Seismo-acoustic Wavefield Simulations

Lukas Krenz, Sebastian Wolf, Gregor Hillers, Alice-Agnes Gabriel, Michael Bader
Seismic Risk Open Science Day

October 12, 2021

Observations and Motivation

- Otaniemi project
- Enhanced geothermal system (EGS), stimulated in June and July 2018 in the region of Helsinki
- Thousands of induced earthquakes
- No event exceeded threshold magnitude
- Observations of ground shaking and audible disturbances collected by Macroseismic questionnaire of the Institute of Seismology, University of Helsinki[1]

[1] G. Hillers et al. "The 2018 Geothermal Reservoir Stimulation in Espoo/Helsinki, Southern Finland: Seismic Network Anatomy and Data Features". In: *Seismological Research Letters* (2020).

Objective and Model Setup

- Create “discomfort maps” from free surface output (or from receivers)
- Kinematic point source
- Geometry with realistic topography
- Ignore shallow Helsinki bay Laajalahti
- Earth modelled by elastic wave equation, air by acoustic wave equation
- In the future: More complexity (e.g. bay, rheology, dynamic rupture source)
- Thus, analytical methods not sufficient, need numerical approach

SeisSol

What

- (An)**Isotropic elastic** seismic wave propagation
- **Acoustic** wave propagation
- Viscoelastic wave propagation
- Off-fault plasticity
- Poroplasticity
- Dynamic earthquake rupture

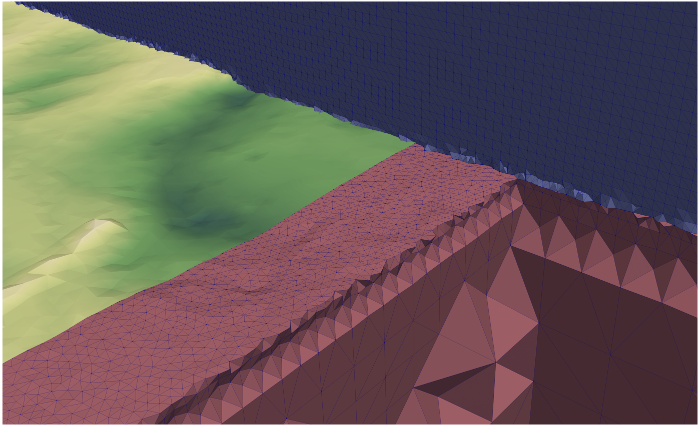
How

- Numerics: ADER-DG
- Unstructured tetrahedral meshes with local time-stepping
- Optimized parallel implementation

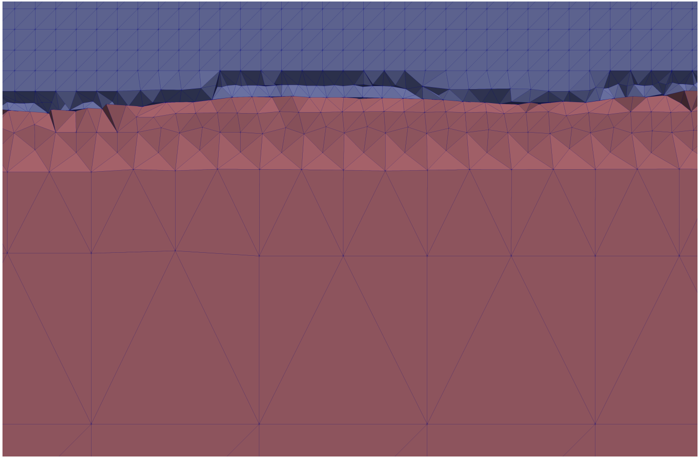
Available (**open-source**) at `https://github.com/SeisSol/SeisSol/`.

