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3D Finite-Difference Modeling of Acoustic Radiation from Seismic Sources

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Introduction

Shallow seismic events often generate acoustic signals observable at local or even regional distances. We are using a 4th-order, staggered-grid finite-difference code to investigate the effects of various source parameters on the acoustic (or infrasound) signals transmitted from the ground into the atmosphere. The P, S, and Rayleigh waves can all radiate some acoustic energy into the air; these typically produce conical wavefronts since their phase velocities along the surface exceed the air's acoustic velocity. Another acoustic arrival with a spherical wavefront can be generated from the vicinity of the epicenter of a shallow event, due to the strong vertical ground motions directly above the source. We compare the relative effectiveness of different source mechanisms as acoustic sources. For point sources at a fixed depth, double-couples with almost any orientation produce stronger acoustic signals than isotropic explosions, because of their larger S and Rayleigh waves. Increasing source depth reduces the strength of the Rayleigh-induced and epicentral air waves. Low-velocity material at the surface acts to increase the vertical seismic motions there, which in turn enhances the acoustic signals.

The seismo-acoustic interface

A modern 4th-order finite-difference code can introduce spurious behavior at high-contrast interfaces like the ground surface. Preston, Aldridge, and Symons (2008) showed that switching from 4th to 2nd order spatial differencing at the air-rock interface stabilizes the FD routine to accurately transmit acoustic waves into the atmosphere.

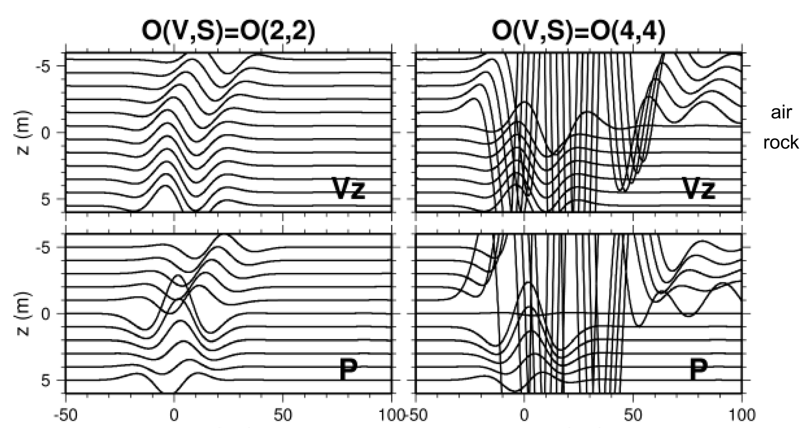

Figure 1. Order-switching at the interface. Vertical velocity and pressure traces for rock-to-air transmission (from bottom to top). On the right, 4th-order differencing across the boundary leads to spurious amplification in the air. 2nd-order differencing at the boundary (left) produces correct amplitudes for the transmitted wave. All velocity traces are plotted at the same scale; pressure traces in air are scaled by 10^4 relative to those in rock.

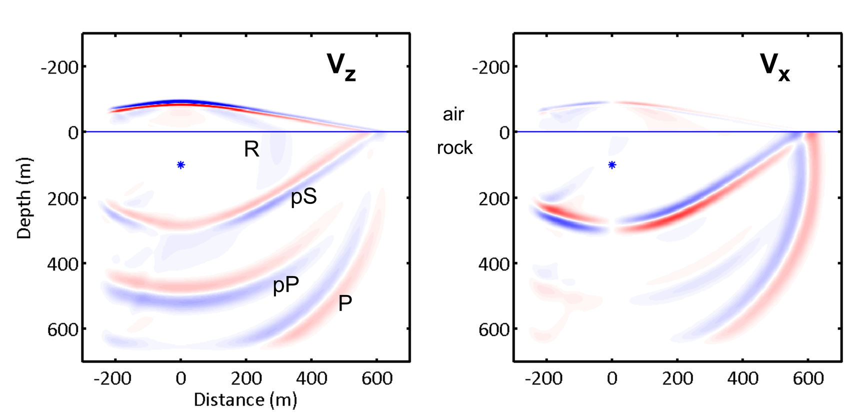

Figure 2. Seismo-acoustic wavefronts. Timeslices of vertical (left) and radial (right) velocities at 0.2 s after an underground explosion in a uniform elastic halfspace beneath an acoustic halfspace.

