EARTHWORM AUTO-EARTHQUAKE LOCATION PERFORMANCE AND RECENT IMPROVEMENTS IN SEISMIC DATA ACQUISITION, PROCESSING, ARCHIVING AND DISSEMINATION AT KANDILLI OBSERVATORY AND EARTHQUAKE RESEARCH INSTITUTE

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Abstract. The Kandilli Observatory Real-Time Automated Seismic Data Processing System (KORTASDPS) has been one of the most important infrastructure developments in the last 5 years at Kandilli Observatory and Earthquake Research Institute (KOERI), Boğaziçi University. KORTASDPS uses the Earthworm (EW) software suite for its real-time processing of seismic data. Primary functions of EW are to serve as real-time data server and auto-detect and locate earthquakes. Performance evaluation of EW was done by comparing its hypocenter catalogs from years 2004 and 2005 with catalogs produced by the National Earthquake Monitoring Center (NEMC) which relies on manual detection and location techniques. In general EW performance is highest in northwest Turkey where station density and relative station sensitivity are high. Catalog correlations reveal that this area has an estimated 3.1 low magnitude threshold for a 90% earthquake auto-detection and location reliability. For the rest of the country this low magnitude threshold estimate ranges between 4.4 and 4.6. Three points have been proposed to improve EW auto-detection and location accuracy. These are more accurate timing of emergent phases, use of reliable S phases and an increase in the effective seismic network density with more sensitive and reliable stations. Already expansion and modernization of KOERI's seismic network in 2004 and 2005 have resulted in clear improvements in EW's auto-detection and location performance. A one month pilot analysis was made to understand the nature of the consistent large numbers of EW cataloged seismic events that do not correlate with NEMC. Results show that after careful manual relocation of these events that the majority are not found in either NEMC's preliminary or final catalog and that these events represent almost one third of all events found in the combined EW and NEMC catalogs. Since 2003 the KOERI re-designed digital broadband network has increased from 4 to 33 stations and international shared broadband stations from 2 to 10. The past and planned increases of more sensitive and higher quality seismic stations has and will continue to improve the performance of EW's auto-detection and location reliability and provide a source of information rich data to be used for ongoing and future seismological research.

1. Introduction

Since the devastating August 17, 1999, Mw 7.4 Izmit Turkey earthquake it was realized the necessity to modernize the earthquake monitoring and seismic data acquisition infrastructure at Kandilli Observatory and Earthquake Research Institute (KOERI), Boğaziçi University both to monitor real time seismicity as a public service and to provide a high-quality easy to access digital seismic waveform database for research. To achieve these goals a small group of scientist informally called the "Broadband Group" was formed. This report summarizes the completion and ongoing activities within this group as of December 2005 pertaining to changes in the seismic data acquisition processing and dissemination infrastructure of KOERI. Topics covered are; development, current design, management and performance of the Kandilli Observatory Real-Time Automated Seismic Data Processing System

(KORTASDPS) re-design and expansion of the digital broadband seismic station network, and real-time seismic data exchange and archiving.

2. Kandilli Observatory Real-Time Automated Seismic Data Processing System (KORTASDPS)

The development of the KORTASDPS (Childs and Kömeç, 2003) began in early 2001. By November of the same year KORTASDPS was auto-locating its first events whose number has currently reached over 27000. The real-time processing core of KORTASDPS uses the Earthworm (EW) software suite, initially developed by the United States Geological Survey in Menlo Park, California (Johnson et. al. 1995). The EW suite is composed of stand alone modules, each module works interactively locally or across a network. The modularity allows seismic network operators to adapt EW to a wide variety of seismic network configurations. Open source code has enabled the expansion and improvement of the EW module suite from contributors worldwide, further increasing its flexibility and robustness.

KORTASDPS was designed to fit the needs of the KOERI real-time earthquake monitoring operations conducted by the National Earthquake Monitoring Center (NEMC) and to feed its seismic data in near real-time to an automated archiving system for post processing. Software from both commercial and freeware sources runs presently on 10 core PCs communicating across a “closed” data network. The primary function of each PC connected to the KORTASDPS closed data network belongs to 1 or 2 of the five operational sub-systems.

1. Field PCs are used to configure digital seismic instrumentation and backup data at the station in the event of failed data communication line.

