Numerical simulations of acoustic and infrasonic waves in the coupled ground-atmosphere system: synergy between balloon and ground sensors

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Introduction: Scientific Problematic

- Objectives:
  Through atmospheric signals,
  - constrain ground model
    (seismic events)
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  - Infrasound monitoring (*cf.* CTBTO).

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  - Infrasound monitoring (*cf.* CTBTO).
- How: balloon sensors (*vs.* ground).
  - ✘ more difficult to deploy,
  - ✓ more versatile (smaller, more mobile),
  - ✓ *in situ* probe.

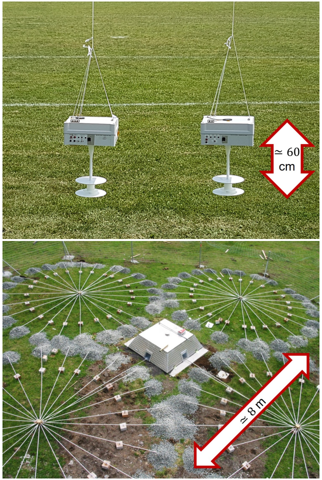

Figure 1: Top: ISAE balloon sensors (credit: ISAE). Bottom: CTBTO IS49 ground sensor (credit: CTBTO).

Overview

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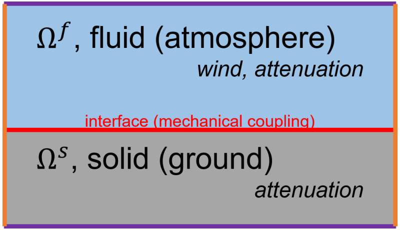
Equations



- Base: SPECFEM-DG 2D ([Brissaud et al., 2017]).

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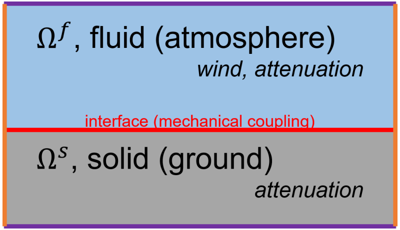

- Base: SPECFEM-DG 2D ([Brissaud et al., 2017]).
- System:

$$\begin{cases} \textbf{Navier-Stokes equations} & \text{in fluid domain,} \\ \textbf{elastodynamics equations} & \text{in solid domain,} \\ \textbf{mechanical coupling} & \text{on fluid/solid interface,} \\ \text{absorbing boundary conditions} & \text{on top/bottom boundaries,} \\ \text{periodic boundary conditions} & \text{on left/right boundaries.} \end{cases}$$

Numerical Method

- Discretisation: **weak formulations** and **spectral finite element method**.
  - Continuous in solid domain ([Komatitsch and Vilotte, 1998], [Tromp et al., 2008]).
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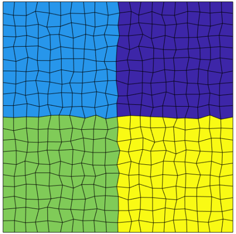
- **Explicit** time integration scheme (fifth order strong stability Runge-Kutta).
- **Parallel computing**: MPI (1 CPU $\leftrightarrow$ 1 subset of the mesh).



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Seismic Hammer - Overview

- 2017 experiment, collaboration with JPL [Krishnamoorthy et al., 2018].

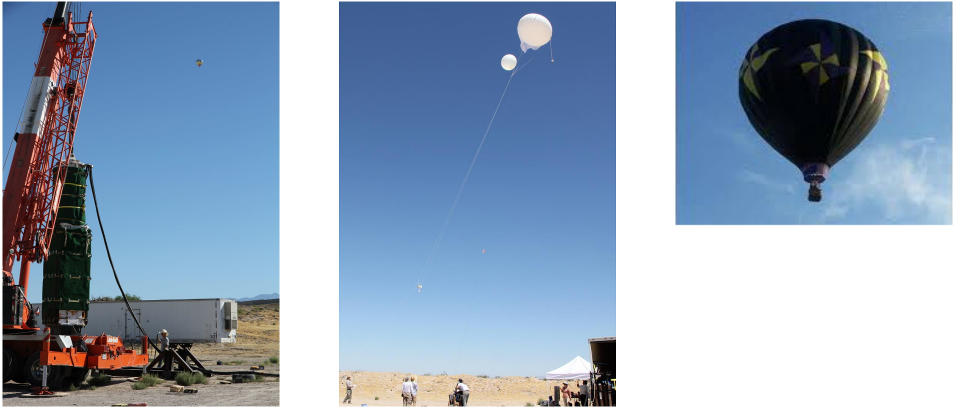

Figure 2: Left to right: seismic hammer, tethered balloon, hot air balloon.

