E
ELECTRONIC SEISMOLOGIST

Scisola: Automatic Moment Tensor Solution for SeisComP3

by Nikolaos Triantafyllis, Efthimios Sokos, Aristidis Ilias, and Jiří Zahradník

ABSTRACT An automatic moment tensor is a significant product of regional seismic networks and an essential piece of information for real-time seismological applications, like shake maps or tsunami warning. In this article, we present scisola, a new software for automatic moment tensor (MT) retrieval, based on the ISOLated Asperities (ISOLA) MT inversion code and SeisComP3 real-time processing system. Scisola connects SeisComP3 with the ISOLA FORTRAN codes by retrieving event, station, waveform, and instrumental response data from SeisComP3 and passing the information to ISOLA. The Green's function calculation and centroid spatiotemporal grid search are done in parallel mode in scisola, thus the computational time is significantly reduced. The user has full control of all calculation aspects, for example, frequency range of inversion and station selection through the creation of magnitude-based rules. Scisola is programmed in Python and provides a complete graphical user interface (GUI) and a database for storing the results. The automatic solution is stored in the database, and the user is able to revise it through a GUI. The software provides a complete logging of processing steps, extended graphical output, a text file useful for e-mail dissemination, and a handful of quality indexes of the solutions. The code's performance was tested against manual MT solutions and proved to be efficient.

Online Material: Installation guide, short presentation on browsing, configuration information, and evaluation test of the scisola software, including screenshots from the software.

INTRODUCTION

Moment tensors (MTs) are a key element in many real-time seismological applications, such as shake maps or tsunami warning. Therefore, it is imperative to have a reliable, rapid, and automated MT computation. Modern seismic networks with broadband sensors and real-time digital telemetry allow such calculations and open the way to implement automated MT procedures.

MTs are determined automatically with global data and, in a few cases, with regional data. An automatic MT procedure for strong earthquakes ($\mathbf{M} > 5.5$) has been implemented by the Global Centroid Moment Tensor (Global CMT) project (http://www.globalcmt.org, last accessed October 2015; Dziewonski *et al.*, 1981; Ekström *et al.*, 2012), the U.S. Geological Survey (http://earthquake.usgs.gov/), and the Earthquake Research Institute (ERI) in Japan (Kawakatsu, 1995). The GeoForschungsZentrum (GFZ) German Research Centre for Geosciences (http://www.gfz-potsdam.de/en/home/, last accessed October 2015; Saul *et al.*, 2011) provides automatic MT solutions using global data as well. The Berkeley Seismological Laboratory of the University of California (http://seismo.berkeley.edu/) developed the TDMT_INV software (Dreger, 2003) that computes automatic MTs for regional networks and earthquakes larger than M_w 3.5. This software, with adjustments, is used also by other centers, for example, the Japan National Research Institute for Earth Science and Disaster Prevention (http://www.bosai.go.jp/e) and the Mediterranean Network (MedNet) of Italy (http://mednet.rm.ingv.it), as well as by independent researchers in the United States, Europe, and Asia. The first automatic MT inversion procedure in the European–Mediterranean region was presented by Bernardi *et al.* (2004). Other services that realize respective efforts are the Swiss Seismological Service (http://www.seismo.ethz.ch/prod/tensors/index_EN) and the Earthquake and Volcano Information Center of Japan (http://wwweic.eri.u-tokyo.ac.jp/index-e.html). Available computer codes for MT calculation at regional and local distances include, for example, ISOLated Asperities (ISOLA) by Sokos and Zahradník (2008, 2013), FMNEAREG by Delouis *et al.* (2008) and Maercklin *et al.* (2011), KIWI by Cesca *et al.* (2010), and the code of Yagi and Nishimura (2011).

The MT retrieval software package ISOLA has a FORTRAN core for speed that is paired with a user friendly MATLAB (www.mathworks.com/products/matlab, last accessed October 2015) graphical user interface (GUI). It has been widely applied during the last 10 years to earthquakes of magnitudes ranging from M_w 0.2–9, at epicentral distances from ~1 to ~1000 km (e.g., for research applications, see Agurto *et al.*, 2012; Quintero *et al.*, 2014). ISOLA has been used routinely since 2006 at the University of Patras, Seismological Laboratory, Greece, (http://seismo.geology.upatras.gr/) to compute MTs for $M_w > 3.5$ events in western Greece. Since 2012, the code has been implemented at the National Observatory of Athens (http://bbnet.gein.noa.gr/), at the

University of Tehran (http://irsc.ut.ac.ir/tensor.php), and at the Colombia Geological Service (http://seisan.sgc.gov.co/RSNC/index.php/tm). Most recently, ISOLA has been converted for automatic operation under the name amt (Triantafyllis *et al.*, 2013) with the use of Linux operating system bash code and other useful tools like nmxptool (Quintiliani, 2007).

