Real-time Seismic Monitoring in the Greek Region: An Example from the 17 October 2005 East Aegean Sea Earthquake Sequence

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INTRODUCTION

Modern seismic networks can record high-quality digital data and transmit them back to a data-collection center in near real-time. This allows seismologists to monitor any ongoing seismic activity efficiently by determining the parameters of each earthquake, such as epicentral location and local magnitude. In addition, more recent developments during the last decade have made possible the inversion of regional waveforms for moment tensor derivation (*e.g.*. Ekström *et al.*, 1998; Kao and Jian, 1999; Pondrelli *et al.*, 2002). All such waveform processing can be performed fully automatically, giving scientists the opportunity to have a detailed picture of the seismicity in near real-time.

The Greek region exhibits the highest seismicity in Europe and has experienced destructive earthquakes several times in the past (Papazachos and Papazachou, 1997). Therefore, it is particularly important to be able to monitor any seismic activity quickly and efficiently. The newly installed Hellenic broadband seismic network (HL) offers such capabilities by providing digital three-component waveform data recorded at 22 stations that cover the Greek region. This paper describes the network operation and routine waveform data processing, using as an example case the recent seismic unrest in the eastern Aegean Sea close to the Turkish coast. The analysis presented here also gives the first results on the spatial/temporal distribution of this seismic sequence and the faulting mechanism of 15 events with moment magnitudes between 3.9–5.6.

HELLENIC BROADBAND SEISMIC NETWORK (HL)

Since 1997 a new effort has been underway to upgrade the seismic network operated in Greece by the Institute of Geodynamics of the National Observatory of Athens (NOA-IG) (Figure 1). In the first stage, an upgrade from analog to digital instrumentation was implemented, taking into consideration the possibility for the network to link outstations to Athens via dedicated telephone lines. These lines can be used for not only the digital seismic signals but also other signals up to the available baud rate (64 kb). The second stage involved upgrade of the seismic

network monitoring and acquisition system by implementing *SeisComP* freeware software (Heinloo and Trabant, 2004). This made possible the inclusion in the autolocation procedure of other stations available in the Eastern Mediterranean Region (*i.e.*, GEOFON and MEDNET VBB [very broadband stations]; Hanka and Kind, 1994; Mazza *et al.*, 1998), which improved locations, especially around the Hellenic Trench. The resulting Hellenic Seismic Broadband Network (HL) currently operates with a dedicated Web page (http://bbnet.gein.noa.gr/) and provides automatic locations for earthquakes with local magnitude greater than 3 that occur in Greece and adjacent regions. Consequently, e-mails are released to the European-Mediterranean Seismological Centre (EMSC-CSEM) for information (http://emsc-csem.org/).

