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A LOW COST ACCELEROMETER NETWORK FOR GENERATION OF SHAKE MAPS

G. Tanırcan(1), Y. Kaya(2) and H. Alcik(3)

(1) Assoc. Prof. Dr., Boğaziçi University.KOERI, birgore@boun.edu.tr
(2) Dr., Researcher, Unviersity of British Columbia, kayaya@mail.ubc.ca
(3) Dr., Engineer, Boğaziçi University.KOERI, alcik@boun.edu.tr

Abstract

A small scale and affordable local Strong Motion (SM) network of three MEMS based sensors is set up in Tekirdağ region in Turkey in 2015. The recorded raw data is transmitted to a central server over Internet via 3G modem. Through customized Matlab software, the SM network is fully capable of calculating the selected SM parameters on a central sever in real-time. The calculated SM parameters are then compared to predefined thresholds, and a central voting system installed on the server detects earthquakes in the vicinity of the local SM network. The functionality of the network has been tested and validated using several shake table tests. Since the installation of the Tekirdağ SM network, several small scale earthquakes have been recorded. Although the ultimate expectation of this deployment is to capture moderate to large magnitude events, small event recordings have also been very useful to find out the performance of the software developed, as well as the hardware at free field conditions. Real time features of the network and the software has been tested successfully during small earthquakes. The results also showed that instrument self-noise is low enough to record large magnitude events but, the high frequency component of the ground motions is underestimated due to the sensitivity of the sensor used. The SM network can be used efficiently to record moderate to strong earthquakes in near field in order to create rapid shake maps, providing that the sensor is replaced with an upper quality ensembles.

Keywords: shake map, MEMS sensor, strong motion parameters

1. Introduction

Loss estimation systems assess earthquake shaking (shake maps), building damage, and casualty distributions (loss maps) in several minutes after a damaging earthquake. This information is then immediately sent to emergency response and rescue organizations. The primary component of a loss estimation system is the creation of shake-map. Ground motion empirical relations, primary inputs of an earthquake (e.g., epicenter, depth, and magnitude), and the recorded ground motions in the vicinity of the affected area are used in the shake-map algorithms, for instance EXTREMUM [1,2], PAGER [3], QLARM [4] and ELER [5].

Accuracy of shake map estimations depends on the Ground Motion Prediction Equations (GMPE) used in the shake-map algorithm. Current GMPEs are still insufficient to take into account source dominated ground motion variabilities, micro scale effects of propagation path, and near surface geologic conditions; therefore, those shake-map algorithms may give misleading results in loss distributions. In fact, during the Mw7.1 Erciş-Van Earthquake (eastern Turkey) in 2011, PAGER algorithm estimated the number of casualties 15 times higher due to the uncertainty in the calculation of the epicenter. For the same event, ELER software failed in producing the realistic intensity distribution due to point source assumption at the epicentral area. In reality, the largest intensity was observed in the city of Erciş, which is located approximately 50km northwest of the epicenter (74% of the total casualty) [6].

These loss maps can be improved with the help of increasing the number of recorded ground motion data. A local strong ground motion network can process earthquake ground motions in real-time; therefore, rapid and more realistic shake-maps can created. While the necessity of such local strong motion network in densely populated cities is an inevitable fact, the high cost of installation of the systems constitutes the biggest obstacle for dissemination.

In recent years, many Micro Electro Mechanical System (MEMS) based accelerometers have been successfully used in seismological and earthquake engineering projects. This is basically due to the increased precision obtained in these downsized instruments. The generation of shake-map in MEMS based strong motion networks has been efficiently implemented in many projects around the world; for instance, Community Seismic Network [7] and Quake-Catcher Network [8].

The goals of this study are 1) to create a pilot strong motion network, 2) to develop a Matlab-based software that will automatically process the strong motion data in real-time, and 3) to develop new tools, techniques, and algorithms to create shake-map for urban areas after a damaging earthquake. Upon successful results achieved during shake table tests, an affordable pilot network of three MEMS based accelerometers was deployed at Tekirdağ city center, where the closest coastal point to the moderate size earthquake activities in the Marmara Sea, Turkey. It is hoped that affordable price (~US$ 2000 per station) of the instrument encourage other local authorities to implement similar strong motion networks for emergency response.