The rapid evolution (within the last 10 years) of the seismological software SeisComP3 (http://www.seiscomp3.org/; Weber *et al.*, 2007) is well known to the seismological community. SeisComP3 is a widely distributed software package for acquisition or real-time data exchange and real-time earthquake monitoring. The amt implementation paved the way for an automatic MT calculation procedure based on the ISOLA code that is tightly connected to SeisComP3.

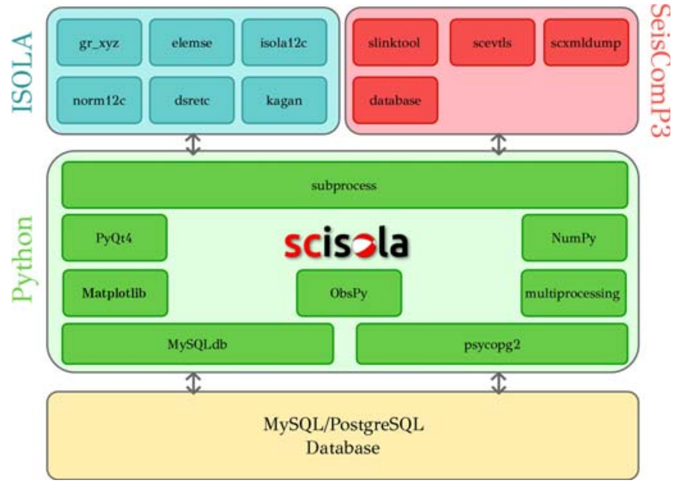
The aim of this article is to present scisola, a Python open-source code, available as a SeisComP3 add-on for automatic MT calculation in real time.

OVERVIEW

The implementation of scisola is based on various software tools and packages. Scisola is written in Python; it uses the ISOLA FORTRAN software as its main core (Sokos and Zahradník, 2008, 2013) and other Python packages. The main packages are ObsPy (Beyreuther *et al.*, 2010) for purposes such as data handling and instrument response removal, Matplotlib (Hunter, 2007) and NumPy (van der Walt *et al.*, 2011) for plots and numerical calculations, and PyQt4 for constructing the GUI. Furthermore, it also uses standard Python library packages like subprocess for Python wrapping of the necessary modules, multiprocessing for parallelizing computations (such as the Green's functions calculation and the MT inversion procedure), MySQLdb (Dustman, 2010), and psycopg2 (Di Gregorio, 2010) for manipulating database queries, such as handling stations and stream information and saving results. In Figure 1, scisola's architecture, including the above-mentioned tools, is presented.

ISOLA, the computational core of scisola, uses a point-source approximation to invert complete waveforms at regional and local distances for the CMT. Green's functions are calculated in 1D velocity models by the discrete wavenumber method of Bouchon (1981) and Coutant (1989), including the near, intermediate, and far-field terms. The MT is obtained by the least-squares, time-domain minimization of the L2-norm misfit between the observed and synthetic waveforms, whereas the centroid position and time of an event are calculated by a spatial and temporal grid search. The computational options include inversion of either the full MT, the deviatoric MT, or the double-couple (DC) constrained MT. The MT decomposition is performed according to equation (8) of Vavryčuk (2001).

Scisola reports a few parameters that assist the user to estimate the solution quality; for example, waveform fit is expressed through variance reduction ($VR \le 1$), $VR < 0$ implies no correlation. The MT inversion stability is characterized by condition number (CN), which is the ratio between the largest and smallest singular value of the Green's matrix. Small



▲ **Figure 1.** Schematic diagram of scisola's architecture scheme. Arrows depict the links of scisola to SeisComP3, ISOLated Asperities (ISOLA) codes, and MySQL/PostgreSQL database through the subprocess and the MySQLdb and psycopg2 Python packages, respectively. The color version of this figure is available only in the electronic edition.

(typically < 3–5) and large (typically > 10) CN values indicate a well- and ill-posed waveform inversion, respectively. For exact definitions, see Křížová *et al.* (2013). The focal mechanism variability and space–time resolution of the centroid is expressed through the Focal Mechanism VARiabilty (FMVAR) and Space–Time VARiability (STVAR) indexes, described in detail in Sokos and Zahradník (2013). FMVAR and STVAR quantify the focal-mechanism variation within the high-correlation region and the size of this region in the space–time grid search, respectively (see the Discussion section).

These quality measures have been implemented to assist users to avoid disseminating formally correct but physically meaningless results (e.g., results obtained from very few stations, which might produce a completely wrong focal mechanism, although the waveform fit is excellent). Currently, the solution quality is not reported in scisola using a single-number index; the use of the above metrics is enough to estimate the quality. For example, a solution with large CN indicates an ill-posed problem, which would alert the user not to trust the solution. Similarly, large values of FMVAR and STVAR would indicate instability of the solution. Users are able to produce their own quality rules by combining VR, CN, FMVAR, and STVAR in order to handle the appropriate dissemination of results.

