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# AUTOMATIC MOMENT TENSOR DETERMINATION FOR THE HELLENIC UNIFIED SEISMIC NETWORK

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**Abstract**

*Modern seismic networks with broadband sensors and real time digital telemetry made Moment Tensor (MT) determination a routine procedure. Automatic MT's are now provided by global networks and a few very dense regional networks, within minutes after a significant event. An automatic MT determination wasn't possible for the broader Hellenic area since seismic station density wasn't sufficient. The creation of the Hellenic Unified Seismic Network (HUSN) provided the opportunity to apply an automated MT procedure using the available broad band data from almost one hundred stations. Thus the ISOLA code was extended towards the automatic operation based on Linux OS shell scripts, stand alone Fortran codes and SAC2000. Software supports both manual and automatic mode; at the first case, the user manually runs the program with the desired input parameters while at the latter, the system monitors a mailbox or RSS feed and if it receives an appropriate notification triggers the MT inversion procedure based on certain conditions. As it is setup now it calculates automatically the moment tensor of earthquakes larger than 3.5Mw using data from HUSN. Application of an automated MT inversion procedure for HUSN will provide important real time information for studies like ground motion evaluation, tsunami warning etc.*
***Key words:*** *focal mechanism, inversion, ISOLA.*

**Περίληψη**

*Τα σύγχρονα σεισμικά δίκτυα έχουν μετατρέψει τη διαδικασία αντιστροφής του τανυστή σεισμικής ροπής σε διαδικασία ρουτίνας. Οι αυτόματες λύσεις παρέχονται πλέον από παγκόσμια δίκτυα καθώς και από μερικά περιφερειακά δίκτυα, μέσα σε λίγα μόλις λεπτά από τη γένεση ενός σεισμού. Η αυτοματοποιημένη διαδικασία υπολογισμού του τανυστή σεισμικής ροπής δεν ήταν εφικτή για την Ελλάδα καθώς η πυκνότητα του δικτύου δεν ήταν επαρκής. Η δημιουργία όμως του Ενιαίου Εθνικού Δικτύου Σεισμογράφων (ΕΕΔΣ) με περίπου εκατό σεισμολογικούς σταθμούς εξασφάλισε αυτή τη δυνατότητα. Έτσι το λογισμικό ISOLA επεκτάθηκε ώστε να χρησιμοποιηθεί ως μια αυτοματοποιημένη διαδικασία η οποία βασίζεται σε εντολές κελύφους λειτουργικού συστήματος Linux, αυτόνομους κώδικες σε Fortran και το πρόγραμμα SAC2000. Το λογισμικό που δημιουργήθηκε υποστηρίζει αυτόματη λειτουργία αλλά και καθοδηγούμενη από το χρήστη. Στην πρώτη περίπτωση, το σύστημα παρακολουθεί ένα ηλεκτρονικό ταχυδρομείο ή ροές RSS και αν λάβει κατάλληλη ειδοποίηση ενεργοποιεί τη διαδικασία υπολογισμού του τανυστή σύμφωνα*



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*με ορισμένες προϋποθέσεις. Στη δεύτερη περίπτωση ο χρήστης έχει τη δυνατότητα να εκκινήσει τη διαδικασία με τις κατάλληλες παραμέτρους. Μέχρι στιγμής το πρόγραμμα μπορεί να εκτελεί αυτόματα τις διαδικασίες υπολογισμού για σεισμούς μεγαλύτερους από 3.5Mw χρησιμοποιώντας τα δεδομένα από το ΕΕΔΣ. Μια εφαρμογή που υπολογίζει αυτόματα τον Τανυστή ροπής για το ΕΕΔΣ θα εξασφαλίσει πληροφορίες σε πραγματικό χρόνο σχετικά με θέματα όπως εκτίμηση της εδαφικής κίνησης, προειδοποίηση για τσουνάμι κτλ..*
***Λέξεις κλειδιά:*** *μηχανισμός γένεσης, αντιστροφή, ISOLA.*