Most HL network stations are equipped with Geotech Instruments DR-24 digitizers at 50-Hz digitization rate (http://www.geoinstr.com/dr24.htm), and Lennartz Le-3D (20 s) seismometers. A few stations operate with Guralp CMG-40T (30 s) seismometers (Figure 2). Thanks to the GEOFON group effort (Hanka and Kind, 1994), a software plug-in (*Seedlink*) for communication with the digitizers has been implemented (Heinloo, personal communication, 2003; see also http://www.gfz-potsdam.de/geofon/seiscomp/). This makes possible replacement of the Geotech ICP system (http://www.geoinstr.com/icp.htm), which was provided to function with the Geotech digitizers (an old *Windows* NT4.0–based monitoring platform that is no longer supported), with the newly implemented *SeisComP* server (Figure 2). The serial interface of the DR-24 digitizers to a Linux PC that implements *SeisComP* software monitoring is made possible via three serial to Ethernet 16-channel multiplexers. Thus, the signal from the DR-24 digitizers is made available to the Linux PC with *SeisComP* and provides data to other Linux PC's that perform data exchange—autolocation—data handling procedures (Figure 2). Lastly, a simplified platform with HTML output to the users handles the operation of the entire system by means of PERL scripts and makes it easy to detect possible problems at various levels (*i.e.*, communication, acquisition, auto processing, etc.). Part of this platform is also available on the public Web page, http://bbnet.gein.noa.gr/.
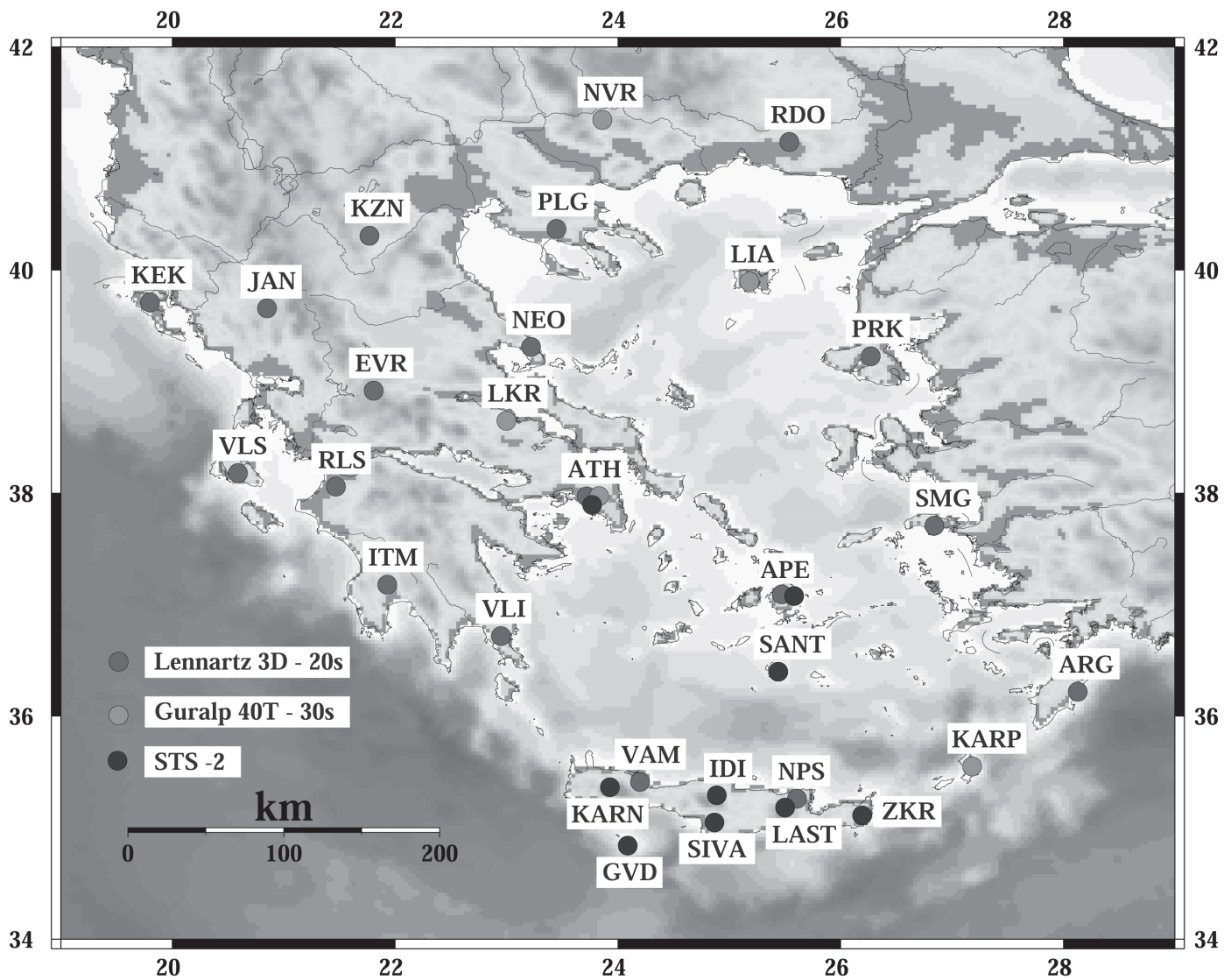
▲ **Figure 1.** Map showing the distribution of the HL Network stations. Also shown are GEOFON (KARN, GVD, SIVA, LAST, ZKR, SANT, APE) and MEDNET (IDI) stations in the Greek region operating with NOA-IG collaboration.

