



# A database of revised fault plane solutions for Italy and surrounding regions

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## Abstract

The analysis of fault plane solutions of earthquakes is carried out in most seismotectonic studies to characterize the tectonic deformation styles and to estimate strain and stress directions in the investigated areas. Nevertheless the data available in the literature, are reported with different formats and notations and, in most cases, only in papery form, so that they are not suitable to be handled by computer procedures and graphic packages. Sometimes the data are reported with typographical errors, inaccuracies and inconsistencies that make them almost useless for other investigators. In some cases several solutions, often very different among each other, are given for the same earthquake by different authors thus requiring a choice be made among them.

We have tried to solve some of these problems, in building a comprehensive database, on a Microsoft ACCESS platform, including most of the mechanisms (presently about 5000) published for the Italian region and more generally for the Mediterranean area.

We tested the perpendicularity of nodal planes and/or *P* and *T* axes of all solutions and, when both axes and planes are given, even their mutual consistency. Moreover from the comparison of planes and axes we were able to detect and sometimes to correct misprints and other types of errors. All the parameters are recomputed uniformly and consistently, keeping track of all the corrections made. We also established an automatic procedure, based on several criteria, to choose the most “representative” solution when more than one is available for the same earthquake.

The MS-ACCESS application also allows to making selections on the earthquake data, to display the plot of the mechanisms and to export data files suitable to be handled by graphic software and user written procedures.

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## 1. Introduction

The study of earthquake focal mechanisms represents a useful tool for the spatial characterization of the causative structures. These data are important for a better definition of the geometry and the typology of the seismogenetic faults as well as for the comprehension of the dynamic processes and the interaction among different portions of the Earth lithosphere. Moreover,

the combination of focal solutions for a given area both in terms of cumulative moment tensor (Kostrov, 1974) or of stress directions compatibility (Gephart and Forsyth, 1984, Gephart, 1990) allows to map the large-scale features of dynamic parameters inside the tectonic plates.

In the last two decades, the availability of the Harvard Global CMT catalog<sup>1</sup> (Dziewonski et al. (1981) and subsequent papers appeared quarterly in *Physics of the*

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<sup>1</sup>Harvard Centroid Moment tensor Project. <http://www.seismology.harvard.edu/projects/CMT/>.

*Earth and Planetary Interiors*) including the moment tensors solutions of most significant earthquakes ( $M \geq 5.5$ ) occurring all over the World starting from 1976, allowed to definitely shed light on the global dynamics of plates and on the gross features of the tectonic stress in the Mediterranean area (Rebai et al., 1992; Muller et al., 1992) and in other seismic regions of the World (World Stress Map, Zoback, 1992). However in the Italian area, which is characterized by very complex short scale tectonics and moderate seismicity, the few dozen of CMT solutions available since 1976 do not alone allow one to definitely resolve the tectonic pattern satisfactorily.

In the last few years two Regional CMT (RCMT) catalogs were also made available to scientific community in the Mediterranean Region. These are the RCMT on-line catalogs continuously updated at *Istituto Nazionale di Geofisica e Vulcanologia* (INGV) of Rome<sup>2</sup> (Pondrelli et al., 2002) and at the *Eidgenössische Technische Hochschule* (ETH) of Zürich<sup>3</sup> (Braunmiller et al., 2002). They include earthquakes recorded by Mediterranean VBB stations with  $M \geq 4.5$  starting from year 1997 and 1999, respectively.

In Italy, only a minority of the seismic areas that have generated strong ( $M \geq 6$ ) earthquakes in the last century (CPTI Working Group, 1999<sup>4</sup>) were activated during the CMT era. Hence, to characterize the other zones (i.e. for seismic hazard assessment), it is necessary to recourse to the first motion solutions available in the literature.

Although the computer codes, like FPFIT (Reasenberg and Oppenheimer, 1985; available at<sup>5</sup>) and FOCMEC (Snoke et al., 1984, available at<sup>6</sup>), usually employed to compute first motion solutions, exhaustively tested by tens of years of widespread usage, are working fine (within the limit of the their theoretical approach at least), the published results of their usage still present a wide range of flaws. The most frequent cause of error is the misuse of terms and notations (for example the confusion between strike and dip direction), but any sort of misprints and inconsistencies are also present on many papers albeit published in authoritative journals. In other cases the reported parameters are not sufficient to constrain the solution at all (whenever for

example only the orientations of planes are reported, without the indication of the slip directions).

