
DELIVERABLE

D23.1 - Advanced tools for the identification and relocation of low-magnitude seismicity

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Summary

Here we present the set of software developed during the project, for detection, location and characterization of low-magnitude seismicity. These software deal with event detection and location (BackTrackBB and PyMPA), source parameter characterization (SPAR) and moment tensor inversion (HybridMT). For each software we describe the methodology, the code structure and provide link where downloading the software and the relevant information associated with it.

1 BackTrackBB – A method for automatic detection and location of seismic sources

1.1 Method

BackTrackBB is a computationally efficient network-based detection and location scheme exploiting the multi-scale, frequency selective coherence of signals' statistical features recorded across the stations of seismic network. The method is composed of two main parts (Figure 1): signal processing, calculating signals' characteristic functions (CFs) by applying statistical time-frequency signal transformation, and detection and location, providing a likelihood of seismic source location by summing the time-delay functions corresponding to the station-pair cross-correlations of CFs projected according to the theoretical travel-time differences. BackTrackBB provides an efficient tool for processing continuous seismic data and increasing the number of detected and located events in complex seismically active environments.

The method has been tested and successfully applied to the analysis of natural seismic energy release activity in subductions zones and active continental faults. During SERA project, BackTrackBB was as well transferred to the analysis of induced seismicity in active mines: Garpenberg mine (in collaboration with INERIS, France) and Rudna mine (in collaboration with IG-PAS, Poland). All the adjustments and improvement of the method developed for the applications of induced seismicity analysis were incorporated into the original version of the method.

1.2 Code

The corresponding code combining Python- and C-based modules is available from the GitHub repository. The code takes as the input continuous data recorded at network's stations and provides as an output a catalogue of detected and located events. An example output for a single located event is shown in Figure 2. The initial version of the BackTrackBB was made public through GitHub in May 2017. The improvements and adjustments developed during the SERA project were incorporated during 2018.

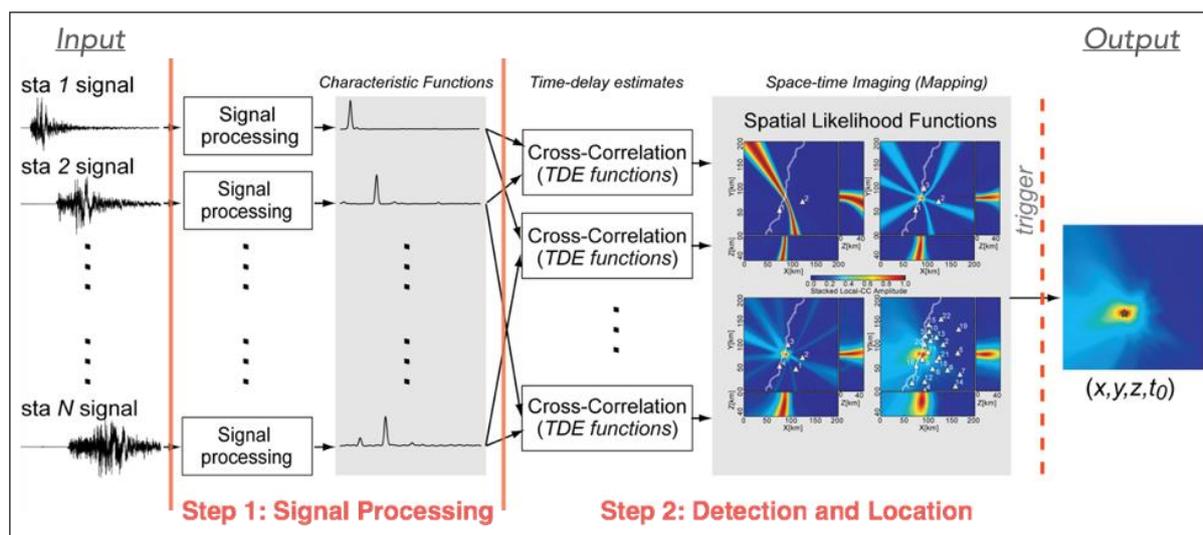


Figure 1: Summary of the BackTrackBB detection and location workflow

1.3 Link to the software

The software can be obtained at the link

<https://github.com/BackTrackBB/backtrackbb>.