2. Method

2.1 Instrument Properties

Kandilli Observatory and Earthquake Research Institute (KOERI) bought several MEMS based DAC-3HBS type (hereafter DAC) [9] strong motion accelerometers, which are designed, produced, and customized to complement the seismic network for quick location & magnitude determination (Erdik, 2014 pers. comm.). These instruments involve three orthogonal MEMS sensors [12] as shown in Fig. 1, and each of which has a noise level of 50 µg a dynamic range of ±2g and with a 24-bit A/D converter.

The same sensors are known to be used for the structural health monitoring [14,15] and for earthquake early warning networks [16]. The GSM modem and the power supply unit in the instrument are encapsulated by an aluminum case housing, and the internal GPS module in it has error free synchronization property. Further properties of the accelerometers are listed in Table 1.

In a previous study, performance and calibration of the instrument have been tested using a small uniaxial shaking table [10]. Following this study, a set of shake table test was performed using sinusoidal excitation with varying amplitude and a central frequency up to 12Hz [11]. Root mean square (RMS) amplitude responses of the instrument were calculated. Results showed that sensor response falls below the -3dB in band limit (half power point) after 4.6 Hz and beyond this range signal is not considered as a usable output. Acceleration RMS noise of the sensor in 0.2-30 Hz frequency band is expected to be between 0.10-0.15 cm/s^2 [13]. This value was also found as 0.12 cm/s^2 using ambient noise data by [11].

The instrument can store real-time data both in ASCII and MiniSEED file formats. The standard of MiniSEED file involves 512-byte-length of sequential data packages, and the length of each data package is variable; therefore, the file may not be ready to be processed until the first data package is stored. For that reason, the MiniSEED file format was modified so that it can be processed at every second in real-time. Another reason of producing second-base data transfer is to facilitate instruments in future early warning networks. A subroutine was coded in assembler language, and it is embedded into the DAC operating system. It creates MiniSEED files with packages of 1-second instead of 512-byte packages.

Fig 1 – Internal view of DAC type strong motion accelerometer

Table 1 – Technical specifications of the DAC instrument

Sensor	ST © LIS344ALH internal
Sensor Range	±2g
Sensor Noise Level	≤ 50 μg/(Hz)$^{1/2}$
Power supply	2.4V to 3.6V
Operation System + Server	Linux SeedLink Server
Time Syncronisation	GPS (1Se Sy and RTC)
Communication	USB, RS-232 and TCP-IP client/server
Data format	miniSEED and ascii
Sampling Rate	Up to 200 samples/s
Memory Card	SD and Memorystick
Relay Contact Control	+

2.2 Detection of an Earthquake through Strong Motion Parameters

A Matlab-based software is developed to calculate Strong Motion (SM) parameters in real-time such as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Arias Intensity (AI), Cumulative Absolute Velocity (CAV), Cumulative Absolute Velocity integrated with a 5 cm/s^2 lower threshold (CAV5), Spectral Acceleration (Sa), Spectral Velocity (Sv), Spectral Displacement (Sd) and Spectral Intensity (SI). The software reads and processes the 1-second length of text files from a user-defined folder. In the current implementation, the sampling frequency is selected as 100 Hz. The real-time raw data is low-pass filtered with 13Hz cutoff frequency. The filtered data is used to calculate the SM parameters at every second, and they are compared with the user-defined thresholds. The software is designed to detect large earthquakes and to create shake-maps if calculated SM values exceed user defined thresholds (i.e [17]) . In addition to threshold level approach, the software has also a voting algorithm. In this approach a threshold and a vote are defined for each SM parameter. The calculated SM parameters are then compared with the predefined threshold every second, and the votes of the SM parameters that exceed the corresponding threshold will be summed at every second. If the total number of vote at any given time exceeds the predefined threshold for three consecutive seconds, an earthquake is automatically registered at the system that will initiate several post-earthquake processing tools. Upon the registry of an earthquake, an event file is created by the Matlab software in a secure directory on the server in order to store the raw data.