2. Data Acquisition PCs interact directly with the seismic stations, record continuous data streams to the hard disk using commercial software, and broadcast the same data stream onto the “closed” data network.

***3. EW* Real-Time Data Processing** PCs primarily run *EW* modules. They receive the broadcasted data stream from the data acquisition PCs and convert this to *EW* format where it is stored, served by request and re-broadcasted onto the data network. Waveforms from this *EW* formatted data stream are fed to a picker, picks are associated into events, events are located, and finally waveforms are automatically assembled into a SAC formatted event files and written to disk. Because these PCs are core to the real-time component of the overall system and because these PCs are relatively difficult to configure on short notice a duplicate or mirror set of computers are run in parallel as a backup.

4. Data Archiving and Public Distribution PCs automatically pull SAC format continuous and event based data files from the data processing sub-system and create duplicate copies on their local hard-drives. This continuous SAC data is now open via FTP access to the public. Each month the data is archived to a stable media. Because of its critical importance this sub-system is also mirrored. In addition one PC utilizing the Seiscomp Software Suite is used to distribute seismic data in real-time both nationally and internationally.

5. The Public Information Access PC is the KORTASDPS web server. Plans are to make available to the public real-time earthquake location, magnitude and waveform images, produced by the KORTASDPS as well as general information regarding the overall system architecture.

3. Performance of KORTASDPS

3.1. INTRODUCTION

The auto-events produced by KORTASDPS EW system can be noise, natural earthquakes, or man made seismic events such as blasts. One of the primary goals of an automated earthquake system is to reduce noise events while simultaneously increasing the detection and accurate location of earthquakes. Unfortunately the suppression of auto-noise-events often leads to the suppression of auto-earthquake-events so an automated system must be optimized or tuned for a given seismic network's particular performance. Nevertheless a well tuned automatic processing system is not by itself sufficient to decrease the false alarm rate while keeping the detection level to a constant. As with all automated systems the quality of input determines the quality of output. Therefore the KORTASDPS system manager must be very familiar with seismic station hardware capabilities, operational status and station site sensitivity in order to understand how to adjust an automated system. Since 2001 the Broadband Group has been managing several key components of KORTASDPS including the EW system. Direct access to the system has enabled long term rudimentary monitoring of its performance and adjustments to its configuration. This section presents results from the analysis of EW system event auto-locations from years 2004 and 2005.

The earthquake catalog of the NEMC was used to gauge the performance of EW's auto-event locations. As of December 2005 the NEMC continues to manually detect and locate earthquakes throughout Turkey. A seismic analyst is on-site 24 hrs/day 7 days/week. EW is used by the NEMC as a way of coalescing seismic data from the variety of commercial seismic hardware and software into a single seismic data server which is then accessed by the analyst when an earthquake is visually detected on the monitor trace displays. As of December, 2005 there are 42 broadband (3 component), 59 short period analog (single component), and 1 short period digital (3 component) stations flowing into the EW data server in real-time for a total of 102 stations. Analog stations are centrally digitized. Since 2003 the Broadband Group has been monitoring and quantifying KOERI's seismic network performance on a station by station level. Daily State of Health (DSOH) reports are produced for all digital stations and include data recovery percentage, voltages, timing status, and other aspects related to monitoring the health and infrastructure of KORTASDPS. In addition Event State of Health (ESOH) reports are produced when a teleseismic event is large enough to be recorded across the entire network (Childs and Komec, 2003). This allows the determination of a simple dead or alive statistic for all stations especially the analog section of the network which currently comprises 58% of KOERI's network. The freely distributed state of health information is used by decision makers, station maintenance operators, researchers and earthquake monitoring staff. It has been invaluable towards better understanding the quality of input to the EW auto-location system.

3.2. EFFECTIVE SEISMIC NETWORK

Because EW's auto-event detection and location performance is intrinsically linked to the state of the seismic network feeding it an attempt was made to determine the actual "effective seismic network" separately for years 2004 and 2005. In order to be part of the "effective seismic network" a station needed to be installed for a minimum of 8 months of a given year and have had a performance rating of 60% or greater. The latter performance criteria required, for digital stations, a data recovery percentage of 60% or greater for the period in operation and for analog stations a 60% or greater performance based upon ESOH reports. The results of the elimination criteria are below shown in Table 1. The "Effective Seismic Network" criteria for year 2005, though not stringent, eliminated 26% of the then operating stations from the network. This agrees will with ESOH reports which on average show a seismic network functional health of approximately 75%. General observations during relocation of small magnitude events for this study pointed out that some effective network stations consistently recorded readable first arrival phases while other nearby effective network stations provided consistently no data at all so the rudimentary criteria used in this study as an "effective seismic network" could for later work be improved to take into account a station's sensitivity and signal to noise ratio.