1.4 References

Poiata, N., Satriano, C., Vilotte, J.-P., Bernard, P., and Obara, K. (2016). Multi-band array detection and location of seismic sources recorded by dense seismic networks, *Geophys. J. Int.*, 205(3), 1548-1573, doi:10.1093/gji/ggw071.

Poiata, N., Vilotte, J.-P., Bernard, P., Satriano, C., and Obara, K. (2018). Imaging different components of a tectonic tremor sequence in southwestern Japan using an automatic statistical detection and location method, *Geophys. J. Int.*, 213(3), 2193–2213, doi:10.1093/gji/ggy070.

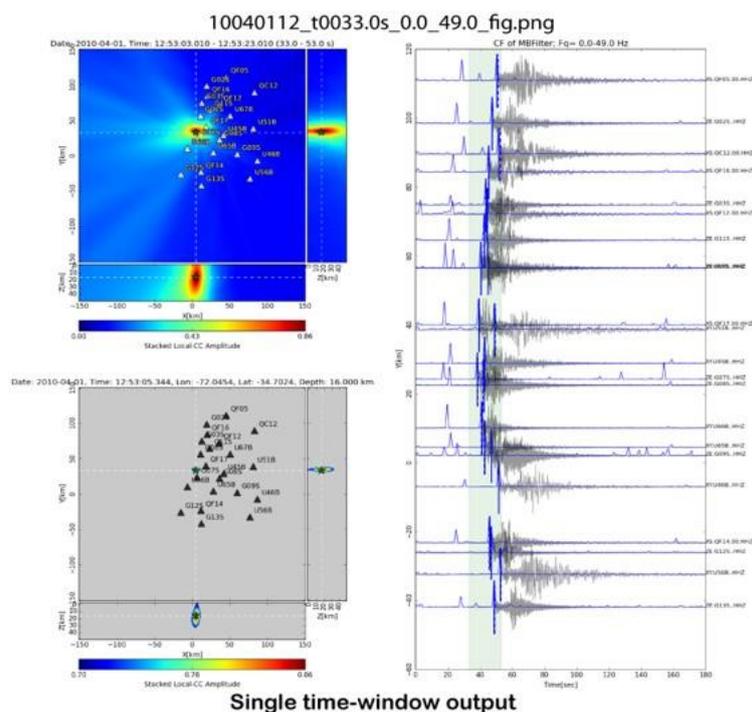


Figure 2: Example output provided by BackTrackBB

2 PyMPA – A software package for phase match filtering

2.1 Method

PyMPA is a software based on matched filtering search for earthquakes that resemble previously (well) located events, termed templates (e.g., Shelly et al., 2007; Peng and Zhao, 2009; Yang et al., 2009; Kato et al., 2012; Zhang and Wen, 2015). The algorithm, which exploits ObsPy routines (Krischer et al., 2015), is versatile and supports most commonly used seismic data and earthquake catalogue formats.

PyMPA is designed to augment the network detection capability in terms of standard earthquakes (Figure 3), or any other seismic signal like explosions and/or low-frequency tremors, by using advanced routines different from the faster standard amplitude-ratio STA/LTA methods.

The technique allows to improve earthquakes catalogues decreasing the completeness magnitude and is particularly useful in detecting micro-seismicity below the background noise level or during a strong aftershocks sequence when the network sensitivity is lower. Statistics from cross-correlations analysis, also allow finding repeating earthquakes (e.g. Figure 4) often related to seismic transients or slip on small fault patches.