Meshing

- Source is 6.2 km deep
- Sound observations northeast from source, Munkkivuori neighborhood
- Domain size: 8 km^2
- Vertical direction: 7 km
- Very large meshes: $>$ 11 billion DoFs for 30Hz



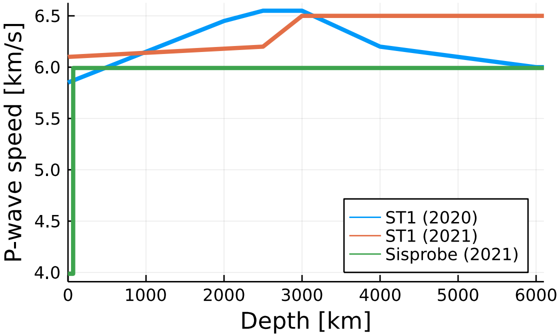
Meshing: The interface



Velocity Models

Currently comparing three models

- ST1 (2019)[2]
- ST1 (2021),[3]
- Sisprobe, full inversion (currently simplified 1D version)[4]



[2] G. Kwiatek et al. "Controlling fluid-induced seismicity during a 6.1-km-deep geothermal stimulation in Finland". In: *Science Advances* 5.5 (2019)

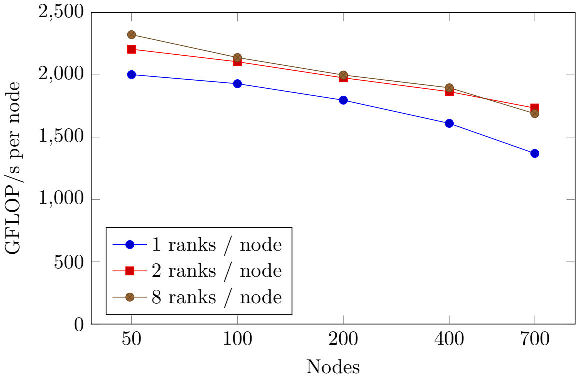
[3] M. Leonhardt et al. "Seismicity during and after stimulation of a 6.1 km deep enhanced geothermal system in Helsinki, Finland". In: *Solid Earth* 12.3 (Mar. 2021)

[4] Roméo Courbis, Sisprobe

Computational Aspects

- Use project on CSC's Mathi "QuakeSounds" with 17.6 million billing units
- SeisSol scales very well to all available nodes[5]
- Data (e.g. seismograms) are going to be archived in standard formats to comply with FAIR data policy

Strong scaling on Mahti. Larger numbers are better.



[5] L. Krenz et al. "3D Acoustic-Elastic Coupling with Gravity: The Dynamics of the 2018 Palu, Sulawesi Earthquake and Tsunami". In: *arXiv preprint arXiv:2107.06640* (2021)

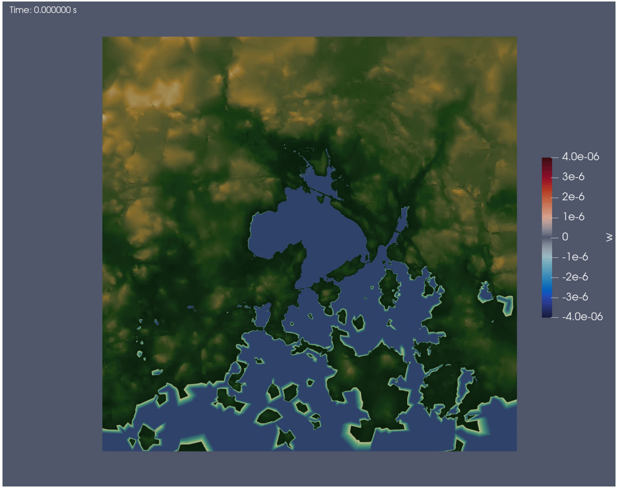
Measuring Sound

- Simple $\rightarrow$ compute receiver, compute sound in dB
- Defined as

$$20 \log_{10} \left(\frac{p^{\text{rms}}}{p^{\text{ref}}} \right) dB$$

  with measured average (over small window) pressure p^{rms} and reference pressure p^{ref}
- Humans perceive sounds with different loudness, depending on frequency
- Use weighting factors (via digital filtering) to get loudness from volume
- We need to resolve at least 20Hz, better up to 50Hz.

Results: Topography Effects



Conclusion

- Sound induced by geothermal energy crucial for acceptance
- Discomfort maps can help to visualize the problem
- Sound can be measured from synthetic seismograms/audiograms
- Complex model, thus need for numerical simulations
- High-frequency requirement leads to large simulations
- SeisSol can run this model (**efficiently**) on large machines
- $\rightarrow$ use SeisSol on *Mahti*
- First results promising