Near-Real Time Moment Tensors for Earthquakes in Greece provided by the Dept of Geophysics, Aristotle University of Thessaloniki (AUTH –solutions)

Zafeiria Roumelioti[1*], Christoforos Benetatos[1*], Anastasia Kiratzi[1] and Douglas Dreger[2]

[1] *Department of Geophysics, Aristotle University of Thesaloniki, P.O. Box 352-1, 54124 Thessaloniki, Greece (contact person: AK email:Kiratzi@geo.auth.gr)*
[2] *Seismological Laboratory, Berkeley University, USA*

* The first two authors have equally contributed to this work

Abstract

Near real time moment tensors (MT) of earthquakes in Greece and its surroundings, which have been distributed by the Aristotle University of Thessaloniki (AUTH) since March 2006 to August 2007, are compared to fast moment tensors computed by other agencies. We compare the best double-couple parts of the solutions for 30 events of Mw=3.6 to 5.8, for which AUTH and at least two other agencies have released fast MTs, and find that 97% of the AUTH fast solutions are comparable to the majority of other similar computations. The preliminary Mw distributed in AUTH MT alerts is found, on average, 100% equal to independent Mw computations.

Introduction

Near real time computations of earthquake moment tensors is becoming part of the standard, routine analysis conducted by large seismological agencies as broadband instrumentation rapidly replaces short period seismometers.

Since March 2006 the Department of Geophysics of the Aristotle University of Thessaloniki (AUTH) has been computing preliminary moment tensors (MT) for earthquakes in Greece and the surrounding lands. The fast MTs are electronically distributed to the European Mediterranean Seismological Centre (EMSC, http://www.emsc-csem.org) and to those registered to the relative e-mail list of AUTH, within minutes or few hours after the earthquake occurrence.

In this report we present an evaluation of the semi-automatic MT solutions of AUTH through comparisons with corresponding solutions published, through EMSC, by other agencies. We also compare preliminary estimates of Mw to check its reliability.

The upgrading of the permanent seismological network of the Aristotle University of Thessaloniki

The near-real time moment tensor computations started in parallel with the upgrade of the seismological stations of AUTH in late 2005 – beginning of 2006. Prior to 2006, all permanent seismological stations of AUTH were equipped with short period (S13) seismometers. Within the last 1.5 year, the largest part of the permanent network has been gradually upgraded through the installations of broadband, CMG-3ESP (100s), sensors. Currently AUTH operates eleven broadband stations and receives, in real-time, data from fourteen more, either through direct communication with other Nanometrics (NAQS) servers or through seedlink. Exchange data come from broadband stations of the National Observatory of Athens (NOA; http://bbnet.gein.noa.gr), the University of Patras Seismological Laboratory (UPSL; seismo.geology.upatras.gr), GEOFON and MEDNET.

In Figure 1 we have plotted the locations of the broadband stations that have been used so far in the near-real time MT computations. More information on the AUTH permanent seismological network can be found at http://seismology.geo.auth.gr.

Figure 1: Broadband stations of AUTH, UPSL, NOA, GEOFON and MEDNET gradually incorporated in AUTH near real-time moment tensor computations in the period from March 2006 to August 2007. The number of available broadband stations is continuously increasing.

The method

The computation procedure followed in AUTH is based on the Time-Domain Moment Tensor inversion method (TDMT_INV) developed at the Berkeley Seismological Laboratory (Dreger and Helmberger, 1993; Pasyanos et al., 1996; Dreger, 2002, 2003). The TDMT_INV code has been already in use, among others, by the Northern and Southern California Seismic Networks (NCSN and

SCSN) in the United States, the Japan National Research Institute for Earth Science and Disaster Prevention (NIED; www.fnet.bosai.go.jp/freesia/index.html) and INGV (http://earthquake.rm.ingv.it/tdmt.php) in Italy for near real-time computation of moment tensors. In Greece, the method has been applied many times for studying specific earthquake sequences (e.g. Benetatos et al., 2002, 2005; Roumelioti et al., 2004; Karabulut et al., 2005), although not in a near real-time manner.

In the TDMT method, full waveforms of the three recorded components of motion are low-pass filtered and inverted to derive the moment tensor. The tensor is then decomposed into a scalar seismic moment, double couple (*DC*) orientation components and a percentage of compensated linear vector dipole (*CLVD*). Synthetics for the three fundamental faults are combined with three 1-D velocity models proposed for the Aegean area (e.g. Novotny et al., 2001; Karagianni et al., 2005) to form a library of Green's Functions, computed with the code of Saikia (1994), which are used to match the observed waveforms. The filtering of the observed data and the Green's functions used to match the solutions depend on the magnitude of the event. Usually, data for earthquakes of Mw>5.0 are band-pass filtered in the range 0.02 – 0.05 and data for smaller earthquakes are filtered in the range 0.05 – 0.08 or 0.05 – 0.10 Hz. We usually invert a time window of 120 seconds, although this can vary (from 60 to 180 sec) depending on the magnitude of the event or the signal/noise ratio, i.e. in cases when a second event follows closely in time we are forced to shorten the inverted time window of the studied event. The quality of a solution is determined by the goodness of the fit between synthetic (*s*) and observed (*d*) waveforms, which is quantified through the Variance Reduction, *VR*, a measure defined as:

$$VR = \left(1.0 - \frac{\int [d-s]^2 dt}{\int d^2 dt}\right) \times 100 \qquad (1)$$

For each solution, the inversion is run with the point source depth at various levels (incremental step of 2 km within the range 2 to 30 km for shallow ($h \leq 40$ km) events and step of 5 km for intermediate-depth events). The optimum solution is identified as the one for which both the variance reduction and percent of double couple are maximized.

