ISOLA A Fortran code and a Matlab GUI to perform multiple-point source inversion of seismic data.

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Abstract

In this paper a software package for multiple or single point source inversion is presented. The package consists of ISOLA-GUI, a user-friendly MATLAB-based interface, and the ISOLA Fortran code, which is the computational core of the application. The methodology used is similar to Kikuchi and Kanamori (1991) but adjusted for regional distances. The software advantage is the graphical interface that provides the user with an easy to use environment, rich in graphics and data handling routines, while at the same time the speed of Fortran code is retained. Besides that, the software allows the results to be exported to popular software packages, like Generic Mapping Tools while at the same utilizing them for quality plots of the results. The modular design of ISOLA-GUI can be used by users for the addition of additional routines in all the stages of the processing. An example of the method's ability to get a quick insight into the complexity of an earthquake is presented, using records from a moderate size event.

Keywords: seismology, moment tensor determination, iterative deconvolution, extended source, graphical user interface

1. Introduction

Precise knowledge of seismic source parameters is a prerequisite for understanding physical processes on faults during earthquakes. Although important information can be extracted even from the first few seconds of the seismic record (such as earthquake location, its fault-plane solution, etc.), detailed studies have to include complete seismograms. These kind of studies can provide further constraints on the hypocentral depth and earthquake moment, providing valuable information on a region's deformation style. Therefore modern seismological networks can provide, in an automated way, the moment tensor of the event in addition to the hypocentre and magnitude. On the other hand a variety of methods to invert waveforms into spatio-temporal evolution of the rupture process and resulting slip distribution have been developed. While the growing amount of global, regional and local data, and increasing facility to retrieve them in near-real time through the Internet, are challenging enough to steadily update the modelling methods.

Several codes are available to invert the teleseismic data into point- or multiple-point source moment-tensor models, including the slip distribution models (Dreger and Helmberger, 1993; Kikuchi and Kanamori, 1991; McCaffrey et al., 1991). Regional data can be inverted by, for example, the codes of Dreger and Helmberger, 1993 and Ammon, 2001[1]. Complexity of regional and local studies, compared to the teleseismic ones, is obvious: at distances of the order of 10^0 to 10^3 km seismic signals are not solely composed of a few simple phases, high frequencies are abundant, interference waves (such as, for example, Lg) may predominate on records, and near-field effects can be significant. Ray methods, applicable at teleseismic distances, have to be replaced by full-wave methods, representing complete wavefields. Several frequency-wavenumber methods can be used, such as, for example, the discrete wavenumber method (Bouchon, 1981). As a rule, these demand far more computer power than the ray methods. The other reason for computer speed is due to the fact that the waveform inversion has to include grid search. Indeed, although seismic moment tensor is related to records via linear relations, optimization of the source position and timing (not precisely known from standard location) makes the inversion non-linear. All these factors call for the use of a fast computer language e.g. Fortran. However, other

[1] Web address: http://eqseis.geosc.psu.edu/~cammon/HTML/MTinvDocs/mtinv01.html

factors call for tools with extended processing and plotting capabilities, like Matlab. It is because source retrieval is a complex process, consisting of a series of related stages, requiring an interactive approach and great deal of graphical representation. Typically, to avoid the need for detailed (unknown) structural models, relatively low frequencies should be extracted from the data, but, long period signals may fall below the (natural or instrumental) noise level. Thus selection of usable records and their careful processing is crucial, and, together with the selection of a suitable frequency band, requires extensive interpretational experience. Matching records with synthetics, while simultaneously solving problems of non-uniqueness of the inversion (e.g. recognising poor resolution of some of the parameters), is another reason, for an interactive graphical mode.

Therefore, in this paper we present a new software package, that is based on an extension of the Kikuchi and Kanamori method to regional and local distances which efficiently combines the Fortran and Matlab skills. Fortran for the power and speed for compute-intensive wave propagation modelling and source inversion (Green's functions) and Matlab for quick and user-friendly data handling, control of the inversion process and plotting of the results. The name of the package is ISOLA, since the retrieved point-source moment tensors (called subevents) represent isolated asperities, or slip patches of the fault. The package has been developed since 2003 and although some preliminary versions of the Fortran part were released on the Internet (Zahradnik et al., 2005)[2], this is the first presentation in a journal. The package depends on Matlab for the GUI display, data pre-processing and plotting. The Fortran codes exist as standalone executable files, that are called by the ISOLA-GUI, in order to perform tasks like Green's function calculation and inversion. Users may decide to use just the Fortran codes but the use of the Matlab based ISOLA-GUI simplifies and accelerates the whole procedure, substantially. Besides Matlab graphics, GMT (Wessel and Smith, 1991) is used in all the stages of the procedure, in order to produce publication-quality figures of the retrieved moment tensors. The M_map software package [3] is also used mainly for plotting maps within the Matlab environment.