AUTOMATIC MOMENT TENSOR ALGORITHM

In the following sections, we describe the main phases of the automatic MT calculation in scisola. The whole procedure is based on the user-provided configuration; done via a GUI (Ⓔ Figs. S13–S16, available in the electronic supplement to this article), such a configuration allows tuning of the code for different seismic networks and seismic events. Basically, the user creates rules that instruct the software on how to handle large and small events, which stations to use in both cases, and so on. Because this procedure is not straightforward and needs a careful selection of parameters, scisola's option to run the code off-line is the best strategy to find the proper values before trying the on-line operation.

Trigger of the Automatic MT Procedure with Proper Input Parameters

Triggering of the automatic MT calculation can be performed in two ways: automatic and manual. In the automatic mode, scisola is watching the SeisComP3 output in real time using the watcher Python package of the scisola code; and, when an earthquake alert is issued, it triggers the automatic MT procedure with proper input parameters. The watcher listens to SeisComP3 for a new event declaration within a time range predefined at scisola's configuration. Scisola performs various checks at the incoming earthquake notification, such as event uniqueness, magnitude, location threshold, and so on. After these checks, the watcher triggers the automatic MT calculation process using the specific event parameters and related user settings, while simultaneously waiting for a new incoming event. Alternatively, the automatic MT procedure can be executed manually through Python scripting.

Station Selection According to Epicentral Distance

Just after the triggering, station selection based on epicentral distance starts, and scisola retrieves all stations and relevant stream information from its database, which is being populated using the SeisComp3 database at the initial scisola configuration. At the next step, streams are selected based on accepted stream types and according to blacklisted stations or streams that are defined in scisola's configuration. Thereafter, scisola calculates the distance and the azimuth of the stations and finally selects those stations that are within a distance range based on rules defined by the user. The epicentral distance range selection rule is based on an event's magnitude, provided by SeisComP3, and the idea is that more distant stations are used for larger magnitude events. In this way, the user guides the code to avoid clipped stations and stations affected by the finite source dimension. The latter is related to the point-source approach used in scisola, which is valid if epicentral distances are greater than fault length and the highest inverted frequency is lower than the source corner frequency (reciprocal of the source duration). The parameters can be roughly estimated from empirical relations (e.g., Somerville *et al.*, 1999). For example, for magnitudes 6, 4, and 2, the characteristic fault length is ~10, 1, and 0.1 km, and the corner frequency is ~0.3, 3, and 30 Hz, respectively.

Data Extraction

The next step is to eliminate the unavailable streams from further processing according to the information provided by the SeedLink server. Scisola retrieves seismic waveforms in mini-SEED format through the SeedLink package of the scisola code. The time window for extraction is set automatically according to the event origin time and the time window length used in inversion (tl). The time window starts at the origin time and has to be chosen large enough to include complete waveforms even at the most distant stations; the tl parameter is defined by the user at the scisola configuration. Finally, scisola removes streams that have gaps or are clipped.

Correcting for Instrument Response and Aligning Waveforms in Time

During this step, raw data are processed as follows: (1) rotation to a geographic coordinate system (vertical, north, east) is done based on stream information from the SeisComP3 database; if the orientation is not specified, these streams are removed from further processing; (2) scisola applies instrument correction to seismic waveforms based on SeisComP3 defined metadata, displacement waveforms are used in inversion; and (3) waveforms are aligned according to the origin time and resampled to the same sampling frequency.

Station Selection According to Azimuthal Distribution

Besides epicenter distance, scisola also allows station selection based on their azimuthal distribution. Eight azimuthal sectors of equal size are *a priori* defined; at the scisola configuration, the user sets the maximum number of stations per sector and the minimum number of sectors needed for calculations. If the number of stations in a sector exceeds the maximum number, scisola will select those stations that have smaller epicentral distance and higher priority based on user settings in the scisola configuration. If the minimum number of azimuth sectors is not reached, the inversion procedure stops.

Compute Green's Functions

At this step, the code computes Green's functions, using a 1D crustal velocity model, defined at the scisola configuration. Green's functions are later convolved with six elementary MTs to form elementary seismograms (Sokos and Zahradník, 2008; Křížová *et al.*, 2013). The temporal variation of each elementary moment rate is a delta function. The centroid spatial grid search in scisola is restricted to a depth search (i.e., the centroid is searched under the epicenter following a grid step defined by the user), thus Green's functions are calculated for a number of trial source depths under the epicenter provided by SeisComP3. The depth distribution of the trial sources is defined by the user in the scisola configuration. To speed up computation, Green's functions are calculated in parallel mode using multiple threads through the multiprocessing Python package. Specifically, scisola executes a thread of the inversion procedure for each trial depth.

