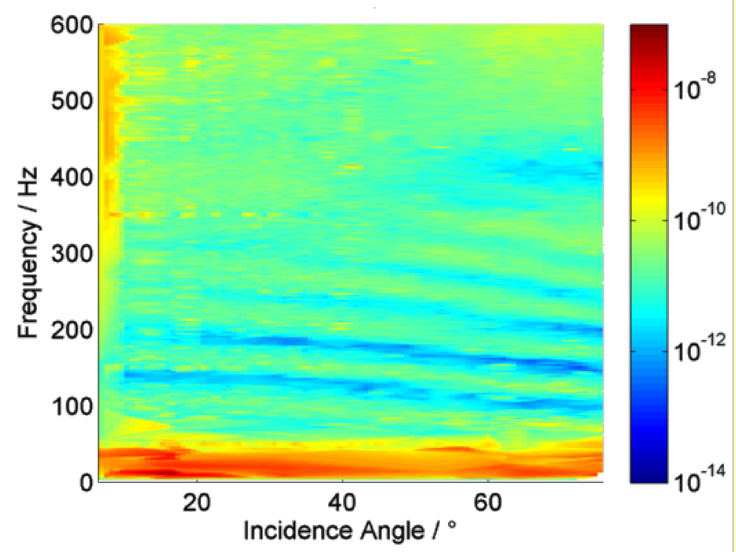
Sketch of the used measurement setup:
The angle of incidence is marked as the angle between ground surface and the vector pointing to the source of the acoustic signals.

The applied acoustic damping reduced the amplitude of the sound pressure significantly by a factor of 10 (for frequencies above 100 Hz) up to a factor of 40 (frequencies above 600 Hz). Soil velocity was reduced much less: at the surface roughly by a factor of 3 for frequencies up to 350 Hz and a factor 5 – 10 above this value; with increasing depth the reduction of soil velocity decreased. **This indicates that propagating soil vibrations excited outside of the box contribute to the measured seismic signal considerably.**

Measurement of an Aircraft Overflight

For several aircraft overflights sound pressure and soil velocity were recorded. With the coordinates of the trajectories of the aircraft we calculated the direction of incidence of the acoustic signal hitting the ground. The measured data were synchronised with the trajectory using a GPS clock while the time of propagation from aircraft to sensor was taken into account.
For a geophone at the surface we show a plot of the ratio of the spectral power of sound pressure over the spectral power of soil velocity which is a measure of coupling strength from acoustic signals into the ground, versus angle to the source and frequency. The data were recorded while a single jet aircraft overflight approached the sensor setup.

Observation:
Several frequency bands of increased and decreased coupling strength are observed the frequency of which decreases with increasing angle of incidence. They are equally spaced in the frequency domain and the coupling strength varies between minima and maxima by more than one order of magnitude.



Explanation:
The acoustic signal alone does not show these features – they result from propagation of the vibrations in the soil. The alternating bands of increased and decreased coupling strength can be explained as an interference pattern of seismic waves: the soil vibrations excited directly by the incident acoustic wave superpose with the seismic wave reflected at a boundary layer in the ground.
Literature predicts a phase change of -π for the seismic wave reflected at the surface [3,4] which holds true in our evaluation as well. Thus, the path difference for maximal constructive interference is given by:

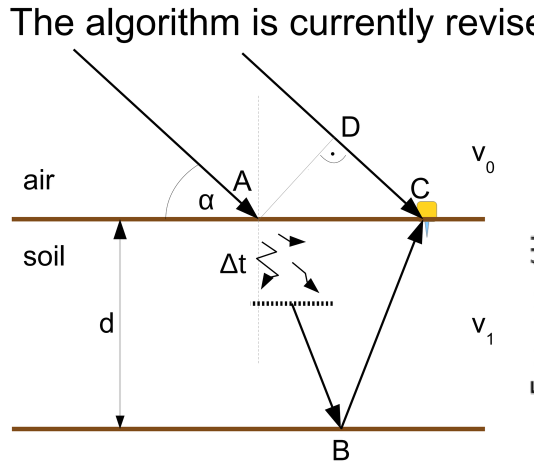
$$\Delta x_{max} = (k+1/2)\lambda \quad (k=0,1,\ldots)$$

With this we can calculate the theoretical frequencies of constructive interference. To fit the measurement data to the theoretical expression it might be necessary to take into account a certain time delay for the exchange of energy from the sound pressure wave to the matrix wave of soil particles.