TABLE 1. Effective Seismic Network Configurations for Years 2004 and 2005

Year	Broadband Digital (3 Component)	Short Period Digital (3 Component)	Short Period Analog (1 Component)	Total Stations "effective network"	Effective network density (km^2/station)
2004	18	1	36	55	14172
2005	30	1	36	67	11634

3.3. CORRELATION BETWEEN AUTO AND MANUAL LOCATIONS

The EW auto-location catalogs for years 2004 and 2005 were correlated with the final 2004 and preliminary 2005 earthquake catalogs produced by the NEMC. The 2005 NEMC preliminary catalog was used for 2005 because a completed "final" catalog was not available during the data processing stage of this analysis. It was necessary to eliminate months April and July of 2004, and February, March and May of 2005 from both catalogs because these sections of the EW catalogs were not available. Correlation of catalogs was completed to the end of November 2005. With exception to some stations to the north and south of the Marmara Sea in northwestern Turkey the NEMC manually locates earthquakes throughout Turkey using essentially the same seismic network configuration as that of EW. Nevertheless some critical location procedures and criteria are different as shown below in Table 2. Most notably NEMC has a 5 phase minimum and uses S phases which reduce the minimum number of stations required for a solution to 3. EW has a 4 station minimum and does not use S phases. EW's automatic event detection and location software flowchart and software is shown in Table 3. Each EW software module has its own configuration file which the system manager uses to control its behavior. In this way an EW system can be very specifically tuned to the needs of the seismic monitoring operations.

TABLE 2. Event detection and location criteria and procedures used by EW and the NEMC.

EW Earthquake Auto Location Criteria	NEMC Manual Earthquake Location Preliminary Catalog Criteria	NEMC Manual Earthquake Location Final Catalog Criteria
Automatic event detection and location (Table 3 for details)	Manual visual event detection by onsite analyst	Same
Only P phases used	P and S phases used	Same
Minimum of 4 stations	No Minimum	Minimum of 3 stations
M_D determined but not used.	M_D determined. M_L for larger magnitudes.	Same + M_B determined
No max azimuthal gap criteria	No max azimuthal gap criteria	Max azimuthal gap criteria of 200 used as a general guideline, exceptions are allowed
No max RMS residual criteria	No max RMS residual criteria	Max RMS residual criteria of 1.0 used as a general guideline, in some cases exceptions are allowed
Single 4 layer Velocity model	Velocity model identical to EW's	Velocity model identical to EW's

TABLE 3. EW's automatic event detection and location software flowchart.

EW Software Module Name	Functional Description
PICK_EW	Continuously time-picks real-time seismic trace data fed from the EW data server
BINDER_EW	Associates picks into events and creates a preliminary location with an event ID. Though not common associated events that have high residuals can be terminated by binder_ew.
EQPROC	Module head which collects information from binder_ew and pick_ew to determine when an event is ready for secondary location processing.
EQBUF	Buffers information received from eqproc
EQCODA	Determines coda length for hypoinverse M_D calculations
EQVERIFY	Tests for noise events and eliminates them.
HYP2000_MGR	Manages EW location data inflow and outflow from hypoinverse (hyp2000). Creates final location. Though not common associated events that have high residuals can be terminated by hyp2000_mgr.