AUTOMATIC LOCATION AND MAGNITUDE ESTIMATION

Since summer 2003, after the implementation of *SeisComP* software at the HL network, a further attempt was made to introduce an automatic alert system for location and local magnitude in the broader region of Greece. First, the *Autoloc SeisComP* shareware (http://www.gfz-potsdam.de/geofon/seiscomp/) was adopted for the HL network application, using not only the NOA-HL stations but also seven GEOFON and MEDNET stations operating in Greece. Second, data from eight more mainly MEDNET and also GEOFON stations operating in South Italy, Malta, Albania, Bulgaria, Turkey, and Cyprus were added, improving locations at the neighboring border regions as well as around the highly active Hellenic Trench.

Automatic processing consists of two stages: Vertical component waveforms are band-pass filtered with different frequen-

cies assigned for each station and standard STA/LTA detection is implemented; and in a parallel processing procedure, predefined windows (in our case 200 sec after the detected pick) are convolved with Wood-Anderson instrument response and the maximum amplitude is determined for local magnitude (M_L) estimation (Richter, 1935). After a pick association procedure, *Autoloc* utilizes the LocSAT standard location program (IDC, 1999), which locates events by fixing the focal depth at 10 km and uses a travel-time lookup table derived from the IASPEI91 model. Detailed description of the procedure can be found on the Web page http://www.gfz-potsdam.de/geofon/seiscomp/. M_L is estimated using the maximum amplitudes determined in the automatic processing and the epicentral distances computed from the location. M_L is computed by taking into consideration the Hutton and Boore (1987) attenuation factor:

$$M_L = \log_{10}(A) + 1.110 \log_{10}(D) + 0.00189\, D + 3.591, \qquad (1)$$
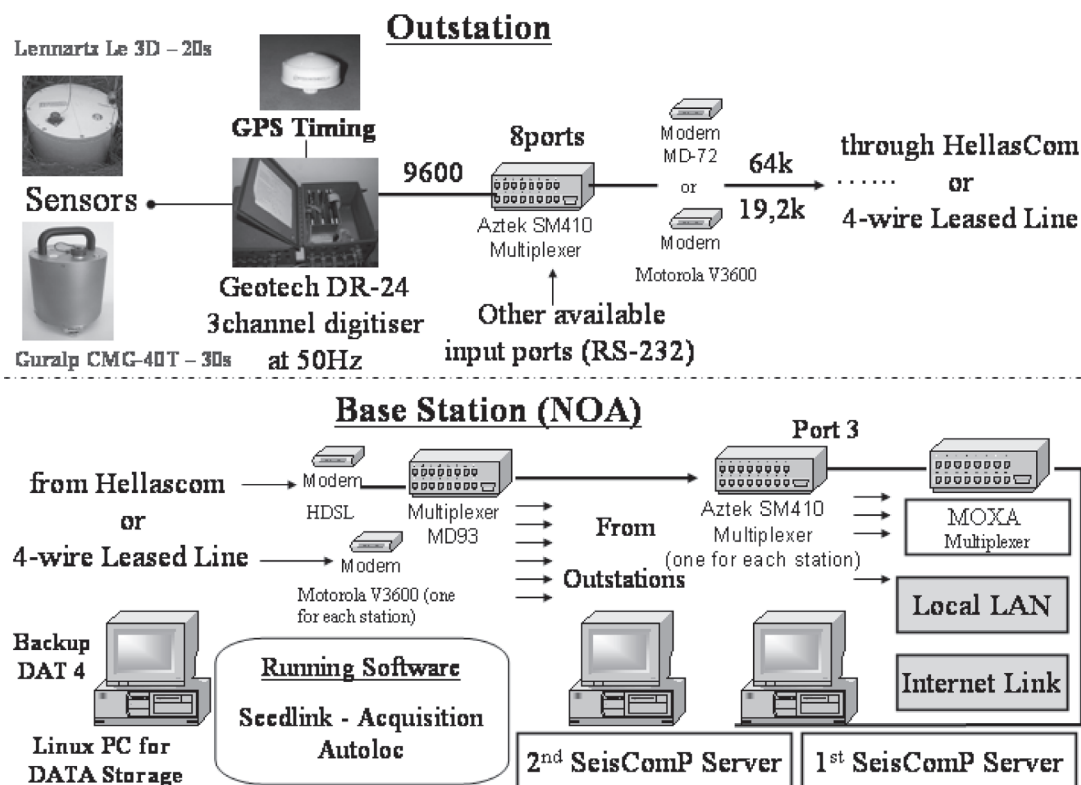
▲ **Figure 2.** Block diagram describing network components and their operation at outstations and the central data handling places (see text for details).