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  - 1 ”soft” (4 layers, low seismic velocities),
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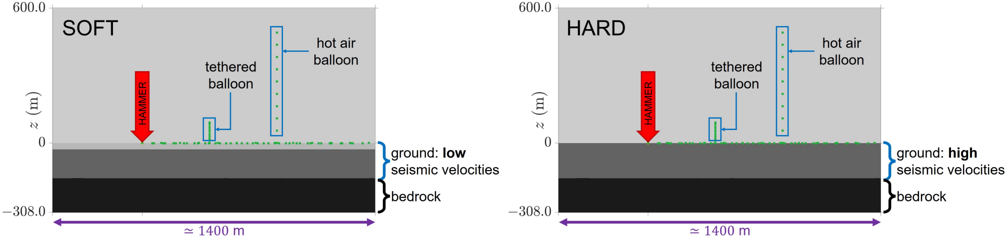

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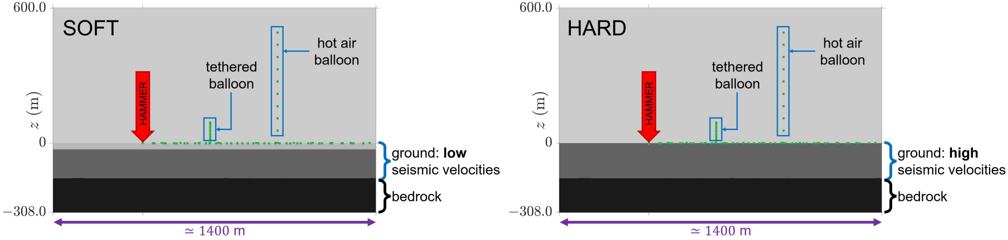

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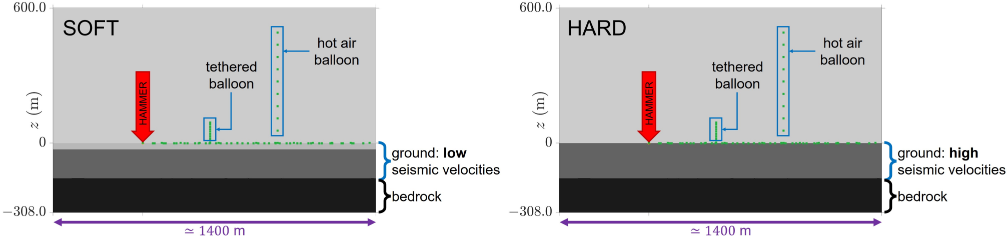
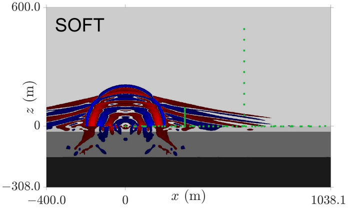
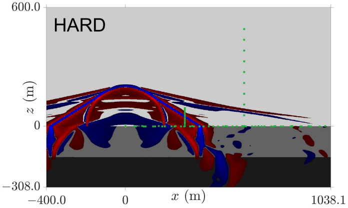


- Atmospheric model: isothermal.
- Source: vertical point force in the solid domain.