Effect of source mechanism

The interaction of the P, S, and surface wave radiation patterns for different source mechanisms with the ground surface will affect the amplitudes of the resulting acoustic waves. For the examples below, we buried a point source 100 m below the surface of a uniform elastic halfspace with ρ = 2.2 gm/cm³, α = 3 km/s, β = 1.75 km/s. The overlying acoustic halfspace had properties appropriate for air near sea level: ρ = 0.001 gm/cm³, α = 0.35 km/s. We modeled the signals from an isotropic explosion and shear dislocations with 3 different orientations – 45° dip-slip, vertical dip-slip, and vertical strike-slip.

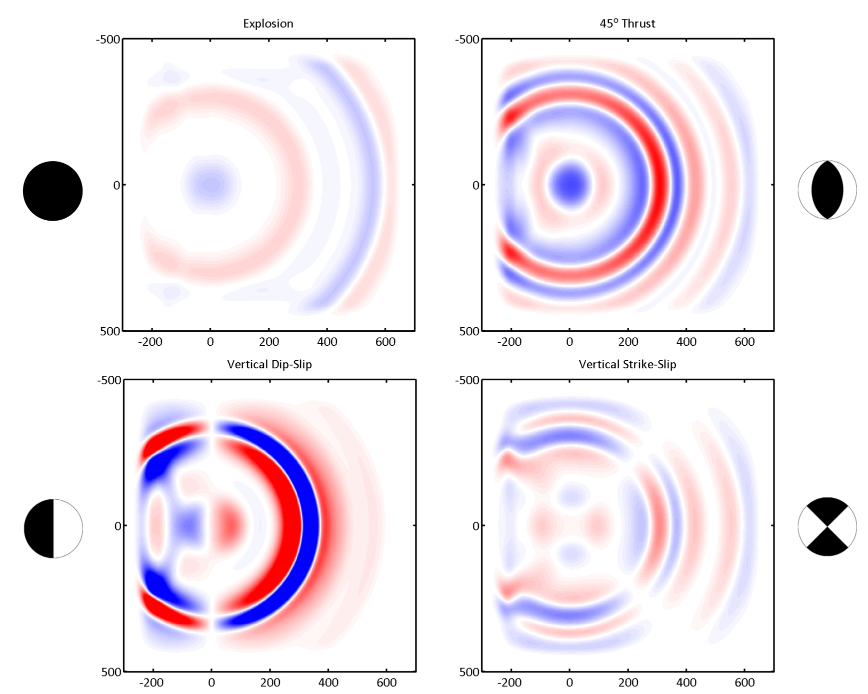

Figure 3. Pressure in air, looking down on the epicenter. Plots show the wavefield in the air at t = 0.2 s for 4 different source mechanisms, all with the same static moment and depth (100 m). The same color scaling was used for all cases. The explosion (top left) produces the weakest signals in the air; the Rayleigh wave from the vertical dip-slip event generates the strongest air waves (bottom left).

Effect of source depth

Source depth has a very strong effect on the amplitudes of the acoustic waves transmitted into the atmosphere. We demonstrated this influence using an explosive source at 6 different depths from 25 m to 150 m. For the greatest depths, acoustic radiation from the P wavefront dominates. As the event moves shallower, the Rayleigh wave becomes the more prominent acoustic source. In addition, the epicentral air wave, caused by near-field uplift above the source, also increases.

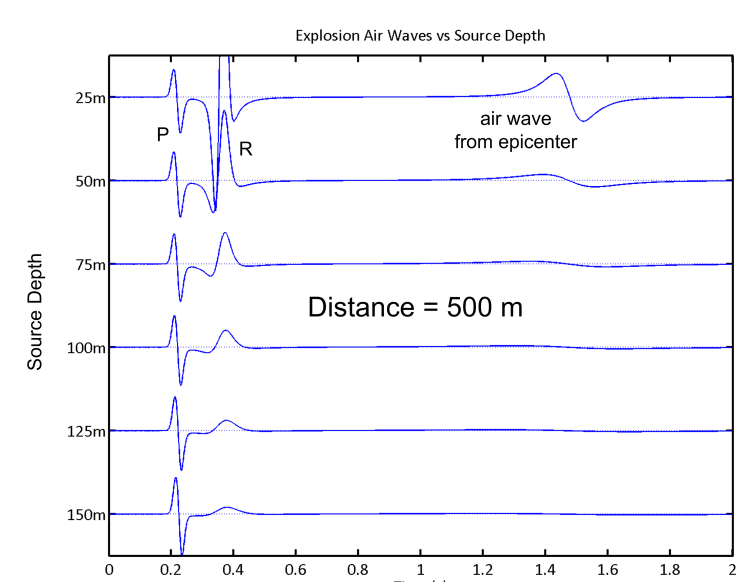

Figure 4. Pressure in air vs. source depth. Pressure in air just above the surface at a range of 500 m from the epicenter, for explosions at depths from 25 m to 150 m. As expected, the Rayleigh amplitude (R) decreases with depth. Note that the epicentral air wave that arrives at about 1.5 s also drops rapidly in amplitude as the source moves deeper.