where A is the peak-to-peak maximum amplitude in meters divided by 2 and D is the hypocentral distance in kilometers. The first results are sent to EMSC-CSEM via e-mail (http://www.emsc-csem.org/), and the main HL public Web page is updated every three minutes if more measurements (*i.e.*, phase picks, amplitude calculations) are made available.
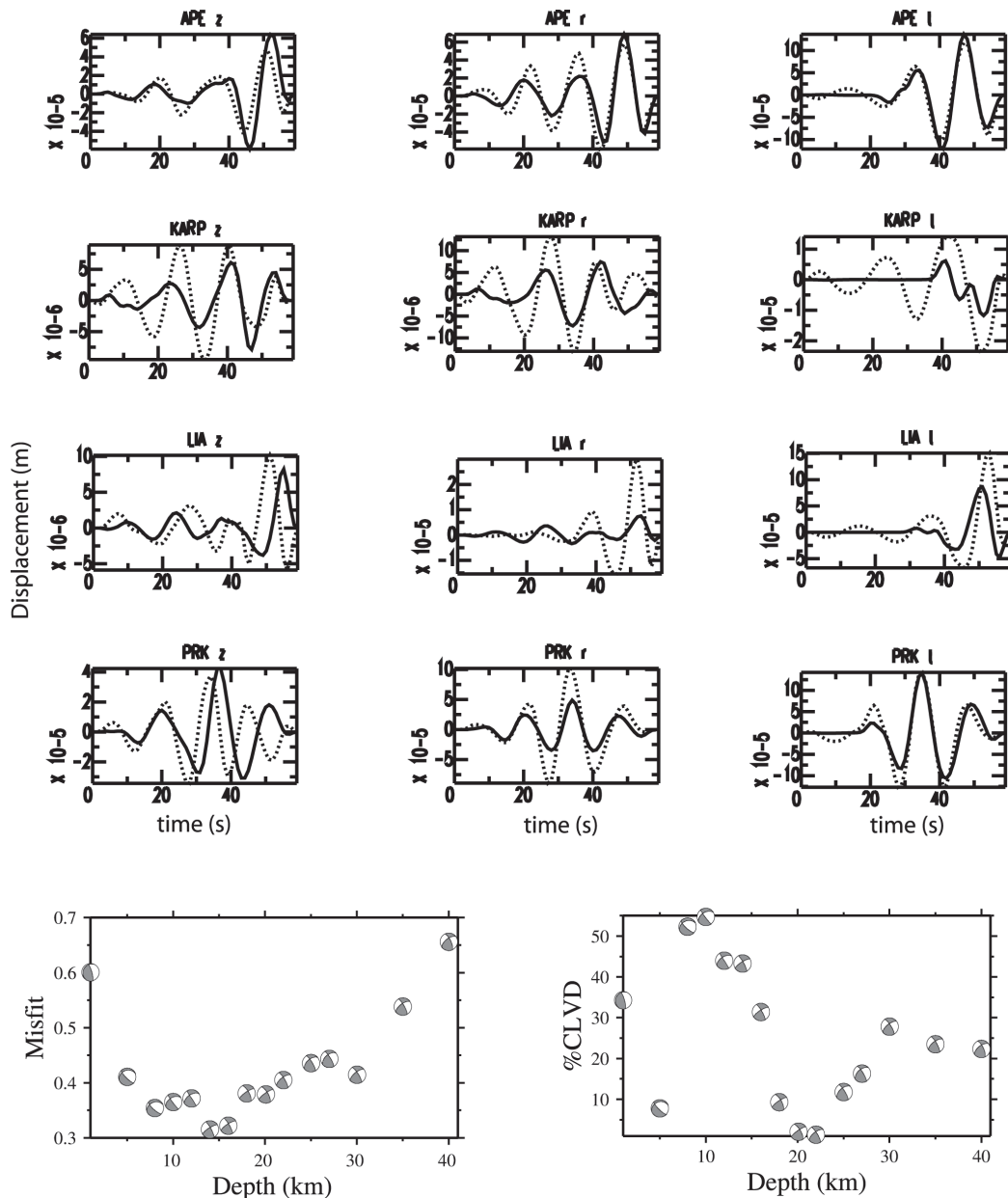
ROUTINE MOMENT-TENSOR INVERSIONS