[2] Web address:http://seis30.karlov.mff.cuni.cz/
[3] Web address: http://www.eos.ubc.ca/~rich/map.html

ISOLA-GUI offers access to all the inversion procedures through modules that perform specific tasks e.g. data import, filter, inversion, plotting etc. Modules can run in parallel and most of them "remember" user's response or try to suggest suitable values of the parameters, in order to speed up the processing. Although most of the input parameters are self-explanatory, "tooltips" have been added for some of them. However these are not a substitute of the program's manual, which contains an extensive description of the method with examples. The user is urged to study the manual prior to the application of the inversion.

The objective of this paper is to inform the research community about the package and its broad variety of options. Specific details of the software use are presented in the manual accompanying the program package. Earthquake physics in this paper is reduced to a necessary minimum and the reader is referred to the paper describing previous applications of the code to the 2003 Lefkada, Greece, earthquake of magnitude Mw6.3 (Zahradnik et al., 2005). The code has proved useful also for other M5+ earthquakes at distances up to 400 km (Adamova et al., 2006; Tselentis et al., 2006), but also for weaker M3+ and M4 events at local distances (e.g. see the moment tensor solutions routinely provided by the University of Patras Seismological Laboratory (UPSL) to the European Mediterranean Seismological Centre (EMSC)[4]).

2. Program description

ISOLA-GUI presented here was created using the *guide* tool of Matlab and its purpose is to allow easy interaction with the Fortran codes (mainly input file preparation and output file display) as well as fast data pre-processing, Green's function calculations and graphic output of the results. The software is rich in graphics and the various plots are created using a combination of Matlab's graphic capabilities as well as GMT software (Wessel and Smith, 1991; Wessel and Smith, 1998). A lot of care has been taken to produce a software package that will be easy to handle, will help the user judge the accuracy of the inversion results, and will produce fast and comprehensive output, accurate results and publication ready plots. The program has been created with Matlab 6.5 under Windows operating system but has been tested with newer Matlab versions (Matlab 7.0) as well as with other operating

[4] Web address: http://www.emsc-csem.org/index.php?page=current&sub=qmt

systems (Linux) and can work after minor modifications, mainly in the system call commands and in the text file structure.

The program starts by running the ISOLA m-file, which generates the main user interface (Fig.1). From this main GUI the following functions are available a) data format conversion, b) data inspection, filtering, shifting, c) crustal model definition, d) data pre-processing and source definition and e) Green's function calculation, inversion and plotting of results. These functions are described in detail in the following sections.

2.1. Data (format conversion – inspection) (Utilities I, II)

Although ISOLA's native format is quite simple (4 column ascii files, i.e., time, EW, NS, Z component) an option for format conversion from SAC [5] and Guralp Compressed Format (GCF) to ISOLA native format, is provided. The conversion is accomplished using Matlab codes (m-files) freely available on the Web[6] (Thorne, 2005)[7]. These m-files and the accompanying GUI codes can be used as a guide for any user that wishes to implement his specific data format conversion. Alternatively, the data format conversion can be done using an external program. Besides the format conversion, a few options are provided for data quality assessment prior to moment tensor inversion. The user can test various filters, perform instrument correction, integrate or shift the data etc. These tasks are of major importance since in many cases the data contain various spurious signals, e.g. trends, that can affect the inversion, while at the same time these are not easily recognizable in the time series data (Zahradnik and Plesinger, 2005). It is therefore recommended that these tests are applied prior to any inversion attempt.

2.2 Crustal model

The crustal model to be used in all the subsequent steps of the analysis (like Green's function calculation, polarity checking etc) is defined just once during the ISOLA-GUI execution, using the *crustmod* tool. The P and S velocities (Vp, Vs), density, and P and S quality factors (Qp, Qs) are typed in text boxes or read from text files while

[5] Web address: http://www.llnl.gov/sac/
[6] Web address: http://www.guralp.net/
[7] Web address: http://gcc.asu.edu/mthorne/saclab

the Matlab code takes care of the proper formatting, that is important for the ISOLA Fortran codes. A few facilities are available for creation of plots of Vp, Vs velocities with depth and calculation of Vs or density values using empirical relations. The code as it stands supports a single crustal model for all the stations but future versions will support multiple crustal models.

2.3 Data pre-processing – source definition

The data pre-processing part (instrument correction, alignment, integration, decimation etc) must be carried out carefully, since any error introduced at this stage can cause significant errors in the inversion step. Using ISOLA-GUI the user can apply all the above corrections on the data and at the same time have a visual control of the results. The user is guided by the program in performing all the tasks in the proper order, while the GUI keeps track of user's last response and stores files in proper folders. In this way the process is fast and well controlled (Fig.2). If there is a need for some special correction or data processing a new module can be easily added in the procedure with minimum Matlab programming.

Definition of trial source positions for the event source is done through a GUI code, named *sourcepre* which has been specially designed to automate and simplify this task. Two options (the "point" or "extended" source) are available to the user. By point we mean trial sources that are located under the epicentre while with the extended source option, sources on a horizontal line or on a plane with arbitrary orientation can be defined. The "point" source option is used for a first approximation of the inversion problem and depends on the quality of the given epicentre. Using this type of inversion can indicate the inversion's preferred depth for the event, but if the epicentre is wrong the results could be misleading. Thus in many cases it may be desirable to rerun the inversion around the epicentre, using trial positions on a plane, or on a few horizontal planes at different depths. In this way the inversion will find the optimum position of the event in space. The option of an arbitrary trial plane may be useful when studying the fine structure of the source in the nodal planes. The ISOLA-GUI creates all the necessary files for the Green's function calculations – inversion, along with plots of the source distribution (in geographical and Cartesian coordinates) for user inspection. Under the Matlab environment the plots are produced

using the M_Map tool, but GMT format files are created too, thus the user can produce customized maps latter.

