A user-friendly probabilistic earthquake source inversion framework for joint inversion of seismic, geodetic, and gravitational signals - The Grond toolkit

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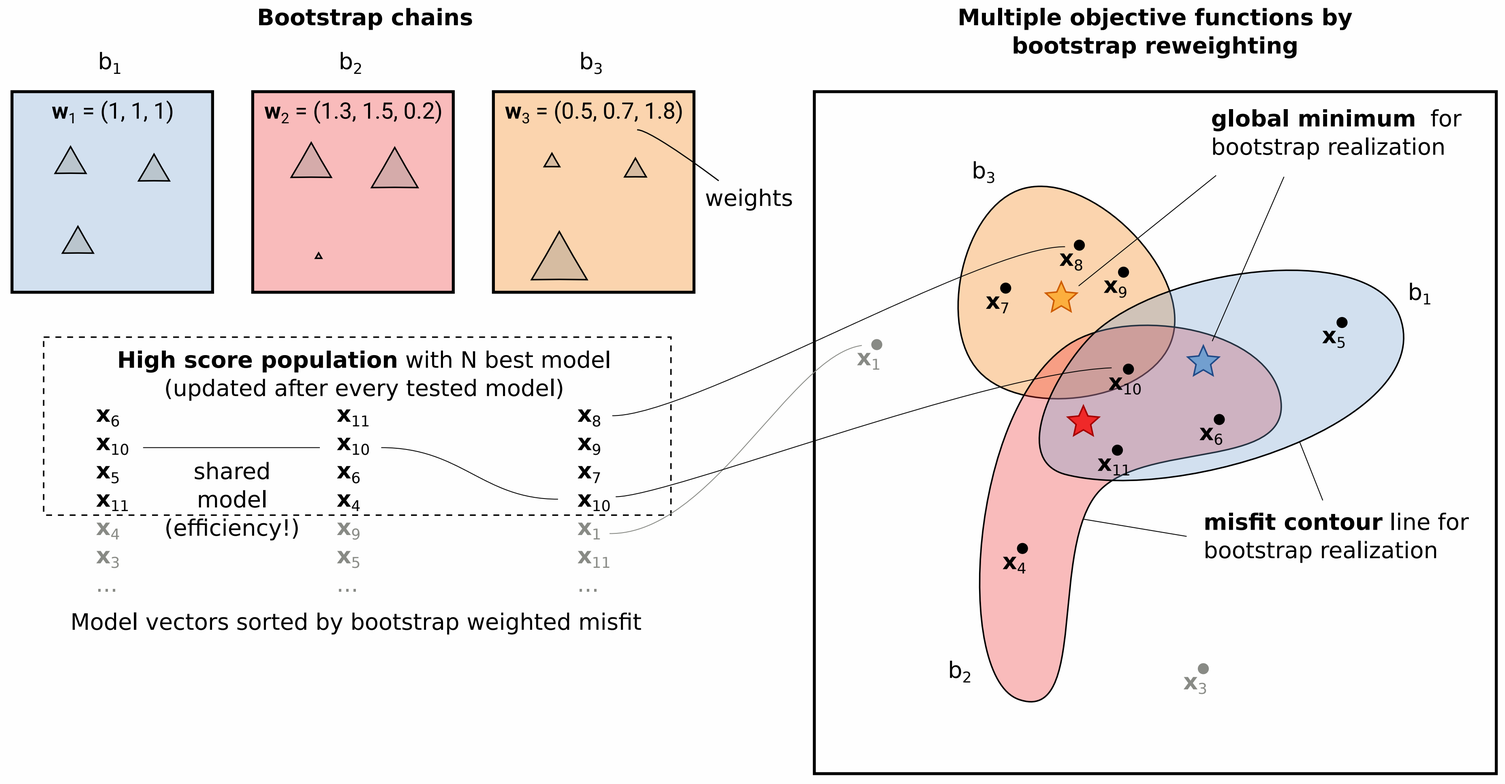
Seismic source and moment tensor waveform inversion is often ill-posed or non-unique if station coverage is poor or signals are weak. Three key ingredients can help in these situations: (1) probabilistic inference and global search of the full model space, (2) joint optimisation with datasets yielding complementary information, and (3) robust source parameterisation or additional source constraints. These demands lead to vast technical challenges, on the performance of forward modelling, on the optimisation algorithms, as well as on visualisation, optimisation configuration, and management of the datasets. Implementing a high amount of automation is inevitable.

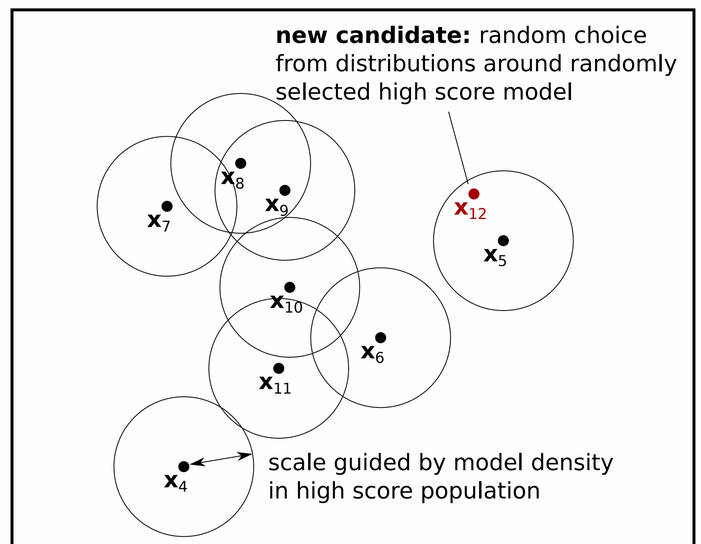
To tackle all these challenges, we are developing a sophisticated new seismic source optimisation framework, Grond. With its innovative Bayesian bootstrap optimiser, it is able to efficiently explore large model spaces, the trade-offs and the uncertainties of source parameters. The program is highly flexible with respect to the adaption to specific source problems, the design of objective functions, and the diversity of empirical datasets.