We apply a linear, time-domain moment-tensor inversion method with a point-source approximation to model the waveform data (Randall *et al.*, 1995). Green's functions are calculated using the reflection method of Kennett (1983) as implemented by Randall (1994), while moment-tensor elements are estimated by minimizing the least-square misfit between observed and predicted waveforms. Due to the limited lower frequency cutoff of the data (~0.05 Hz), we expect the quality of the inversion results to depend greatly on the velocity model chosen for Green's functions calculation. We used different velocity models derived from various tomography studies in the Greek region for different stations in an effort to mimic the three-dimensional velocity variation. The validity of these models and the reliability of the inversion results are thoroughly discussed in a separate control study (Konstantinou *et al.*, 2005). For the example case of the East Aegean Sea events presented here, we calculated Green's functions using models

derived from a surface-wave tomography study over the whole Aegean region (Karagianni *et al.*, 2005).

Data preparation prior to the inversion includes the reduction of velocity waveforms to displacement and rotation of the horizontal components into radial and transverse. The rotation is performed with respect to the epicenter reported by EMSC-CSEM/HL-alert after inverting arrival times available from different regional seismic networks. Both the data and the Green's functions are bandpass-filtered between 0.05–0.08 Hz using a two-pole Butterworth filter and aligned according to their arrival times.

The data are inverted assuming a vanishing isotropic component and a delta source time function. Inversions are repeated initially using a depth interval of 5 km, followed by a finer one of 2 km around the depth that exhibited the minimum misfit. We evaluate the quality of the moment-tensor solutions utilizing a scheme proposed by Kao and Jian (1999) that makes use of the average misfit (quality range *A–F*, with *A* indicating a misfit smaller than 0.3 and *F* larger than 1.1) and CLVD or non-double-couple component (quality range 1–4, with 1 indicating CLVD smaller than 20% and 4 larger than 80%). All routinely determined moment-tensor solutions for events with M_w greater than 3.9 can be accessed via the HL dedicated Web page and are sent to EMSC-CSEM using e-mail. A representative example of the inversion (event 2 in Table 1) is shown in Figure 3.

▲ **Figure 3.** Moment-tensor inversion results for event 2 (see Table 1). Solid lines represent the observed waveforms and dashed the synthetic ones, respectively. Diagrams showing variation of misfit and CLVD percentage versus depth.