Method implementation

The effort to deliver reliable moment tensor solutions and moment magnitudes in near real time is still in its development stages, i.e. the procedure is semi-automatic. After the duty analyst is informed for the occurrence of a "felt" or significantly large magnitude earthquake he/she initiates the semi-automatic procedure by extracting the broadband waveform data from the AUTH data server and preparing the input file with the preliminary epicentre information and the names of the stations to be included in the inversion. A series of scripts and codes are then triggered to perform correction for the instruments' responses, filtering in several frequency windows and multiple inversions to perform the grid search for the optimum depth. The percentages of *VR* and *DC* are automatically plotted versus depth and the analyst chooses the best solution. Example of the graphical output is shown in Figure 2. As we are still in the stage of fully automating the procedures, in the cases for which *VR* is less than 70%, the analyst must manually check individual stations and improve the solution prior to distributing it. If the initial runs provide satisfactory results (*VR*>70%), the entire procedure is completed within 5-10 minutes after its initiation.

Reviewed solutions are distributed through electronic mail to EMSC and subscribers to a MT alerts dedicated mail list and are also posted to the web page (http://seismology.geo.auth.gr; links to Seismological Station and moment tensors). The web page includes detailed information on each preliminary solution, i.e. the preliminary source parameters that triggered the inversion (latitude, longitude, depth, origin time), the region of occurrence, the computed Mw, a plot with waveform fits and detailed information on the moment tensor solution and a map with the beach ball and the distribution of stations used.

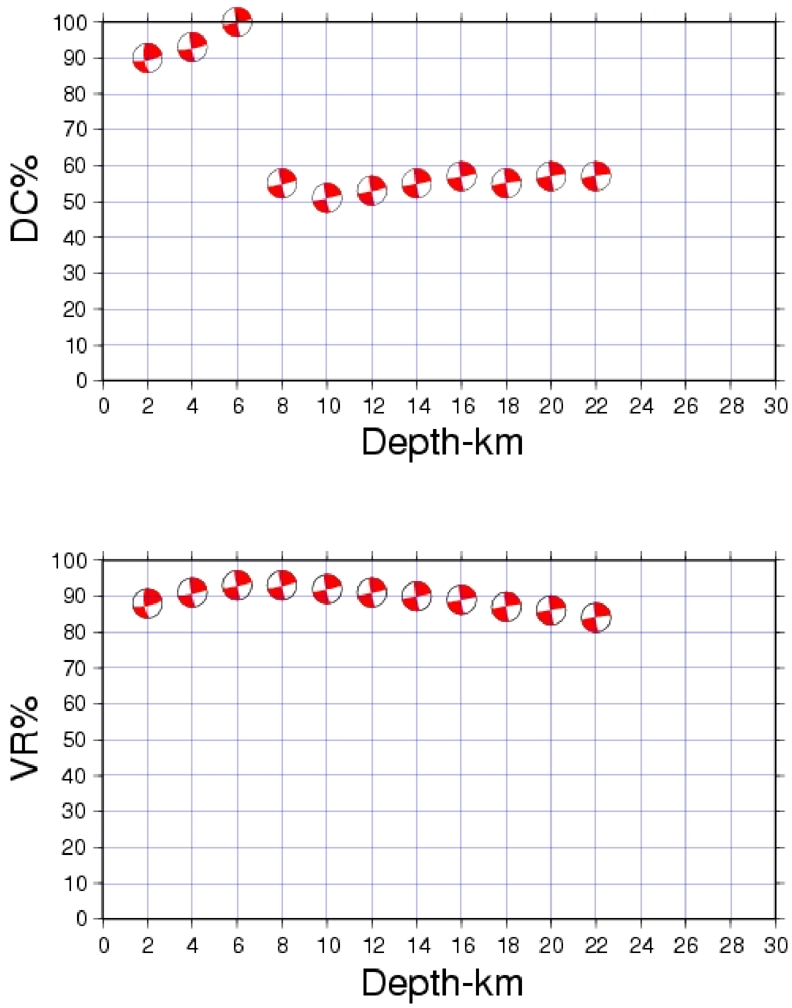

Figure 2: Example of the graphical output of the semi-automatic implementation of TDMT_INVC in AUTH. Percentages of Variance Reduction (*VR*) and Double Couple (*DC*) component in the solution are plotted against tested source depths. The analyst checks the possible changes in moment tensor solution with depth and chooses the solution with the largest *VR* and *DC* percentages.

Furthermore, next to each preliminary solution appears a quality factor, which has been assigned by the analyst based on the *VR*% and the number of stations that were successfully inverted. We assign a quality of:

- A to the best solutions, i.e. with *VR*>80% and at least three stations contributing to the result
- B when *VR*=70%-80% or *VR*>80% but with only one or two stations contributing to the solution

• C when *VR*=60%-70%

Solutions with *VR*<60% are not considered reliable yet and thus are not distributed. Figures 3-5 show typical examples of quality A, B and C solutions, respectively.