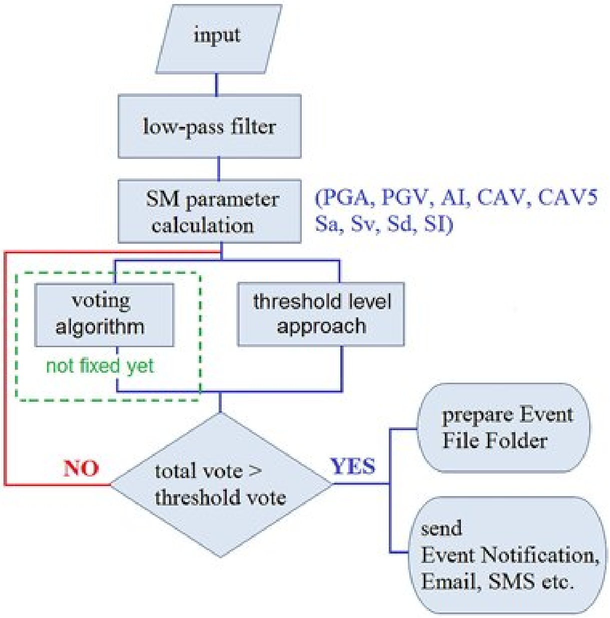
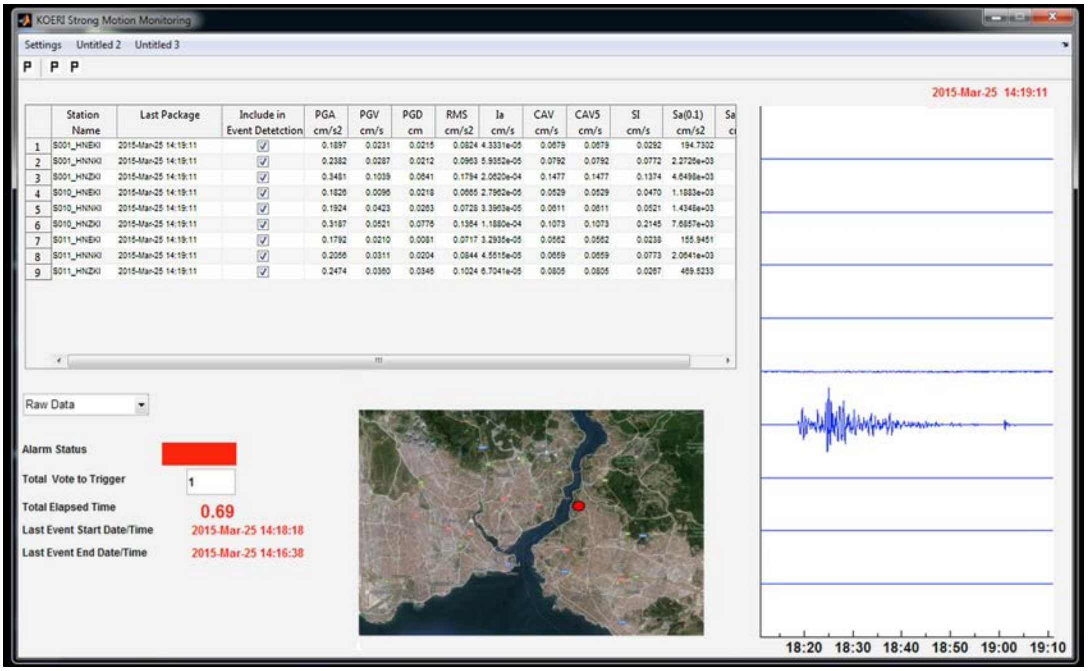


Fig 2 Flowchart of the routine.

The user interface of the software enables users to monitor the calculated SM parameters in two different view modes: tabular and graph as can be seen in Fig. 2. The geographical locations of the instruments are indicated as color-dots in the geomap where the color indicates the amplitude of the SM parameter being monitored. This information is then immediately relayed to the emergency responders via e-mail and SMS.

A test setup is prepared at the earthquake lab of the KOERI in order to validate the functionality of the software during several earthquakes. The test involved one DAC instrument and a reference force balance instruments [18] on a small shake table (Fig. 3). The DAC is connected to the local strong motion network via Internet and is excited with the 1999 Kocaeli (Mw7.4) and the 1978 Tabas (Mw7.4) earthquakes. The recorded vibrations are automatically transmitted to the Matlab software on server at KOERI via Internet, and the SM parameters are then calculated in real-time. The calculated SM parameters under both earthquake excitations triggered the local strong motion network (Fig. 3). Ratio of the SM parameters of the reference signal and DAC response are listed in Table 2. In general, DAC has fairly well recorded the input signal both in time and frequency domain, peak accelerations were slightly underestimated, though. The PGV and the CAV values are recoreded with higher precisión. On average, correlation coefficient between velocity time histories produced by DAC and reference instruments is calculated as 92%. The largest relative difference between elastic response amplitudes (with 5% critical damping) is 33% at periods between 0.1-0.4 seconds, probably due to high frequency limit of the sensor. Time and frequency domain characteristics of the Kocaeli Earthquake, YPT station recordings (NS component, scaled in shaking table limits) of the reference signal (in black) and DAC response (in red) can be seen in Fig. 4, as an example.