Some justification to such an amount of defects, involving about 42% of the published data we have examined, can be adduced due to the warped nature of angular data representation and to the coexistence of several different notation conventions and reference systems. Even the widespread usage in the literature of at least two different conventions for the definition of the Cartesian components of the seismic moment tensor (the “Aki-Richards” and the “Harvard CMT” ones) makes the interpretation of data susceptible to some misunderstandings. Everybody can understand how the unconditioned acceptance of wrong or unreliable data may result in misinterpretations and in some cases even in true mistakes in the investigations where those data are referenced.

A further source of uncertainty concerns cases where several solutions (often very different from each other) are available for the same earthquake from different authors. This implies an ambiguity that cannot be immediately settled but requires an evaluation of the quality of the computations and/or the “authoritativeness” of the source of the data.

We attempt here to solve some of these problems associated with unreliable published fault plane solutions for Italy and surrounding regions. The revised database will be reliable for other investigators to use in seismotectonics and seismic hazard studies of the region.

## 2. Data acquisition and check

We built a database application, using Microsoft ACCESS, to systematically and conservatively collect the data found in the literature. The area of interest was originally limited to the Italian peninsula and surrounding zones and had been extended in time progressively to cover the entire Mediterranean area. With the word “systematically” we mean that all the parameters reported in the papers are included in the database and with “conservatively” that all the data are taken “as they are” with the format adopted by the authors of each work. For example the coordinates can be collected both as degrees, minutes and seconds as well as decimal degrees; also the input data may concern one or both nodal planes or  $P$  and  $T$  axes.

In general, if the data are published in journals of wide diffusion and availability, we refer to the original sources. In cases when the original paper was not easily reachable we had recourse to indirect sources (data republished by others) but keeping anyhow a track of the original reference. The papery data were manually input by a data acquisition mask and stored in a comprehensive database file including about 130 fields.

<sup>2</sup>European-Mediterranean Regional Centroid-Moment Tensors. <http://www.ingv.it/seismoglo/RCMT/>.

<sup>3</sup>Swiss Moment Tensor Solutions. <http://seismo.ethz.ch/info/mt.html>.

<sup>4</sup>Parametric catalog of Italian Earthquakes (CPTI). <http://emidius.mi.ingv.it/CPTI/home.html>.

<sup>5</sup>FPFIT, FPLOT and FPPAGE Linux version Focal Mechanism determination. <http://www.seismo.unr.edu/ftp/pub/ichinose/LINUX/fpfit.tar.gz>.

<sup>6</sup>FOCMEC: FOcal MEchanism Determinations. <http://www.vt.edu/outreach/vtso/focmec/>.

At present time we had examined more than 130 papers for a total of about 5000 solutions.

To perform the consistency checks, the recorded data have been exported to an ASCII file and then processed off-line by a Fortran program that, depending on the input parameters given by the original source, computes some or all of the following quantities:

- (i) angle between the outward normals of the two nodal planes,
- (ii) angle between the slip vectors of the two planes,
- (iii) angle between the  $P$  and  $T$  axes,
- (iv) parameters of one nodal plane from the other one,
- (v) parameters of  $P$ ,  $T$  and  $B$  axes from nodal planes,
- (vi) parameters of nodal planes from  $P$  and  $T$  axes,
- (vii) parameters of best double couple nodal planes from moment tensor,
- (viii) parameters of  $P$ ,  $T$  and  $B$  axes from moment tensor,
- (ix) moment tensor components from  $P$  and  $T$  axes and
- (x) moment tensor components from nodal planes.

All these computations were made, using a library of Fortran routines that is widely described in a companion paper (Gasperini and Vannucci, 2003). Our testing program signals the deviations from the orthogonality of planes or axes and the differences between original and recomputed parameters of planes or axes exceeding three degrees, as well as all significant discrepancies between original and recomputed moment tensors components.

The most common errors found are  $90^\circ$  or  $180^\circ$  rotations of strikes and/or rakes, probably due to the use of wrong or inaccurate formulations. But also relevant deviations from orthogonality of planes, slip directions and axes (up to some tens of degrees) were sometimes detected. The reasons of the latter deviations appear inexplicable for works that used one of the standard codes cited above, while they are easier to understand when mechanisms are computed graphically or by self-written procedures. A common cause of discrepancy between planes and axes is the wrong indication of the dip direction in place of the strike of the fault, which results in a positive difference of  $90^\circ$  of the latter parameter. This is probably due in some cases to the misinterpretation of the printout of the FPFIT program that actually indicates the dip direction and not the fault strike. In few cases we also found that the strike was computed adding  $90^\circ$  to the dip direction instead of subtracting the same value thus bringing to a positive difference of  $180^\circ$ .