17 OCTOBER 2005 EAST AEGEAN SEA SEISMIC SEQUENCE

The seismic sequence started on 17 October 2005 at 04:31 (UTC) with a M_w ~3.9 event that was followed by a stronger one (M_w ~5.3) at 05:45. Seismic activity continued the same day with a M_w ~5.6 event at 09:46 and numerous smaller events, culminating in another M_w ~5.6 earthquake at 00:40 on 21 October. All of these events were recorded by the HL network stations and located by the automatic alert system. To check the consistency of the automatic locations, we selected all events with local magnitudes equal to or larger than 3.9 and relocated them with *HYPO2000* (Klein, 2002) using manually picked arrival times and a simple two-layer over half-space velocity model (layer 1: 6 km/s—15 km: layer 2: 6.75 km/s—25 km; half-space 8.05 km/s). Figure 4A shows these locations for the period 17–31 October, as compared to locations of the same events obtained from the automatic location procedure (Figure 4B). The locations obtained using manual picks clearly delineate a ENE-WSW–trending fault segment. On the other hand, the automatic locations look more diffuse, but all of them appear to be in proximity to the seismogenic volume (the average shift between manual and automatic epicentral locations is at most 10 km).

Moment-tensor solutions have been estimated for 15 events of this sequence (Table 1). Most of them have a solution with quality equal to or higher than C2, while the solutions of the larger events (M_w > 5.3) are very similar to those reported by
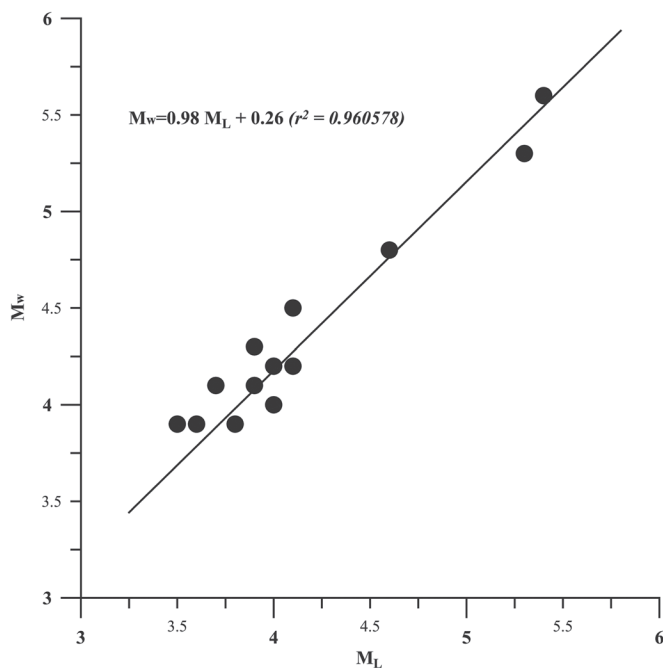
Table 1
Source Parameters of 15 Chosen Events with Estimated Moment-tensor Solutions