## 1. Introduction

Automatic Moment Tensors (AMT) are provided by global networks and a few very dense regional networks. Global CMT (http://www.globalcmt.org) (Ekström et al., 2012) already supports a global AMT procedure for strong earthquakes for a few decades. Automatic solutions for global networks are as well provided by GFZ German Research Centre for Geosciences (http://edoc.gfz-pstsdam.de/gfz) (Saul et al., 2011). Berkeley Seismological Laboratory of University of California (http://seismo.berkeley.edu/), since 1993 developed a software (Dreger, 2002) that calculates AMT for regional networks and earthquakes larger than 3.5Mw. It has also been used at the Japan National Research Institute for Earth Science and Disaster Prevention (http://www.bosai.go.jp/e) and by independent researchers along USA, Europe and Asia. This distribution with different variations has been used by the Mediterranean Network (MedNet) of Italy (http://mednet.rm.ingv.it). Services that have performed respective efforts are the Swiss Seismological Service (SED) (http://www.seismo.ethz.ch) and the Earthquake and Volcano Information Center of Japan (http://wwweic.eri.u-tokyo.ac.jp/index-e.html); the last one applies a different approach. The creation of the Hellenic Unified Seismic Network (HUSN) provided the opportunity to apply an automated MT procedure using the available broad band data from almost one hundred stations. Thus the ISOLA code (Sokos and Zahradník, 2008) was extended towards automatic operation.

## 2. Method Description

### 2.1. ISOLA Moment Tensor Algorithm

The ISOLA moment tensor retrieval algorithm is based on the point source iterative deconvolution method; similar to (Kikuchi and Kanamori, 1991) multiple point source method for teleseismic events. In ISOLA the full wavefield is considered, and Green's functions are calculated by the discrete wavenumber method (Bouchon, 1981) and (Coutant, 1989) for local or regional distances. Moment tensor of subevents is found by least-square minimization of misfit between observed and synthetic waveforms, while position and time of subevents is optimized through grid search. The computational options include inversion to retrieve the full moment tensor (MT), the deviatoric MT, and pure double-couple MT. Finite-extent source inversions may also be performed in the case of a large event. The code has been extensively used at the University of Patras, Seismological Laboratory (UPSL), Greece, (http://seismo.geology.upatras.gr/), to routinely compute moment tensors for Mw > 3.5 events in western Greece, and, since 2012, at the National Observatory of Athens (http://www.noa.gr/). Besides that ISOLA has been used in various research studies worldwide e.g. (Sokos et al., 2012), (Gallovič et al., 2009), (Benetatos et al., 2012), (Fojtíková et al., 2010), (Reinoso, 2011), (Choi et al., 2010) and (Tan, 2012). Although ISOLA code is complemented by a Graphical User Interface (GUI) that simplifies its use during manual analysis of a seismic event, an automatic version of the code could be important for many applications e.g. rapid moment tensor estimation for shakemap generation or tsunami warning.

### 2.2. Algorithm Implementation for Automatic Use

The main phases of the automatic MT inversion procedure can be described as follows:

1. trigger the AMT inversion procedure



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2. select stations based on the earthquake's location
3. retrieve data from selected stations
4. correct retrieved data for instrument effect and align them in time
5. compute green's functions
6. compute inversion
7. plot/distribute results

Figure 1 shows the flowchart diagram of automatic MT inversion process.

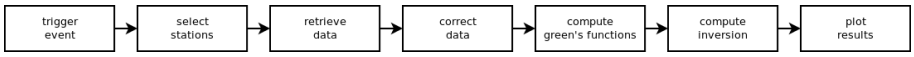


**Figure 1 - Diagram of algorithm's procedure.**

To implement these main phases of the automatic MT inversion algorithm we use the Bash scripting language of Linux OS. Bash is a high-level programming language and thus makes the process of developing/maintaining the code much simpler. During software development a Bash module was created for each main phase (Figure 1) and finally all modules were connected with each other. Besides Bash we use a few other programs also; like the GMT suite (Wessel and Smith, 1998) for distance determination between stations and epicentre, Nmxptool (http://mednet.rm.ingv.it/nmxptool.php) for data retrieval, Sac2000 (Goldstein et al., 2003) for data correction etc, all codes are open source. In the following paragraphs we describe in detail the main phases of the automatic MT inversion procedure.