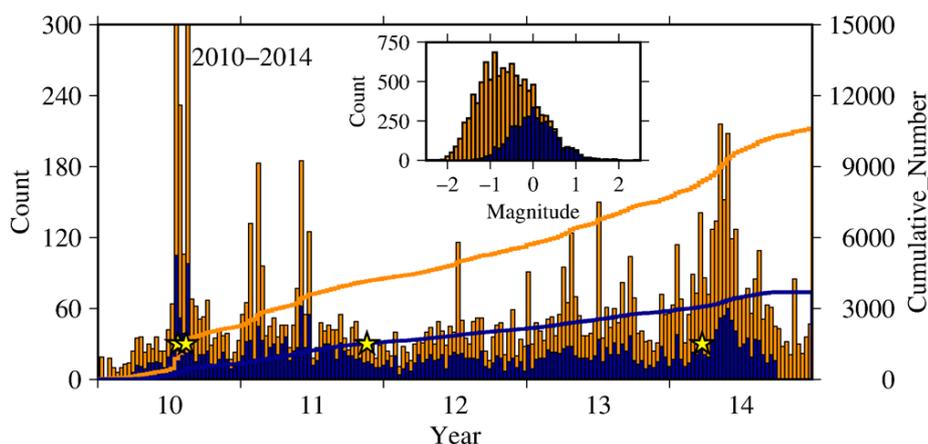


Figure 3: 5 years template events along the Alto-Tiberina fault (blue histograms) as recorded by ATF test bed and augmented detections by PyMPA (orange). Solid lines represent the cumulative number of earthquakes. In the inset the magnitude distribution of the templates in comparison with the augmented catalog. The completeness magnitude is decreased by 0.5. Stars indicate the timing of earthquakes between magnitude 2 and 2.8

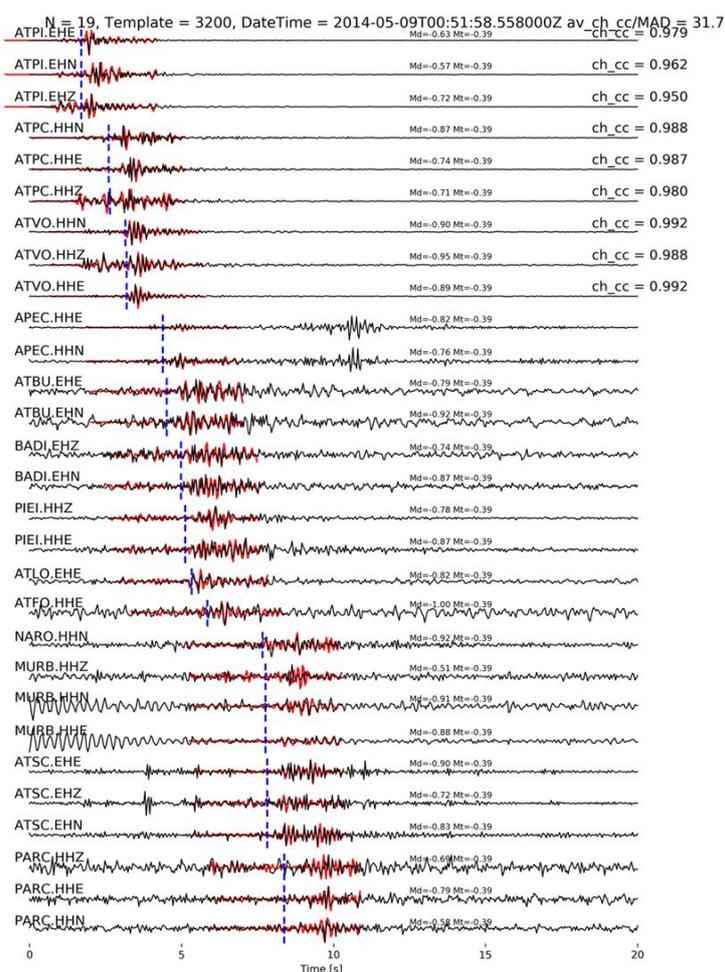


Figure 4 : Detection of a repeater with an average cross-correlation value of 0.98 along the Alto-Tiberina fault. Seismic data from ATF test bed (black waveforms) and a template (red) are overlapped. On the left of the panel, we list the station and channel codes, and on the right the corresponding value of cross-correlation between the two events. The template event (a magnitude $M=-0.4$) allows to detect a $M=-1.0$ repeater.