ID	Origin Time	Lat (°N)	Lon (°E)	Depth (km)	M_L	Mo (dyn*cm)	M_w	φ	δ	λ	μ	ε	Q
1	2005/10/17 04:31:27	38.10	26.51	7	3.6	0.695E+22	3.9	172	86	−8	0.53	0.19	C2
2	2005/10/17 05:45:18	38.14	26.59	14	5.3	0.957E+24	5.3	331	79	16	0.31	0.21	B2
3	2005/10/17 06:16:07	38.14	26.50	10	3.7	0.149E+23	4.1	137	86	55	0.61	0.22	C2
4	2005/10/17 07:05:49	38.13	26.63	10	3.8	0.814E+22	3.9	351	79	−28	0.54	0.04	C1
5	2005/10/17 08:28:53	38.11	26.56	5	4.0	0.218E+23	4.2	343	84	45	0.59	0.12	C2
6	2005/10/17 08:34:45	38.11	26.51	8	4.0	0.126E+23	4.0	323	75	−10	0.61	0.15	C2
7	2005/10/17 09:46:57	38.14	26.59	8	5.4	0.245E+25	5.6	239	77	171	0.43	0.02	B1
8	2005/10/17 12:43:29	38.11	26.49	8	3.9	0.174E+23	4.1	166	82	−42	0.59	0.21	C2
9	2005/10/18 16:00:49	38.13	26.52	5	3.9	0.135E+23	4.1	319	47	−44	0.62	0.14	C2
10	2005/10/19 10:11:32	38.17	26.68	7	4.1	0.581E+23	4.5	330	57	−17	0.32	0.03	B1
11	2005/10/20 21:40:04	38.15	26.67	7	5.4	0.276E+25	5.6	148	86	−17	0.26	0.15	B2
12	2005/10/23 14:59:39	38.12	26.72	8	3.5	0.745E+22	3.9	171	88	−2	0.70	0.07	C1
13	2005/10/29 14:48:42	38.13	26.50	8	4.1	0.192E+23	4.2	251	69	152	0.66	0.10	C1
14	2005/10/31 05:26:41	38.11	26.52	8	4.6	0.201E+24	4.8	324	90	27	0.37	0.06	B1
15	2005/10/31 06:48:24	38.13	26.65	10	3.9	0.276E+23	4.3	355	86	−30	0.51	0.15	C2

Column headers: φ: strike; δ: dip; λ: rake of plane 1t; μ: misfit; ε: CLVD amount; Q: quality factor.
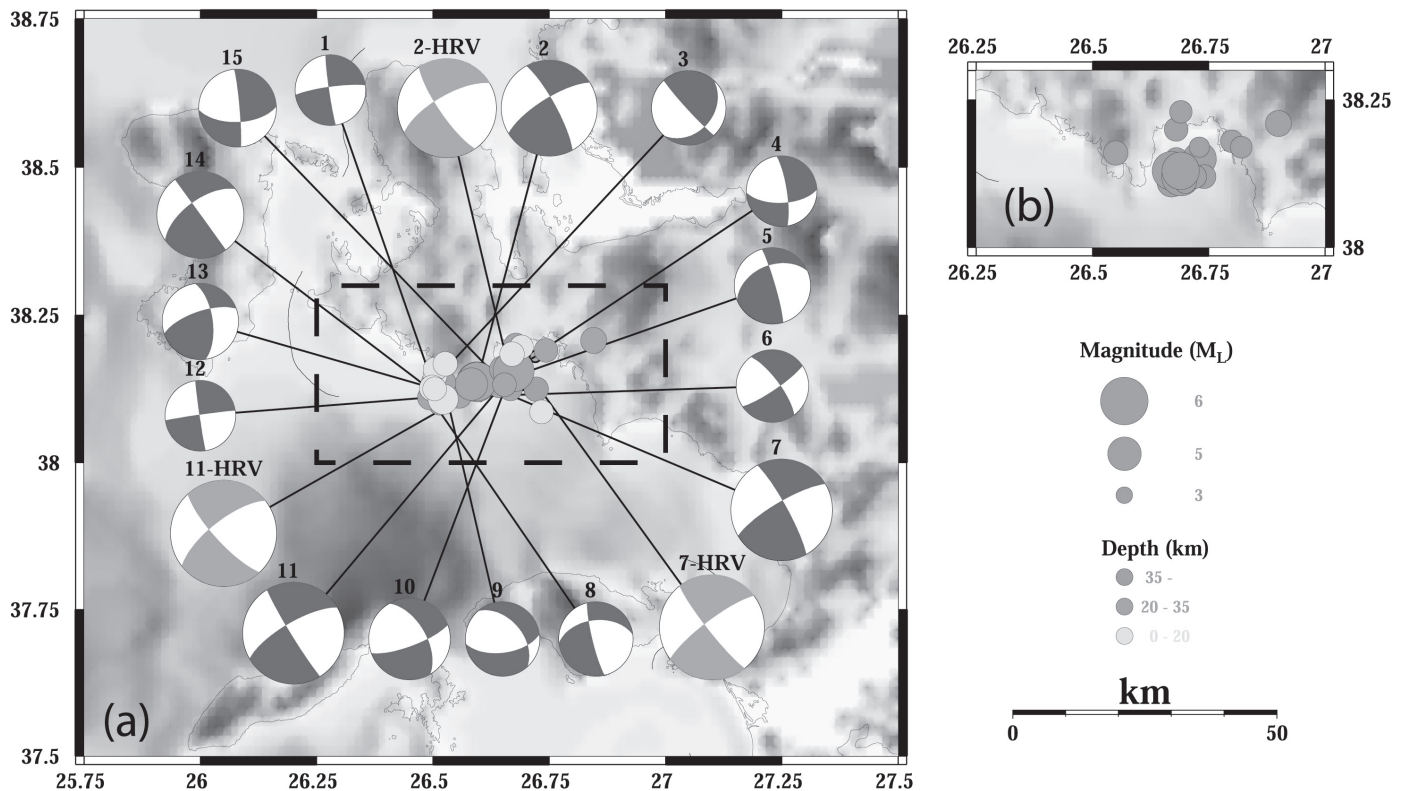
▲ **Figure 4.** (A) Map of epicenters for events with $M_L > 3.9$, relocated using manually picked arrival times and *HYPO2000*, that occurred during the late October 2005 East Aegean Sea earthquake sequence. In addition, NOA-IG and HRV moment-tensor solutions are presented for 15 selected events (see Table 1). (B) Map of the area highlighted in A by the dashed line box showing epicenters determined by the *Autoloc* alert procedure.

