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

Léo Martire¹, Q. Brissaud², R. F. Garcia¹, R. Martin³

¹ISAE (DEOS-SSPA), Toulouse, France, ²Caltech, Pasadena, USA, ³OMP-GET, Toulouse, France

EGU - Friday, 13th of April, 2018











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Introduction: Scientific Problematic

- Objectives: Through atmospheric signals,
 - constrain ground model (seismic events)
 - constrain sources and/or constrain atmospheric model (atmospheric events)

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Introduction: Scientific Problematic

Objectives:

Through atmospheric signals,

- constrain ground model (seismic events)
- constrain sources and/or constrain atmospheric model (atmospheric events)
- But why?
 - Planetary applications (e.g. Venus).
 - Infrasound monitoring (cf. CTBTO).

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Introduction: Scientific Problematic

- Objectives: Through atmospheric signals,
 - constrain ground model (seismic events)
 - constrain sources and/or constrain atmospheric model (atmospheric events)
- But why?
 - Planetary applications (e.g. Venus).
 - Infrasound monitoring (cf. CTBTO).
- How: balloon sensors (vs. ground).
 - x more difficult to deploy,
 - ✓ more versatile (smaller, more mobile),
 - ✓ in situ probe.

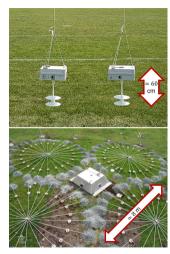


Figure 1: Top: ISAE balloon sensors (credit: ISAE). Bottom: CTBTO IS49 ground sensor (credit: CTBTO).

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Equations

 Ω^f , fluid (atmosphere) wind, attenuation interface (mechanical coupling) Ω^S , solid (ground)

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

attenuation

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Equations

 Ω^f , fluid (atmosphere)

wind, attenuation

interface (mechanical coupling)

 Ω^s , solid (ground)

attenuation

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

Navier-Stokes equations elastodynamics equations mechanical coupling absorbing boundary conditions periodic boundary conditions in fluid domain, in solid domain, on fluid/solid interface, on top/bottom boundaries, on left/right boundaries.

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Numerical Method

- Discretisation: weak formulations and spectral finite element method.
 - Continuous in solid domain ([Komatitsch and Vilotte, 1998], [Tromp et al., 2008]).
 - Discontinuous in fluid domain ([Brissaud et al., 2017]).

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Numerical Method

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 - Discontinuous in fluid domain ([Brissaud et al., 2017]).
- **Explicit** time integration scheme (fifth order strong stability Runge-Kutta).

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Numerical Method

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 - Discontinuous in fluid domain ([Brissaud et al., 2017]).
- **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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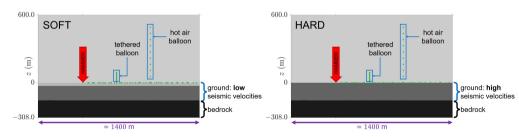
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Seismic Hammer - Overview

- 2017 experiment, collaboration with JPL [Krishnamoorthy et al., 2018].
- Ground models: 2 types (same bedrock).
 - 1 "soft" (4 layers, low seismic velocities),
 - 1 "hard" (1 layer, high seismic velocities).



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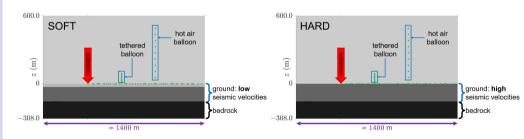
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• Atmospheric model: isothermal.

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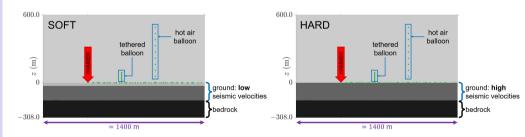
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Seismic Hammer - Overview

- 2017 experiment, collaboration with JPL [Krishnamoorthy et al., 2018].
- Ground models: 2 types (same bedrock).
 - 1 "soft" (4 layers, low seismic velocities),
 - 1 "hard" (1 layer, high seismic velocities).