Shallow velocity profile

We can use the seismo-acoustic FD code to model local signals from underground sources in realistic geologic structures. In this case, we considered low-velocity layering at shallow depths, using the velocity profile for the SPE site proposed by Rowe et al. (2012). An explosive point source was fired at a depth of 50 m, below the shallow waveguide caused by the layering at the top of the model. The slower layers cause significant reverberations in the ground motions at the surface, which then couple into the acoustic waves in the air.

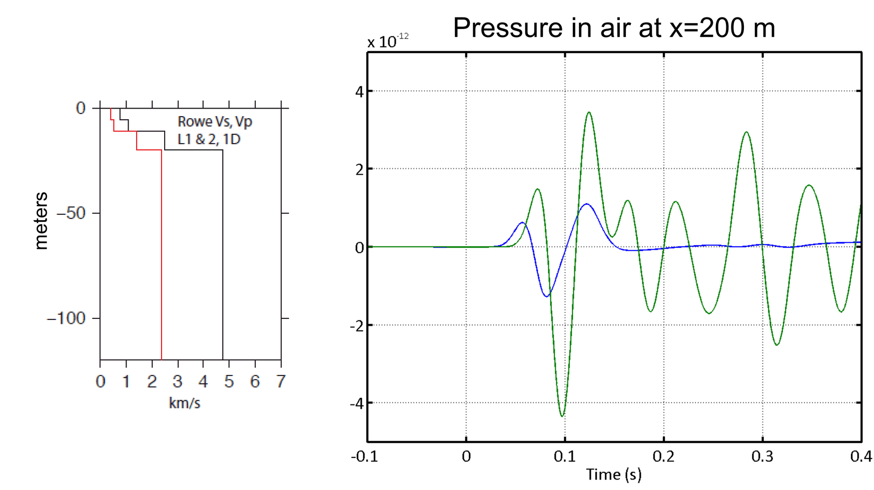

Figure 5. Effect of near-surface weathered layers. The layered model shown at the left produces the pressure wave in air shown by the green trace on the right. Without the near-surface layers, a uniform halfspace gives the blue trace.

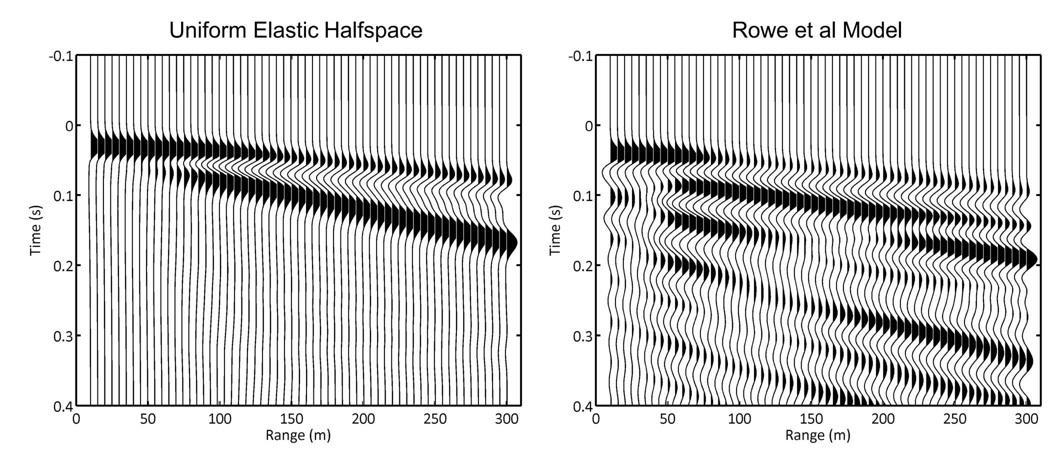

Figure 6. Pressure in air along ground surface. Profiles of acoustic signals just above the ground surface, for a uniform elastic halfspace (left) and the SPE velocity model of Rowe et al. 2012 (right). The low-velocity shallow layering introduces strong reverberations in the P and S arrivals and a dispersed Rayleigh wave.