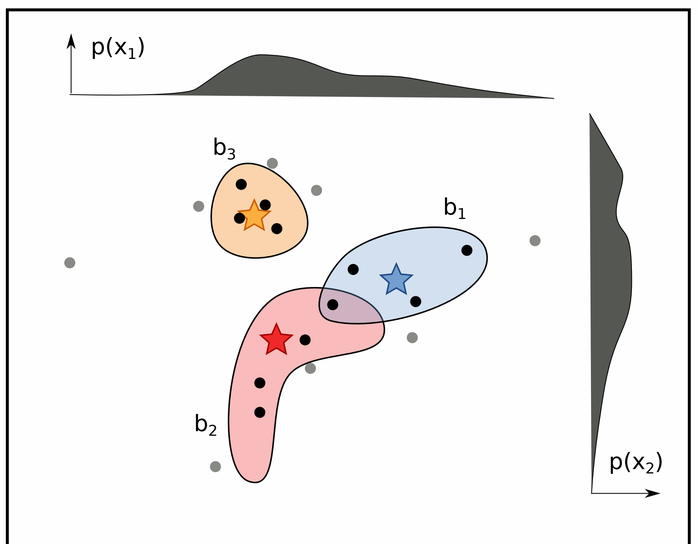
It uses an integrated, robust waveform data processing, and allows for interactive visual inspection of many aspects of the optimisation problem, including visualisation of the result uncertainties. Grond has been applied to CMT moment tensor and finite-fault optimisations at all scales, to nuclear explosions, to a meteorite atmospheric explosion, and to volcano-tectonic processes during caldera collapse and magma ascent. Hundreds of seismic events can be handled in parallel given a single optimisation setup.

Grond can be used to optimise simultaneously seismic waveforms, amplitude spectra, waveform features, phase picks, static displacements from InSAR and GNSS, and gravitational signals.

Grond is developed as an open-source package and community effort. It builds on and integrates with other established open-source packages, like Kite (for InSAR) and Pyrocko (for seismology).







The BABO (Bayesian bootstrap optimization) algorithm is a multi-objective function global optimization (directed search). Bayesian (block) bootstrap is used to form the ensemble of objective functions.The algorithm is capable of finding multiple minima, irregularly shaped minima and **assesses** parameter **trade-offs and uncertainties** in a probabilistic sense.

Grond

The **inversion framework** *Grond* is an open source, Python based framework to tackle source parameter estimation problems.

https://pyrocko.org/grond

Features:

- robust data handling
- config files for humans *and* machines
- easy to use
- modern code
- integrated plotting
- data quality checks

Contributions welcome!

Highly customizable data fitting options

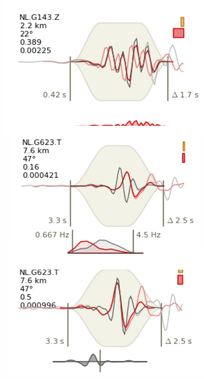
a) time domain fitting with automatic trace alignment

b) amplitude spectrum fitting

c) cross-correlation based waveform shape fitting

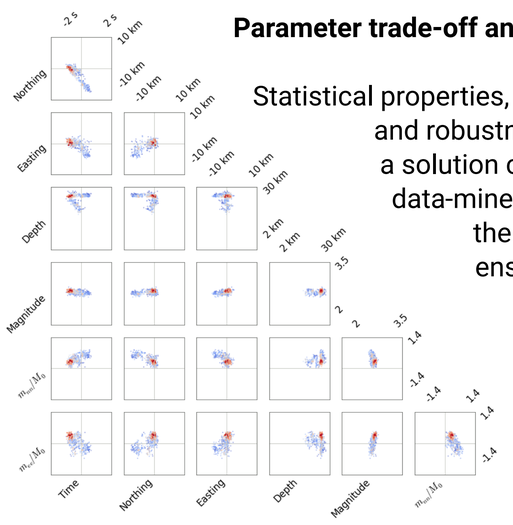
d) envelopes and more...

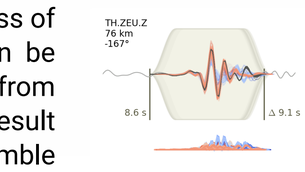
+ Geodetic and gravitational data fitting...

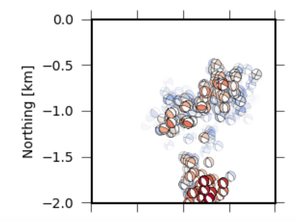


Parameter trade-off analysis:

Statistical properties, errors, and robustness of a solution can be data-mined from the result ensemble







Forward modelling in *Grond* is based on the Pyrocko-GF framework which allows fast and flexible forward modelling of displacement and other geophysical observables. Pre-calculated Green's functions are stored and managed in ready-to-use databases. In this way, we can separate the computationally expensive operations from any source modelling. Pyrocko wraps different numerical forward-modelling codes, such as QSEIS, QSSP, PSGRN/PSCMP to calculate Green's function databases. Several different source models are available.