2.2 Code

PyMPA is designed to detect microseismicity from the cross-correlation of continuous data and templates. PyMPA is an open source seismological software and consists of some separate utilities for input preparation, the main program, and output post-processing tools to obtain a catalogue and verify events. The code repository with some examples is stored on GitHub, and is free to be cloned on your Mac, Windows or Linux platforms. It supports Python 2.7, 3.5, 3.6 and 3.7 releases and uses ObsPy for reading and writing seismic data, and for handling most of the event-station metadata. A flowchart of the main program is shown in Figure 5. Matched-filter correlations are calculated using a vectorised python function or using ObsPy v.1.2.0 `correlate_template` function allowing to select time or frequency domain.

Together with the manual, we also provide some practical examples. Python scripts, updates and modifications are automatically verified using TRAVIS, for testing and deployment (<https://travis-ci.org/>). This package is distributed under the LGPL GNU Licence, Copyright PyMPA developers 2019.

In addition to PyMPA, we develop other tools external to the main code to manage the input-output preparation and validation for (1) downloading data from Observatories and Research Facilities for European Seismology–European Integrated Data Archive (ORFEUS-EIDA) servers, (2) evaluating data quality, (3) selecting earthquakes as templates from a reference catalog, (4) trimming and filtering them from continuous waveforms, (5) avoiding redundant detections in the output, and (6) validating new events. During the SERA project, we improve the code for a more flexible use by adding controls on (1) the memory usage, (2) the quality of the input templates, and (3) the maximum number of channels.

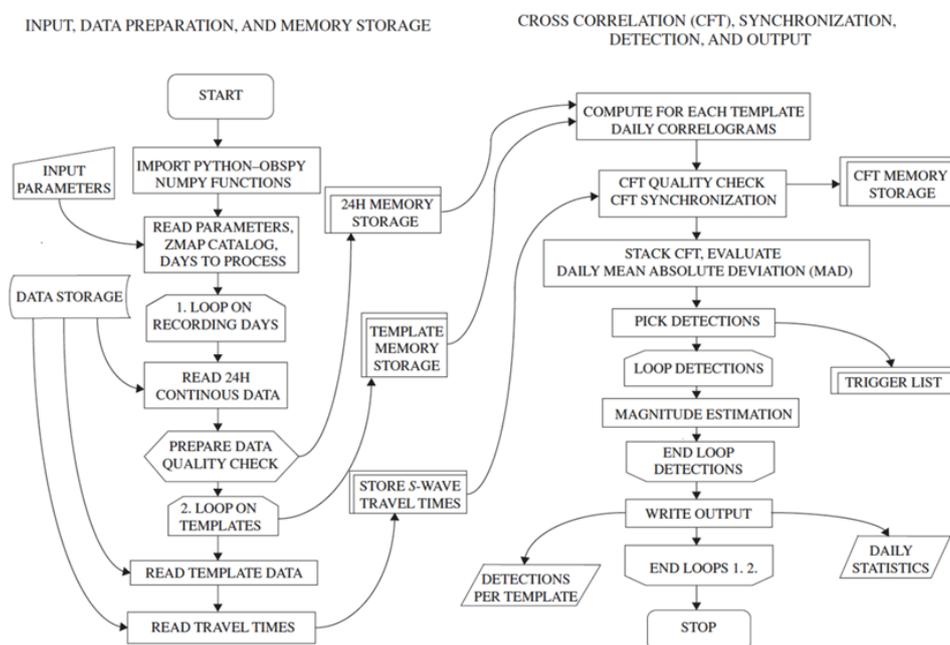


Figure 5: Flowchart of the main program for template matching

2.3 Link

The software can be obtained at the link:

<https://github.com/avuan/PyMPA37>

2.4 References

Vuan, A., Sukan, M., Amati, G., and Kato, A., (2017). Improving the Detection of Low-Magnitude Seismicity Preceding the Mw 6.3 L'Aquila Earthquake: Development of a Scalable Code Based on the Cross-Correlation of Template Earthquakes, BSSA <https://pubs.geoscienceworld.org/ssa/bssa/article-abstract/525813/improving-the-detection-of-low-magnitude?redirectedFrom=fulltext>

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Yang, H., Zhu, L., and Chu, R. (2009). Fault-plane determination of the 18 April 2008 Mount Carmel, Illinois, earthquake by detecting and relocating aftershocks, *Bull. Seismol. Soc. Am.* 99, 3413–3420.

