Automated moment tensor inversion

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Abstract

We are developing a new, fully automated tool for full-waveform moment tensor (MT) inversion. It includes automated data retrieval and data selection according to presence of various instrumental disturbances. Data covariance matrix generated from before-event noise serves as an automated frequency filter and station weighting according S/N ratio. The software is programmed as much versatile as possible in order to be applicable in other regions and for events ranging from local to regional. It shares some similarities with the broadly used ISOLA software in terms of the inversion methods and input/output file structures, but most codes have been re-written from the scratch for maximum computational efficiency. Opposed to ISOLA, whose advantage is in a friendly manual processing of individual events using Matlab GUI, the new codes are intended rather for (i) massive automated application on large sets of earthquakes and/or (ii) near real-time applications.

Goals of the project

New software for moment tensor inversion, especially for:

- (Near) real-time applications
- Processing large datasets of historical data into moment-tensor catalogs

Properties of the software

- Automated: no user interaction necessary
- Robust: check data quality
- Scalable: from local to regional events
- Universal: applicable in different regions
- Fast: efficient enough to be run in near real-time
- Reliable: evaluate the uncertainty and quality of the result

Technical solution

Programmed as *Python* module, using *ObsPy* framework:

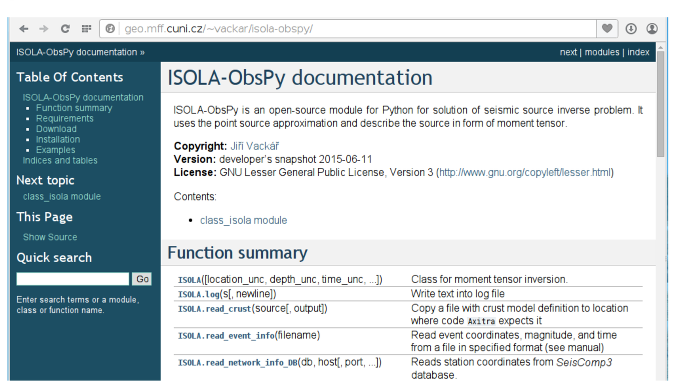

Figure 1: Webpage with the documentation

Program schema

- input: location, approx. magnitude
- load network configuration file / SeisComP DB
- load waveforms & instrument responses files / ArcLink
- disturbance detection
- create 3-D space + time grid to seek the centroid
- calculate Green's functions in grid points (Axitra) in parallel
- create covariance matrix
- solve inverse problem in each grid point in parallel
- plot the results

Disturbances detection

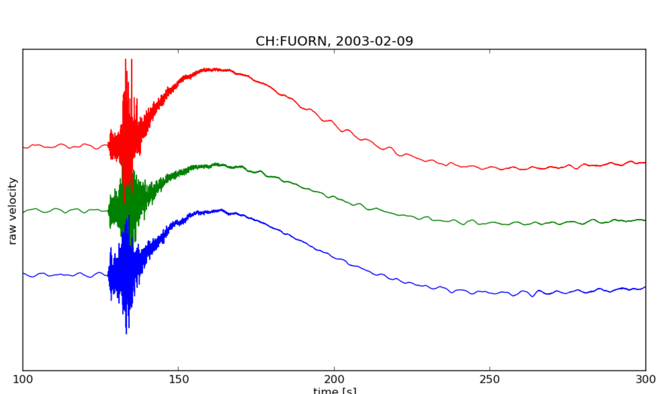

Figure 2: Typical example of long-period disturbance, which is caused by seismometer tilt or instrument malfunction. Such disturbances are detected using *MouseTrap* code [Vackář et al., 2015] and removed from processing

Covariance matrix

Inverse problem with no a priory information [Tarantola, 2005]:

$$\tilde{\mathbf{m}} = \left(\mathbf{G}^T \mathbf{C}_D{}^{-1} \mathbf{G}\right)^{-1} \mathbf{G}^T \mathbf{C}_D{}^{-1} \mathbf{d}_{obs} \quad (1)$$

- model parameters (result)
- data vector
- forward problem matrix
- data covariance matrix

The matrix is calculated from auto-/cross- covariance of before-event noise.
The matrix works as automated frequency filter and station weighting to emphasize the high-SNR data.