Invert for Centroid Moment Tensor

As soon as the instrumentally corrected waveforms and elementary seismograms are available, the inversion procedure starts. Although the code offers various options for source inversion (e.g., full MT, deviatoric, DC-constrained, and so on), the deviatoric type is predefined, because it is adequate in most cases. The inversion frequency band is set according to the scisola configuration, being based on event's magnitude, that is, large events should be inverted using larger periods. The inversion frequency band is also affected by the crustal model; for example, full waveform modeling is commonly feasible up to epicentral distances of ∼10 minimum shear wavelengths (Fojtíková and Zahradník, 2014). Finally, a temporal range for the grid search of the centroid time is defined a few seconds before and after the origin time. The temporal grid search is additional to the spatial grid search (i.e., search of the centroid under the epicenter), thus we come up with a spatiotemporal grid search. The grid search is made in parallel mode using multiple threads such that one thread per spatiotemporal grid point is used.

Plot and Generate Results

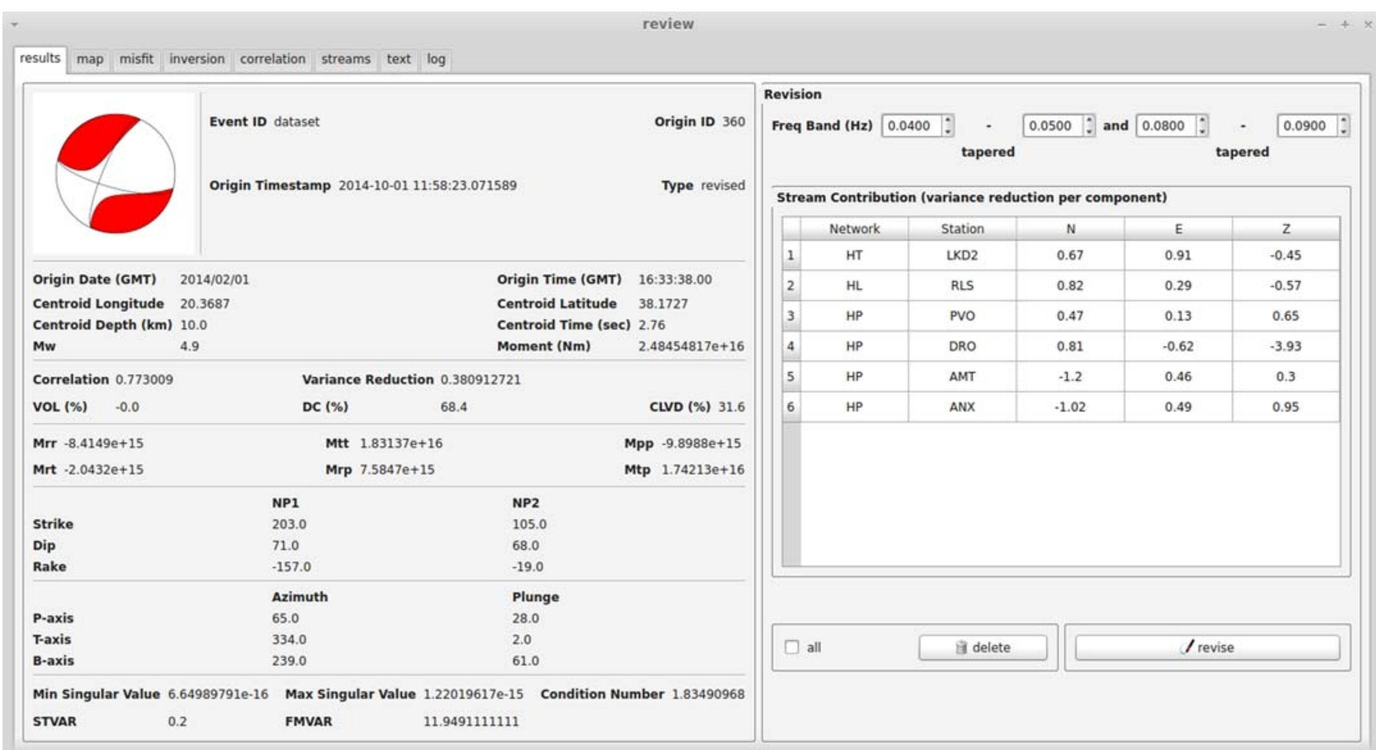
After the MT calculation run, scisola produces a number of output files; for example, a text file of results suitable for distribution over the web. In addition, scisola generates a series of plots: a map containing the focal mechanism and the location of stations contributing to the inversion, a plot of observed and synthetic waveforms, a simple plot demonstrating the best focal mechanisms for each trial depth, and a comprehensive plot of correlation contours with resulting focal mechanisms at each spatiotemporal grid point (the so-called correlation plot; Ⓔ Fig. S8). Finally, the results are stored in scisola's database to enable modern data management.