Zhang, M., and Wen, L. (2015). An effective method for small event detection: Match and locate (M&L), *Geophys. J. Int.* 200, 1523–1537.

3 SPAR- Source PARAmeter Estimator

3.1 Method

We have developed the software SPAR using a probabilistic description of the inverse problem related to the source parameters. The goal is to retrieve source parameters (seismic moment, corner frequency and high-frequency spectral fall off), within the anelastic attenuation contribution (the constant quality factor Q) from the inversion of the single station displacement spectrum (e.g. Figure 6). We use the generalized Brune's model to describe the source contribution (Brune 1970) and a simplified description of the Green's propagator, that accounts for geometrical spreading and radiation pattern in a 1D velocity structure and a frequency independent quality factor.

The inversion is built on a probabilistic framework based on the conjunction of states of information between data and model, to jointly retrieve the model parameters. The final solution of the problem is the joint probability density function (PDF) in the model space, that can be used to extract statistical indicators for the parameter description. Specifically, we select the mean value as the expected value of a single parameter and the square-root of the variance to assess the uncertainty.

We assume that the a-priori distribution in the data space is Gaussian-like around the observations, with covariance matrix related to the signal-to-noise ratio. Also, we assume that the forward modelling provides data normally distributed around the prediction, with an unknown uncertainty related to the simplified model used to describe the observations. Integration of the joint probability provides an a-posteriori PDF, that accounts for the a-priori PDF in the model space and has a Gaussian-like distribution, with total covariance matrix related to the sum of the model and data covariances. Under the additional assumption of diagonally-dominated covariance matrix, with all constant eigenvalues, the best-fit solution corresponds to the minimization of the L2 norm between observations and model predictions.

Following this approach, we first search for the maximum of the a-posteriori PDF through the basin hopping technique (Wales, 2003) that couples a global exploration built on a Markov chain with a local deterministic maximization. The technique performs a local perturbation of coordinates, then a local minimization reaching at each time step a new final solution, which is accepted or rejected according to a Metropolis criterion, based on a constant temperature value. Feedback control systems are implemented to increase the average size of the perturbations, when the solution lies for a while around the same location.

The individuation of the maximum of the PDF allows to estimate the diagonal elements of the covariance matrix based on the MSE related to the best model. In addition, integration of PDF is performed in the vicinity of the maximum likelihood solution, circumscribing the domain around the maximum outside which the a-posteriori PDF can be considered zero (e.g. Figure 7). Then we compute statistical indicators (mean, variance and correlation coefficients) on source parameters and anelastic attenuation through integration of the PDF. Definition of quality criteria based on the signal to noise ratio and similarity of the marginal PDFs with a Gaussian function enable us to define the frequency domain for the inversion and to automatically get rid of unconstrained solutions.

After this phase we thus come out with a set of source parameters, computed at single station for the same earthquake, together with along-path averaged quality factors. Final estimation of source parameters per single event is obtained as weighted mean of the single station solutions, where weights are related to the inverse of the variances. Also, final uncertainty accounts for single station uncertainties.

After the computation of the source parameters, derived parameters with consistent uncertainty propagation are: the source radius, computed using the Brune's model (Brune 1970), the stress drop,

computed using the Eshelby relationship (Eshelby 1957), the apparent stress and the radiated energy, from integration of the theoretical spectrum, using the parameters derived from the inversion (Boatwright and Fletcher 1984) and the Savage-Wood seismic efficiency, as the ratio between the radiated energy and the total energy (Savage and Wood 1971).

Main advantages of the technique are: the capability to search for the best fit solution, escaping from local minima and investigating the shape of almost horizontal valleys in the cost function; the robustness in the evaluation of the uncertainties, that account for between-parameter correlations; the ability to automatically discard unconstrained solutions, enabling for the use of the technique over massive datasets. Actual main limitations of the methods are related to the use of a constant frequency independent quality factor and to the neglect of the site effects.