The comparison of the results of the various computations indicated above allows for most solutions to readily infer the source of error and to chose the correct parameters to be used to recompute the defective

ones. Our experience showed that the most reliable parameters are usually the  $P$  and  $T$  axes directions probably because, due to the intuitiveness of the definition, their correctness is easy to verify even visually. Our Fortran program was able in most cases to choose automatically the most reliable parameters as well as to suggest the possible solution to the observed discrepancy. However we also had recourse to manual adjustments and to the comparison with the plot of the mechanisms (when reported in the papers). The visual inspection of the plotted mechanism was also useful to reconstruct some solutions, otherwise not fully constrained by numerical data, for which only the strikes and the dips of the two planes (but not the rakes) were reported in the paper.

In Table 1 a summary of the results of the checks performed by our testing code is shown. Although about 42% of the solutions was found to contain defective or incomplete data we were able to recover the most of them, so that the final database includes about 96% of the processed data. The solutions that can be reliably used for further analyses are in all 4777, corresponding

Table 1  
Summary of results of checks performed on processed solutions

Type of data	Number	%
<b>All examined</b>	<b>4995</b>	<b>100.0</b>
Correct FPS parameters	2922	58.5
FPS parameters with some defects	2073	41.5
<b>Recoverable</b>	<b>1855</b>	<b>37.1</b>
Wrong axes, correct planes and rakes	116	2.3
Wrong planes or rakes, correct axes	1295	25.9
Only strike and dip of two planes (polarity determined from figures)	444	8.9
<b>Unrecoverable</b>	<b>218</b>	<b>4.4</b>
Axes and/or planes not perpendicular	129	2.6
Undetermined	89	1.8
<b>Correct + recovered</b>	<b>4777</b>	<b>95.6</b>
Lacking of earthquake identification parameters (date, location, magnitude)	151	3.0
Usable solutions	4626	92.6
Duplicate solutions	1681	
<b>Distinct earthquakes</b>	<b>3314</b>	<b>100.0</b>
Earthquakes with only one mechanism	2511	75.8
Earthquakes with more than one mechanisms	803	24.2