A catalog correlation criteria of less than 5 s difference in origin time and 50 km in epicentral distance difference was used in the analysis to follow however other more liberal and stringent criteria are shown in Table 4 to give a broader perspective of the results. Table 4 clearly shows that large percentages of earthquakes from both the EW and NEMC catalogs are uncorrelated. For the NEMC the uncorrelated percentages, relative to the total catalog event count, range from 67-74% for both years using the first 2 more stringent correlation criteria shown in Table 4. Comparing the auto-locations with the NEMC final catalog does not necessarily reduce the percentage of uncorrelated NEMC earthquakes as the numbers of both uncorrelated and correlated events can increase however the number of correlated events does increase significantly. Correlation to the end of August of a finished not yet distributed section of the NEMC "final" 2005 catalog which became available late in the study revealed that the number of correlated events in the 2.5 s to 25 km and 5s to 50 km criterion categories increased by 22%. To evaluate the EW auto-location catalogs events produced by seismic network noise must first be removed. Monitoring has shown that the 2004 EW catalog has an average of 65% noise events which if accounted for would give an uncorrelated percentage ranging from 45-52%. For 2005 noise event monitoring was discontinued however pilot studies for April and June of 2005 have shown that the percentage of auto-noise-events for the EW system has decreased dramatically to less than 30%. This may be due to the addition of 27 digital broadband 3 component and 3 short period analog stations during years 2004 and 2005. This noise-event value can fluctuate monthly on average by approximately 10% as shown by 2004 data so a conservative 40% noise-event value estimate was used for year 2005. Based upon the noise estimate uncorrelated earthquakes for EW's 2005 catalog range from 78-82% using NEMC's preliminary catalog and the first 2 more stringent correlation criteria shown in Table 4. For years 2004 and 2005 NEMC uncorrelated percentages of total earthquake catalog remain relatively constant while those of the EW catalog have increased by 58-73%. In addition the percentage of correlated events remains low at 33% and 31% of the total NEMC catalog and 55% and 22% for the EW catalog for years 2004 and 2005 respectively (using <5 s <50 km correlation criteria). Further analysis of EW's uncorrelated seismic events is discussed in section 3.5.

TABLE 4. NEMC and EW event catalog correlation results for years 2004 and 2005

YEAR 2004 (months April and July are not included in the analysis)			
Correlation Criteria (Origin Time and Epicentral Offset)	Uncorrelated NEMC Final Catalog with uncorrelated percentages of total catalog	Correlated Events	Uncorrelated EW Catalog with uncorrelated percentages of total catalog (noise events removed)
<2.5 s <25 km	2106 71%	844	931 52%
<5 s <50 km	1978 67%	972	804 45%
<10 s <100 km	1873 63%	1077	699 39%
<20 s <200 km	1762 60%	1188	588 33%
YEAR 2005 (months February, March, May and December are not included in the analysis)			
Correlation Criteria (Origin Time and Epicentral Offset)	Uncorrelated NEMC Preliminary Catalog with uncorrelated percentages of total catalog	Correlated Events	Uncorrelated EW Catalog with uncorrelated percentages of total catalog (estimated noise events removed)
<2.5 s <25 km	2651 74%	914	4114 82% estimate
<5 s <50 km	2461 69%	1101	3927 78% estimate
<10 s <100 km	2277 64%	1285	3743 74% estimate
<20 s <200 km	2090 59%	1472	3556 71% estimate

In order to better understand the nature of correlated and uncorrelated NEMC earthquakes, epicenter plots were produced for both 2004 and 2005 grouped into magnitude ranges 2.0-2.9, 3.0-3.9, and 4.0-6.0. Results from 2005 which are nearly identical in character to year 2004 clearly show the effect of network sensitivity as detected by an unbiased observer, the EW auto-locating system.

The magnitudes in the range 2.0-2.9 (Figure 1a) shows the best correlation in the northwest and moderately good correlation in north central Turkey. In northwestern Turkey the overall effective network density is higher and a concentration of more sensitive 3 component broadband sensors exists. In north-central Turkey relative effective network density is lower however the predominantly analog seismic stations in this area are consistently healthy. In the west and southwest there is a higher rate of uncorrelated events. This can be explained by the sparse network in areas such as the Izmir region where only 2 to at best 3 stations exists nearby. However in the Bodrum, Gökova Bay region of southwestern Turkey only 9 out of 152 earthquakes located by the NEMC associated with the EW catalog. The network in this region is composed of a semi-circle arrangement of 4 broadband stations and one short period analog station which half surround the events in question. A look at the ESOH and digital data recovery reports for 2005 shows that broadband station FETY was non-operational for July-October during approximately half of the uncorrelated events in this region and short period station YER was non-operational from March-July during approximately 30% of the uncorrelated events. So the effective network during approximately 80% of the uncorrelated events consisted of 4 stations. This combined with weak arrivals from low magnitude events, noisy station sites (three broadband stations are located at radio tower sites on windy ridges and one broadband is located immediately adjacent to an industrial park) and the non-use of solution constraining S phases may best explain why the EW system failed to locate events in this area.