2.4 Green's function computation – Inversion

The Green's function calculation is performed using the frequency wavenumber method (Bouchon, 1981). The code is written in Fortran but the user controls its use through the ISOLA-GUI, using the *greenpre* tool. We have tried to limit the number of input parameters as much as possible, thus the user has to specify only the maximum frequency of the Green's function computation. Then the code automatically generates the Green's functions and the corresponding elementary seismogram files, while at the same time it stores everything in the proper folders.

The inversion is the core of the procedure and is performed using another ISOLA-GUI tool called *invert*, presented in Fig.3. The user can select the type of inversion (Full, Deviatoric, Double Couple (DC), Fixed), the frequency band of the inversion, the number of subevents and the time span of their occurrence. Various helpful features are included, like a special option for automatic calculation of station weights, based on the maximum amplitude of the displacement record, and a tool for plotting correlation and focal mechanism *vs* source position and its time shift (Fig.4). Besides the correlation, the double couple percentage of the solution (DC%) can also be plotted, since in many cases it can provide indication about problematic inversion results. The correlation plot is quite important and a major advantage of the software is that the user can have visual control of the inversion results, while the inversion progresses, and actually drive the inversion procedure based on this diagram and relevant constraints, e.g. polarity measurements, rupture velocity, the assumed tectonic style in the area, etc. The application of constraints may be desirable depending on the resolution of the inversion parameters. For example, for the case of low resolution the constrained (fixed) focal mechanism may prevent "wild jumping" of subevents in space and time. In this sense, a requirement for user to select his preferred choice of the subevent position and time is quite common and definitely improves the results compared to the fully automatic run, which is based only on the absolute value of the correlation. In any case both user's and automatic selection of subevents are possible during the inversion procedure.

2.5 Plotting of results

The last step is the plotting of the inversion results, in particular the moment tensor solution and the best fit between data and synthetics (Fig.5). Again, a special tool was designed, named *plotres* that uses Matlab and GMT graphic capabilities to prepare quality plots of the results. The variance reduction per tested source and the corresponding focal mechanism can be plotted together on a graph in order to inspect the inversion convergence through the whole computation. An option for comparing the computed focal mechanism solution with the available first motion polarities is also available. The plotting tool was designed primarily for users with limited knowledge of usage of GMT or Matlab graphics. Nevertheless our intention was not to prepare a GMT front-end but help users produce nice maps quickly. Experienced users can easily produce custom plots using the output text files with the inversion results. Additionally, Matlab programmers can easily add their own special features to the *plotres* tool, such as creation of a text file with the moment tensor solution, suitable for email notification.

3. Case study, Zakynthos 2006 seismic sequence

To demonstrate the use of the software, we present the moment tensor analysis for a strong earthquake that occurred on April 11, 2006 at 17:29 UTC, offshore of Zakynthos island in western Greece, (EMSC location Lat:37.7^{o}N, Lon:20.9^{o}E, Mw=5.6). The event was recorded by three broad band instruments of PSLNET, a new satellite telemetry network, starting operation in 2006 and belonging to the Seismological Laboratory of the University of Patras (Tselentis et al., 2006). This event was the strongest from a series of medium size earthquakes (more than 5 events of Mw>4.5) that affected the island of Zakynthos for a period of two months causing moderate damage to the island's structures[8]. The records of this event, as SAC files, are included with the program distribution to serve as an example. The same event will be used here to demonstrate the analysis using ISOLA-GUI.

[8] Web address: http://www.itsak.gr/Zakynthos_2006SMR.pdf

Initially the data are converted to ISOLA native format using the specially designed *SACimport* tool. Then the quality of the records and the signal to noise ratio at various frequency bands are checked using the *datafilt* tool in order to define the proper frequency band for the inversion. The next step is to prepare the crustal model that will be used in the analysis, in this case it is the model previously proposed by (Haslinger et al., 1999) during local earthquake tomography studies in western Greece. The model is converted to the proper format using the *crustmod* tool. Next steps involve input of event information, selection of stations to be used in the inversion and raw data pre-processing which are done using the *eventinfo*, *stationselect* and *datain* tools (Fig.1). At this point we can decide on single or multiple point source inversion and prepare the necessary trial source position and Green's function files using the *sourcepre* and *greenpre* tools, respectively. We will present both single and multiple source inversion for this event, starting with the first one.