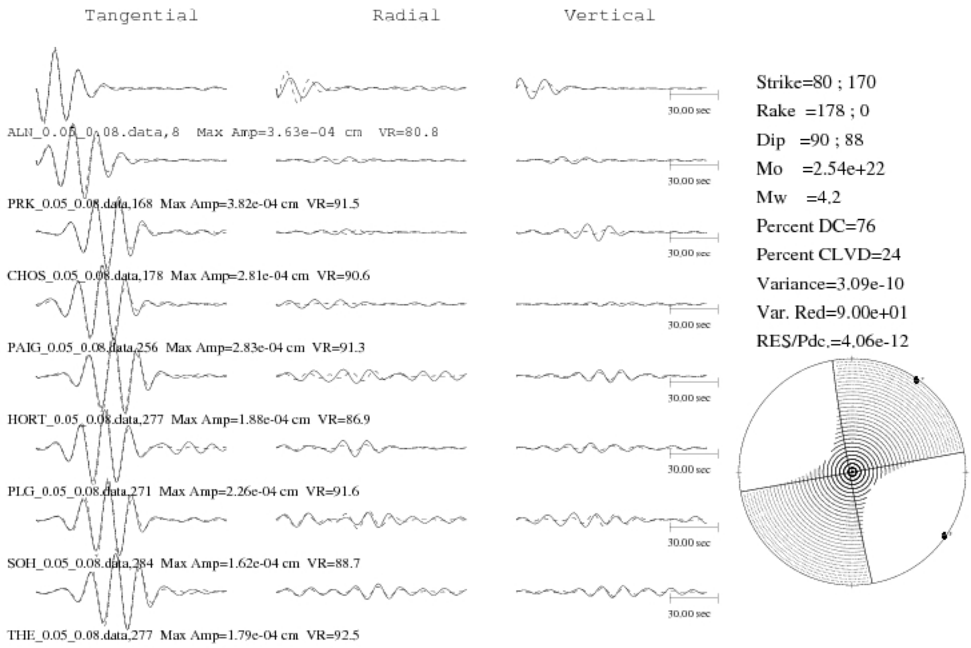

Figure 3: Typical quality A solution of the moment tensor and waveform fit

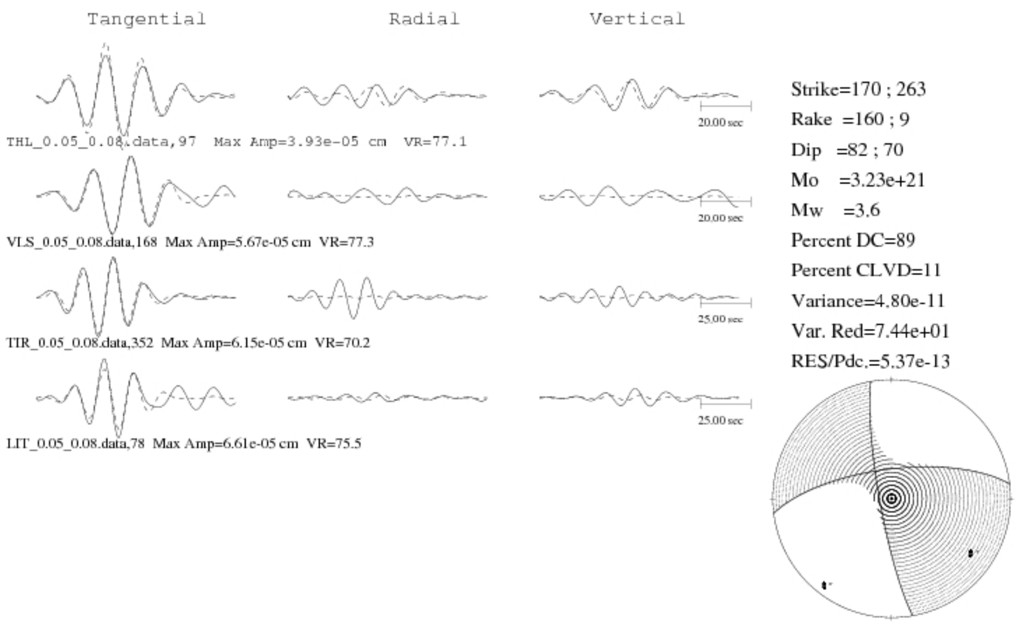

Figure 4: Typical quality B solution of the moment tensor and waveform fit

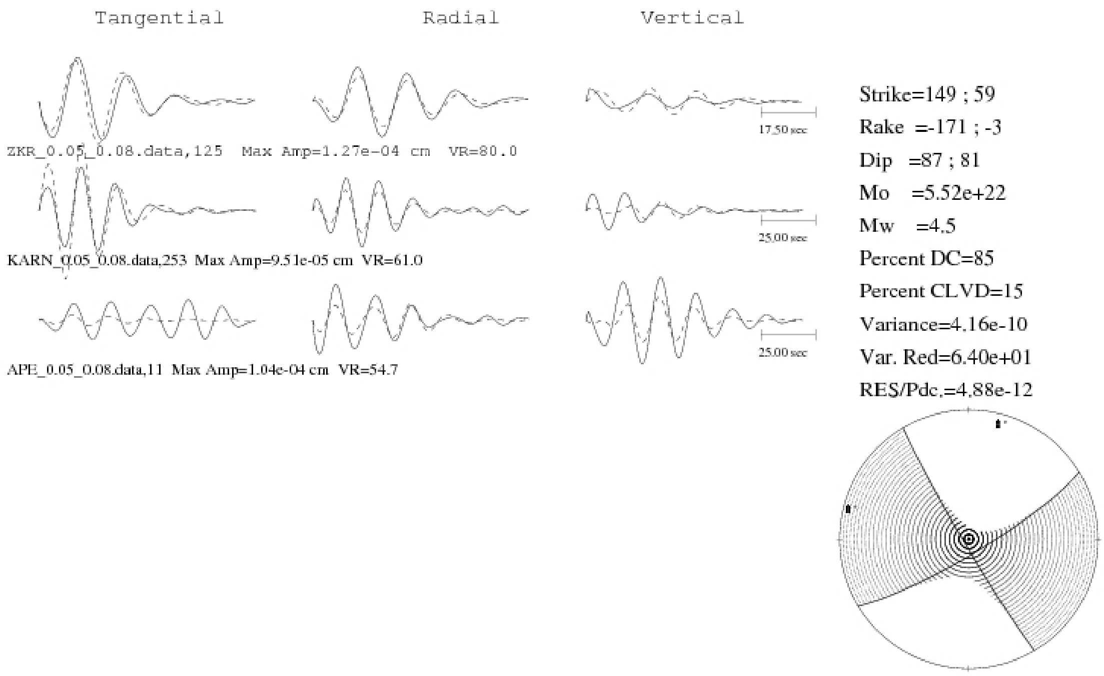

Figure 5: Typical quality C solution of the moment tensor, waveform fit and map with station distribution.