2015-Mar-25 14:19:11

	Station Name	Last Package	Include in Event Detetction	PGA cm/s2	PGV cm/s	PGD cm	RMS cm/s2	Ia cm/s	CAV cm/s	CAV5 cm/s	SI cm/s	Sa(0.1) cm/s2
1	S001_HNEKI	2015-Mar-25 14:19:11	☑	0.1897	0.0231	0.0215	0.0824	4.3331e-05	0.0679	0.0679	0.0292	194.7302
2	S001_HNNKI	2015-Mar-25 14:19:11	☑	0.2382	0.0287	0.0212	0.0963	5.9352e-05	0.0792	0.0792	0.0772	2.2726e+03
3	S001_HNZKI	2015-Mar-25 14:19:11	☑	0.3481	0.1039	0.0641	0.1794	2.0620e-04	0.1477	0.1477	0.1374	4.6498e+03
4	S010_HNEKI	2015-Mar-25 14:19:11	☑	0.1826	0.0096	0.0218	0.0665	2.7962e-05	0.0529	0.0529	0.0470	1.1883e+03
5	S010_HNNKI	2015-Mar-25 14:19:11	☑	0.1924	0.0423	0.0263	0.0728	3.3963e-05	0.0611	0.0611	0.0521	1.4348e+03
6	S010_HNZKI	2015-Mar-25 14:19:11	☑	0.3187	0.0521	0.0776	0.1364	1.1880e-04	0.1073	0.1073	0.2145	7.6857e+03
7	S011_HNEKI	2015-Mar-25 14:19:11	☑	0.1792	0.0210	0.0081	0.0717	3.2935e-05	0.0562	0.0562	0.0238	155.9451
8	S011_HNNKI	2015-Mar-25 14:19:11	☑	0.2066	0.0311	0.0204	0.0844	4.5515e-05	0.0659	0.0659	0.0773	2.0641e+03
9	S011_HNZKI	2015-Mar-25 14:19:11	☑	0.2474	0.0360	0.0345	0.1024	6.7041e-05	0.0805	0.0805	0.0267	469.5233

Alarm Status 🟥
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Last Event End Date/Time 2015-Mar-25 14:16:38

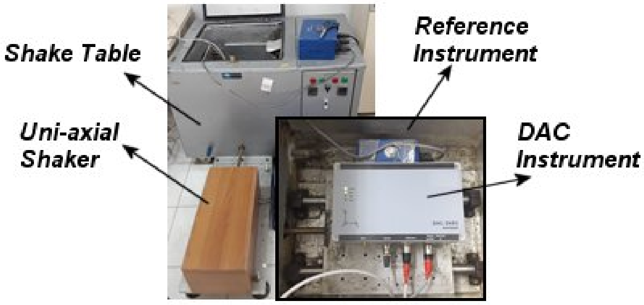


Fig 3 (up) User interface of the software. Realtime recordings are on the right panel. SM parameters are listed on the left. (down) Uniaxial shake table set up.

Table 2 Ratio of SM parameters calculated from reference and DAC recordings

Ratio (DAC /Reference)	PGA (m/s^2)	PGV (m/s)	AI (m/s)	CAV (gs)	SA(g) (T=0.2s)	SA(g) (T=0.3s)	SA(g) (T=1.0s)
YPT-NS	0.86	0.96	0.85	0.93	0.79	0.93	0.96
YPT-EW	0.83	0.94	0.83	0.95	0.83	0.86	0.94
TBS-EW	0.80	0.91	0.79	0.89	0.75	0.85	0.92
TBS NS	0.91	0.89	0.79	0.90	0.74	0.81	0.96