In the magnitude range of 3.0-3.9 shown in Figure 1b the ratio of correlated to uncorrelated events has clearly increased relative to Figure 1a. With exception to the Aegean and Mediterranean Sea offshore regions uncorrelated and correlated events are mixed up in the same areas. This reflects that the majority of these events are above the intrinsic minimum magnitude threshold of the network. Figure 2 points out that this intrinsic minimum network detection magnitude threshold is approximately 3 for the manual event location procedure used by the NEMC. For earthquakes located in the offshore regions onshore stations are recording emergent arrivals and azimuthal gap can be very large.

Emergent arrivals are often timed late by EW (0.5 to 3 s error) and the lack of S phases in auto-locations of such events can lead to very unreliable locations. These events may fail at any of 4 levels of the auto-processing. They may; fail to auto-associate, be rejected by the associater after initial association, be rejected by the final hypoinverse location process, or at least have a very large error in origin time and location. KOERI's EW auto-picker configuration has not been tuned. It remains the same as used by the Northern California Seismic Network (NCSN) run by the U.S. Geological Survey in Menlo Park whose seismic station density is more than 10 times greater than that operated by KOERI. Impulsive arrivals for the NCSN are in plentiful supply and the auto-picker is tuned for this. Perhaps the configuration for the EW picker could be better configured or even modified to more accurately time emergent arrivals common with sparse networks without losing the ability to pick impulsive onsets.

In the magnitude range of 4.0-5.5 (Figure 1c) there is nearly a 100% catalog correlation. Only a few events located principally far offshore in the west and southwest remain uncorrelated. Station sensitivity and density are sufficient in this magnitude range for reliable real-time auto-locations.

