Dynamic rupture inverse modeling of apparent source spectra

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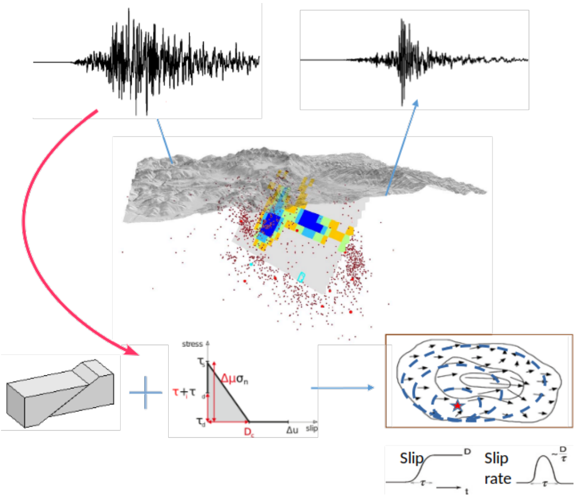
Dynamic source inversion

Dynamic forward calculation

- Rupture propagation is controlled by physics (and laboratory) based friction law.
- Prescribed fault plane and a friction law with its parameters.

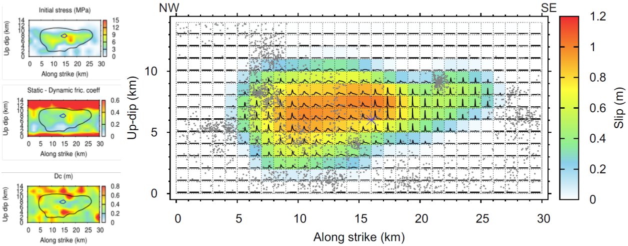
Dynamic source inversion

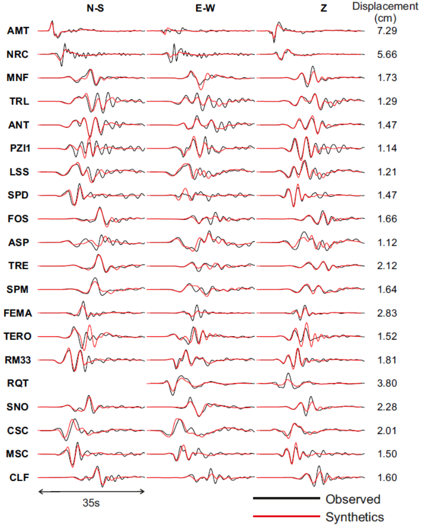
- Uses observed data (seismograms) to constrain the dynamic parameters.
- Can be regarded as a physical constraint on kinematic rupture propagation.



Dynamic source inversion of the 2016 Mw 6.2 Amatrice earthquake

- Data: low-frequency (up to 0.5-1Hz) displacements at stations within 50km from the source
- Best fitting model (out of ∼1M models visited by McMC) has variance reduction 62%

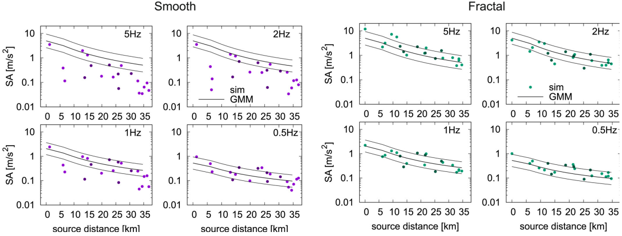


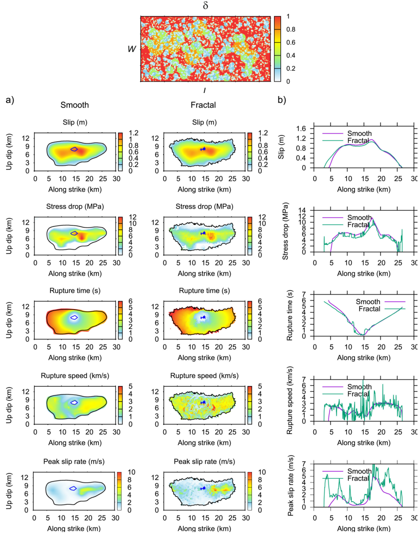


Gallovič et al. (2019)

Broadband dynamic modeling: How to introduce small-scale heterogeneity to smooth dynamic models?