Seismic Hammer - 1% Saturated Snapshots

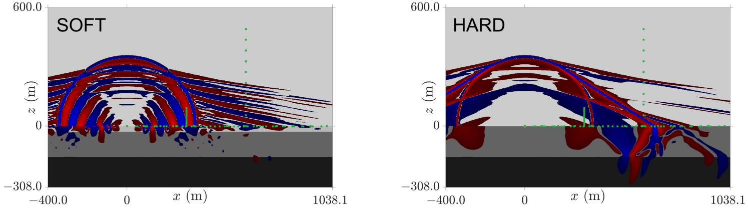
- $t = 0.6$ s:





Seismic Hammer - 1% Saturated Snapshots

- $t = 1.0$ s:



Numerical simulations of waves in the ground-atmos. system

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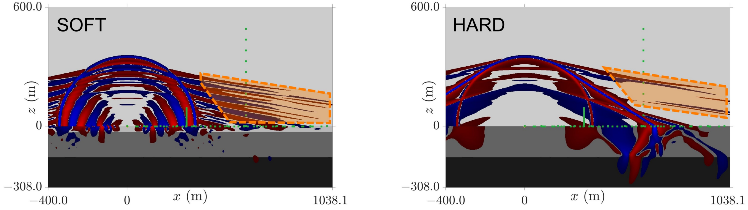

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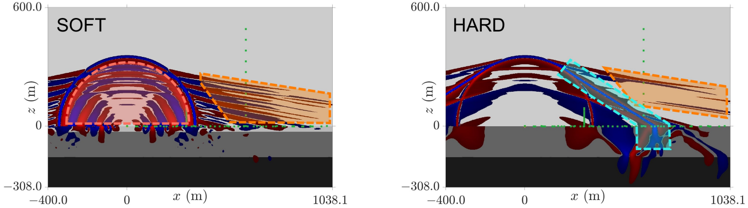
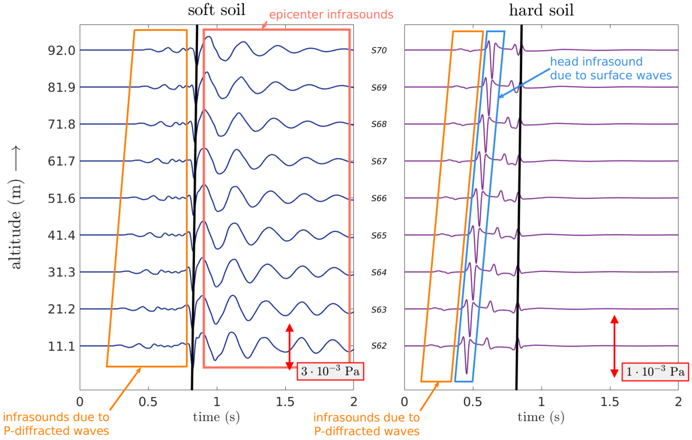


- Low-amplitude infrasounds, from P diffracted waves.
- Soft soil:
  1. Strong impact zone oscillations (multiple P-wave reflections) $\Rightarrow$ epicentre infrasounds (at ground resonance frequency).
  2. $v_s < c \Rightarrow$ no surface wave induced head wave.
- Hard soil:
  1. Few impact zone oscillations.
  2. $v_s \gg c \Rightarrow$ high amplitude surface wave induced head infrasound.

Balloon Barograms

- Barograms for balloon sensors 300 m away from source:



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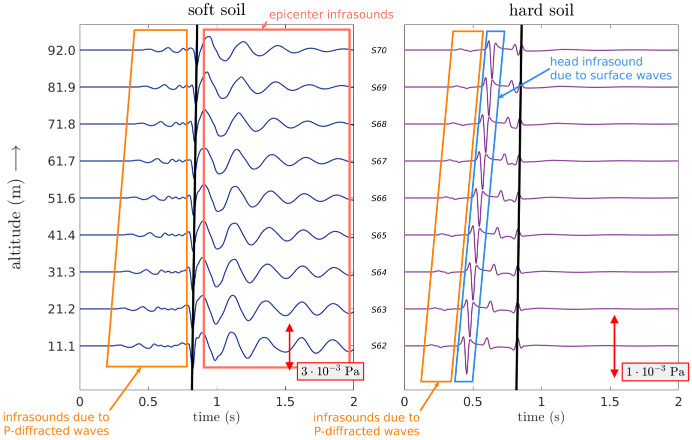

- Head infra-sounds' amplitudes are conserved with altitude.