MOMENT TENSOR SOLUTION REVISION

The revision panel is shown on the right side of Figure 2. Scisola supports the revision of the automatic MT solution by an operator, and this can be achieved in two ways—by manual removal of individual, automatically selected streams and/or by changing the frequency range of the inversion. The VR of each component based on the automatic inversion is depicted, and this can assist the user to decide which components to remove, such as the ones with the worst fit. Nevertheless, this is not always straightforward. Stations with large amplitudes may have an instrumental disturbance; these signals could be well fitted, but actually just these should be removed from the inversion (Zahradník and Plešinger, 2005, 2010). This is why we do not support the idea of repeating the automatic inversion by simply keeping only stations with large VR.

Scisola Database

The scisola software uses a MySQL database. The usage of a well-known database that can be assessed by external tools supports better data management. Thus, the user has an easy way to search through results, upload them on a webpage, or send them via e-mail. This can be achieved through many utilities or programming languages that can connect to a MySQL database. The purposes of the scisola database are to (1) save station



▲ **Figure 2.** Scisola's inspection and review window. Inversion results are depicted on the left side of the window, and the right side is used for the revision process by changing the inversion frequency range and/or by selecting or deselecting components. The tabs at the top part allow the user to navigate to other outputs, such as waveform fit, correlation plot, inversion log, and so on. The color version of this figure is available only in the electronic edition.

and stream information retrieved from the SeisComP3 for latter usage, (2) save event information and the MT calculations, and (3) save the extensive configuration of scisola.

DISCUSSION

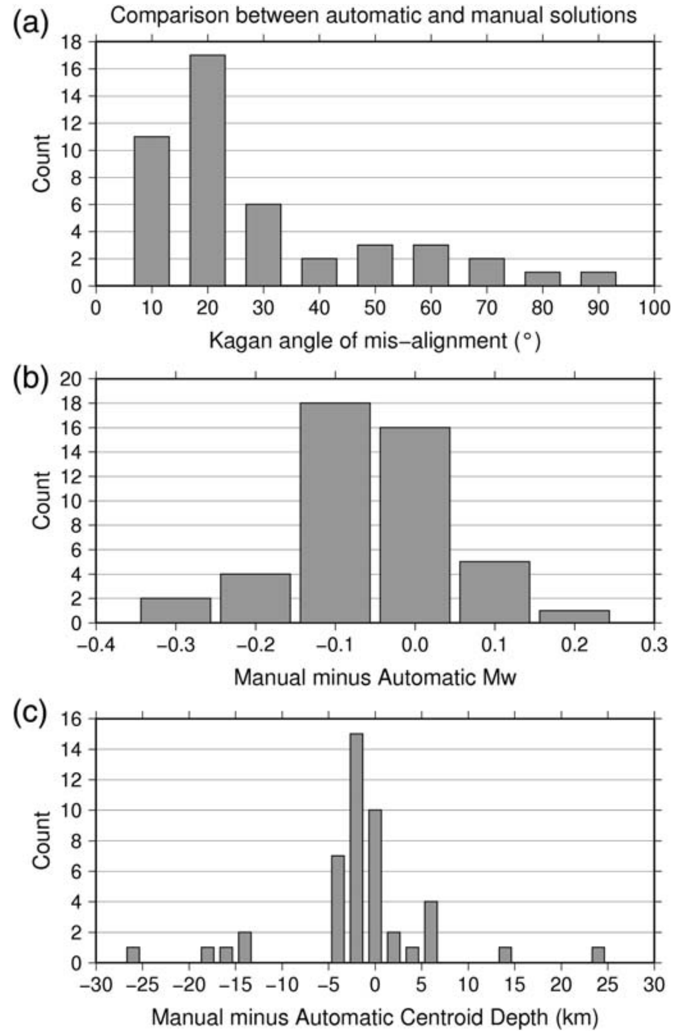
Automatic and Manual Procedure Comparison

The quality of the automatic MT solutions, produced by scisola, was preliminarily evaluated using data from the Hellenic Unified Seismic Network (HUSN), Greece (see Data and Resources). A total of 46 earthquakes that occurred from 2 January 2014 to 25 June 2014 in Greece were tested, and the automatic MT solutions were compared against the manual solutions provided by the Geodynamics Institute of the National Observatory of Athens (GI-NOA; http://bbnet.gein.noa.gr/, last accessed October 2015) (see Ⓔ Table S3). This is not a completely straightforward comparison. For example, GI-NOA is also using data from its strong-motion network and various crustal models according to the event's location. Because the strong-motion data were not available to us and we used a single crustal model for all tested events, we cannot exclude the possibility that some of the focal mechanism differences between manual and automatic solutions are due to these differences.