3.1 Single source inversion

We select deviatoric point source inversion for a series of trial source positions lying at various depths below the epicentre position determined by EMSC. The total trial sources tested were ten with a 3km vertical separation, spanning depths from 3 to 30km. This type of inversion will indicate the preferred centroid depth, and it is a logical first step during the moment tensor study. Using the *invert* tool inversion parameters such as the frequency band for the inversion, and parameters of the time search can be set. For this single source inversion run we used frequencies extending from 0.037 to 0.062Hz with cosine tapering applied to both ends (Fig.5a). Using the same tool, during the inversion run, a plot of correlation and focal mechanism *vs* source position and its time shift, is constructed. Such a plot is presented in Fig.4 where it is clear, from correlation maximum, that the preferred solution is at a depth of 6km (source number 2 corresponds to this depth) for a time shift of 3.16sec. The results of the inversion are plotted later using the specially designed *plotres* tool (Fig.5a,b). What is interesting from the single source results is that the double couple percentage (DC%) is really low for this event, indicating that the possible effect of the source complexity can be 'mapped' into a large but only apparent CLVD value. Of

course this is just one explanation for the large CLVD value but it motivates us to display the use of ISOLA, for multiple source inversion.

3.2 Multiple source inversion

Multiple source inversion is another key point of ISOLA method. Usually this type of inversion is performed for large earthquakes using data at teleseismic distances, but with ISOLA it is possible to perform the same type of inversion using local or regional data. In this way more details of the seismic source can be revealed.

In order to run a multiple source inversion a set of possible source positions has to be defined; this is accomplished with the *sourcepre* tool. In Fig.8 a map of the trial source positions for the studied event is displayed. In this multiple source inversion run, we use source positions located on a horizontal plane at a depth of 6km (the depth preferred in the single source inversion) having a spacing of 12km; thus we use a grid of 25 trial source positions. Using this set of sources and the appropriate Green's functions, we start running the inversion and subsequently searching for two elementary sources, using the *invert* tool. The selected frequency band for the inversion is extended to higher frequencies (0.02 – 0.13Hz, with cosine tapering) in order to obtain detailed information about the source rupture process. During the inversion ISOLA pauses and asks the user to accept the automatically detected optimum source position and time, or to propose a different solution for the first subevent. Creating a plot of all the possible solutions assists the user to decide if the proposed automatic solution is acceptable. We need to note here that ISOLA automatically proposes a solution based on the maximum correlation. This solution can differ greatly in the DC percentage when compared with another "nearby" solution with a slightly smaller correlation value. Having a tool that displays this in an efficient graphical way allows the user to explore all the concurrent solutions and choose one, based on various assumptions. Such a plot for the first subevent is presented in Fig.6. The automatic solution is marked with a larger beachball, while an option for plotting results for a single source is also available (Fig.7).

After a detailed check and a combined use of the above diagrams, one can easily identify other possible solutions which have slightly smaller correlation and thus

haven’t been automatically proposed by the program. For example, source 8 at time shift 0.6sec, or source 13 at time shift 4.6sec, have similar correlation and focal mechanism, but differ significantly from the automatically chosen solution in their source position and DC percentage. At this point, based on what has been described already, we select, source position 13 and time shift of 4.6sec as our preferred solution instead of the automatically proposed 4sec. The focal mechanism is the same for both solutions, but the DC percentage increases from 60% to 95%, with just a 3% difference in correlation. Such a choice is perhaps better compatible with the tectonic regime in Zakynthos, since it explains the first sub-event as a pure shear source. Following the same procedure for the second sub-event, we end up with an explanation of the waveforms as being due to rupture of two pure-shear sources (Fig.8). The focal mechanism of the second subevent is different from the first one, suggesting a complicated rupture, and possibly explaining the large CLVD part for the single source solution. Nevertheless, final conclusions concerning the rupture history of this event would need special care (Zahradnik et al 2007, submitted), and a full physical justification of the DC percentage would require more efforts, well beyond the scope of the present paper.

Conclusions

The moment tensor analysis of local and regional events is a standard procedure applied to broad band seismic networks worldwide, in many cases even as an automatic procedure. In all such applications the inversion is performed for a single point source. The programs ISOLA and ISOLA-GUI presented in this paper allow an easy application of the iterative deconvolution method of Kikuchi and Kanamori 1991, for local and regional events, thus the method can be used for both single and multiple source geometry. The Matlab based GUI facilitates easy data handling while at the same time providing complete user control during all the processing steps and easy graphical display of the results, using both Matlab and GMT capabilities. The waveform inversion is done using the Fortran ISOLA code, in order to take advantage of language speed, while user interaction even during the inversion is within the Matlab environment. Various tools are available for the user to explore the data quality, adjust the computational parameters, correct the data and display inversion results in a publication-ready form. The modular design of the GUI allows the easy

upgrade as well as the inclusion of user-created additional modules, using elementary skills in the Matlab programming language. The software, the manual and examples files are available for download at http://seismo.geology.upatras.gr/isola/, for the Windows operating system, while a Unix/Linux version will be available soon.

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Figure Captions

Figure 1. Main ISOLA Matlab GUI.

Figure 2. ISOLA-GUI tool for data pre-processing.

Figure 3. ISOLA GUI used for the inversion calculations.