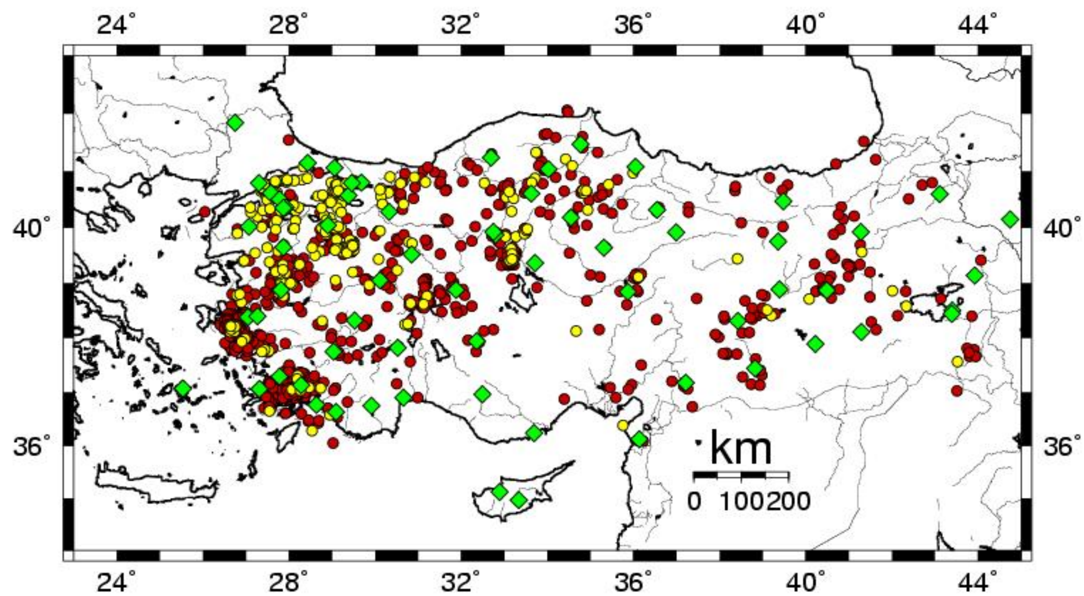

Figure 1a

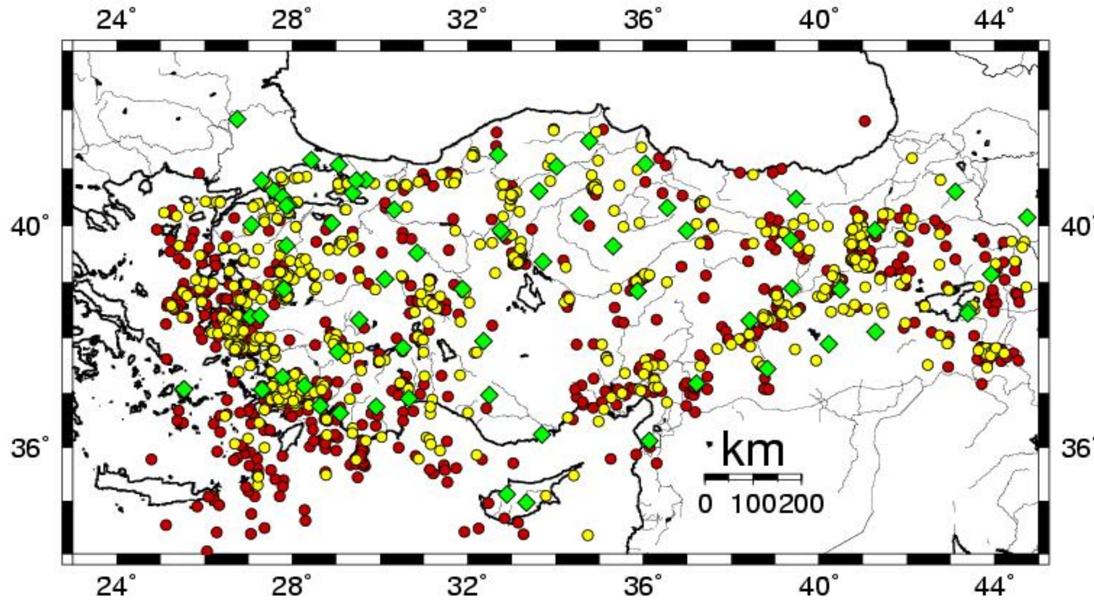

Figure 1b

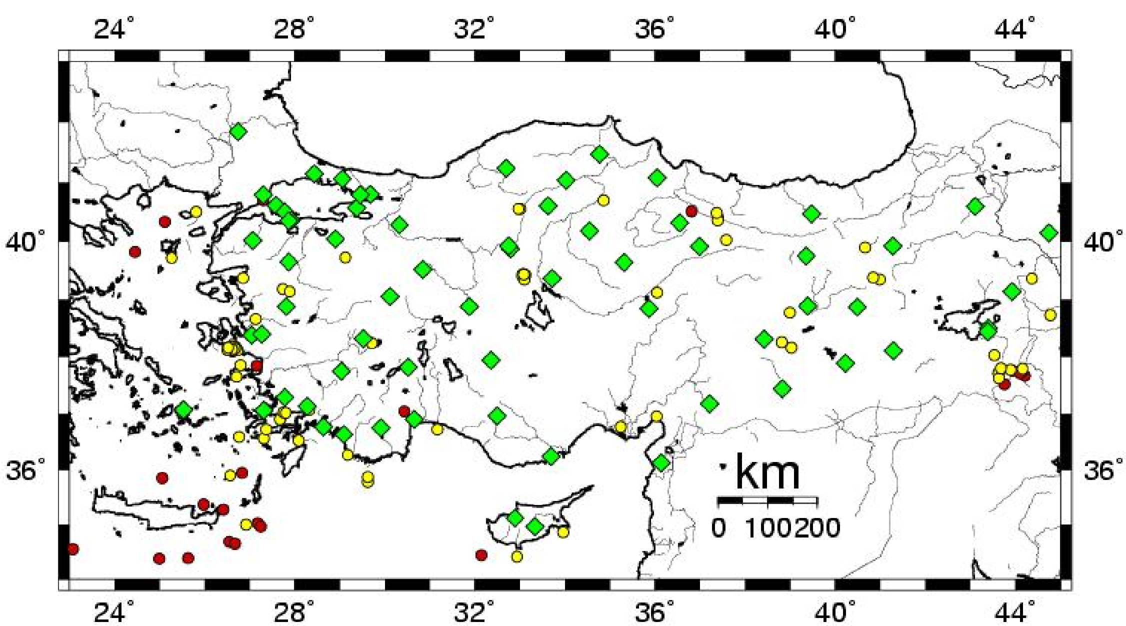

Figure 1c

Figurs 1a, 1b, and 1c. Correlated EW vs. NEMC catalog events (yellow dots) and uncorrelated NEMC catalog events (red dots) from 2005 less months of February, March and May using a criteria of <5 s in origin time difference and <50 km epicentral difference. Stations belonging to the year 2005 "effective seismic network" are shown as green diamonds. ***(1a)*** Magnitude range 2.0-2.9. Note relatively good performance of the EW system in the northwest as demonstrated by a higher density of correlated events. For earthquakes occurring in areas outside of the northwest where network coverage is sparse there are not a sufficient number of good quality station recordings per earthquake for an automatic system to perform well. ***(1b)*** Magnitude range 3.0-3.9. Above the effective seismic network's average intrinsic low magnitude threshold of 3.0 there is no clear polarization of correlated and uncorrelated events with exception to offshore regions where azimuthal gaps and epicentral distance to first 3-4 stations are both large considerably hampering accurate auto-locations. In this magnitude range EW's location reliability is clearly improving relative to figure 1a but still remains below 100%. ***(1c)*** Magnitude range 4.0-2.9. In this magnitude range EW auto-locations show nearly 100% correlations to the NEMC catalog. As with figures 1a and 1b uncorrelated events are still found in difficult to locate offshore areas.