- Motivated by multiscale/fractal model of fracture energy proposed by Ide and Aochi (2005).
- Template applied to smooth dynamic model parameters (prestress, strength and D_c)
- Improved fit to GMPEs at higher frequencies

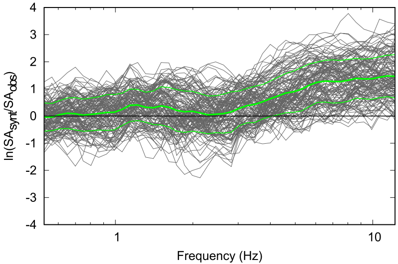




Gallovič and Valentová (2023), JGR

What can earthquake source spectra tell us about source?

- Fractal model generates ∼omega-square spectrum
- Release the assumption on the omega-square radiation
  and use the observed earthquake spectra as input data for dynamic source inversion
- Additionally constrain the small-scale source characteristics in a more data-driven approach.



Comparison of the synthetic station-specific source spectra (apparent source spectra) of fractal model with empirical estimates of Amatrice earthquake.

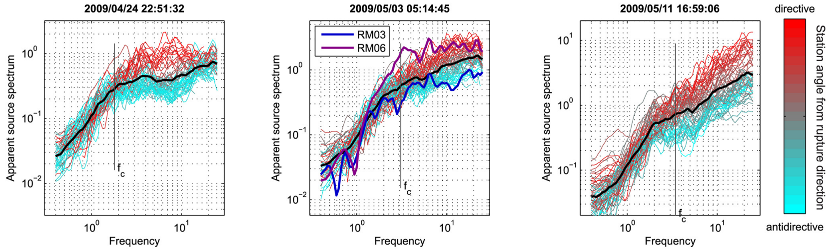
Data: GIT apparent source spectra

- Decomposition of acceleration S-wave amplitude spectra A_{ij} at station j for event i:

$$\log_{10} A_{ij}(f) = \log_{10} \mathbf{S}_{ij}(f, M_i) + \log_{10} P_{ij}(f, r_{ij}) + \log_{10} G_j(f)$$

where S_{ij} corresponds to **apparent source spectra** of event i at station j, P_{ij} and $G_j(f)$ correspond to path and site term, respectively.

- Decomposition performed over large number of events in Central Italy and stations using the so-called generalized inversion technique (GIT, Bindi et al., 2009; Oth et al., 2008)
- In frequency range 0.5-25 Hz
- Apparent spectra show various complexities, e.g., directivity

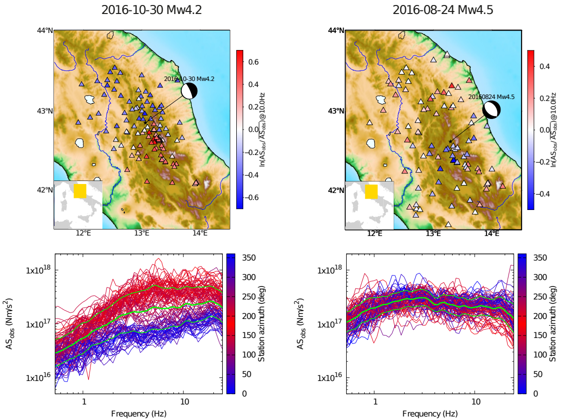


Pacor et al. (2016)

Example events: two M4 in Central Italy

Directive event:

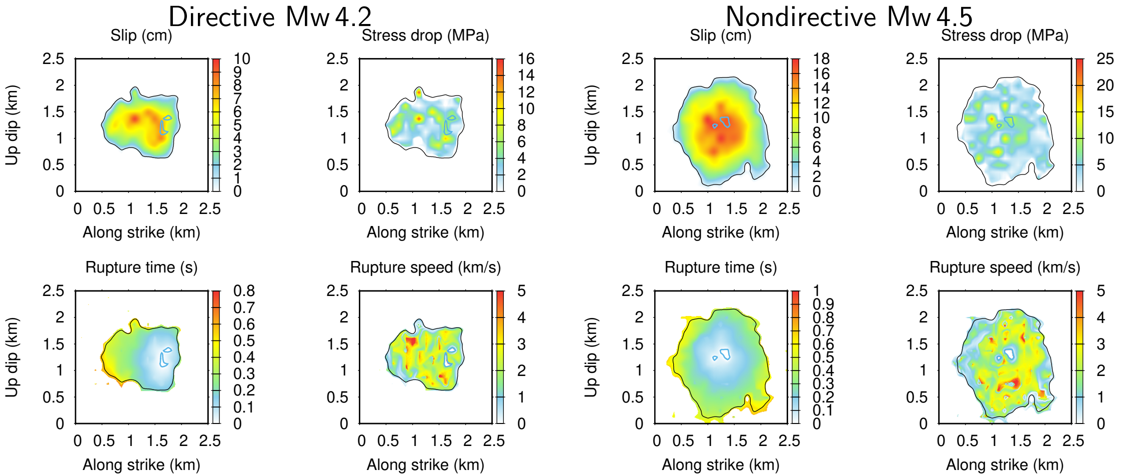
- 2016-10-30 Norcia Mw 4.2 aftershock at depth 10km
- Assuming vertical fault plane (strike agrees with fault orientation in CI)
- Directivity observed over the inspected frequency range (including azimuth-dependent corner frequency), distance independent



Nondirective event:

- 2016-08-24 Amatrice Mw 4.5 aftershock at depth 6km
- Assuming SW dipping fault plane (similar to Amatrice mainshock)
- Spectra are similar in the full azimuth range

Maximum aposteriori models



unilateral rupture towards South $\sim$ circular rupture propagation

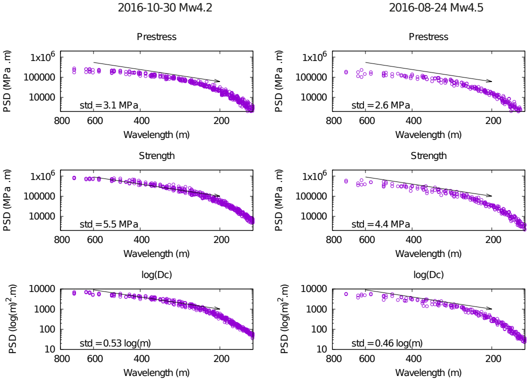
Small scale heterogeneities in stress drop, slip and rupture velocity

Conclusions

- Using apparent source spectra as data for Bayesian dynamic source inversion, we are able to reveal various characteristics of $\sim$M 4 earthquakes
- Since the inversion is performed up to high frequencies (25Hz), we obtain rupture complexities even on small spatial scale
- The information can be used to generate dynamic models with realistic high-frequency radiation.

Future plans

Inspecting spectral (spatial) properties of small scale heterogeneities



- Dynamic parameter perturbations (with respect to the mean model) averaged over the model ensemble show k^{-1} decay in their spectra
- Rescaling the models from M4 to larger
- We aim to generate dynamic models/dynamic scenarios with the same characteristics (von Karman correlation function with Hurst exponent 0)

Thank you!

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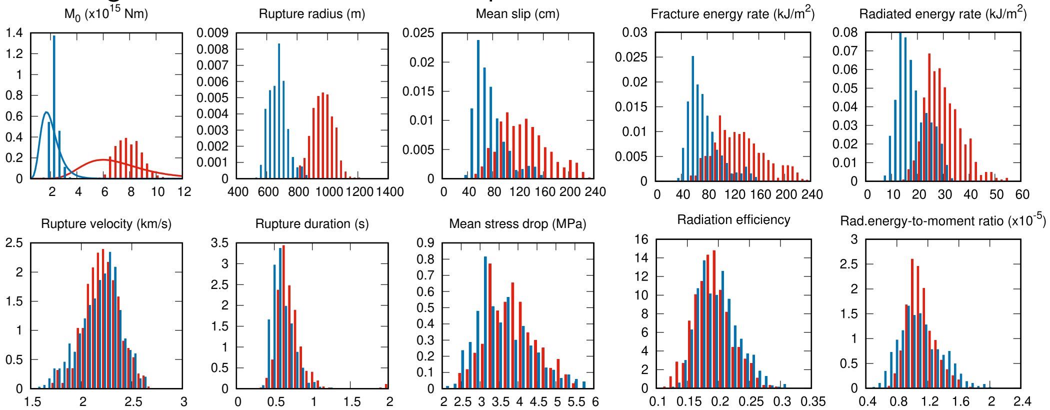
Mean characteristics of the model ensemble