## 2.3. Detailed Description of Main Stages

### 2.3.1. Trigger the Moment Tensor Procedure

There are two options to trigger the AMT inversion procedure, when the code is in automatic mode. Either through email, i.e. the program is monitoring an email account for incoming messages (in IMS 1.0 format, http://www.isc.ac.uk/standards/isf/download/ims1_0.pdf) or through RSS feeds. Once a valid trigger is declared i.e. the events parameters fulfil some criteria e.g. the automatic magnitude is larger than 3.5 and the epicentre is located within some geographical limits, the inversion procedure is triggered.

### 2.3.2. Select Stations Based on the Earthquake's Location

Just after a trigger is declared, station selection starts. It is based on a list of station coordinates and on event's automatic location. Based on these the program selects those stations that are within a predefined epicentral distance from the earthquake. An additional constrain is the total number of selected stations, which cannot exceed a predefined limit. Such a constrain is important e.g. in places where the station density is high a large number of data could be selected that could delay the inversion procedure significantly and in the same time provide redundant information only. Thus a fixed number of twenty stations was selected as a maximum; the program selects stations based on epicentral distance then sorts them according to this distance and selects the first twenty. It is also possible a station to be flagged by the user as not suitable for inversion, then the selection procedure will ignore it.

### 2.3.3. Retrieve Data from Selected Stations

The next step is to retrieve data for the selected stations. There are two possibilities up to now, a) to retrieve data from a NAQS server and b) to retrieve data from a Seedlink/SeisComP server (http://www.seiscomp3.org/). The Nmxptool is used for retrieving data from a NAQS server and the arclink_fetch client from the Seedlink/SeisComP server. Data are converted in SAC format (Goldstein et al., 2003) and stations whose data contain gaps or have less than three components are removed from the subsequent analysis. A test on the minimum number of available data is also



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done here and if the available stations aren't enough the procedure stops, the minimum number of stations was set at four.

#### 2.3.4. Correct Retrieved Data

After the data retrieval the program corrects them in four steps. During the first step the instrumental effect is removed, then data are aligned according to origin time, cut according to a predefined duration and finally resampled. All corrections are done using SAC2000 macros.

#### 2.3.5. Compute Green's Functions

In parallel with the data correction, the Green's function computation starts. The code computes using a 1D crustal model (only one crustal model is currently possible) and the centroid trial position-station geometry the corresponding green's functions. These are later convolved with a delta time function and six elementary focal mechanisms in order to form elementary seismograms that will be used in the inversion (Sokos and Zahradnik, 2008). The centroid horizontal position is kept fixed at the epicentre location, provided by the automatic solution, but its depth is varied. In detail, starting from the automatic depth estimation, twenty trial sources are defined above it and twenty bellow it, the depth grid step is fixed at 2km. In order to reduce time the elementary seismogram calculation per trial centroid position is done in parallel.

#### 2.3.6. Compute Inversion

As soon as corrected data and elementary seismograms are available the inversion procedure starts. Although the code offers various options for source inversion e.g. full moment tensor, deviatoric etc; the deviatoric type is predefined since it is adequate for most cases. The inversion frequency band is also kept fixed at 0.04 to 0.09Hz, since this is suitable for moment tensor inversion in local and regional distances (Roumelioti et al., 2011). Finally the centroid time is grid searched three seconds before and three seconds after the origin time. This step is important since it can capture small errors associated with event location, crustal model etc (Sokos and Zahradnik, 2008).

#### 2.3.7. Plot/distribute Results

Finally, when the inversion procedure ends, the program a) produces text files suitable for email distribution, containing the results from the inversion and a graphic representation of the focal mechanism and b) updates a web page with the relevant information (http://seismo.geology.upatras.gr/amt). In the same web page the results of this paper are given in a graphical and numerical form.

## 3. Automatic and Manual Procedure Comparison

The automatic algorithm was tested using data from HUSN (Hellenic Unified Seismic Network). A total of fifty events triggered the system during six months of operation and we present here a statistical evaluation of the results. Comparison of the automatic solution validity is done against the manual MT solutions provided by GI-NOA (http://www.gein.noa.gr/el/). We make use of the so-called Kagan angle (Kagan, 1991) to calculate the difference between automatic and manual solution. This angle expresses the minimum rotation between two double couple focal mechanisms and is used here as a measure of the automatic solution quality. According to (Kagan, 1991) minimum angle is $0^o$ (same mechanism) and the maximum value is $120^o$ suggesting maximum divergence between two focal mechanisms. An acceptable agreement is represented by angles of the order of some tens of degrees, while a strong variance is given by angles larger than 50°-60° (Vannucci et al., 2004).