Figure 4. Plot of correlation *vs* time shift, source position and focal mechanism for the single source inversion. The largest correlation was obtained for source 2 (6km depth) and 3.16sec time shift. The focal mechanism shading changes according to double couple percentage, while for diagram clarity, we only plot solutions having double couple percentage larger that 70%. The preferred solution is depicted by a larger beachball.

Figure 5a. Waveform comparison for the single source inversion.

Figure 5b. Moment tensor solution results, output by ISOLA-GUI for the single source inversion.

Figure 6. Correlation diagram for the first sub-event during the multiple source inversion. The horizontal axis is the time shift , the vertical axis is the trial source number and contours are correlation values. The focal mechanism shading changes according to double couple percentage. Only solutions having double couple percentage larger that 70% are plotted. The preferred solution is depicted by a larger beachball.

Figure 7. Correlation plot for the first sub-event. Horizontal axis is time shift and the vertical axis shows correlation; the automatic solution proposed by the program is depicted by an arrow.

Figure 8. Plot of the twenty-five trial source positions, along with the final results for the multiple source inversion.

Figures

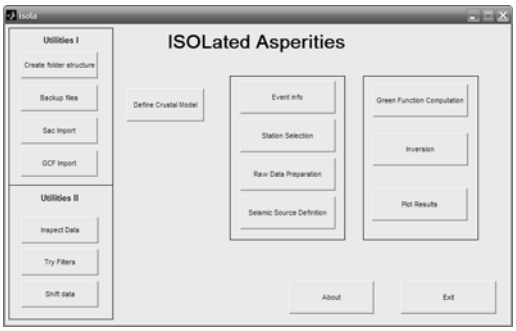

Fig.1

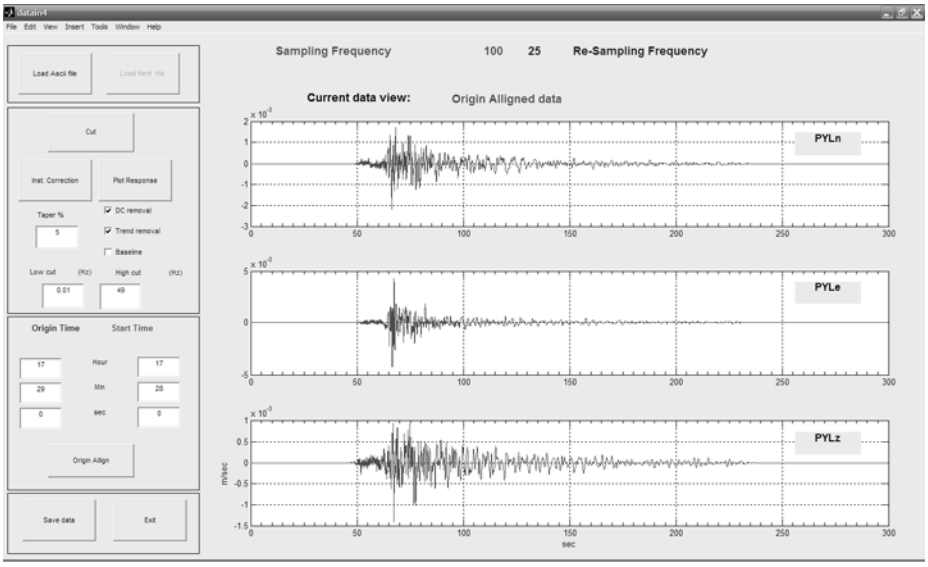

Fig.2

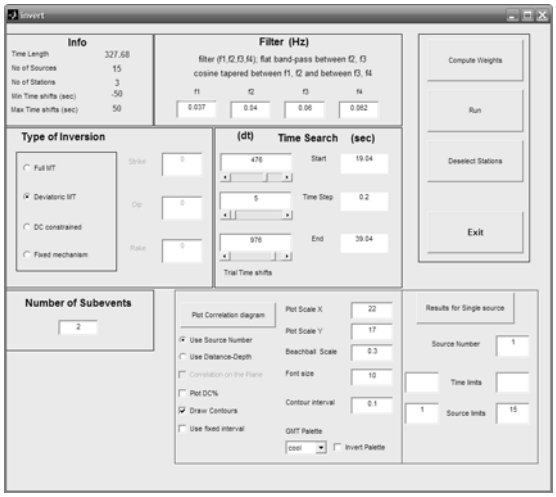

Fig.3

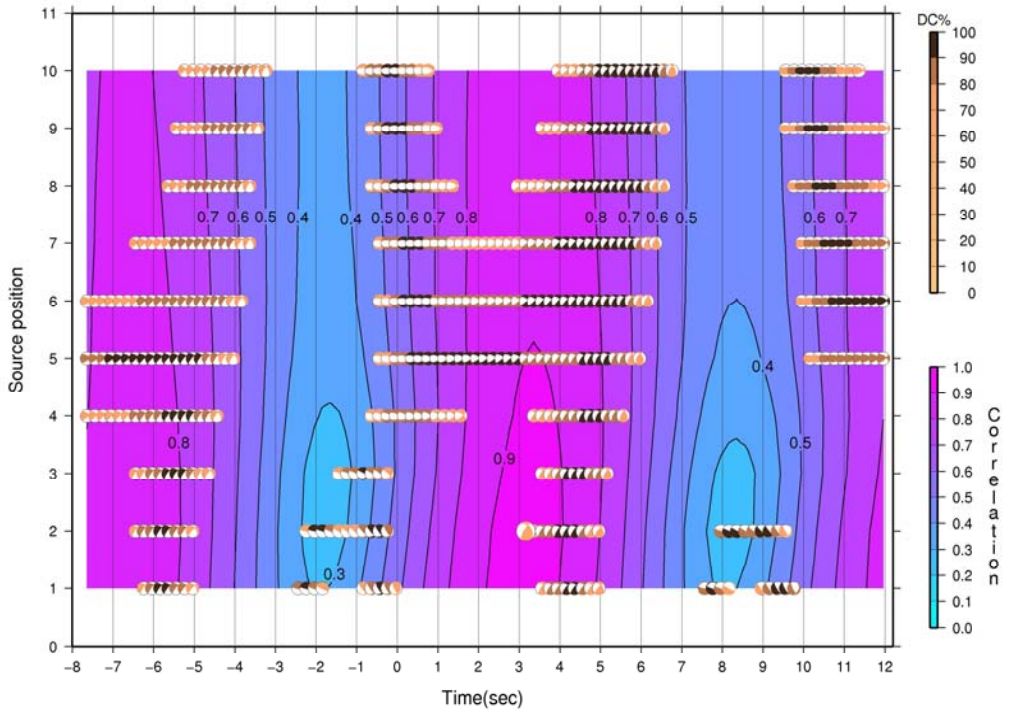
Source position
Time(sec)
DC%
Correlation
0.7 0.6 0.5 0.4
0.4 0.5 0.6 0.7 0.8
0.8 0.7 0.6 0.5
0.6 0.7
0.8
0.3
0.9
0.4
0.5

Fig.4

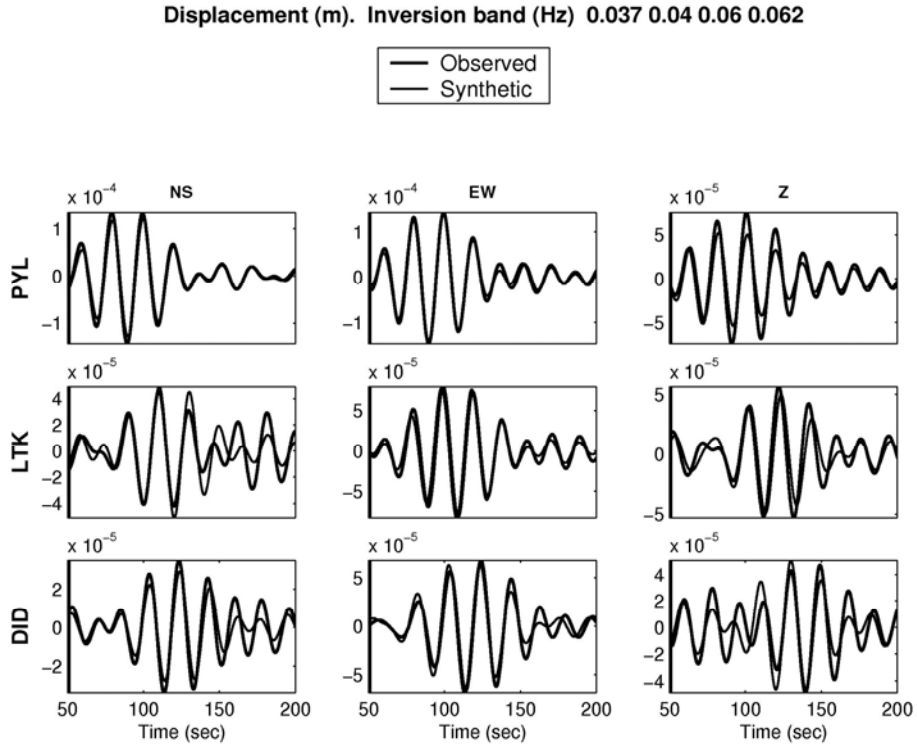
Displacement (m). Inversion band (Hz) 0.037 0.04 0.06 0.062
Observed
Synthetic
NS
EW
Z
PYL
LTK
DID
Time (sec)