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

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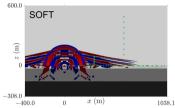
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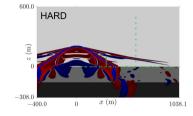
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Seismic Hammer - 1% Saturated Snapshots

• t = 0.6 s:





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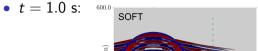
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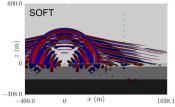
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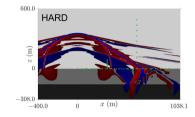
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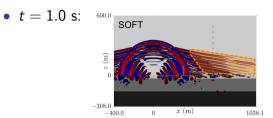
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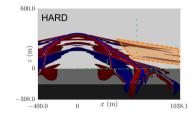
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Seismic Hammer - 1% Saturated Snapshots





• Low-amplitude infrasounds, from P diffracted waves.

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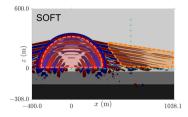
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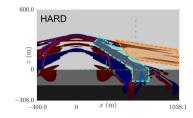
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Seismic Hammer - 1% Saturated Snapshots

• t = 1.0 s:





- Low-amplitude infrasounds, from P diffracted waves.
- Soft soil:
 - Strong impact zone oscillations (multiple P-wave reflections)
 ⇒ 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.

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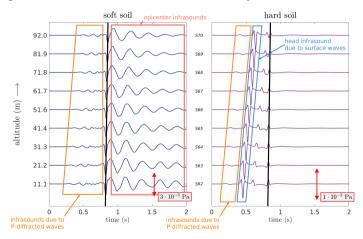
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Balloon Barograms

• Barograms for balloon sensors 300 m away from source:



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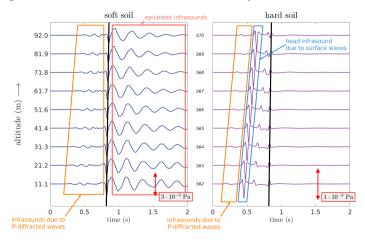
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Balloon Barograms

• Barograms for balloon sensors 300 m away from source:



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

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Earthquake: Larger Scales

Models:

• Ground: CRUST1.0.

• Atmosphere: MSISE00-HWM93.

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Earthquake: Larger Scales

- Models:
 - Ground: CRUST1.0.
 - Atmosphere: MSISE00-HWM93.
- Source: 2 types of fault slips (45° and 0° dip).
 - 5 km depth.
 - $M_w = 2.5$, $f_0 = 2$ Hz.

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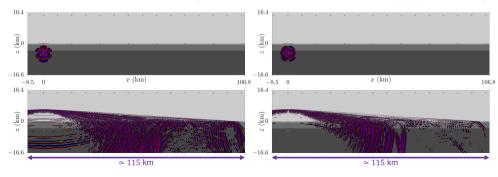
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Earthquake: Larger Scales

- Models:
 - Ground: CRUST1.0.
 - Atmosphere: MSISE00-HWM93.
- Source: 2 types of fault slips (45° and 0° dip).
 - 5 km depth.
 - $M_w = 2.5$, $f_0 = 2$ Hz.
- 1% saturated snapshots (left: 45°, right: 0°, top: t = 1 s, bottom: t = 18 s):



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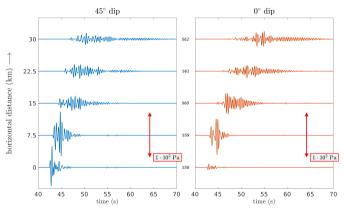
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Stratospheric Barograms

• 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).

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Atmospheric Explosions: Even Larger Scales

• Models:

- Ground: soft, illustrative only.
- Atmosphere: MSISE-HWM for latitude 66°, high wind gradients.

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Atmospheric Explosions: Even Larger Scales

• Models:

- Ground: soft, illustrative only.
- Atmosphere: MSISE-HWM for latitude 66°, high wind gradients.

Sources:

- 3 atmospheric explosions,
- z = 1, 30, 90 km,
- intensity scaled with density.