Comparisons of AUTH near-real time MTs solutions

Since March 2006, we have e-mailed to EMSC 111 preliminary moment tensor solutions. Having, by now, a significant preliminary MTs set, our primary concern is to investigate how reliable these results are, at least compared to other near-real time contributions. We therefore compare our MTs with corresponding results that have been posted to EMSC by other seismological institutes. The institutes that provided MTs for a significant number of common, with AUTH, events are the National Observatory of Athens (NOA; 48 events), Instituto Nazionale di Geofisica e Vulcanologia (INGV; 23 events), University of Patras Seismological Laboratory (UPSL; 18 events) and Swiss Seismological Service (ETHZ; 17 events).

Among these institutes, INGV computes fast MTs through the use of the Regional Centroid Moment Tensor (RCMT, Ekström et al., 1998; Arvidsson and Ekström, 1998; Pondrelli et al., 2004), which inverts fundamental-mode intermediate-period surface waves at regional distances, while the other three agencies use full waveform inversion schemes. More specifically, NOA uses the linear time-domain inversion method proposed by Randall et al. (1995) (e.g. Melis and Konstantinou, 2006), UPSL uses the ISOLA code, an extension to regional distances of the Kikuchi and Kanamori (1991) iterative deconvolution method (e.g. Sokos and Zahradnik, 2007; http://seismo.geology.upatras.gr/isola/) and ETHZ uses the inversion code described in Giardini (1992) (e.g. Bernardi et al., 2004).

Overall, within the period March 2006 – August 2007 we had 30 events for which AUTH, as well as at least two other agencies, computed fast MTs. Parameters of all these events and mechanisms are summarized in Table 1.

Table 1

Source parameters of earthquakes in Greece and its surroundings for which AUTH, as well as at least two other agencies, distributed fast moment tensor solutions (μ is a parameter discussed in the text).

No	Date ddmmyy	Time hh:mm:ss.s	Lat (°)	Lon (°)	h km	Mw	μ	Strike (°)	Dip (°)	Rake (°)	Agency
1	040406	22:05:02.5	37.657	20.908	10	5.5	0.00	286	41	47	AUTH
						5.4	0.42	315	69	-84	NOA
						5.5	0.80	227	36	144	ETHZ
						5.5	0.22	354	26	112	INGV
						5.4	0.63	223	67	53	KOERI
						5.3	0.18	358	24	118	USGS
						5.5	0.20	359	25	117	HARVARD
2	100506	07:01:42.8	40.541	23.470	10	4.4	0.00	97	50	-68	AUTH
						4.3	0.19	108	57	-52	NOA
						4.3	0.50	154	86	-48	KOERI
3	240606	02:49:26.4	38.438	20.413	10	4.6	0.00	223	74	161	AUTH
						4.6	0.16	326	63	29	NOA
						4.5	0.14	229	87	168	UPSL
						5.0	0.43	200	30	161	ETHZ
						4.9	0.30	230	42	-172	INGV
4	120706	13:35:13.1	38.381	22.304	10	3.7	0.00	91	53	-122	AUTH
						3.7	0.06	321	47	-47	NOA
						3.6	0.18	306	37	-71	UPSL
5	120706	14:40:55.5	38.810	26.752	15	4.3	0.00	113	47	-76	AUTH
						4.7	0.47	128	77	-10	NOA
						4.3	0.43	332	79	42	KOERI
6	200706	15:57:40.0	37.465	21.549	45	4.0	0.00	132	47	65	AUTH
						3.9	0.23	141	36	80	NOA
						3.9	0.42	180	29	122	UPSL
7	080806	21:20:07.0	40.169	19.784	10	4.7	0.00	145	49	77	AUTH
						4.7	0.50	194	67	131	NOA
						4.7	0.58	30	54	160	ETHZ
						4.9	0.48	20	40	154	INGV
8	280806	22:49:01.0	38.134	20.354	20	4.5	0.00	131	85	91	AUTH
						4.5	0.38	306	70	-78	NOA
						4.5	0.34	294	75	-72	UPSL
						4.7	0.13	38	7	-175	INGV
						4.6	0.74	234	68	-121	KOERI
9	180906	16:57:27.8	37.554	20.857	25	4.3	0.00	155	67	77	AUTH
						4.1	0.35	171	86	114	NOA
						4.2	0.51	292	82	-59	UPSL
10	201006	18:15:24.9	40.265	28.054	15	4.8	0.00	83	51	-139	AUTH
						4.8	0.36	342	76	2	NOA
						4.7	0.94	157	80	168	KOERI
11	231106	13:21:42.1	40.033	20.530	42	4.4	0.00	176	76	154	AUTH
						4.2	0.30	166	83	127	NOA
						4.5	0.48	290	10	19	INGV
12	211206	18:30:52.7	39.409	23.552	10	5.0	0.00	231	85	-158	AUTH
						4.9	0.35	325	78	31	NOA
						5.2	0.24	236	59	-168	ETHZ
						5.2	0.08	140	67	-16	INGV
						5.1	0.39	67	83	141	KOERI
13	020207	12:06:28.6	39.529	20.634	10	4.6	0.00	214	60	-132	AUTH
						4.6	0.32	114	89	-27	NOA
						4.8	0.67	289	33	-12	ETHZ
						4.7	0.29	217	38	-140	INGV
14	030207	13:43:20.3	35.783	22.576	60	5.4	0.00	9	86	-10	AUTH
						5.1	0.06	189	89	15	NOA
						5.3	0.09	95	83	-180	UPSL
						5.5	0.61	147	15	-87	ETHZ
						5.4	0.05	99	76	-180	INGV
						5.5	0.17	91	89	179	KOERI
15	250307	18:57:21.3	38.388	20.283	20	5.6	0.00	318	78	18	AUTH
						5.5	0.26	128	82	1	NOA
						5.7	0.42	27	80	160	UPSL
						5.8	0.39	312	51	28	ETHZ
						5.8	0.41	307	50	21	INGV