The technique has been successfully applied to characterize the source parameters for the 2016-2017 Central Italy seismic sequence, for a large dataset of low frequency earthquakes (LFEs) along the Nankai subduction zone, for events recorded by high-quality, very-high frequency instruments in Tsukuba, Central Japan, and for events recorded in the Irpinia Near Fault Observatory (I-NFO).

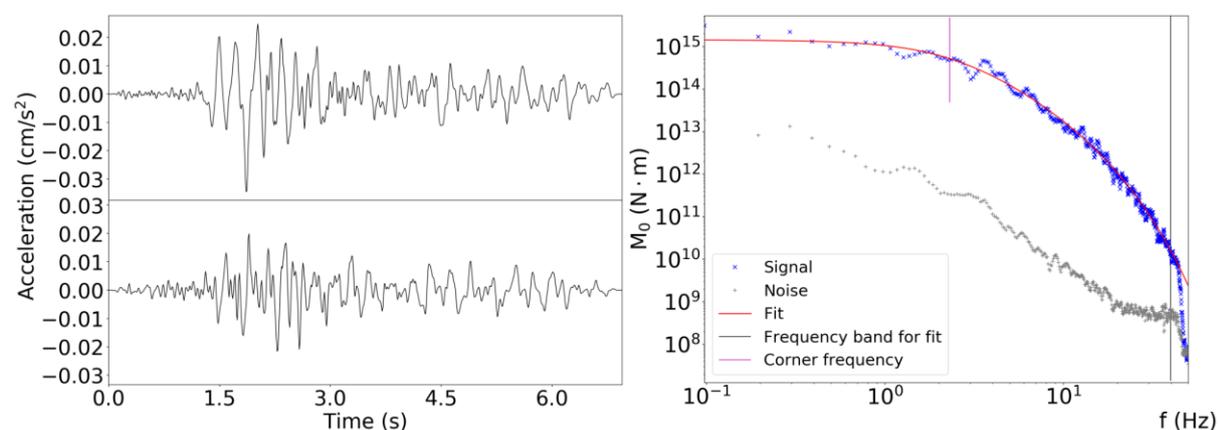


Figure 6 : Example of records analysed by SPAR (left panel); displacement amplitude spectrum and its fit on the right, superimposed to the noise spectrum (right panel).

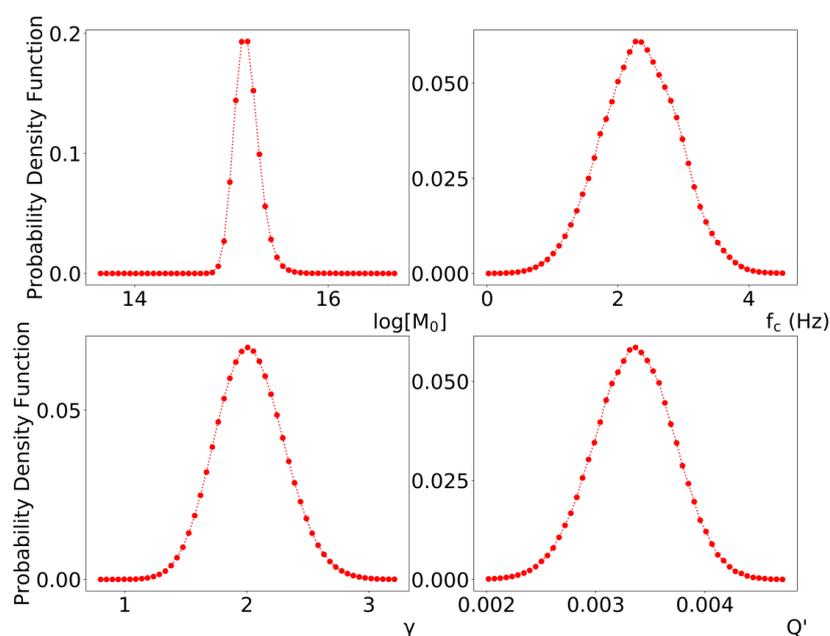


Figure 7: Marginal PDF for each parameter from which the expected value and the uncertainty are estimated.