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Atmospheric Explosions: Even Larger Scales

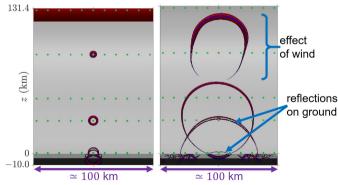
Models:

- Ground: soft, illustrative only.
- Atmosphere: MSISE-HWM for latitude 66°, high wind gradients.

Sources:

- 3 atmospheric explosions,
- z = 1, 30, 90 km,
- intensity scaled with density.

• 1% saturated snapshots (left: t = 15 s, right: t = 105 s):



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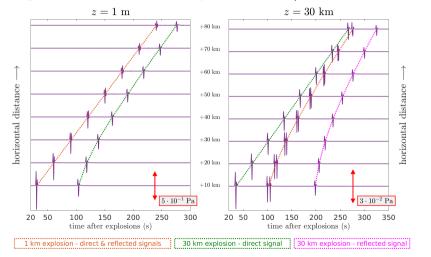
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Barograms: ground vs. stratosphere

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



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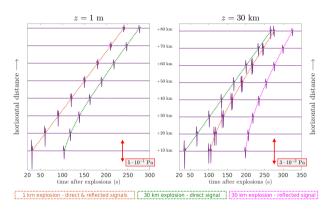
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Barograms: ground vs. stratosphere



• Amplitudes laterally decrease slower at z = 30 km than at ground.

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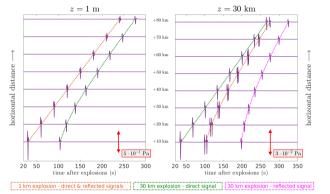
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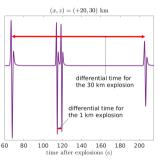
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Barograms: ground vs. stratosphere





- Amplitudes laterally decrease slower at z = 30 km than at ground.
- Differential time (at z = 30 km) can constrain explosions' altitudes.

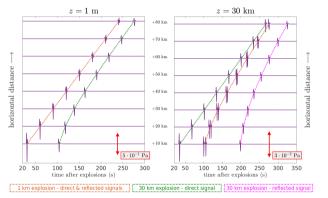
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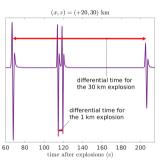
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Barograms: ground vs. stratosphere





• Amplitudes laterally decrease slower at z = 30 km than at ground.

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

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- 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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 - Information on ground structure (cf. hard soil's head wave).
 - Monitoring of epicentre infrasound, without clipping (as opposed to ground stations).
 - Long-range (*cf.* earthquakes):
 - Monitoring of surface waves induced signals, even far away (\simeq 30 km).

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 - Monitoring of epicentre infrasound, without clipping (as opposed to ground stations).
 - Long-range (*cf.* earthquakes):
 - Monitoring of surface waves induced signals, even far away (\simeq 30 km).
 - Stratospheric monitoring (*cf.* atmospheric explosions):
 - Stratospheric barograms study can help constrain:
 - explosions' altitudes,
 - atmospheric parameters (if source is known).

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- 1) What can balloon sensors bring?
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 - Information on ground structure (cf. hard soil's head wave).
 - Monitoring of epicentre infrasound, without clipping (as opposed to ground stations).
 - Long-range (*cf.* earthquakes):
 - Monitoring of surface waves induced signals, even far away (\simeq 30 km).
 - Stratospheric monitoring (*cf.* atmospheric explosions):
 - Stratospheric barograms study can help constrain:
 - explosions' altitudes,
 - atmospheric parameters (if source is known).
- 2) Our simulations can help design new experiments.

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Limitations, and Future Work

- Limitations:
 - Simulations are 2D:
 - geometric attenuation underestimated,
 - but in some cases re-scalable in post-process.

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Limitations, and Future Work

- Limitations:
 - Simulations are 2D:
 - geometric attenuation underestimated,
 - but in some cases re-scalable in post-process.
- 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
 ⇒ prepare inversion.

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Thank you for your attention.

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