In Figure 2 we present the geographical distribution of the automatically analysed earthquakes and the corresponding Kagan angles, plotted as vertical bars. The Kagan angles vary between $2^o$ and $107^o$ with an average value of $37^o$. In general the error's average value is acceptable, but extreme Kagan values exist and it is important for the automatic procedure evaluation to understand what is



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causing them. These higher values are mainly connected with the edges of the seismic network (South Crete, Eastern Aegean etc). One of the problems here, is the large error in the automatic epicentre solution (due to network geometry) that causes subsequent problems in moment tensor inversion since the trial horizontal source position for the inversion is the automatic epicentre. For example, the two events south of Crete had differences between the automatic and manual epicentre location of the order of 30km.

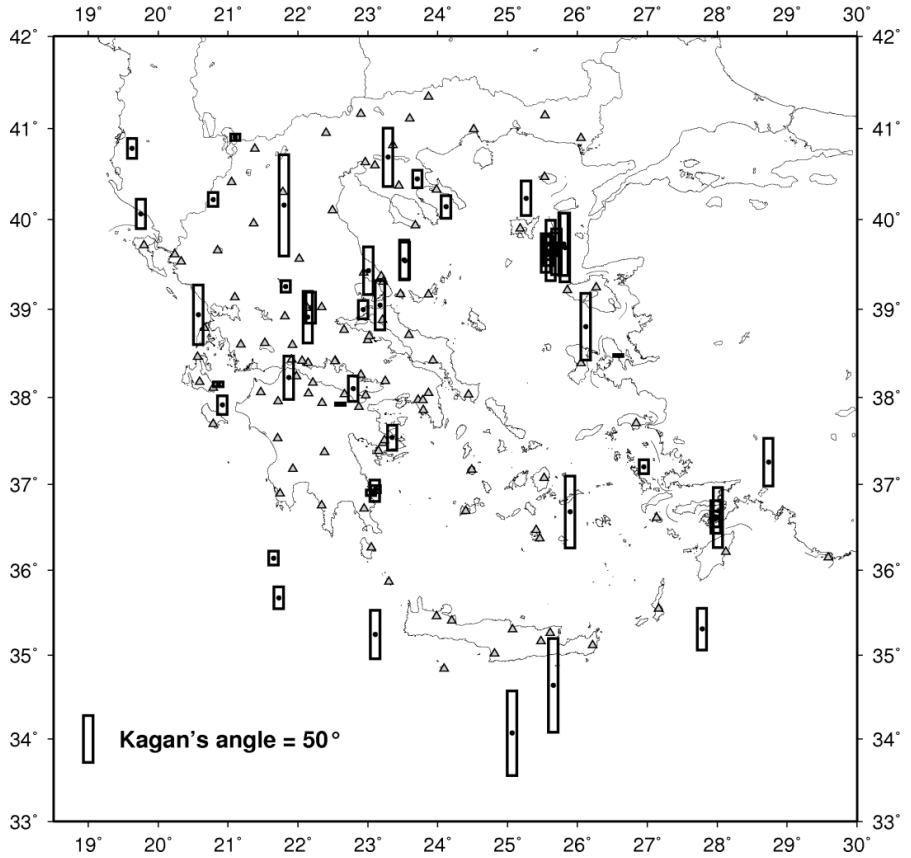


**Figure 2 – Spatial distribution of Kagan's angle shown as bars at the epicentral locations of the analyzed events. Triangles are seismic stations of HUSN.**

Nevertheless, large Kagan angles exist even in cases when the automatic-manual location difference is small. These problems are connected with either the use of different set of seismic data or the use of different crustal models. So far a single crustal model is used in the automatic procedure, the one proposed by (Novotny et al., 2001) using data from Central Greece. While the manual moment tensor solutions are based on region specific crustal models (Evangelidis C. pers.comm.); this could explain large Kagan angles in a few cases. Furthermore the manual solutions incorporate NOA's accelographic network data (http://www.gein.noa.gr/en/networks/accelerographic-network) also, which were not available in the automatic moment tensor inversion procedure. This is an additional explanation for large Kagan angles between manual and automatic solution. Finally another cause of error in the



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automatic solution is the presence of disturbances in the data; such errors are hard to recognize in an automatic procedure and could affect the inversion (Zahradník and Plešinger, 2005).