						5.7	0.12	319	83	6	USGS
						5.8	0.48	29	59	161	HARVARD
16	260307	02:19:33.7	38.321	20.227	10	4.6	0.00	213	83	-152	AUTH
						4.5	0.34	13	67	159	NOA
						4.7	0.58	279	65	3	UPSL
						4.7	0.20	208	72	-166	INGV
17	090407	23:27:15.0	38.542	21.568	10	4.3	0.00	329	58	-56	AUTH
						4.2	0.19	334	51	-37	NOA
						4.4	0.09	330	65	-55	UPSL
18	100407	03:17:54.9	38.573	21.619	10	4.9	0.00	329	52	-52	AUTH
						4.9	0.12	324	43	-63	NOA
						5.0	0.09	333	57	-58	UPSL
						5.1	0.08	329	47	-61	ETHZ
						5.1	0.05	102	49	-121	INGV
						5.1	0.56	268	67	-108	KOERI
19	100407	07:15:40.8	38.653	21.544	10	5.1	0.00	314	56	-61	AUTH
						5.0	0.21	319	70	-66	NOA
						5.2	0.07	97	42	-116	INGV
20	100407	10:41:01.0	38.736	21.597	10	5.1	0.00	316	57	-63	AUTH
						4.8	0.34	353	69	-39	NOA
						5.1	0.13	328	61	-49	UPSL
						5.2	0.29	327	43	-54	ETHZ
						5.3	0.06	102	41	-116	INGV
21	150407	02:16:31.8	38.576	21.551	10	4.2	0.00	306	57	-75	AUTH
						4.1	0.32	140	26	-88	NOA
						4.1	0.33	307	58	-37	UPSL
22	160407	07:38:54.7	41.241	20.006	27	4.9	0.00	316	39	104	AUTH
						4.8	0.24	344	53	162	ETHZ
						4.9	0.25	344	51	148	INGV
23	190407	10:15:44.6	39.702	24.187	10	4.8	0.00	247	90	-178	AUTH
						4.7	0.15	153	76	8	NOA
						4.8	0.29	143	65	-13	INGV
24	070507	01:34:44.6	37.739	21.013	30	4.9	0.00	301	48	83	AUTH
						4.6	0.80	301	66	-57	NOA
						4.8	0.68	30	15	170	UPSL
25	050607	11:50:20.2	38.612	21.590	10	4.8	0.00	94	70	-104	AUTH
						4.7	0.24	318	30	-51	NOA
						4.9	0.51	325	60	-53	UPSL
						5.0	0.44	92	53	-138	ETHZ
						4.9	0.34	320	41	-47	INGV
26	290607	18:09:11.6	39.354	20.220	25	5.5	0.00	142	60	82	AUTH
						5.2	0.31	154	42	98	NOA
						5.5	0.40	138	38	62	ETHZ
						5.4	0.15	344	39	105	INGV
						5.2	0.38	14	36	95	USGS
						5.4	0.28	353	32	130	HARVARD
27	290607	22:21:13.3	39.379	20.145	10	4.9	0.00	107	63	49	AUTH
						4.7	0.49	173	66	155	NOA
						5.2	0.50	306	20	65	ETHZ
						4.8	0.13	333	46	115	INGV
28	170707	18:23:19.0	40.180	21.527	10	4.7	0.00	61	48	-96	AUTH
						4.7	0.25	88	49	-62	NOA
						4.8	0.33	272	34	-42	ETHZ
						4.9	0.22	250	39	-68	INGV
29	270807	06:29:02.7	38.353	20.269	10	4.7	0.00	285	62	-66	AUTH
						4.5	0.27	304	83	-61	NOA
						4.7	0.34	35	82	177	INGV
30	310807	20:52:40.7	36.749	26.225	10	5.0	0.00	244	55	-94	AUTH
						4.9	0.12	72	40	-79	NOA
						5.1	0.30	44	31	-121	INGV

To quantify the variations between different moment tensor solutions for the same event, we adopt the function μ of Pasyanos et al. (1996) which is defined as the root mean square of the difference between the moment tensor elements of different solutions, normalized by their seismic scalar moment:

$$\mu = \sqrt{\frac{\sum_{i=1}^{3}\sum_{j=1}^{3}\left(\frac{M_{1ij}}{M_{01}} - \frac{M_{2ij}}{M_{02}}\right)^2}{8}} \quad (2)$$

The $\sqrt{8}$ is used as a normalization factor, which makes μ vary from 0, in cases of perfect match between the elements of the two compared moment tensors, to 1 in cases of mechanisms that imply opposite motions. For values of $\mu<0.25$ the compared mechanisms are almost the same and above this level the double-couple solutions begin to diverge, reaching unacceptable levels, even for near-real time computations, when they surpass 0.5. Figure 6 shows examples of resemblance or divergence of beach balls as a function of μ.

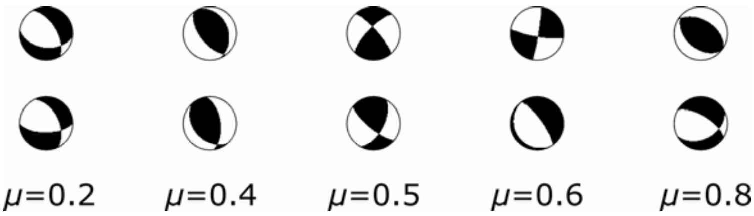

Figure 6: Examples of resembling or diverging beach balls for different values of the MT difference function, μ.