3.2 Code

The code SPAR is built in Python. Its structure (Figure 8) is based on an input which contains information about the data (seismic records), the fixed parameters for the inverse problem (the velocity and density models, the radiation pattern coefficients, etc....) and the forward operator. Then, the method core performs the inversion with the following steps: 1. It computes the maximum likelihood function assuming a unit total covariance matrix and using the basin-hopping technique; 2. It evaluates the elements of the total covariance from the minimum MSE; 3. It defines a region around the maximum likelihood function, such that outside this region the contribution of the a-posteriori PDF can be considered negligible in the integration; 4. It performs the integration of the a-posteriori PDF to extract the marginal PDFs; 5. It extracts mean, variance and between-parameter correlation from the analysis of marginal PDFs; 6. Solutions are required to pass quality criteria, based on similarity of the PDF with Gaussian functions; 7. SPAR computes parameters for the event from single station solutions and derived parameters. The structure is shown in Figure 8.

3.3 Link to the software

Here the link to the software

http://dipsf.fisica.unina.it/~festa/SERA/SPAR_v_0.50.zip

The software will be moved on GitHub; temporarily the documentation can be found at:

<https://supphy.wordpress.com/projects/sera/sera-derivable-d23-1/>

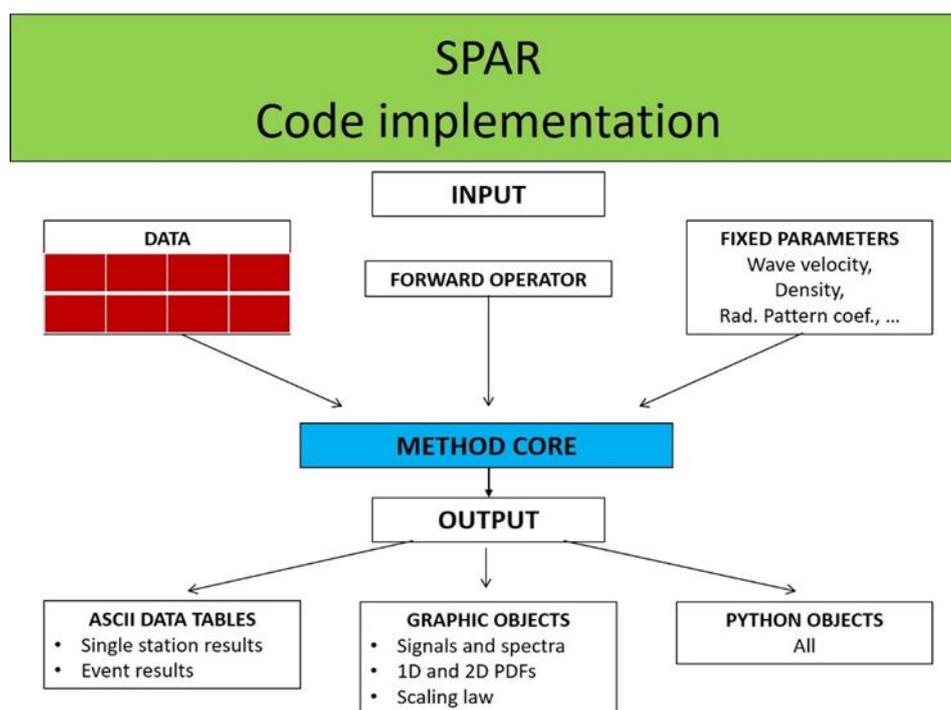


Figure 8 : Input/ Output structure of SPAR

3.4 References

Supino, M., Festa, G., and Zollo, A. (2019). A probabilistic method for the estimation of earthquake source parameters from spectral inversion : application to the 2016-2017 Central Italy seismic sequence, submitted to Geophys. J. Int. link from arXiv: <https://arxiv.org/abs/1811.06049>

