Strong motion seismology from space
Proof of concept

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Some open questions about earthquake dynamics

- **Earthquake source complexity**: geometry and evolution of the rupture front, broad-scale heterogeneity, variability of rupture speed
- Pulse/crack rupture styles: how short are earthquake rise times?
- **Rupture speed**: how usual are supershear ruptures?
- Fault rheology: which weakening mechanisms are dominant in real faults? Is rupture dominated by rheology or by heterogeneities?

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Ripperger et al. (2010)
Source imaging today: Intrinsic limitations

- Source inverse problem: retrieve the space-time distribution of fault slip from seismological, geodetic, field data
- Due to our poor knowledge of the propagation media at small scales, seismic data is usually exploited in a limited frequency band (< 0.5 Hz)
- Data is sparse: the inverse problem is ill-posed (severe non uniqueness), sensitive to regularization and data selection. Different teams often obtain very different models of the same earthquake.
- Low resolution: models suffer from limited spatial resolution (> 10 km).
  - Little detail about the friction law can be retrieved
  - Resulting slip models are notoriously heterogeneous but how much of that spatial variability is real?
Rationale for specs of remote imaging system

- Amplitude sensitivity on ground velocity = few cm/s, dictated by technical capabilities \( \rightarrow \) Strong-motion, near-field seismology
- Wide field of view, several 100km, to capture a M7.8 earthquake on the San Andreas Fault and its largest aftershocks
- Temporal sampling at 1Hz, the *nominal* frequency limit of current inversions
- Spatial sampling at 100m spacing = \( 1/5 \) minimum wavelength at 1Hz considering S wave speeds \( \sim 500 \text{ m/s} \) at shallow depth

Expected outcomes:
- robust source imaging down to few km spatial resolution on the fault
- distinguish between sub-shear and super-shear rupture speed
- distinguish real spatio-temporal complexity of earthquake rupture
- assess the quality of and revisit source images of past earthquakes

*Note:* Pushing to 5-10Hz might yield new constraints on fault rheology (friction)
M7 earthquake scenario setup


Ground motions
Map of velocity in x-direction (m/s) at 0.5 sec

Fault slip rate
Horizontal Slip-Rate (m/s) at t = 0.0 sec

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Scenario ground motions
Fault-parallel ground velocity

Processed ground motions

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Sub-shear vs. super-shear rupture speed

Subshear scenario

Supershear scenario
Sub-shear vs. super-shear rupture

Sub-shear

Super-shear

Map of velocity in x-direction (m/s) at 0.5 sec

Map of velocity in y-direction (m/s) at 0.5 sec

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Direct estimate of surface slip velocity from satellite optical images

Sub-shear

Super-shear

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With surface rupture

Without surface rupture
Imaging rupture complexity
Scenario with a second asperity

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Source inversion

- **Task**: infer spatio-temporal fault slip distribution from recorded ground motions
- **Goal**: quantify the improvements on source imaging provided by the satellite-based system
- **Challenge**:
  - The satellite system would provide unprecedentedly dense sampling of ground motions: several million seismometers!
  - Classical source inversion approaches typically work with <20 stations and do not scale up to an immensely larger ($\times 10^5$) seismic network, several Terabytes of data, $>10^4$ unknown fault parameters.
  
  $\rightarrow$ Source inversion codes are just not ready for that.
- **Alternative**: We tried a more direct path, time-reversal imaging
**Time-reversal source imaging: principles and limitations**

**Principle and properties:**
- Exploit the time-reversal symmetry of the wave equation and the reciprocity principle.
- Recorded motions are time-reversed and applied as surface force sources. Waves back propagated (by simulation) focus on the original source.
- The spatial resolution of focusing is dictated by the sampling wavelength (= S wave speed / sampling frequency).
- Has been applied before for huge earthquakes (Sumatra 2004) with teleseismic data. Never been attempted with near-field data.
Source imaging of the 2004 Sumatra earthquake by time reversal of teleseismic high-frequency data (Hinet array, Japan) (Hjorleifsdottir, 2007)
Time-reversal source imaging: principles and limitations

Limitations:

- Focusing requires recordings over a surface that completely surrounds the source. We have only recordings at the Earth’s surface.
- Partial compensation (at low frequencies) based on teleseismic data.
- Waves defocus right after focusing: serious interference problem when imaging the multiple delayed sources that constitute an extended source.
- Requires iterative time-reversal imaging, perhaps absorbing conditions.
Forward scenario

Time-reversal modeling

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Summary

What can we learn about earthquake physics from 1Hz seismic waves adequate sampled by a satellite system?

From direct observation:
- Distinguish between sub-shear and super-shear ruptures
- Complexity of surface rupture

From source inversion (expected): Complexity of sub-surface rupture at kilometric scale

In progress:
- iterative time-reversal source imaging, jointly with teleseismic data
- assess perturbations by site effects, scattering in the shallow crust

Not discussed: potential for seismic tomography and for quantification of site effects
+ exploiting smaller earthquakes → improved tomography → revisit past earthquakes

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Time-reversal simulations

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