At this point, we limit the comparison to the double-couple part of the moment tensors solely, thus the moment tensor elements are computed based on the reported strike/dip/rake values and we assume that $M_{xy}=M_{yx}$, $M_{xz}=M_{zx}$ and $M_{yz}=M_{zy}$.

Using equation (2) we seek the percentage of our preliminary solutions that exhibit $\mu < 0.5$ compared to corresponding solutions of other institutes and could thus be considered as successful near-real time applications of the TDMT_INV code in Greece.

In Figure 7 we present the μ values, indicating the amount of divergence between the AUTH fast solution and other computations for each event. Event numbers in Figure 7 are the same as in Table 1 where source parameters of the events, as well as the computed μ values are summarized. Out of the total 92 individual MT comparisons, 37 (40%) exhibit $\mu \leq 0.25$ and 42 (46%) $0.25<\mu\leq 0.5$, while only 13 (14%) result in $\mu>0.5$. For most events (18 out of the 30) all reported fast MTs were comparable to those of AUTH. In some cases there are some striking outliers as for example in event 18 where AUTH MT compares excellently with all other reported MTs except one; only in one case AUTH MT fails to compare well with any of the independent computations (event 24). Overall, 29 out of the 30 (97%) MTs are comparable to the majority of independently reported mechanisms and this is particularly encouraging for future applications and further development of the near-real time seismological applications in Greece.

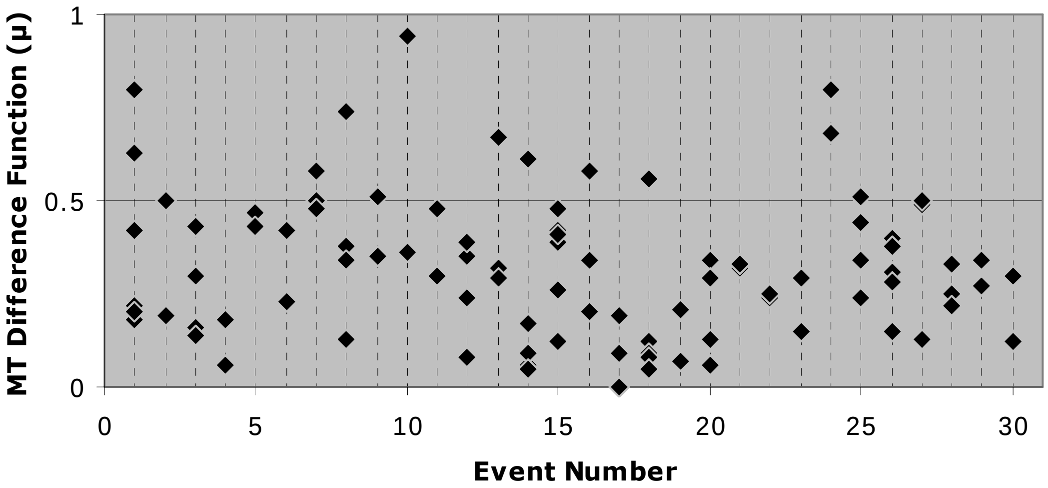

Figure 7: MT Difference values between the AUTH fast moment tensor solutions and corresponding solutions of other agencies (listed in Table 1) for 30 events which occurred in the broader area of Greece in the period from March 2006 to August 2007. X axis is the event number. Events numbers are as in Table 1.

Comparisons of moment magnitudes, Mw

In Figure 8(a-d) we compare AUTH Mw from preliminary moment tensor determinations with Mw reported by NOA, INGV, UPSL and ETHZ. These four institutes have a significant number of common fast MTs with AUTH, while for example Harvard computes MTs only for larger (~ Mw≥5.5) events and therefore we only have four common solutions in our database.

From Figure 8(a) it is evident that Mw reported by AUTH and NOA is practically the same, especially for earthquakes of Mw<4.5. At larger magnitudes, although the data set is far from rich, it seems that NOA reports slightly lower Mw (of the order of 0.1). We believe that this difference is due to the fact that NOA (Melis and Konstantinou, 2006; http://bbnet.gein.noa.gr) uses a "standard" length window of 60 sec in the MT inversions, independently of the earthquake magnitude. As a result, in larger events part of the late energy is not taken into account. However, we are still dealing with a difference of the order of 0.1 in Mw scale, which is much smaller than corresponding differences reported in other magnitude scales.

The data sets for Mw comparisons with the other three institutes (ETHZ, INGV, UPSL) are not statistically significant yet. However, in Figures 8(b-d) we present corresponding plots to see if there is indication for any systematic difference. Figures 8b and 8d show that, compared to ETHZ and INGV, the Mw reported by AUTH may be systematically smaller by 0.1-0.2. This difference appears to take its maxima values at lower magnitudes, where scatter is also greater, while at the very few larger events (Mw>5.0) the Mw computations converge. More data are needed to draw safe conclusions about the existence or not of such systematic difference. If this difference does indeed exist, it may as well be due to the fact that ETHZ and INGV uses longer data windows and lower frequencies in their inversions compared to AUTH. Figure 8c shows that AUTH and UPSL Mw computations are practically the same throughout the entire magnitude range covered by the data.