We used the so-called Kagan (1991) angle to calculate the difference between the automatic and manual solutions. This angle expresses the minimum rotation between two DC focal mechanisms and is used here as a measure of the automatic solution quality. An acceptable agreement between the manual and automatic solution is represented by Kagan angles up to a few tens of degrees, whereas a strong disagreement corresponds to angles larger than 50°–60° (Vannucci *et al.*, 2004). The crustal model used in the automatic procedure of MT calculation is the one proposed by Novotný *et al.* (2001).

In Figure 3a, we present a histogram of the Kagan angle distribution. We note that 34 of the 46 earthquakes have a difference of less than 30°. Besides the focal mechanism, scisola automatic MT inversion provides two other parameters that are of great importance during the first minutes after an event, the moment magnitude (M_w) and the centroid depth (CD). In Figure 3b, we present a histogram of the moment magnitude difference between the manual and automatic MT solutions. According to this, the MTs of 39 out of 46 earthquakes produce almost the same size of seismic source (≤ 0.1 difference). In addition, the maximum M_w difference for the entire evaluation dataset was not greater than 0.3. In Figure 3c, we present a histogram of the CD difference between the manual and automatic MT solutions. According to this, the focal mechanisms of 35 out of 46 earthquakes produce almost the same CD of the seismic source (≤ 4 km difference). The correct and quick retrieval of the M_w and CD are among the main assets of scisola.

The cases in which the automatic procedure produced larger deviations from the manual processing (i.e., higher values of the Kagan angle) are mainly connected with events occurring at the edges of the seismic network. In some cases, the differences in focal mechanisms are due to the use of different



▲ **Figure 3.** Evaluation of the automatic moment tensor (MT) solutions: histograms compare differences between manual and automatic solutions.

data sets employed in the manual and automatic solution or to different crustal models, as we have mentioned. Another possible cause of error in the automatic MT solution is the presence of long-period disturbances in the data (Zahradník and Plešinger, 2005, 2010), so far not yet automatically avoided in scisola. Finally, we want to mention that there are cases in which the manual solution is not well constrained; for example, depth has a poor resolution, which could produce large differences when comparing with the depth derived by the automatic solution.

Estimating the Solution Quality

Scisola reports several parameters related to the quality of the solution (see Overview). To assist the users of scisola to estimate the overall quality of solution, we provide here an example of "good" and "bad" values of these parameters. In Sokos and Zahradník (2013), waveforms of a shallow $M_w \sim 4$ earthquake were inverted using 10 stations at epicentral distances < 100 km and frequencies of ~0.05–0.10 Hz. The obtained values of

VR ~ 0.7, CN ~ 5, FMVAR ~ 10°, and STVAR ~ 0.1 indicated a "good" solution. If selecting just a pair of stations, the situation was different. VR naturally grew (0.8–0.9), because less data had to be fitted, but the other parameters also grew (CN > 10, FMVAR ~ 20–40°, STVAR ~ 0.2), indicating that the solution is "bad." Inverting just a single station, a very good waveform match VR ~ 0.98 was easily obtained; fortunately, the very limited robustness of such a solution could be understood from its FMVAR > 30. It may also happen that we invert a single station, but VR is low (e.g., < 0.5); then we have an indication that data are too noisy and/or the velocity model is inappropriate. In any case, a single-station inversion is always dangerous.

Future Improvements

The results and the experience gained from the automatic MT application indicate a need for a few improvements that can be implemented to make scisola more reliable, fault tolerant, functional, and easier to use.

As mentioned, a single crustal model is currently used in the automatic procedure. Thus, a next step to improve our software is to implement multiple crustal models, which will be selected depending on the geographic position of the seismic event. In several cases, seismic data suffer from various problems, such as noise, disturbances, and so on. Thus, it is clear that the application of advanced signal processing methods to seismic waveforms is key to improving the automatic procedure. Perhaps most important is to detect erroneous waveforms as proposed by Vackář *et al.* (2014) and either to remove them from the processing or to correct the waveforms.

Although the automatic procedure in its present form can process an event within a few minutes (5–10), depending on stations used, computer power, and so on, an important future improvement is to speed up the procedure by means such as precalculated Green's functions. This would also allow the users to perform a fully 3D grid search of the centroid position.

CONCLUSIONS

MTs are needed in a wide range of seismological research applications as well as in routine tasks requiring automatic, quick, and reliable MT calculations. The rapid evolution of SeisComP3 and the implementation of the amt software (Triantafyllis *et al.*, 2013) paved the way for creating scisola, an automatic MT solution retrieval software for SeisComP3 in real time. Scisola supports the automatic MT calculation for regional and local networks and for earthquakes provided by SeisComP3 notification system in real time. Furthermore, it supports sophisticated database handling methods for data management. Moreover, scisola implements a GUI regarding a quick MT revision in case the user wishes to alter the automatic solution. Finally, it supports many configuration options for scisola to be tuned according to the needs of the user or the corresponding regional network. The source code and the user manual of scisola are freely available and can be found at github (https://github.com/nikosT/scisola, last accessed October 2015). Ⓔ The electronic supplement contains the installation guide and a short presentation on the configuration of the software.