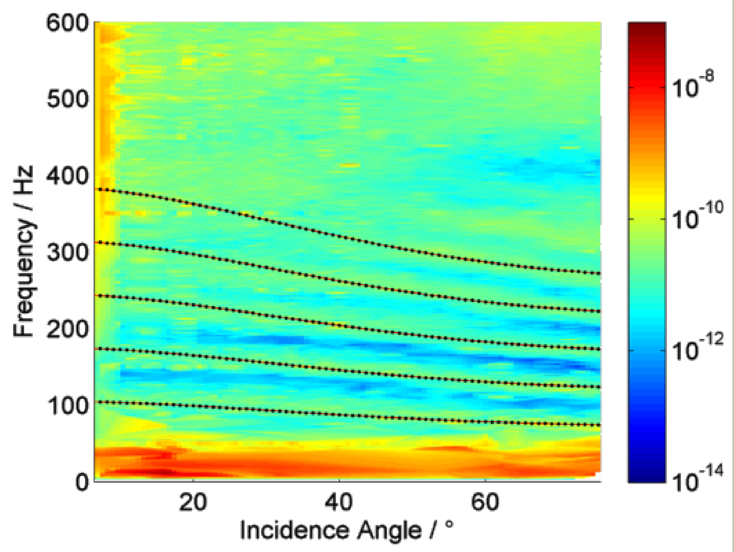
Additional time delay for energy transfer:
Applying a time delay (in the path of the reflected wave) the expression for the frequencies of constructive interference is given by:

$$f_{max} = \frac{(k+1/2)\,v_1}{2d\sqrt{(v_0/v_1)^2 - \cos^2(\alpha)} + \Delta t\, v_1}$$

with v_0 = 343 m/s - the speed of the sound wave, v_1 - the unknown wave velocity in the ground, *d* - the unknown depth of the boundary layer, α - the angle of incidence and *Δt* the applied time delay (see sketch below).
The fit leads to good results which are plotted (for values of k = 1 to 6) in the graph on the right (black dots) together with the calculated values for Δt=0 (red line). The fit parameters are:
v_1 = 255 m/s, *d* = 1.79 m, *Δt* = 1.7 ms (black dots)
v_1 = 246 m/s, *d* = 1.82 m, *Δt* = 0 ms (red line)
The algorithm is currently revised to improve stability of the solutions.



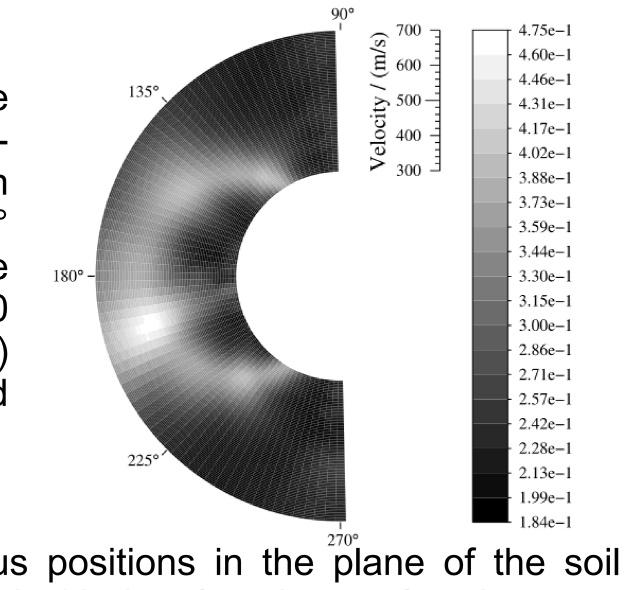
Sketch for interference between soil vibration excited directly by incident acoustic plane wave and reflected soil wave with time delay for energy transfer.