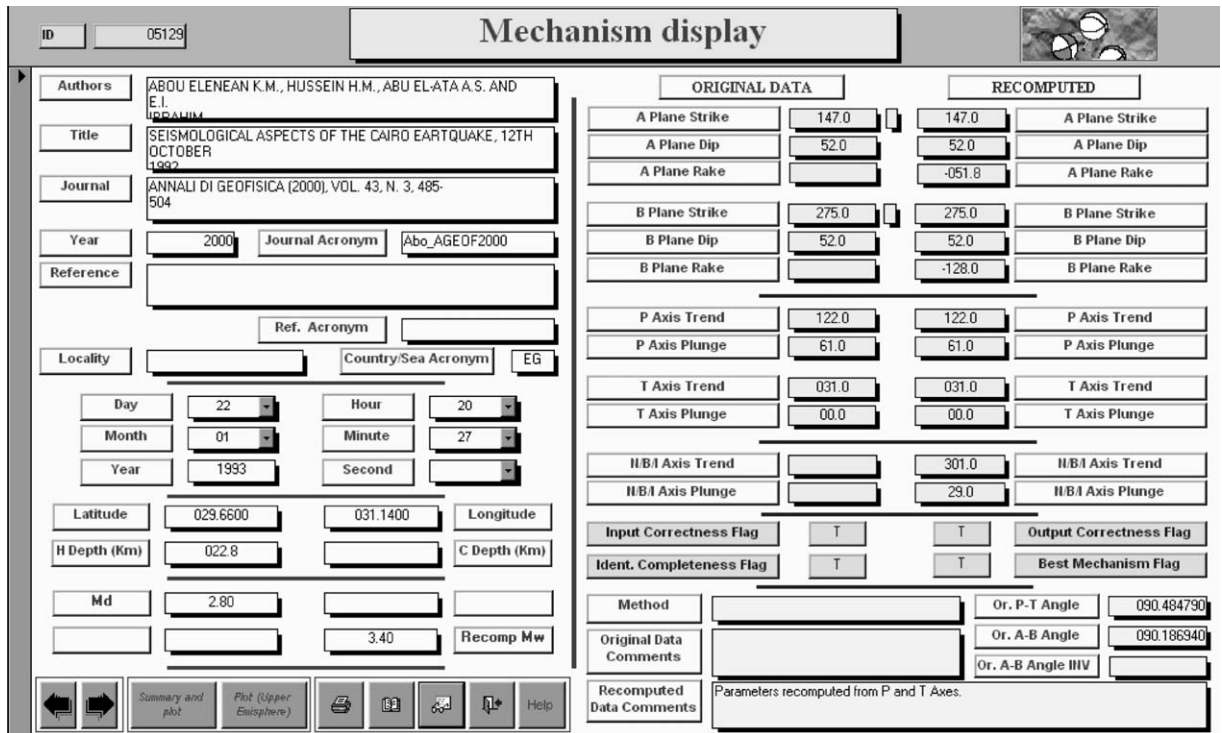


Fig. 1. MS-ACCESS masks for displaying original and re-computed FPS parameters.

to 3314 distinct earthquakes. For 2511 of them we have only one solution while for 803 we have two or more.

After the testing, the recomputed parameters are re-imported to the MS-ACCESS database. This allows the visual comparison between original and recomputed data by an appropriate display mask (Fig. 1). In the comment field a synthesis of the main problems encountered is reported in order to keep track of the choices made to solve them.

### 3. Database features and usage

The MS-ACCESS application we have written guides the user to the desired operation by a set of self-explanatory menus and masks. It allows to import (without any checking) the data of the Global CMT Harvard catalog as well as of the two regional CMT catalogs for the Mediterranean region (INGV and ETH). This operation can be performed by the user, providing the corresponding input files that can be downloaded from the above-mentioned web sites (see footnotes 1–3).

The application also allows any user to make selections on the basis of earthquake source parameters (date, location, magnitude, etc.) as well as of biblio-

graphic data (authors, journal, etc.) by a specific selection mask (shown in Fig. 2). The selected mechanisms can be examined singularly through the display mask of Fig. 1 as well, as they can be exported to external files in order to be plotted by graphical software like that Graphic Mapping Tool (GMT) (Wessel and Smith, 1991; available at<sup>7</sup>), or analyzed by user written procedures and programs. A button of the display mask activates a procedure, making use of GMT and Ghostscript,<sup>8</sup> which displays the “beach-ball” plot of the selected mechanism. Another feature of our application gives the possibility to export the list of the references of selected data in a format suitable to be included in manuscripts. This reduces the workload of the authors and at the same time grants that all the used data are correctly cited.

To simplify the selections in base of the earthquake size as well as to evaluate the moment tensor for further computations, we computed for all mechanisms, when not reported on the sources, an estimate of the scalar seismic moment and of the corresponding moment magnitude. For Italian earthquakes we used the specific

<sup>7</sup>GMT - The Generic Mapping Tools. <http://gmt.soest.hawaii.edu/>.

<sup>8</sup>Ghostscript, an interpreter of the PostScript language. <http://www.cs.wise.edu/~ghost/doc/AFPL/index.htm>

Fig. 2. MS-ACCESS selection mask.

Table 2

Formulas used to compute scalar seismic moment from various types of magnitudes

Region	Formulas	Reference
Italy and surrounding areas ( $34 \leq \text{latitude} \leq 45$ , $6 \leq \text{longitude} \leq 19.5$ )	$\text{Log } M_0 = 19.3 + 0.96 M_s$ $\text{Log } M_0 = 17.9 + 1.21 \text{ mb}$ $\text{Log } M_0 = 17.7 + 1.22 M_I$	Gasperini and Ferrari (2000)
All others	$\text{Log } M_0 = 24.66 - 1.083 M_s + 0.192 M_s^2$ $\text{Log } M_0 = 18.28 + 0.679 \text{ mb} + 0.077 \text{ mb}^2$ $\text{Log } M_0 = 18.31 + 1.017 M_I$	Johnston (1996)

Note that following equivalences are assumed  $M_m = M_s$ ,  $M_d = M_I$ ,  $M = M_I$ . Moment magnitude  $M_w$  is computed using Hanks and Kanamori (1979) definition:  $M_w = 2/3 \text{ Log } M_0 - 10.7$ .

empirical formulas proposed by Gasperini and Ferrari (2000) while for the surrounding regions we employed the relations deduced by Johnston (1996) for stable continental regions (see Table 2). These scalar moment and moment magnitude values can be used consistently and homogeneously for event selections and, together with the double couple Cartesian components of moment tensor (also computed by our Fortran program and stored in the database for each event), for moment summation analyses (i.e. Kostrov, 1974).