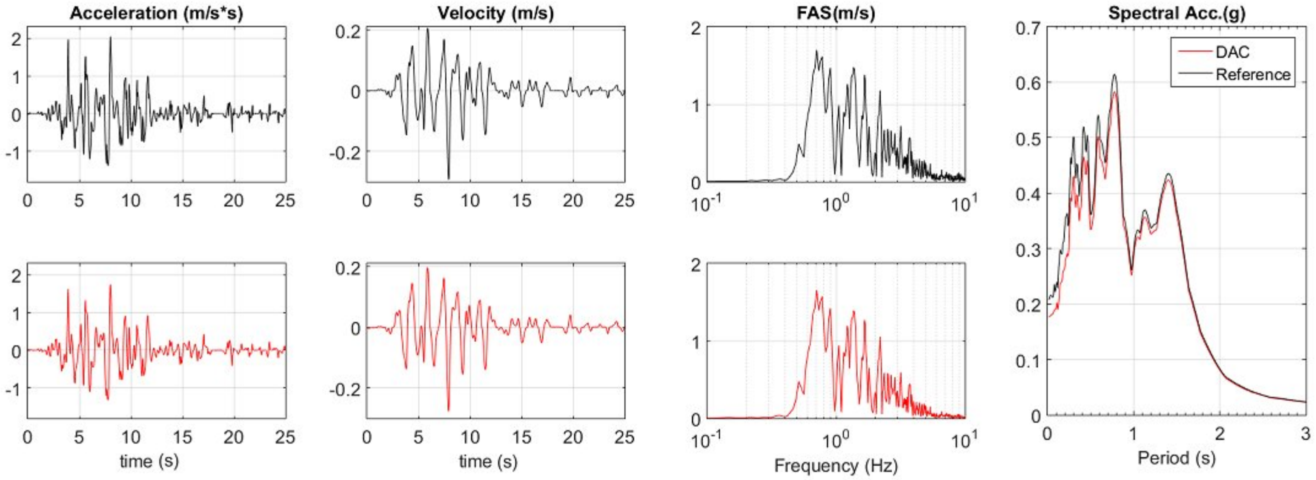


Fig 4 YPT-NS acceleration and velocity traces (scaled in shaking table limits) of the reference signal (upper traces in black) and DAC response (lower traces in red) and Fourier Amplitude Spectrum (FAS) of the acceleration recordings (right) 5% damped spectral acceleration(Sa) of the recordings.

2.3 A Pilot Strong Motion project in Tekirdağ City

Seismic hazard studies on the Marmara region have revealed that unbroken segments of the North Anatolian Fault in the Marmara Sea have the potential of producing an M7+ earthquake and hence pose to great threat to population close by [19,20]. Tekirdağ, with a population of 190.000, is exposed to earthquake hazard due to its proximity to an unbroken Central Marmara segment (CMS). In the last two decades at least twenty five earthquakes of ML>3.5 occurred on the CMS off the coast of Marmara Ereğlisi. Considering the high seismic activity at the region, a test network has been set up at Tekirdağ (Fig. 5). Three sensors have been installed in May 2015 and kept active for 6 months. Instruments were deployed at one-storey governmental & municipality offices (Fig. 6). Within this period, the network recorded several small size earthquakes. Largest two of them are listed in Table 3. Acceleration traces of these events at DSI station are given in Fig.7. In general, vertical accelerations include higher noise than horizontal accelerations at all stations. Peak horizontal accelerations (PHA) of the M4.5 event vary between 3.9-6.4 cm/s^2 (Table 3). Two nearby permanent stations of national strong motion network [21], which are 250m-750m away from SKI and PBM stations, respectively, have comparable values (4.6-4.7 cm/s^2).

Instrument noise range was also seeked by using ambient noise data at free field. Power Spectral Density (PSD)s of the DAC and the reference instrument were calculated using 5 minutes portion of noise recordings. PSD of DAC shows a downward trend between -20 dB and -40 dB band range, which are higher than seismic noise level defined by [22]. It is, on the other hand, above the PSD of the ML4.5 event at frequencies lower than 0.4Hz, implying that recordings of small size earthquakes are noise contamianted at low frequency.

Fig 8 shows the waveforms of the ML4.5 earthquake at DSI, SKI and PBM stations and the 1999 Mw7.4 Kocaeli Earthquake at near field GBZ station. Comparing the PSDs of the Kocaeli event and that of DAC instrument, it can be assumed that the DAC instrument self noise is low enough to record large size earthquakes.