Revealing uncertainties in the obtained parameters



Rupture size and mean slip follow magnitude scaling. Duration similar resulting from rupture geometry - unilateral and circular.

Mean rupture velocity, mean stress drop and scaled parameters (radiation efficiency and E_R/M_0) similar: due to tectonic setting or are the parameters unresolved?

Method

Bayesian inversion (Gallovič et al., 2019)

- Markov chain Monte Carlo sampling by the Parallel tempering method (Sambridge, 2013)
- Prior constraints: M_0 with uncertainty, weak nucleation around prescribed hypocenter (< 1 MPa), nonnegative friction drop and prestress, $D_c >$15 mm
- Assuming Gaussian data errors to calculate misfit $S = \frac{1}{2\sigma^2} \sum \ln^2 \left(\frac{\mathrm{AS_{obs}}}{\mathrm{AS_{synt}}} \right)$

Dynamic rupture modeling: FD3D_TSN code (Premus et al., 2020)

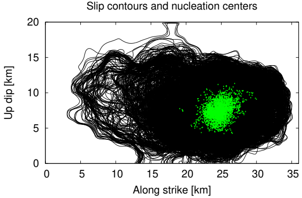
- Fault 2.5x2.5km embedded in homogeneous space (v_p=6km/s,v_s=3.5km/s)
- 4th-order finite-differences in a cartesian box (Madariaga et al., 1998) with slip-weakening friction implemented by traction-at-split-node (Dalguer and Day, 2007) and PML absorbing boundaries (FD grid 10m, time step 0.4ms)
- Ported to GPU using ACC directives - up to 10x faster than CPU
- Freely available on github: https://github.com/fgallovic/fd3d_tsn_pt

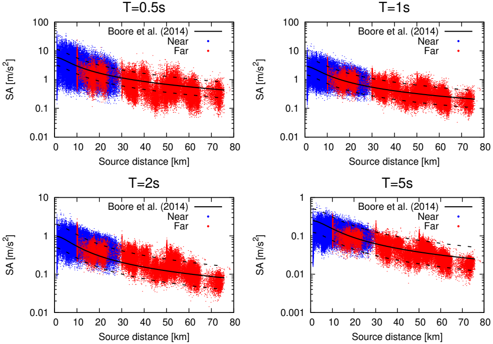
Calculation of apparent spectra

- Apparent source time function: integrating shifted slip rates $\dot{s}$ over fault towards station j: $\mathrm{ASTF_{synt}}(t, x_j) = \int_S \mu \dot{s} \left(\xi, t - \frac{|x_j - \xi|}{v_s} \right) \mathrm{d}\xi$
- Synthetic apparent spectra are obtained as Fourier amplitude spectra of the second time derivative of ASTF

Generating dynamic rupture scenarios constrained by GMPEs

- Adopting the same methodology of dynamic source inversion, but the fit is evaluated against ground motion intensity measures (SA at 0.2-2Hz).
- Assuming strike-slip fault 36x20km and a set of 18 phantom rock-site stations at distances 10-80km, we obtained a scenario database of ∼3000 events of Mw 5.8-6.8 with properties similar to real events (scaling relation, rupture velocity and stress drop range, energy budget).
- Analysing the residuals, we found underestimation at highest frequencies due to too coarse model grid (1.2km) leading to source models not complex enough/depleted at high frequencies.
- Decreasing the model grid size increases the computational cost for McMC sampling.





Gallovič and Valentová (2020), Valentová et al. (2021)