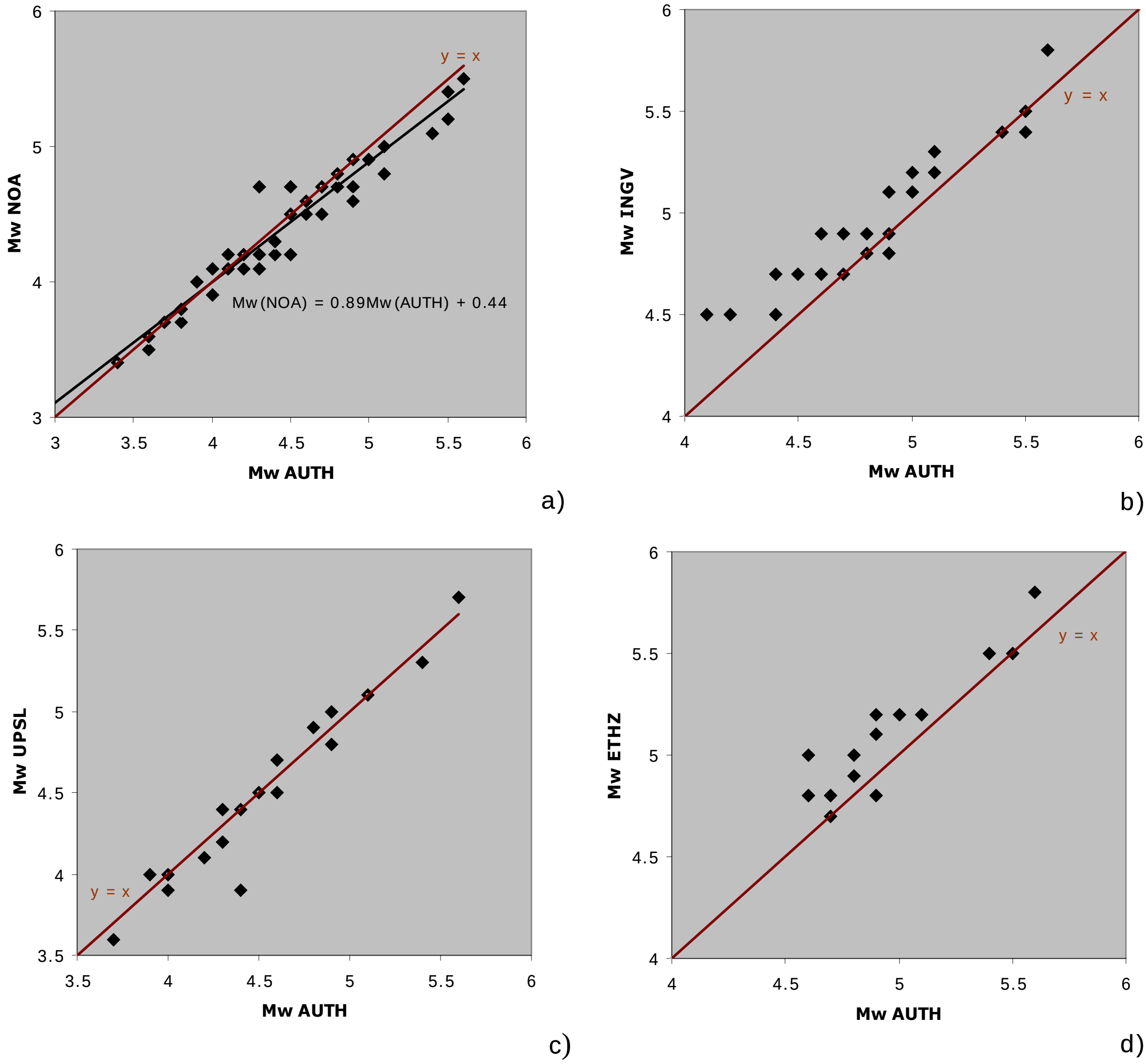

Figure 8. Comparison between Mw reported in fast MT solutions of AUTH versus corresponding Mw reported by a) NOA for a total of 48 common events in the EMSC moment tensors catalog, b) INGV for 23 common events, c) UPSL for 18 common events and d) ETHZ for 17 common events.

Finally, in Figure 9 we have plotted all Mw comparisons with all institutes (including the very small set of values from comparisons with Mw reported by Harvard, USGS and KOERI) to check the overall performance of AUTH Mw. On average, the comparison of Mw is excellent and one can hardly separate the least-squares regression line from the line corresponding to the one-to-one ratio. It is once more verified that independent Mw computations present great consistency and thus Mw is the most robust magnitude determination.

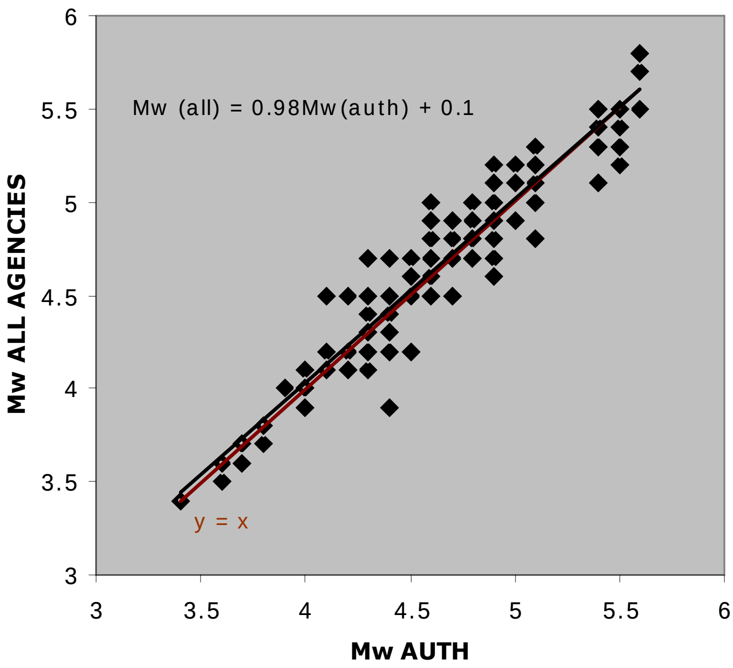

Figure 9. Comparison between Mw reported in fast MT solutions of AUTH versus corresponding Mw reported all other institutes (NOA, INGV, UPSL, ETHZ, KOERI, USGS and HARVARD). The data set includes 121 individual Mw comparisons.