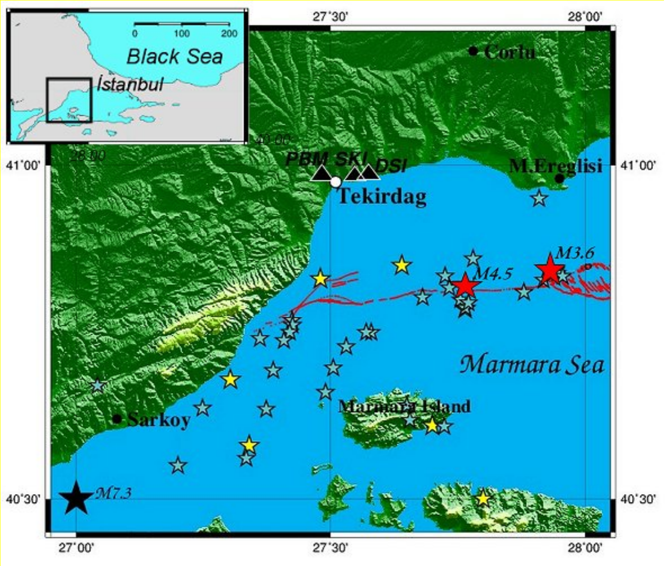
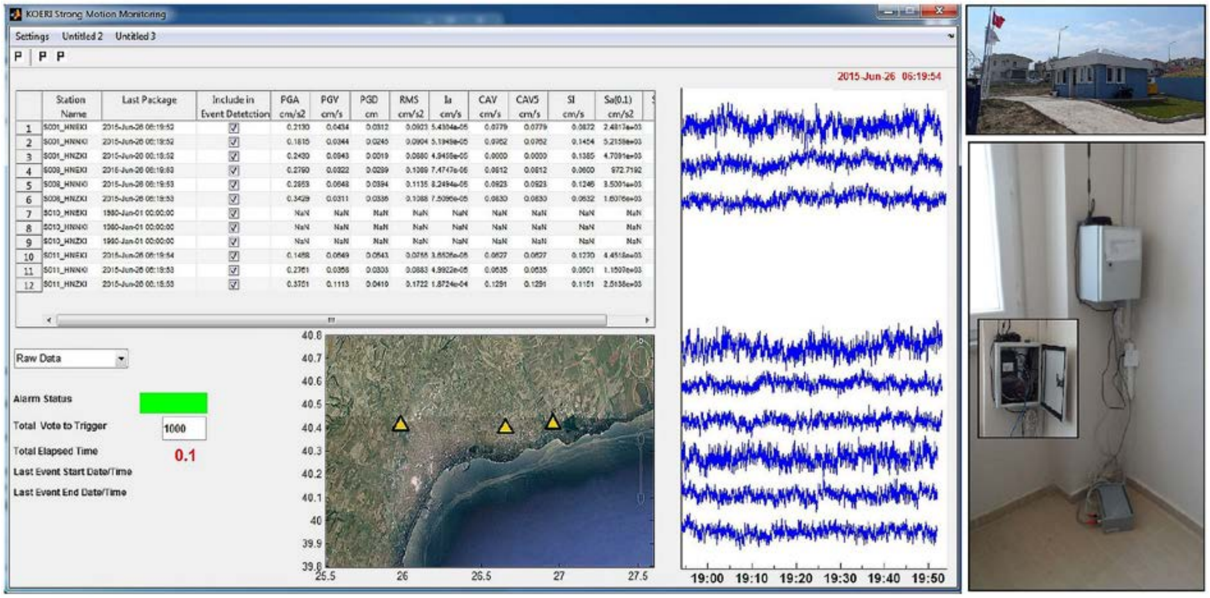


Fig 5 . Distribution of the earthquakes with 3.5<M<4.5 occurred since 2000 [23]. Location of the 2015 ML4.5 and ML3.6 earthquakes is given with a red star. Big black star shows the largest magnitude (M7.3) event in the 20th century. Faults beneath the Sea of Marmara is given with red lines