Fig.5a

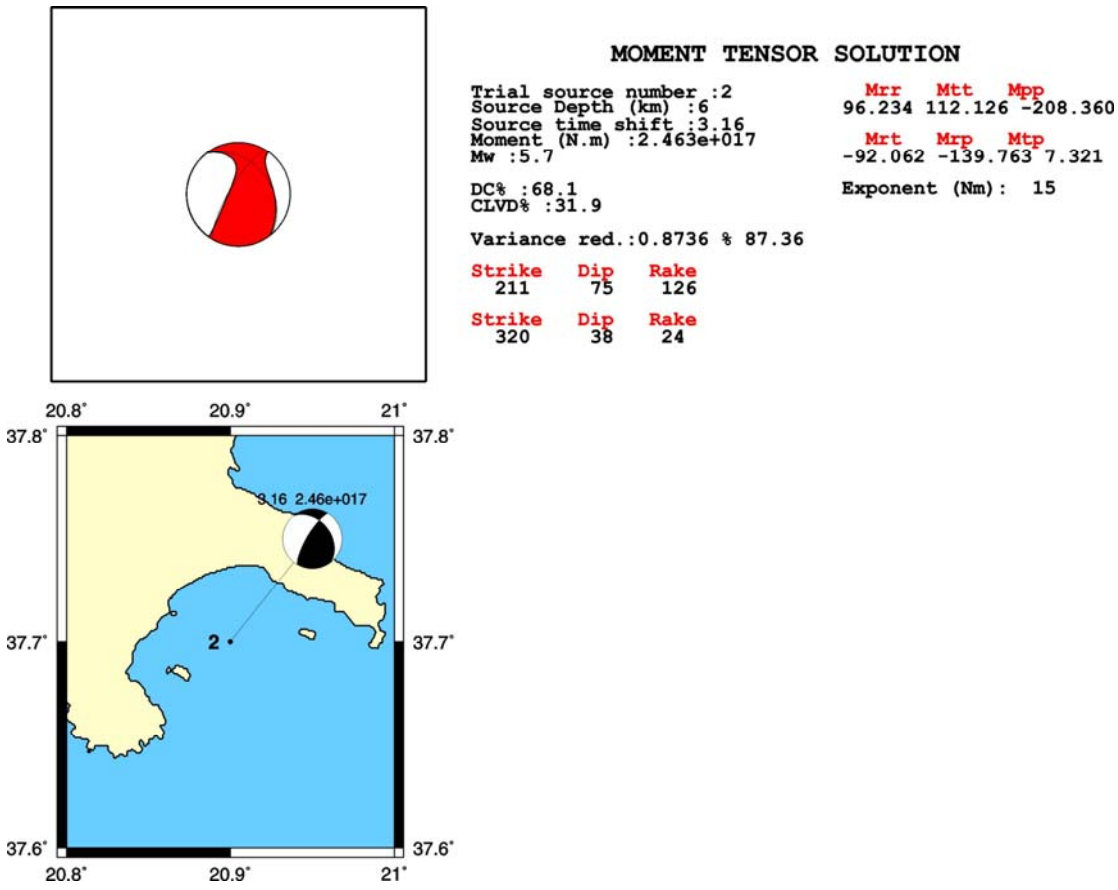
MOMENT TENSOR SOLUTION
Trial source number :2
Source Depth (km) :6
Source time shift :3.16
Moment (N.m) :2.463e+017
Mw :5.7
DC% :68.1
CLVD% :31.9
Variance red.:0.8736 % 87.36
Strike Dip Rake
211 75 126
Strike Dip Rake
320 38 24
Mrr Mtt Mpp
96.234 112.126 -208.360
Mrt Mrp Mtp
-92.062 -139.763 7.321
Exponent (Nm): 15
20.8° 20.9° 21°
37.8° 37.7° 37.6°
3.16 2.46e+017
2

Fig.5b

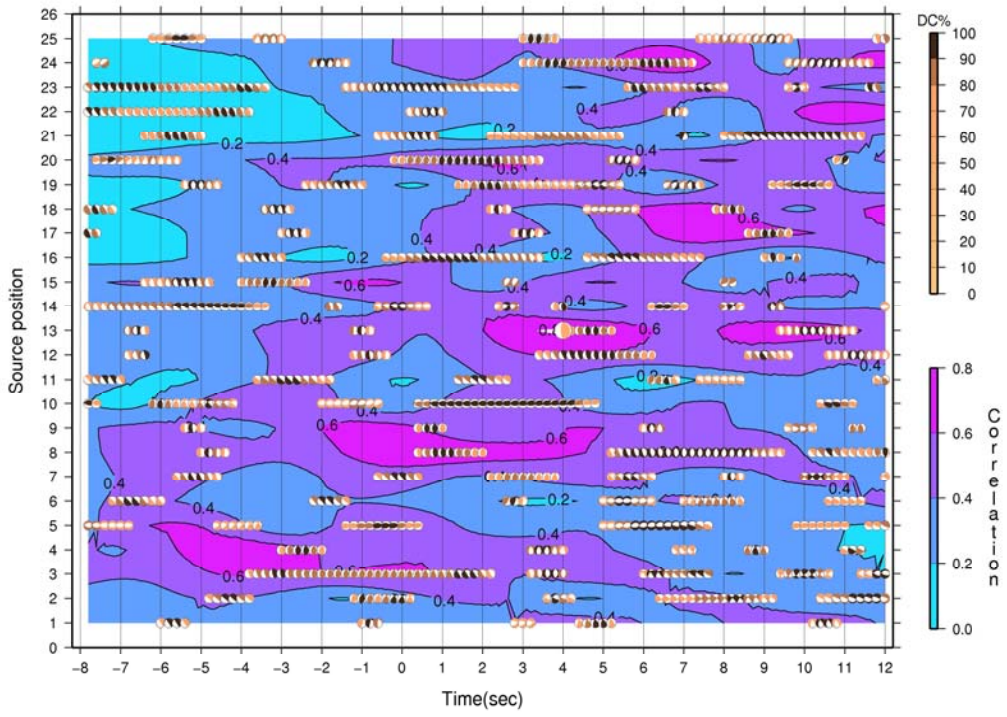
Source position
Time(sec)
DC%
Correlation