Conclusions – Future Orientation

We compared fast double-couple solutions distributed by AUTH and at least two other agencies for 30 events of Mw=3.6-5.8, which occurred in Greece within the period March 2006 to August 2007. The results show that 97% of AUTH solutions (29 out of 30) are comparable to the majority of independently reported mechanisms. It must be noted that within the aforementioned period of time AUTH distributed a total of 111 fast MTs. However, at this point there are no independent data to evaluate the remaining 71 solutions. Currently, there is a continuous effort to review all these preliminary solutions and evaluate them in this way.

Using a significantly larger data set, AUTH Mw is also compared to Mw reported by other agencies and is found to be, on average, 100% comparable to independent estimations. At the present stage and as our data set continuously increases we try to correlate Mw with other magnitudes used in Greece, such as the local magnitude, ML.

The future target of AUTH, as far as moment tensors are concerned, involves the following activities:

1. To fully automate the inversion procedure and thus to achieve quick dissemination (from few up to 30 minutes after the event occurrence) of all moment tensor solutions.
2. To be able to report preliminary MTs for all earthquakes of M>4.0 that occur in Greece.
3. To improve the performance of the inversion method in areas where currently used 1D velocity models do not satisfactorily work, mainly through path calibration or even incorporation of 3D Green's function, wherever required.

4. To achieve stable moment tensor solutions for smaller magnitude earthquakes (M=3-4), in the vicinity of densely populated areas.
5. To perform manual reviews of all near real-time solutions at least twice per year and update the database with the reviewed solutions.

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References

Arvidsson, R. and G. Ekström (1998). Global CMT analysis of moderate earthquakes $M_W \geq 4.5$ using intermediate period surface waves, Bull. Seism. Soc. Am. 88, 1003 – 1013.

Benetatos, Ch., Roumelioti, Z., Kiratzi, A., and N. Melis (2002). Source parameters of the M6.5 Skyros island (North Aegean Sea) earthquake of July 26, 2001, Annals of Geophysics 45 (N. ¾), 2002.

Benetatos, Ch., Kiratzi, A., Roumelioti, Z., Stavrakakis, G., Drakatos, G. and I. Latoussakis (2005). The 14 August 2003 Lefkada Island (Greece) earthquake: focal mechanisms of the mainshock and of the aftershock sequence, Journal of Seismology 9, 171 – 190.

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

Dreger, D. (2002). Time-Domain Moment Tensor INVerse Code (TDMT_INVC) Version 1.1, Berkeley Seismological Laboratory, pp. 18.

Dreger, D. (2003). TDMT_INV: Time Domain Seismic Moment Tensor INVersion, International Handbook of Earthquake and Engineering Seismology, W. H. K. Lee, H. Kanamori, P. C. Jennings and C. Kisslinger (eds.), Vol. B, pp 1627.

Dreger, D. and D. Helmberger (1993). Determination of source parameters at regional distances with single station or sparse network data, J. Geophys. Res. 98, 8107 – 8125.

Giardini, D. (1992). Moment tensor inversion from MEDNET data (1). Large worldwide earthquakes of 1990, Geophys. Res. Lett. 19, 713 - 716.

Ekström, G., Morelli, A., Boschi, E. and A. M. Dziewonski (1998). Moment tensor analysis of the central Italy earthquake sequence of September – October 1997, Geophys. Res. Lett. 25, 1971 – 1974.

Karabulut, H., Roumelioti, Z., Benetatos, C., Kömec Mutlu, A., Özalaybey, S., Aktar, M. and A. Kiratzi (2005). A source study of the 6 July 2003 (Mw 5.7)

earthquake sequence in the Gulf of Saros (Northern Aegean Sea): Seismological evidence for the western continuation of the Ganos fault, Tectonophysics 412, 195 – 216.
Karagianni, E., Papazachos, C., Panagiotopoulos, D., Suhadolc, P., Vuan, A. and G. Panza (2005). Shear velocity structure in the Aegean area obtained by inversion of Rayleigh waves, Geophys. J. Int. 120, 127 – 143, doi: 10.1111/j.1365-246X.2005.02354.x.
Melis, N. and K. Konstantinou (2006). Real-time seismic monitoring in the Greek region: an example from the 17 October 2005 east Aegean sea earthquake sequence, Seism. Res. Lett. 77 (4), 364 – 370.
Novotný O., Zahradník, J. and G.-A. Tselentis (2001). North-Western Turkey earthquakes and the crustal structure inferred from surface waves observed in Western Greece. Bull. Seismol. Soc. Amer., 91, 875-879.
Pasyanos, M., Dreger, D., and B. Romanowicz (1996). Towards real-time determination of regional moment tensors. Bull. Seismol. Soc. Am. 86, 1255– 1269.
Pondrelli, S., Morelli, A. and G. Ekström (2004). European – Mediterranean regional centroid-moment tensor catalog: solutions for years 2001 and 2002, Phys. Earth Planet. Int. 145, 127 – 147.
Randall, G., Ammon, C. and T. Owens (1995). Moment tensor estimation using regional seismograms from a Tibetan Plateau portable network deployment, Geophys. Res. Lett. 22, 1665–1668.
Roumelioti, Z., Benetatos, C., Kiratzi, A., Stavrakakis, G. and N. Melis (2004). A study of the 2 December 2002 (M5.5) Vartholomio (western Peloponnese, Greece) earthquake and of its largest aftershocks, Tectonophysics 387, 65 – 79.
Saikia, C. K. (1994). Modified frequency-wavenumber algorithm for regional seismograms using Filon's quadrature; modeling of L_g waves in eastern North America, Geophys. Journ. Int., 118, 142-158.
Sokos, E. and J. Zahradnik (2007). ISOLA a fortran code and a Matlab GUI to perform multiple-point source inversion of seismic data, Computers and Geosciences, in press.
Wessel, P., and W.H.F Smith (1998). New improved version of the Generic Mapping Tools released, EOS Trans. AGU 79, 579.