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

Sebastian Heimann, Marius Isken, Daniela Kühn, Hannes Vasyura-Bathke, Henriette Sudhaus, Andreas Steinberg, Gesa Petersen, Marius Kriegerowski, Simon Daout, Simone Cesca, and Torsten Dahm

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 process, including visualisation of the result uncertainties. Grond has been applied to CMT source parameterisation or additional source constraints, usually on the optimisation algorithms, as well as on visualisation, optimisation configuration, and management of the datasets. Implementing a high amount of automation is inevitable.

Grond can be used to optimise simultaneously seismological, geodetic, 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). http://https://pyrocko.org/grond

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!

Bootstrap chains

![Bootstrap chains diagram]

Grond uses multiple objective functions by bootstrap reweighting

![Multiple objective functions by bootstrap reweighting diagram]

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.

High score population guides generation of new candidates

![High score population guides generation of new candidates diagram]

Remaining search space converges to interesting regions

![Remaining search space converges to interesting regions diagram]

Problem inherent uncertainty tells us when to stop! When bootstrap populations tend to become disjoint, uncertainty will not decrease if we continue.

Highly customizable data fitting options

- time domain fitting with automatic trace alignment
- amplitude spectrum fitting
- cross-correlation based waveform shape fitting
- envelopes and more...

+ Geodetic and gravitational data fitting...

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 OSES, QSSP, PSS2N/PSSCMP, to calculate Green's function databases. Several different source models are available.

![Forward modelling diagram]