We started with the covariance matrix for Gaussian random stationary with zero mean [Tarantola, 2005, Example 5.1].

$$\mathrm{C}_D = \begin{pmatrix} c(\tau_0) & c(\tau_1) & \cdots & c(\tau_{n-1}) \\ c(\tau_1) & c(\tau_0) & \cdots & c(\tau_{n-2}) \\ \vdots & \vdots & \ddots & \vdots \\ c(\tau_{n-1}) & c(\tau_{n-2}) & \cdots & c(\tau_0) \end{pmatrix} . \quad (2)$$

We assume the seismic noise to be Gaussian, zero-mean, and stationary, so the last covariance matrix is valid for one component of a station. With assimption of ergodicity, the covariance may be avaluated as correlation (auto-correlation in this case). For discrete time series, the correlation has form

$$c^{fg}(\tau) = (f \star g)[\tau] \stackrel{\text{def}}{=} \frac{1}{2N+1} \sum_{m=-N}^{N} f^*[m]\, g[m+\tau] . \quad (3)$$

The covariance matrix for more stations (here only two components per station for brevity) is then

$$\mathrm{C}_D = \begin{pmatrix} \mathrm{C}^{NN}_{st1} & \mathrm{C}^{NE}_{st1} & 0 & 0 \\ \mathrm{C}^{EN}_{st1} & \mathrm{C}^{EE}_{st1} & 0 & 0 \\ 0 & 0 & \mathrm{C}^{NN}_{st2} & \mathrm{C}^{NE}_{st2} \\ 0 & 0 & \mathrm{C}^{EN}_{st2} & \mathrm{C}^{EE}_{st2} \end{pmatrix} , \quad (4)$$

Where blocks on the diagonal C^{XX}_{stZ} are given by eq. 2 and non-diagonal blocks C^{XY}_{stZ} are similar, only the correlation $c(\tau)$ is replaced by cross-covariance $c^{XY}(\tau)$ between components. Behind the zeroes (zero block) is an assumption, that the seismic noise is not correlated between the seismic stations.