Another added value furnished by the database is the choice of the best mechanism among the available duplicates. Effectively this is an operation that cannot be

fully objective and might require some amount of subjective judgement. We have established a series of simple criteria to evaluate the reliability of the solutions that are used to make the choice of the preferable one. The user however is free to accept or reject this choice at its own belief, being that the other (not preferred) solutions are also included in the database. The criteria, listed in decreasing order of importance, are the following:

- (i) correctness of the solution (presence or absence of errors in the published FPS parameters);
- (ii) originality of the source (original sources are preferred with respect to indirect ones);



- (iii) “authoritativeness” of the source, roughly based on the impact factor of the journal or on the diffusion ambit of the publication (international, national, thesis, etc.) where the solution is published;
- (iv) recentness of the publication.

We only took into account objective criteria that can be easily evaluated for any given solution and we did not consider any kind of estimator of the quality of the solution (solution quality factor, number of stations, etc.) as these are given only by a minority of the published solutions. The above criteria all contribute to make the choice of the “best solution” that is reflected in the database by a specific flag indicating the most reliable among the duplicates. This flag can be used, in selection operations in order to extract from the database only one mechanism for each earthquake.

#### 4. Final remarks

The experience we made working on this database showed that the publication of focal mechanisms is subject to a series of indeterminations and inaccuracies that are often neglected by the authors and may prevent a reliable usage for subsequent investigations. This might be in part due to the scarce intuitiveness and the deceptiveness of the formulation in terms of nodal plane angular parameters. In fact the definition of the strike and especially of the rake are rather involved and somehow contradictory (one clockwise the other one counterclockwise) thus may be easily misunderstood. Moreover the nodal planes represent the true surfaces where the seismic slip might have occurred during the earthquake only for double couple mechanisms and only if such the surfaces are really plane.

We have verified instead that the principal axes are less subject to mistakes and inaccuracies and in most cases are the only data that can be reliably used to reconstruct the mechanism parameters. On the other hand these are always physically meaningful even in cases when a double couple is not a suitable model or the fault is not plane. Thus we believe this representation be preferable (if the moment tensor is not available) when publishing the parameters of FPS.

We also found that in critical cases strongly deviating from double couple or when the dip or plunge angles are close to  $0^\circ$  and  $90^\circ$ , the usual resolutions of angular quantities and tensor components (1° and two decimal digits respectively), may not be sufficient to univocally constrain the angular parameters of nodal planes. For example, simulating the rounding to integers of angular quantities and to two decimal digits for moment tensor components, we found that deviations larger than  $3^\circ$  occurs systematically for dip angles lower than  $5^\circ$  and

sporadically up to  $15^\circ$ . These differences in the parameters, that actually affects a minority of the real solutions (less than 1% for the CMT catalog), do not reflect strong deviations in the true orientation of planes but however make more difficult a direct comparison of solutions.

We hope that this work and the companion paper describing the library of subroutines we have written to make the above described computations and checks, could contribute to make easier in the future the analysis of such data. Our MS-ACCESS application allows any user to display all of the parameters (original and recomputed) of each solution, to plot the mechanism, to make selections on the basis of source location, origin time, magnitude, author, title, journal, etc., as well as to export the data files that can be submitted to external procedures and to common graphic packages.

Some improvements are currently in preparation, among them: the addition of newly published mechanisms and the inclusion of the consistency checks and recomputations within the MS-ACCESS application. A further point that must be considered with more care in a future release of the database is the evaluation of the uncertainties and more generally of the reliability of each solution included in the database. Parameter uncertainties are presently available almost only for CMT components, while their reporting is sporadic for first motion solutions. Even this deficiency can be addressed to the inherent difficulties in dealing with spherical data. In this case in fact, the data statistical distribution is not Gaussian as well as the standard deviations of the usual angular parameters (strike, dip, rake, trend and plunge) are not meaningful due to the strong correlation among them. A possible approach could be to estimate, for axes, plane normals and slip directions, the “cones of confidence” (i.e. Fisher et al., 1987) that, for spherical data following the Fisher normal distribution, have the same role of the standard deviations for linear ones, but this would require considerable improvements in the computing codes.

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