$$M_w = 0.98 \, M_L + 0.26 \quad (r^2 = 0.960578)$$

▲ **Figure 5.** Diagram of M_L versus M_w values for the 15 selected events in Table 1. The solid line represents the least-square fit to the data.

the Harvard group (Figure 4A). From these focal mechanisms and the aftershock location distribution, we conclude that the sequence mainly involved left-lateral strike-slip motions. Finally, we compare the magnitudes estimated by the inversion moment with the automatically calculated local magnitudes of the 15 events (Figure 5). This comparison shows that events with M_w larger than 4.0 have on average ±0.1 units difference as compared with local magnitude estimates, while events with smaller M_w have a difference of ±0.2 units. This agrees well with the results published by Uhrhammer *et al.* (1996) and other studies showing that $M_L \approx M_w$ with an error estimate of ±0.2 units.

CONCLUSIONS

Near-real-time seismic monitoring and automatic data-processing procedures are important tools for rapid hazard assessment. In Greece a new effort has been underway since 2003 to upgrade the Hellenic Broadband Seismic Network and include automatic procedures for earthquake location, local magnitude estimation, and computation of moment-tensor solutions. The example presented shows the response of the system during an earthquake sequence in the East Aegean Sea close to the Turkish coast during late October 2005.

The main goal of the new system is to inform public officials and the public as soon as possible, and send alerts to other scientific organizations (*e.g.*, EMSC-CSEM). Evaluation of the automatic results, in terms of location and magnitude estimation, showed sufficient agreement with the relocated manually picked hypocenters. The error estimates for automatic locations were at most 10 km for the epicenter and ±0.2 units for magni-

tude, with local magnitude almost equal to M_w computed from moment-tensor solutions. It has to be taken into consideration that the area under study lies at the border of the network and that most of the stations are more than 100 km away. For a local magnitude threshold greater than 3.9 the results proved adequate.

Future prospects include extension of the network in the Aegean Sea region to lower magnitude threshold and improve location and moment-tensor derivation. We further plan to replace some sensors with the aim of improving the bandwidth to facilitate moment-tensor estimation, since it will reduce the dependency on the velocity model and improve the quality of the resulting focal mechanisms. ◙

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