Automatically ploted output

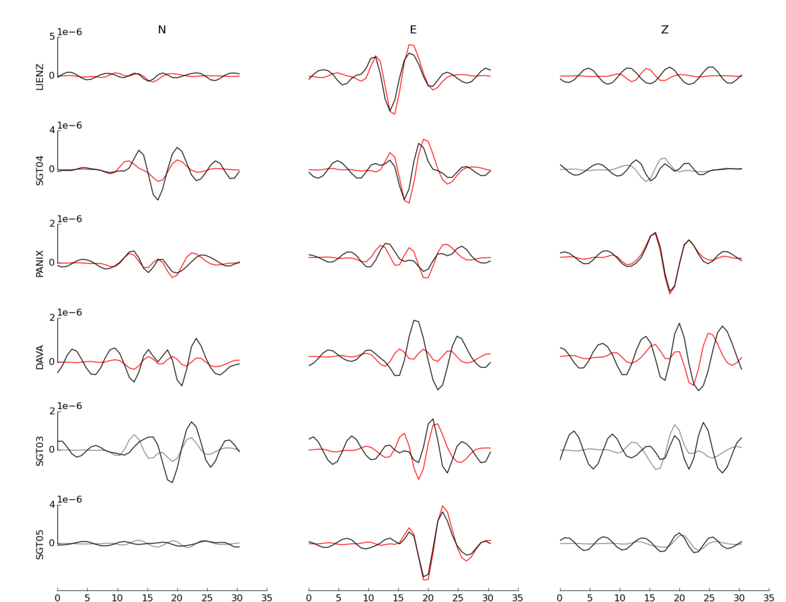

Figure 3: Automatically ploted waveform fit

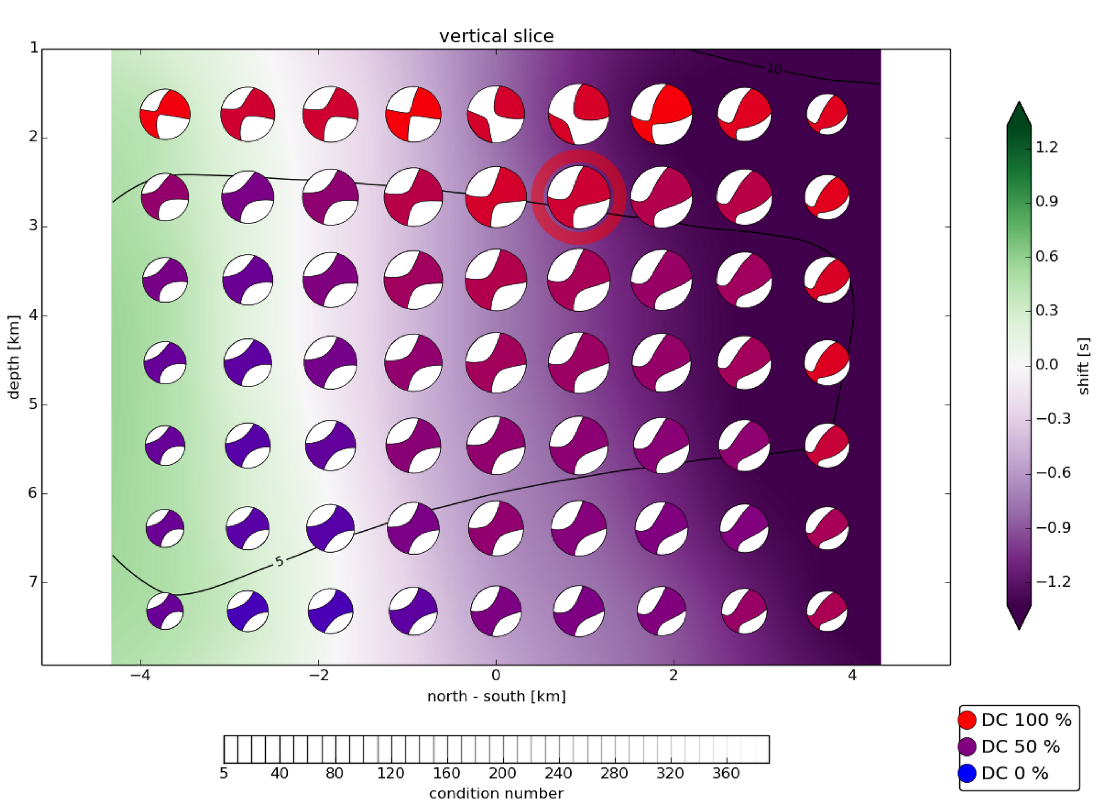

Figure 4: North-south slice over grid of solution. The best solution is highlighted. Sizes of beachballs correspond to variance reduction, their colors shows DC %. Color contours in the background shows inverted centroid time, contour lines displays condition number of the inverse problem, which correspond to solution stavbility. Such slices in 4 direction through the point of the best solution are ploted automatically, as well as horizontal slices in each depth.

Synthetic test 1

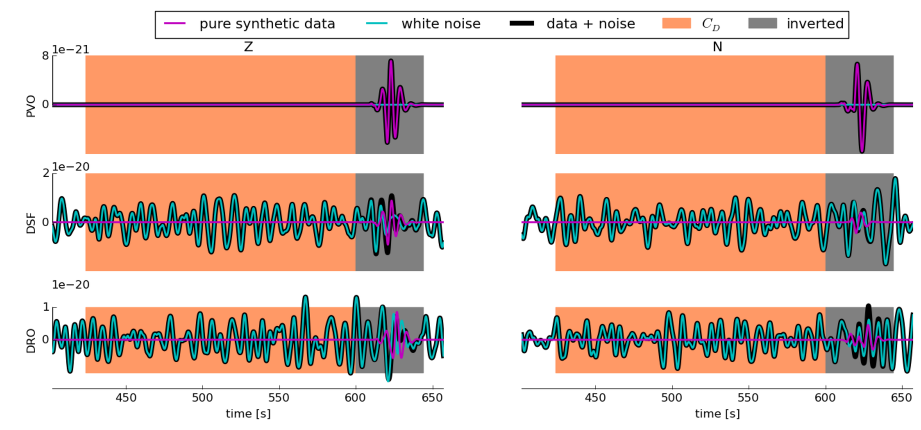

Figure 5: We add strong white noise to 6 of 10 stations. Time windows of the inversion and for calculating the covariance matrix are highlighted.