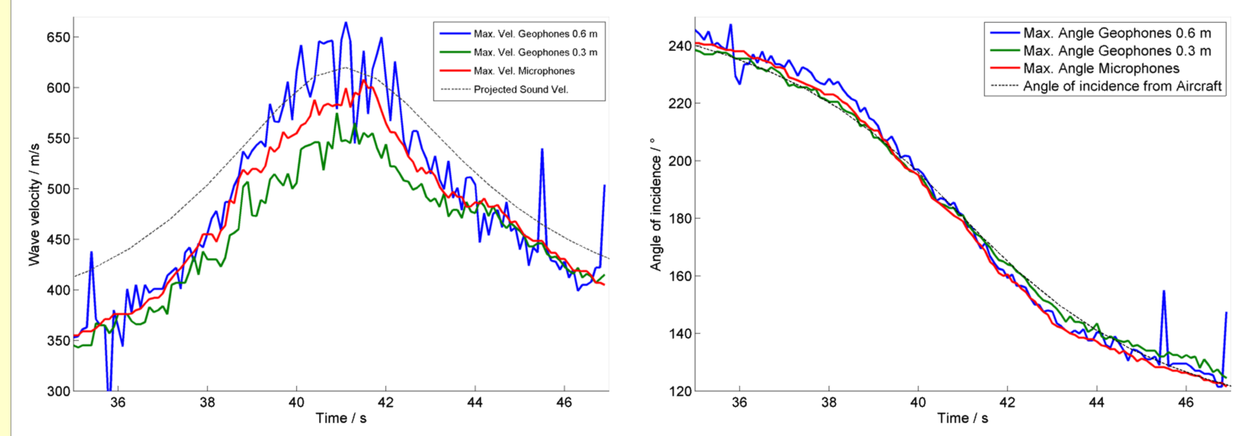
Beam forming

To determine the azimuthal direction and speed (parallel to the surface) of the waves contributing to the measured seismic signals we applied an established beam-forming algorithm to the data: When using an array of sensors and with the assumption of an incident plane wave the wave fronts reach the sensors with certain time delays. The theoretical time delays for a range of angles and wave speeds are computed and the signals recorded at the various positions are shifted backward and summed in a small time interval (e.g. 100 ms). The maximum of this sum signal can be related to the azimuth and horizontal speed of the incident plane wave.

The graph on the right shows the RMS value of the sum of time-shifted signals at one time interval in an azimuth range from 90° to 270° and a wave-speed range of the wave velocity from 300 m/s to 700 m/s. The maximum (brightest spot) is found at the direction of 195° and the wave velocity of 580 m/s.



Microphones were placed at various positions in the plane of the soil surface, the aircraft passed overhead with the elevation angle α between this plane and the vector pointing to the aircraft. The effective wave velocity derived from the microphones follows the actual $v_0/\cos(\alpha)$, the azimuth fits to the true one as well. When using geophone sets buried in different depths for the beam forming the calculated wave velocity follows the projected speed of sound, too (graph below, left). The azimuth of the wave follows the direction from the aircraft to the sensors likewise (graph right).



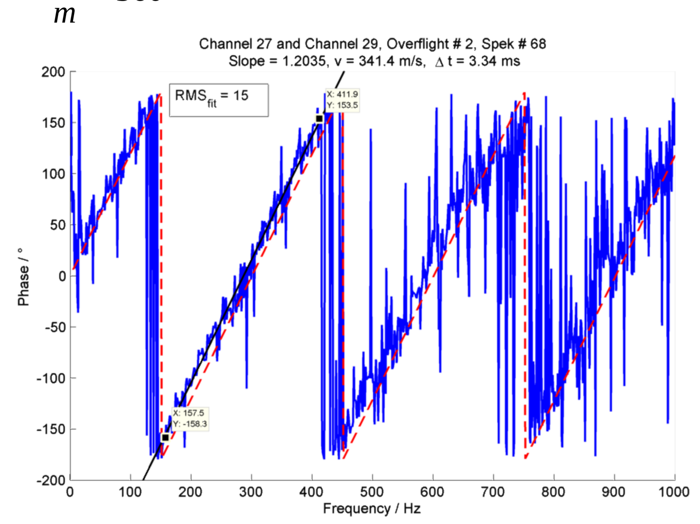
Thus, the main contribution to the measured seismic signal is induced directly and locally by the incident plane acoustic wave. However, smaller contributions from different directions and with a different wave velocity are possible.