Earthquake: Larger Scales

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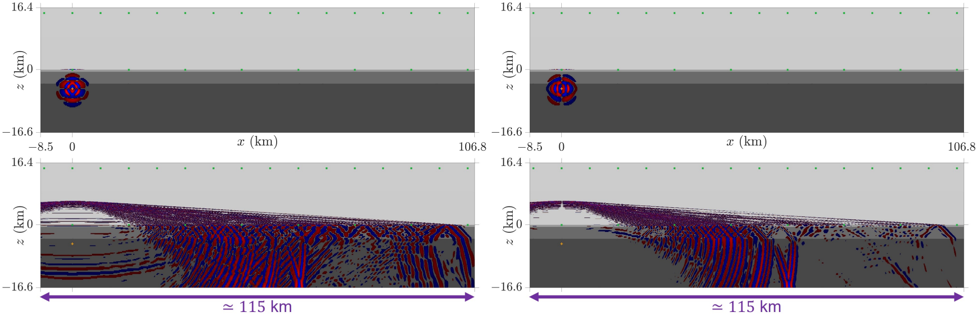
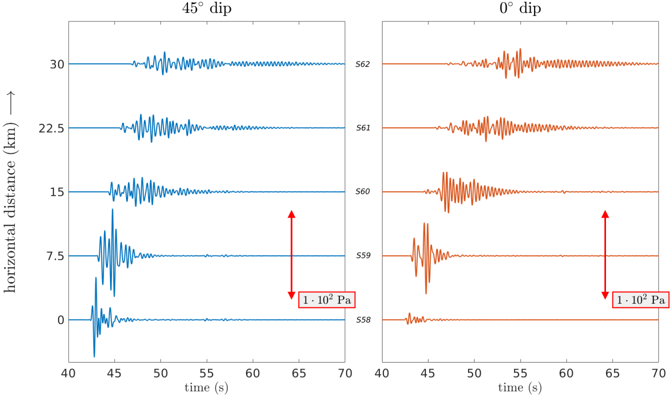
- 1% saturated snapshots (left: 45°, right: 0°, top: $t = 1$ s, bottom: $t = 18$ s):



Stratospheric Barograms

- Barograms for balloon sensors at $z = 15$ km:



- Amplitudes of infrasounds created by surface waves:
  - are conserved with distance,
  - do not depend on the source mechanism (away from source).

Numerical simulations of waves in the ground-atmos. system

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Atmospheric Explosions: Even Larger Scales

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  - Ground: soft, illustrative only.
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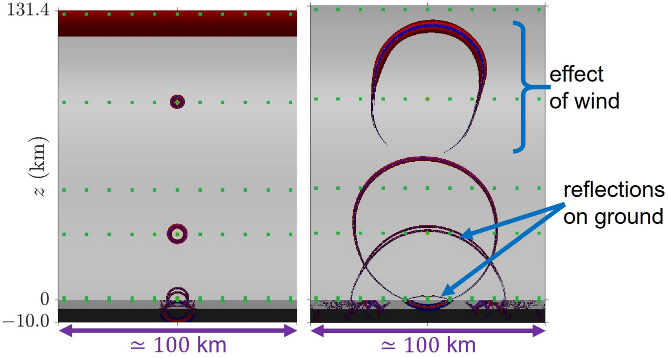
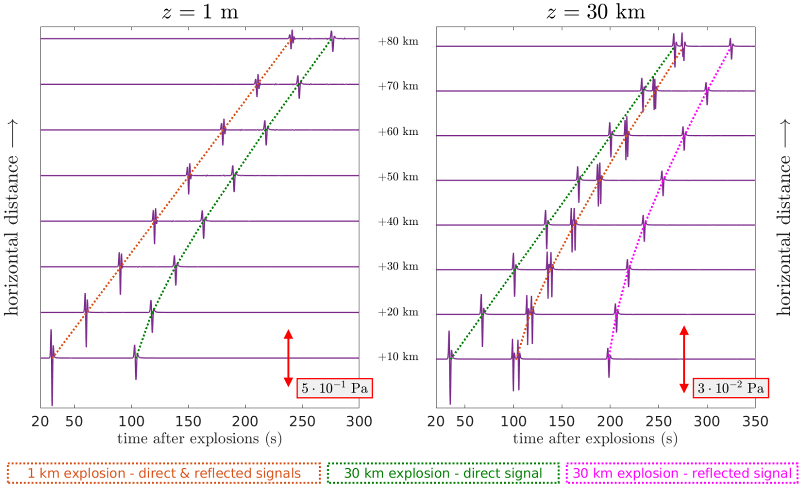
- 1% saturated snapshots (left: $t = 15$ s, right: $t = 105$ s):