	Station Name	Last Package	Include in Event Detetction	PGA cm/s2	PGV cm/s	PGD cm	RMS cm/s2	Ia cm/s	CAV cm/s	CAV5 cm/s	SI cm/s	Sa(0.1) cm/s2
1	S001_HNEKI	2015-Jun-26 06:19:52	☑	0.2130	0.0434	0.0312	0.0923	5.4304e-05	0.0779	0.0779	0.0872	2.4817e+03
2	S001_HNNKI	2015-Jun-26 06:19:52	☑	0.1815	0.0344	0.0245	0.0904	5.1949e-05	0.0762	0.0762	0.1454	5.2158e+03
3	S001_HNZKI	2015-Jun-26 06:19:52	☑	0.2430	0.0943	0.0019	0.0880	4.9458e-05	0.0000	0.0000	0.1385	4.7091e+03
4	S008_HNEKI	2015-Jun-26 06:19:53	☑	0.2790	0.0322	0.0289	0.1089	7.4747e-06	0.0812	0.0812	0.0600	972.7192
5	S008_HNNKI	2015-Jun-26 06:19:53	☑	0.2853	0.0648	0.0394	0.1135	8.2494e-05	0.0923	0.0923	0.1246	3.5301e+03
6	S008_HNZKI	2015-Jun-26 06:19:53	☑	0.3429	0.0311	0.0336	0.1088	7.5096e-05	0.0830	0.0830	0.0632	1.6076e+03
7	S010_HNEKI	1980-Jun-01 00:00:00	☑	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
8	S010_HNNKI	1980-Jun-01 00:00:00	☑	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
9	S010_HNZKI	1980-Jan-01 00:00:00	☑	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
10	S011_HNEKI	2015-Jun-26 06:19:54	☑	0.1488	0.0649	0.0543	0.0765	3.8526e-05	0.0627	0.0627	0.1270	4.4518e+03
11	S011_HNNKI	2015-Jun-26 06:19:53	☑	0.2761	0.0358	0.0303	0.0883	4.9922e-05	0.0635	0.0635	0.0501	1.1509e+03
12	S011_HNZKI	2015-Jun-26 06:19:53	☑	0.3701	0.1113	0.0410	0.1722	1.8724e-04	0.1291	0.1291	0.1151	2.5138e+03

Alarm Status 🟩

Total Vote to Trigger 1000

Total Elapsed Time 0.1

Last Event Start Date/Time

Last Event End Date/Time

Fig 6 (left) User interface of the software. Realtime recordings are on the right panel. SM parameters are listed on the left. (right) Instrument setup at SKI station.

Table 3. Earthquakes recorded by the network

Earthquake Date/Time (UTC)	Location Lat.(N)/ Lon.(E)	ML	Repi (km)	PHA (cm/s^2)		
				PBM	SKI	DSI
29.08.2015/12:47:52	40.84/27.93	3.6	34-40	1.3	1.7	1.8
28.10.2015/16:20:02	40.82/27.76	4.5	24-30	3.9	6.4	5.8

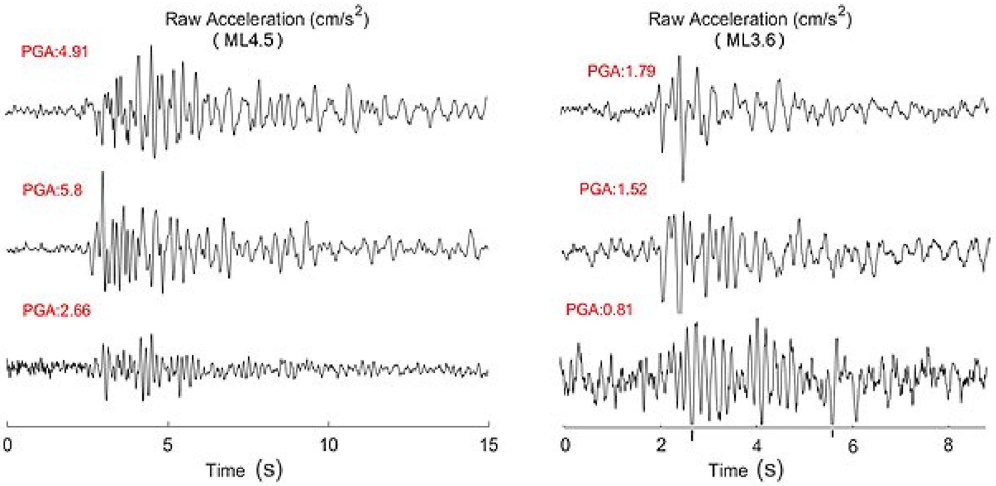


Fig 7 (Left) Raw acceleration recordings (from top to bottom: east-west , north-south and up-down directions) of the ML4.5 and ML3.6 earthquakes at DSI station.