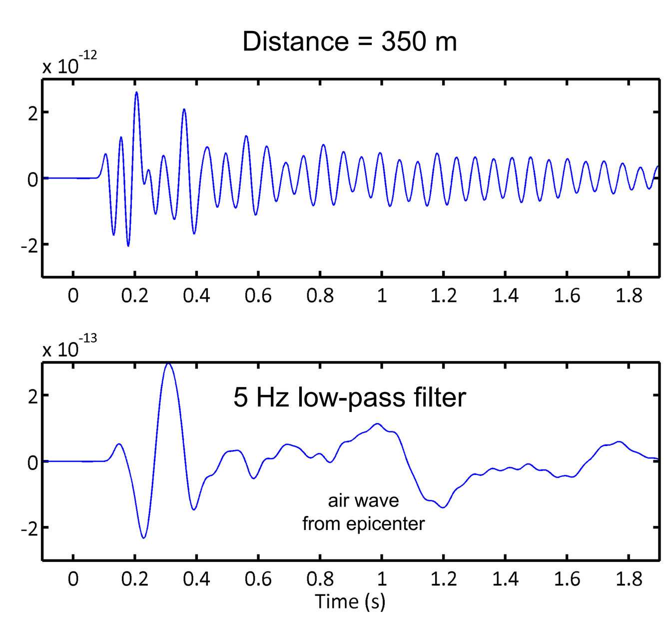

Figure 7. Pressure in air at x=350 m. The crustal profile induces complexity in the seismic arrivals, but the air wave from the epicenter remains simple. The latter results from surface uplift directly above the source, and the layering does not change the shape of this uplift.

Data from SPE-2

The Source Physics Experiments (Snelson et al., 2013) in Nevada recorded close-in seismic and acoustic data from small underground explosions. The plot below shows the acoustic signals observed by a small, 4-element array about 350 m from the epicenter of SPE-2. These sensors recorded both the complex seismic wavetrain and the low-frequency air wave generated near the epicenter.

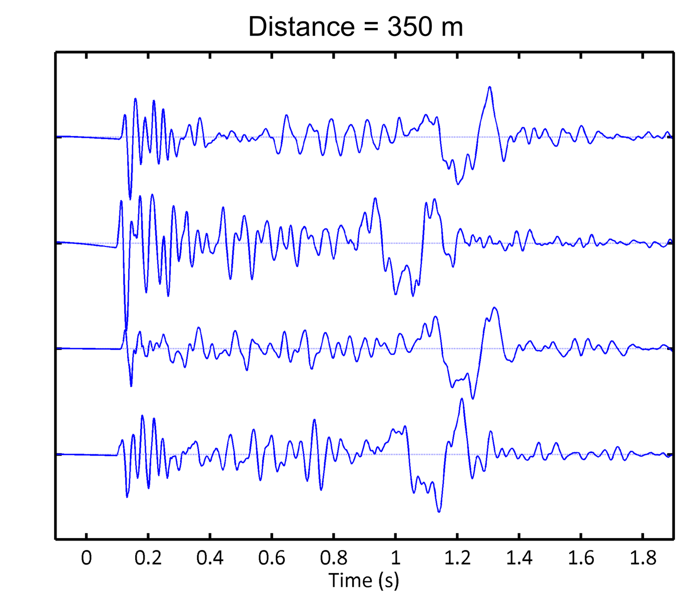

Figure 8. Acoustic data for SPE-2. Pressure signals recorded on four sensors in a small-aperture array 350 m from the epicenter of the explosion. The epicentral air wave near 1.2 s is much stronger here than in the synthetic traces of Figure 7.

Discussion

With careful treatment of the air/rock interface, finite-difference modeling can accurately handle the transmission of energy between the ground and atmosphere. Underground sources generate two types of signals in the air: the ground vibrations of passing seismic arrivals produce conical acoustic waves, and the large motions near the epicenter act as a secondary source at the surface, radiating a hemispherical acoustic wavefront. Our modeling predicts the observed low-frequency character of this epicentral air wave. Recorded signals for SPE-2 show weaker acoustic signals from the seismic arrivals than seen in the synthetics, relative to the amplitude of the epicentral air wave. This could result from effects we have not yet tested, such as attenuation or scattering of the seismic signals.

References

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Rowe, Patton, Yang, and Rougier (2012). Seismic body wave velocities derived from SPE P-wave travel times and Rg phase velocity dispersion – time domain and frequency domain methods. *Seis. Res. Lett.* **83,** 467.

Snelson, Abbott, Broome, Mellors, Patton, Sussman, Townsend, and Walter (2013). Chemical explosion experiments to improve nuclear test monitoring. *EOS Trans. Am. Geophys. U.* **94,** 237-239.

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