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4 HybridMT

4.1 Method

We present the software package hybridMT which allows performing seismic moment tensor inversion and refinement, optimized for earthquake data recorded by regional-to-local seismic networks as well as for acoustic emission activity. The algorithm uses first P-wave amplitudes to invert for unconstrained full, deviatoric, and double-couple constrained moment tensors. Uncertainty assessment is performed by bootstrap resampling. In addition to moment tensor inversion, we also provide the implementation of the hybrid moment tensor technique. This methodology increases the quality of calculated seismic moment tensors from events forming a spatial cluster by assessing and correcting for poorly known path and site effects. We tested hybridMT on synthetic datasets, acoustic emission data recorded during laboratory rock deformation experiments, and induced seismicity data from a geothermal reservoir. The package is supplemented with extensive documentation, tutorials, and a dedicated website.

4.2 Code

HybridMT is a software package for the seismic moment tensor inversion and refinement. The provided software package is designed predominantly for use in MATLAB/shell environments. We also provide the MATLAB implementation of the hybrid moment tensor technique. HybridMT is freely available and distributed under General Public License. An example of MATLAB interface is shown in Figure 9.

4.3 Link

The software can be downloaded at the project website:

<https://www.induced.pl/software/hybridmt>

(the source code is available by downloading the package)

The documentation is at the link

<https://www.induced.pl/download/hybridmt-manual?wpdmdl=2769&refresh=5caaecbf1ed0a1554705599>

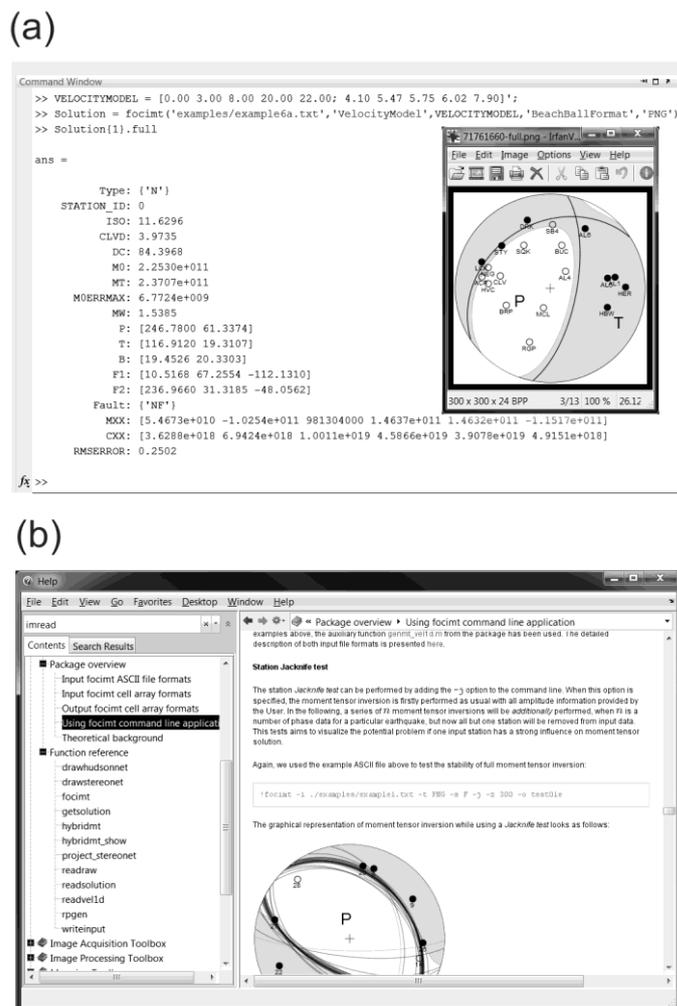


Figure 9: The MATLAB interface for HybridMT

4.4 References

Kwiatek, G., Martínez-Garzón, P., and Bohnhoff, M. (2016). HybridMT: A MATLAB/Shell Environment Package for Seismic Moment Tensor Inversion and Refinement. *Seismological Research Letters* 87 (4), DOI: 10.1785/0220150251

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