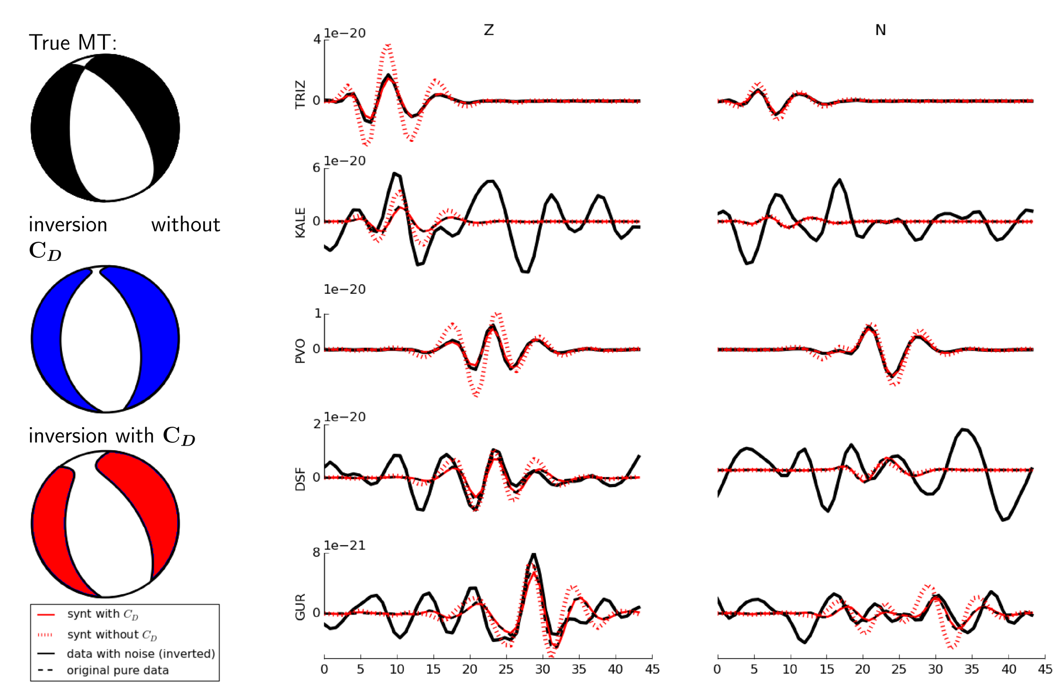

Figure 6: The covariance matrix, which downweight noisy stations, improves the result in terms of waveform fit and agreement of strike/dip/rake with the original MT. The CLVD % seems to be less stable part of the result.

Synthetic test 2

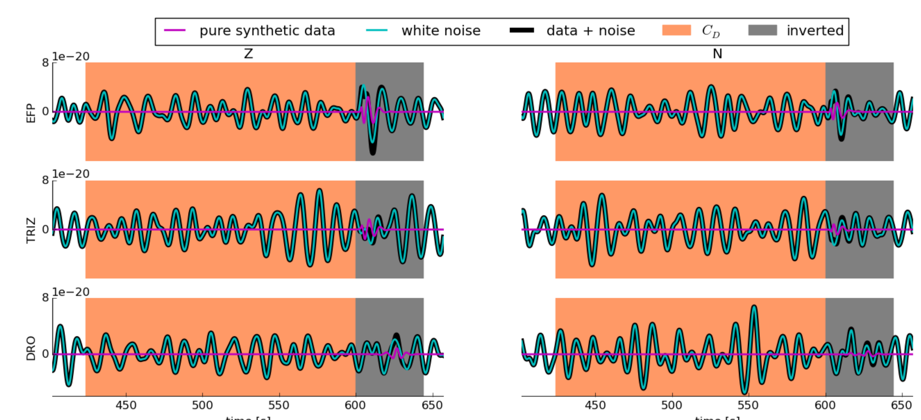

Figure 7: We add strong filtered white noise to all stations. Inverted frequencies are 0.05–0.15 Hz, the noise is filtered by bandpass filter 0.05–0.10 Hz.