DATA AND RESOURCES

The waveform data used in this study were collected by the Hellenic Unified Seismic Network. Plots were made using Generic Mapping Tools v.4.5.13 (www.soest.hawaii.edu/gmt, last accessed October 2015; Wessel and Smith, 1998).

ACKNOWLEDGMENTS

The authors would like to thank Associate Editor Jeremy Zechar, reviewer Jochen Braunmiller, and one anonymous reviewer for their detailed comments, which improved the manuscript. Waveform data from the Hellenic Unified Seismic Network (HUSN) are gratefully acknowledged. One of the authors (J. Z.) has been supported from the Czech Science Foundation Grant GACR-14-04372S. Czech–Greek cooperation under Erasmus+ Programme (CZ Praha07 and G Patra01) is acknowledged.

REFERENCES

Agurto, H., A. Rietbrock, I. Ryder, and M. Miller (2012). Seismic-afterslip characterization of the 2010 M_w 8.8 Maule, Chile, earthquake based on moment tensor inversion, *Geophys. Res. Lett.* **39,** L20303, doi: 10.1029/2012GL053434.

Bernardi, F., J. Braunmiller, U. Kradolfer, and D. Giardini (2004). Automatic regional moment tensor inversion in the European-Mediterranean region, *Geophys. J. Int.* **157,** 703–716.

Beyreuther, M., R. Barsch, L. Krischer, T. Megies, Y. Behr, and J. Wassermann (2010). ObsPy: A Python toolbox for seismology, *Seismol. Res. Lett.* **81,** 530–533.

Bouchon, M. (1981). A simple method to calculate Green's functions for elastic layered media, *Bull. Seismol. Soc. Am.* **71,** 959–971.

Cesca, S., S. Heimann, K. Stammler, and T. Dahm (2010). Automated procedure for point and kinematic source inversion at regional distances, *J. Geophys. Res.* **115,** no. B06304, doi: 10.1029/2009JB006450.

Coutant, O. (1989). Programme de simulation numérique AXITRA, *Res. Rept. Laboratoire de Géophysique Interne et Tectonophysique*, Grenoble, France.

Delouis, B., C. Charlety, and M. Vallée (2008). Fast determination of earthquake source parameters from strong motion records: M_w, focal mechanism, and slip distribution, *EGU General Assembly 2008*, Vienna, Austria, 13 April–18 April 2008.

Di Gregorio, F. (2010). *Psycopg: PostgreSQL Database Adapter for Python*, http://initd.org/psycopg/ (last accessed October 2015).

Dreger, D. S. (2003). TDMT_INV: Time domain seismic moment tensor INVersion, in *International Handbook of Earthquake and Engineering Seismology*, W. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Vol. 81B, Academic Press, San Diego, California, 1627.

Dustman, A. (2010). *MySQLdb: A Python Interface for MySQL*, http://mysql-python.sourceforge.net/ (last accessed October 2015).

Dziewonski, A. M., T. A. Chou, and J. H. Woodhouse (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.* **86,** 2825–2852, doi: 10.1029/JB086iB04p02825.

Ekström, G., M. Nettles, and A. M. Dziewoński (2012). The Global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes, *Phys. Earth Planet. In.* **200/201,** 1–9, doi: 10.1016/j.pepi.2012.04.002.

Fojtíková, L., and J. Zahradník (2014). A new strategy for weak events in sparse networks: The first-motion polarity solutions constrained by