Besides the focal mechanism, moment tensor inversion procedure provides another two parameters that are of significant importance during the first minutes after an event i.e. the moment magnitude and the centroid depth. In Figure 3a we present the comparison between the manual and the automatically retrieved moment magnitude, while in Figure 3b the corresponding centroid depth difference distribution is given. As regards the moment magnitude the automatic and manually derived results are almost identical having an average difference of 0.1 units. This result suggests that the moment magnitude is not so sensitive to the problems we described in previous paragraphs thus it can be regarded as a stable inversion feature. The automatically centroid depth is also similar to the manually derived one although a few extremes exist.

The above results suggest that the automatic moment inversion contributes to the recognition of the size and depth of the seismic source with adequate accuracy a few minutes after an event. This means that it is a valuable tool for estimating ground motions or tsunami hazard.

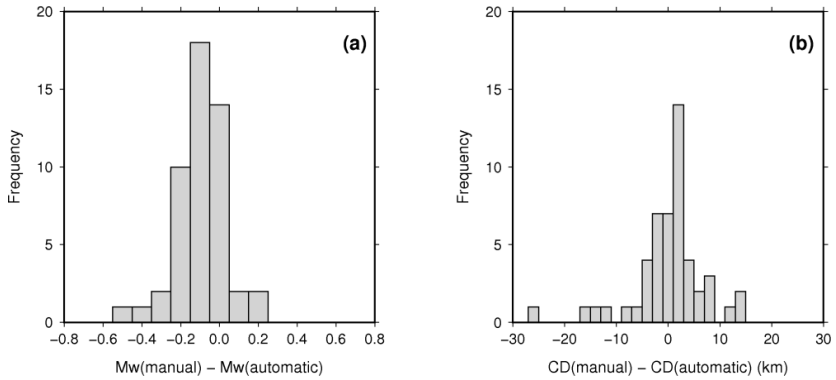


**Figure 3 - a) Histogram of Mw difference between manual and automatic solution b) Histogram of centroid depth (CD) difference between manual and automatic solution.**

## 4. Discussion

In this paper we present the first attempt to establish an automatic moment tensor retrieval procedure in Greece. We are using the waveform data from the Hellenic Unified Seismic Network, a modern digital seismic network of sufficient station density for advanced seismological applications. The ISOLA code, proposed by Sokos and Zahradnik, 2008 was modified in order to implement it in an automatic procedure. Comparison of fifty automatically retrieved moment tensor solutions with the manual ones produced by GI-NOA, revealed the ability of the procedure to accurately retrieve moment tensor under some conditions. Automatic moment magnitude calculation proved to be more robust and this is especially important in cases like shakemap generation or tsunami warning.

Moreover the comparison revealed drawbacks and possible extensions that would increase the reliability of automatic solutions. Based on these outcomes and to gained experience from automatic application of the method we have concluded to few improvements, described in the following paragraph.

As mentioned before 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. Another improvement that can be applied is to choose for the inversion, lower or higher frequency band values according to the



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studied event's magnitude. In several cases seismic data depict various problems e.g. data transmission problems, noise, disturbances (Zahradník and Plešinger, 2005) etc. Thus it is clear that advanced signal processing methods to be applied to seismic waveforms is the key to improve the automatic procedure. These should detect erroneous waveforms and either remove from the procedure or even correct them. Another important point to enhance in the performance of the software is the station selection which should include an estimate of the azimuthal station distribution.

Although the automatic procedure as it is now can process an event within a few minutes (5-10) depending on stations used, computer power etc, it is clear that this has to be improved. This can be accomplished by e.g. pre-calculated green's functions or conversion of serial code to parallel since modern computers are based on parallel processors. This would allow the use of many trial sources and the search of the centroid could be done for a 3D grid surrounding the automatic hypocenter.

## 5. Acknowledgments

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