Barograms: ground *vs.* stratosphere

- Barograms from horizontal arrays of stations ($z = 1$ m, $z = 30$ km):



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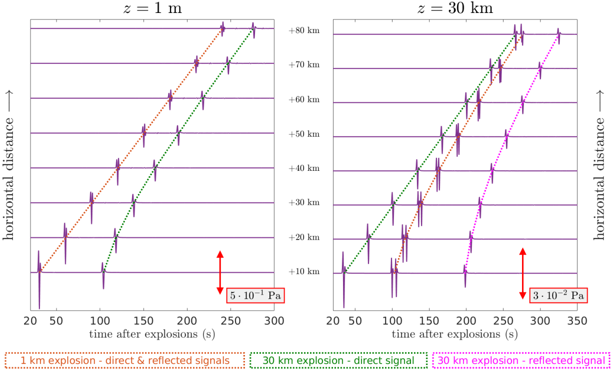

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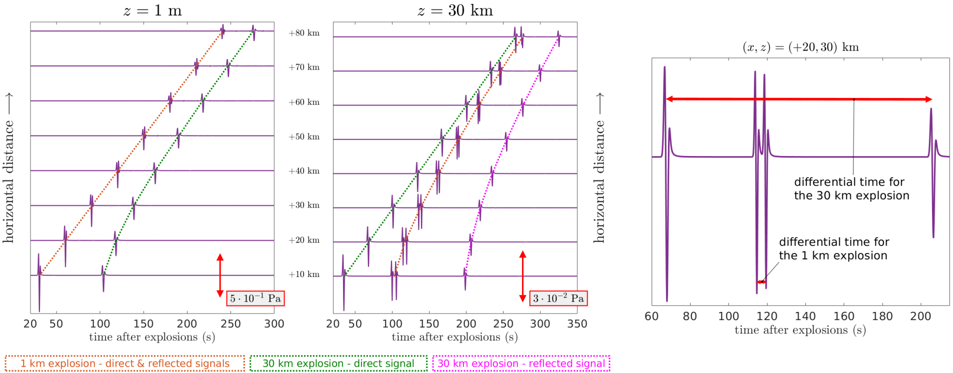

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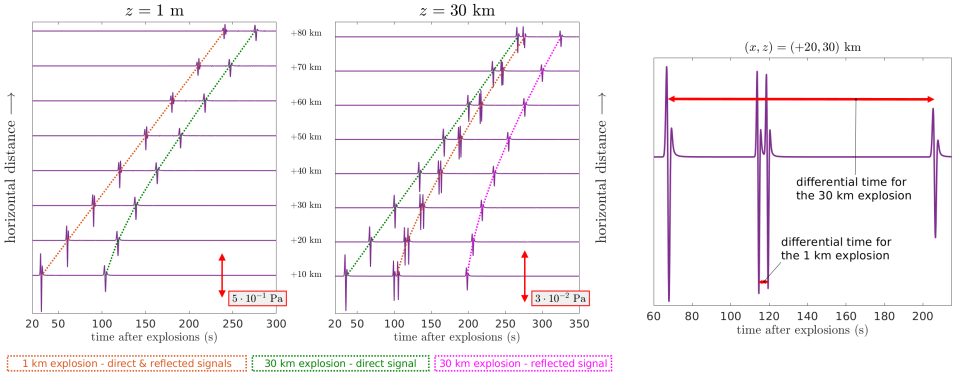

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- Differential time (at $z = 30$ km) can constrain explosions' altitudes.
- Wind is an unknown, but balloon with GPS = wind probe.

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General Conclusions

1) What can balloon sensors bring?

- Short-range (*cf.* seismic hammer):
  - Information on ground structure (*cf.* hard soil's head wave).
  - Monitoring of epicentre infrasound, without clipping (as opposed to ground stations).

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2) Our simulations can help design new experiments.

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- Ouvertures / Future work:
  - 3D simulations:
    - with more complex sources (*e.g.* ocean microbaroms, ...),
    - with more complex topography (*e.g.* mountain ranges, ...).
  - Infer sensitivity of observations to atmospheric models $\Rightarrow$ prepare inversion.

Thank you for your attention.

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