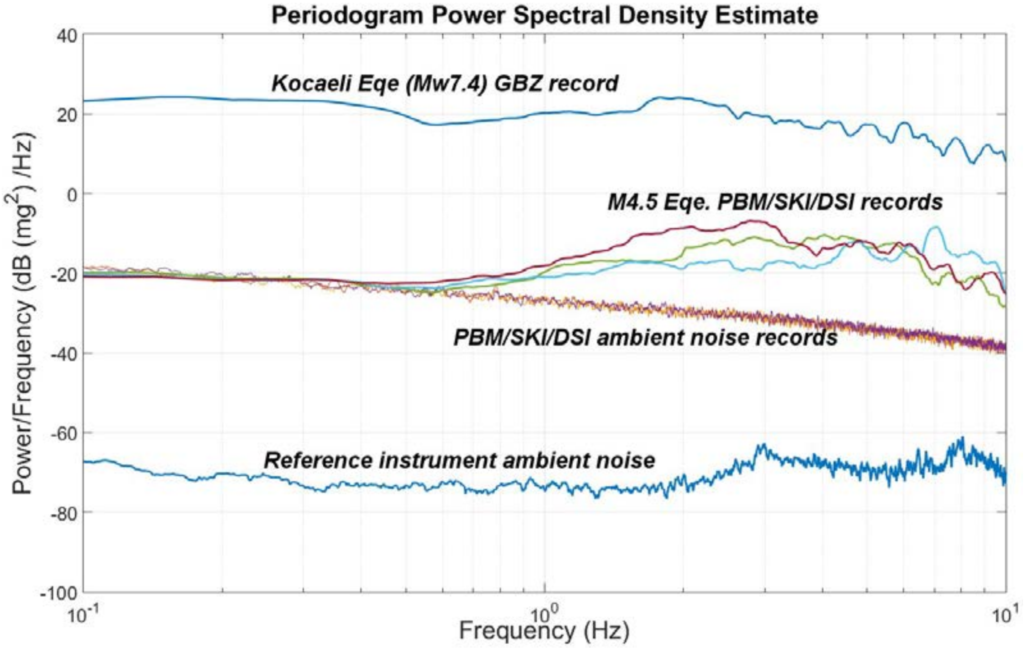


Fig 8 PSDs determined from ambient noise at Tekirdağ DSI stations from DAC instrument and a reference instrument. PSDs of the 1999 Kocaeli Earthquake (Mw7.4) and the 2005 Tekirdağ Earthquake (ML4.5) were also given in the figure for comparison.

3. Conclusion & Future Directions

In this study, synchronized real time data transfer from MEMS based instruments served to create rapid response network in an affordable way. A shake map routine was developed under Matlab software. Functionality of the shake map routine has been investigated through shake table tests. A test network at Tekirdağ was set up and earthquake activities in the Marmara Sea were recorded. Real time features of the network and software worked successfully during these earthquakes. It was observed that instrument self-noise is low enough to record large magnitude events in epicentral area.

In laboratory tests, SM parameters, PGV and the CAV values are well produced with M7+ earthquake recordings (correlation coefficient of 92%, on average). It has been known that structural damage criteria (*e.g.* roof displacement) correlate better with PGV than PGA [24,25] particularly for mid-rise reinforced concrete structures [26]. Hence instruments can be used to portray real-time PGV-based damage impact of an urban region. As reported before in [11], sensor has a tendency to underestimate high frequency component of the ground motion. This fact was also observed in shake table test results. SM parameters such as PGA and short period Sa, which are dominant in high frequency components of the ground motion, had lower values than those of calculated with actual recordings. The network can be efficiently used to record moderate to strong earthquakes in the near field for the purpose of producing PGA-based rapid shake & damage maps, provided that the sensor is replaced with upper quality ensembles.

Further studies are also planned for improving the instrument such as calculation of SM parameters in the instrument, not in the server and also for improving network by increase the number of instruments in the test area for getting precise shaking distribution. Effective voting combination among strong motion parameters will also be considered in the future studies. Hence ultimate goal will be the integration of shake map with loss estimation routines.

4. Acknowledgements

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