Phase Evaluation

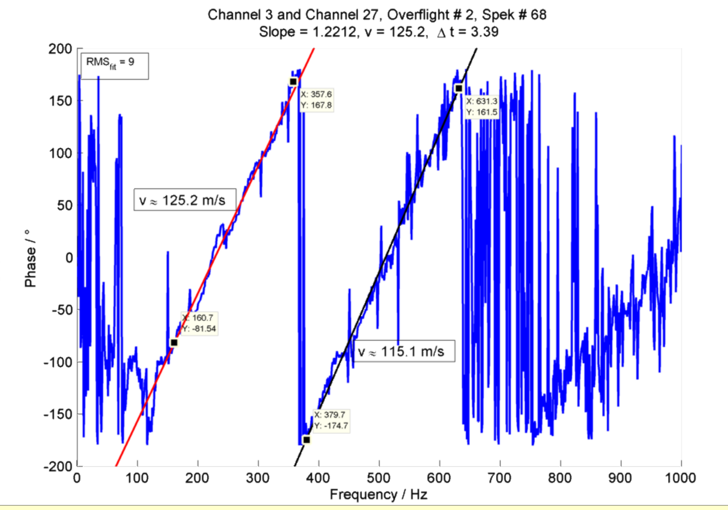
The propagation time of the signal between two sensors can be calculated using the phase information of the complex spectrum of the measured data:
For an unperturbed signal recorded at two spatially separated sensors (and thus showing a time difference *Δt* due to propagation time) the phase difference between those two points increases linearly with frequency. The slope *m* of the phase difference over frequency corresponds to this time delay and with known distance d_{proj} in propagation direction of the wave the wave velocity *v* can be calculated:

$$v = \frac{d_{proj}}{\Delta t} = \frac{d_{proj}}{m} * 360°$$

For the evaluation of the sound wave this leads to very precise results: In the graph to the right from the black fit curve the wave velocity v = 341.4 m/s is derived.
With increasing frequency the SNR of the linear dependency decreases but can still be observed. No phase-offset is observed at f = 0 Hz.



Analysing the phase difference between a microphone just above the surface and a geophone buried in soil (e.g. 0.3 m) we observe a linear dependency in the frequency range from 100 Hz up to 600 Hz. Small deviations can be seen, e.g. the humps at 260 Hz and 430 Hz which might result from the discussed interference with a reflected wave. Fitting the slope in the linear range we obtain wave velocities between 115 m/s and 125 m/s which are very plausible results for the upper soil layer. The linear fits show a phase offset at f = 0 Hz between 70° and 90° (taking into account the 360° periodicity). This offset corresponds to a time delay which decreases with frequency. Whether this is due to the coupling of the acoustic wave into the ground is open.
For frequencies below 100 Hz the linear dependency is no longer given but an oscillation in the phase is observed. Also this might be caused by the interference with a reflected wave. But Rayleigh surface waves might also play a role.



Conclusions

- Interference patterns are observed in seismic signals caused by broadband acoustic jet aircraft excitation. Probably, they are created when a seismic wave reflected at a boundary layer in the ground interferes with the soil vibrations created directly by the acoustic signal. To explain the dependency on the angle of incidence a time delay of few milliseconds needs to be assumed for the transfer of energy from the sound pressure wave to the soil-particle-movement.
- With a beam-forming algorithm we showed that soil vibration excited by acoustic signals is mainly excited locally above the sensor. However, shielding of some sensors indicates that a smaller fraction can also propagate through the ground for some distance. Secondary maxima in the beam-forming results will be evaluated to check for seismic (surface) waves that may propagate with a different velocity.
- Phase differences of the complex spectra can be used to determine wave properties. The obtained results are very precise for the sound pressure wave, for seismic waves the results show good agreement with established seismic methods we performed additionally like seismic refraction survey. A simple time delay cannot explain the findings.

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