Fig.6

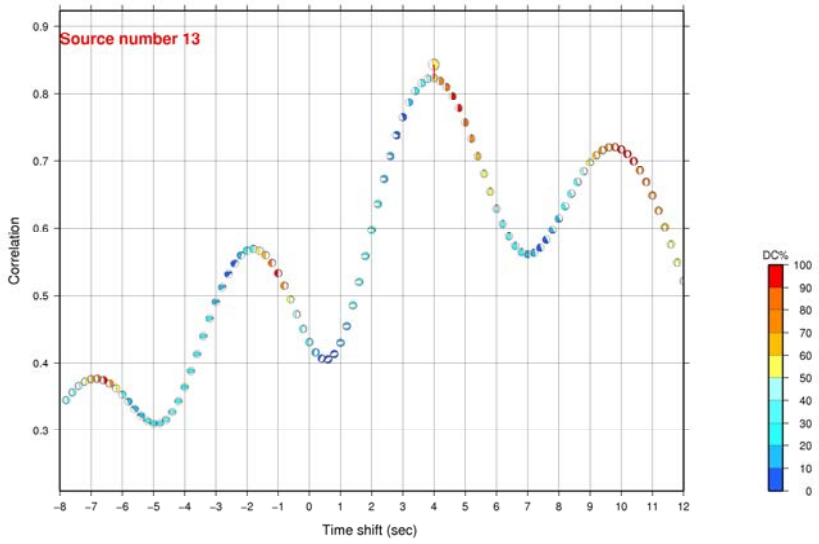

Fig.7

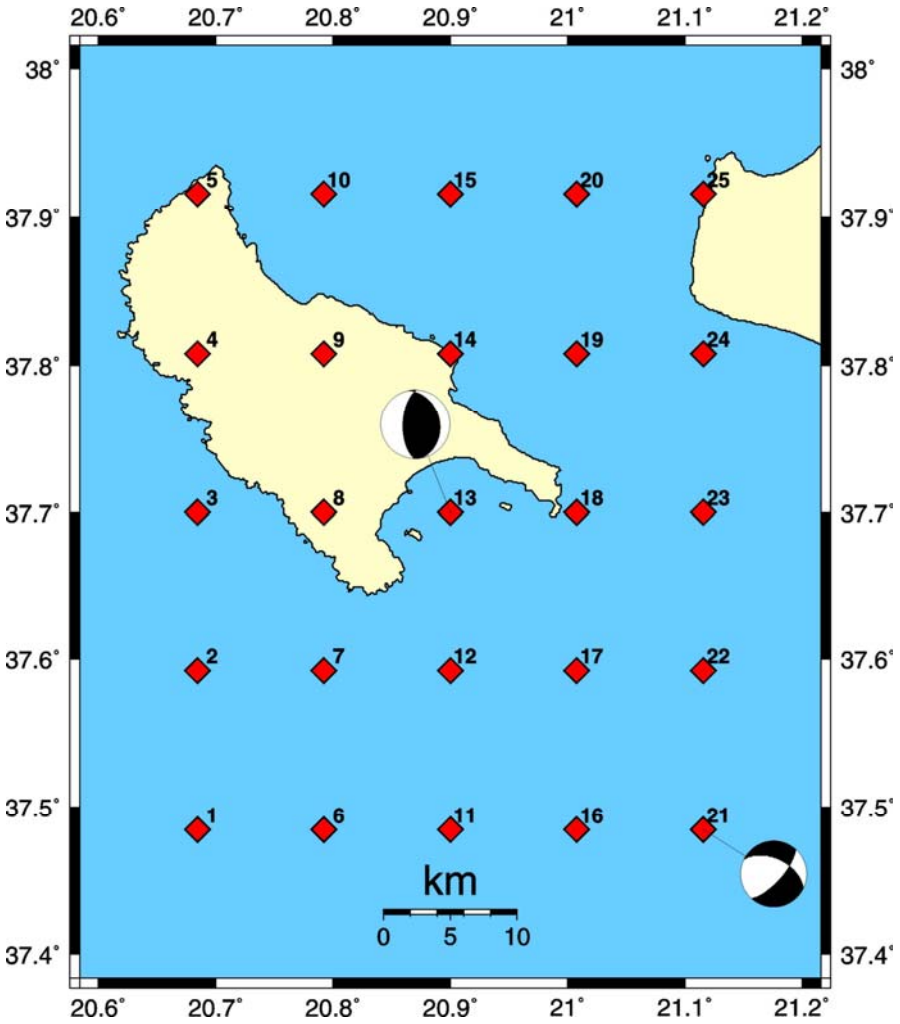

Fig.8