single-station waveform inversion, *Seismol. Res. Letters.* **85,** no. 6, 1265–1274, doi: 10.1785/0220140072.
Hunter, J. D. (2007). Matplotlib: A 2D graphics environment, *Comput. Sci. Eng.* **9,** no. 3, 90–95, doi: 10.1109/MCSE.2007.55.
Kagan, Y. Y. (1991). 3-D rotation of double-couple earthquake sources, *Geophys. J. Int.* **106,** 709–716.
Kawakatsu, H. (1995). Automated near-realtime CMT inversion, *Geophys. Res. Lett.* **22,** 2569–2572.
Křížová, D., J. Zahradník, and A. Kiratzi (2013). Resolvability of isotropic component in regional seismic moment tensor inversion, *Bull. Seismol. Soc. Am.* **103,** 2460–2473.
Maercklin, N., A. Zollo, A. Orefice, G. Festa, A. Emolo, R. De Matteis, B. Delouis, and A. Bobbio (2011). The effectiveness of a distant accelerometer array to compute seismic source parameters: The April 2009 L'Aquila earthquake case history, *Bull. Seismol. Soc. Am.* **101,** 354–365.
Novotný, O., J. Zahradník, and G. A. Tselentis (2001). Northwestern Turkey earthquakes and the crustal structure inferred from surface waves observed in western Greece, *Bull. Seismol. Soc. Am.* **91,** no. 4, 875–879, doi: 10.1785/0120000116.
Quintero, R., J. Zahradník, and E. Sokos (2014). Near-regional CMT and multiple-point source solution of the September 5, 2012, Nicoya, Costa Rica M_w 7.6 (GCMT) earthquake, *J. S. Am. Earth Sci.* **55,** 155–165, doi: 10.1016/j.jsames.2014.07.009.
Quintiliani, M. (2007). *nmxptool: Open-Source and Cross-Platform Software for Nanometrics Seismic Data Acquisition*, http://mednet.rm.ingv.it/nmxptool.php (last accessed October 2015).
Saul, J., J. Becker, and W. Hanka (2011). Global moment tensor computation at GFZ Potsdam, *American Geophysical Union 2011 Fall Meeting 2011*, San Francisco, California, 5–9 December 2011.
Sokos, E., and J. Zahradník (2013). Evaluating centroid-moment-tensor uncertainty in the new version of ISOLA software, *Seismol. Res. Lett.* **84,** 656–665.
Sokos, E. N., and J. Zahradník (2008). ISOLA a FORTRAN code and a MATLAB GUI to perform multiple-point source inversion of seismic data, *Comp. Geosci.* **34,** no. 8, 967–977, doi: 10.1016/j.cageo.2007.07.005.
Somerville, P., K. Irikura, R. Graves, S. Sawada, D. Wald, N. Abrahamson, Y. Iwasaki, T. Kagawa, N. Smith, and A. Kowada (1999). Characterizing crustal earthquake slip models for the prediction of strong ground motion, *Seismol. Res. Lett.* **70,** 59–80.
Triantafyllis, N., E. Sokos, and A. Ilias (2013). Automatic moment tensor determination for the Hellenic Unified Seismic Network, *13th International Congress of the Geological Society of Greece*, Chania, Greece, 5–8 September 2013.
Vackář, J., J. Burjánek, and J. Zahradník (2014). Automated detection of disturbances in seismic records; MouseTrap code, *Seismol. Res. Lett.* **86,** no. 2A, 442–450, doi: 10.1785/0220140168.
van der Walt, S., S. C. Colbert, and G. Varoquaux (2011). The NumPy array: A structure for efficient numerical computation, *Comput. Sci. Eng.* **13,** no. 2, 22–30, doi: 10.1109/MCSE.2011.37.
Vannucci, G., S. Pondrelli, A. Argnani, A. Morelli, P. Gasperini, and E. Boschi (2004). An atlas of Mediterranean seismicity, *Ann. Geophys.* **47,** no. 1, doi: 10.4401/ag-3276.
Vavryčuk, V. (2001). Inversion for parameters of tensile earthquakes, *J. Geophys. Res.* **106,** no. B8, 16,339–16,355, doi: 10.1029/2001JB000372.
Weber, B., J. Becker, W. Hanka, A. Heinloo, M. Hoffmann, T. Kraft, D. Pahlke, J. Reinhardt, and H. Thoms (2007). SeisComP3—Automatic and interactive real time data processing, *EGU General Assembly 2007*, Vienna, Austria, 27 April–2 May 2007.
Wessel, P., and W. H. F. Smith (1998). New, improved version of the Generic Mapping Tools released, *Eos Trans. AGU* **79,** 579.
Yagi, Y., and N. Nishimura (2011). Moment tensor inversion of near-source seismograms, *Bull. IISEE* **45,** 133–138.
Zahradník, J., and A. Plešinger (2005). Long-period pulses in broadband records of near earthquakes, *Bull. Seismol. Soc. Am.* **95,** 1928–1939.
Zahradník, J., and A. Plešinger (2010). Toward understanding subtle instrumentation effects associated with weak seismic events in the near field, *Bull. Seismol. Soc. Am.* **100,** no. 1, 59–73, doi: 10.1785/0120090087.

Nikolaos Triantafyllis
Aristidis Ilias
Department of Computer Engineering and Informatics
University of Patras
26504, Rio
Patras, Greece
triantafyl@ceid.upatras.gr
aristeid@ceid.upatras.gr

Efthimios Sokos
Department of Geology
Seismological Laboratory
University of Patras
26504, Rio
Patras, Greece
esokos@upatras.gr

Jiří Zahradník
Faculty of Mathematics and Physics
Charles University in Prague
V Holešovičkách 2
180 00 Praha 8
Prague, Czech Republic
jiri.zahradnik@mff.cuni.cz

Published Online 2 December 2015