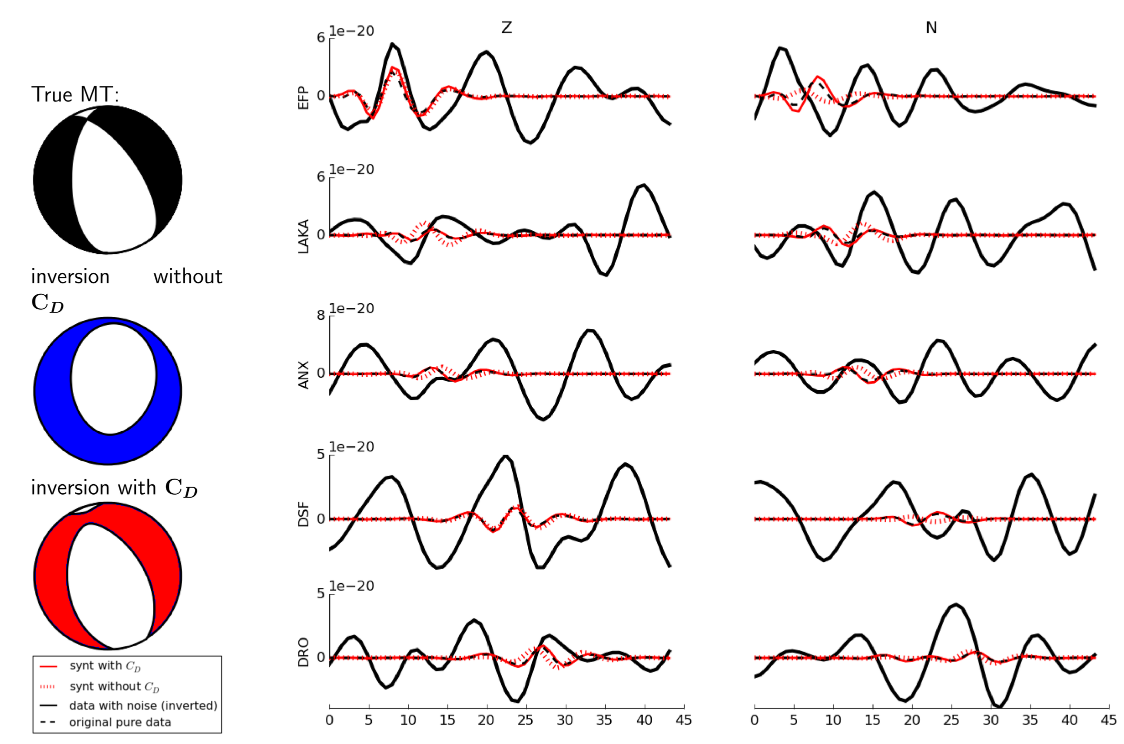

Figure 8: The covariance matrix, which filter out noisy frequencies, comes to the right result. The solution without covariance matrix is completely wrong.

Conclusion

- We develop a new software for automated MT inversion
- It is adaptable from local to regional events
- We do not need exact location on the input
- Inverse problem formulation with noise covariance matrix
  - It improves the results in case of noisy data

Acknowledgement

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References

Tarantola, A. (2005), Inverse problem theory and methods for model parameter estimation. siam.

Vackář, J., J. Burjánek, and J. Zahradník (2015). Automated detection of long-period disturbances in seismic records; MouseTrap code, *Seismological Research Letters*, 86, 442–450. http://geo.mff.cuni.cz/~vackar/mouse/