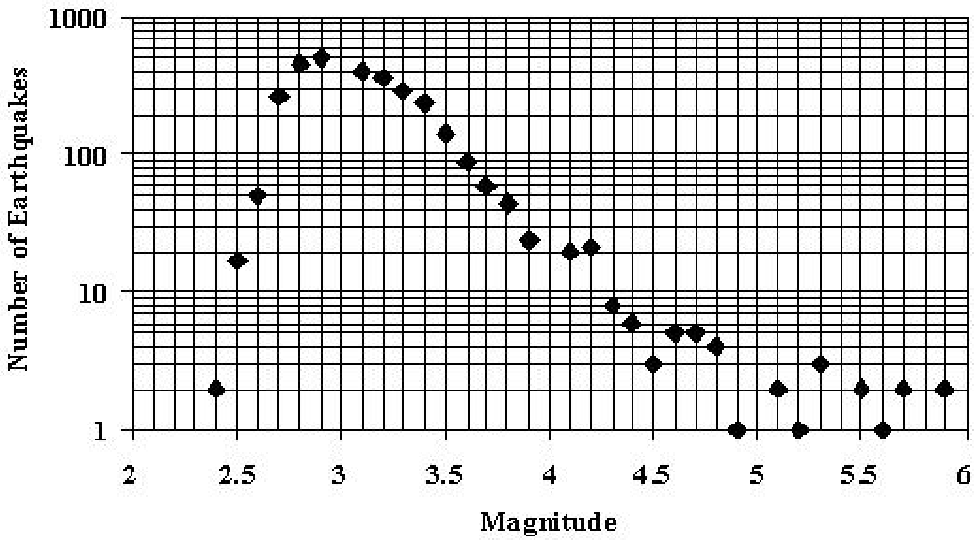

Figure 2. The number of events from NEMC's 2005 earthquake catalog used in this study plotted on a log scale vs. magnitude (90% of which are M_D). Note that the linear trend ends at magnitude 3.0 which represents the average lower magnitude sensitivity for KOERI's seismic network. The NEMC catalog should not be considered complete for events below magnitude 3.0.

3.4. LOW MAGNITUDE THRESHOLD ESTIMATIONS FOR RELIABLE EARTHQUAKE AUTO-DETECTION AND LOCATION

Figure 3 shows EW vs. NEMC earthquake correlation percentages relative to total events located by NEMC in 2005 plotted vs. magnitudes. The same < 5 s difference in origin time and < 50 km in epicentral offset criteria is being used here. If we extrapolate the linear trend of this plot it gives a 4.6 minimum magnitude threshold for 90% reliability of the EW automatic earthquake detection and location for the entire seismic network. A similar 90% reliability plot for the year 2004 (not shown) gives a magnitude threshold of 4.4. These nationwide results are estimates. They can be biased by improper magnitude estimation, incomplete earthquake catalog, limited data above magnitude 4.4 and catalog biasing of the 2.0-4.0 magnitude range from aftershock activity located in areas of sparse network coverage. With exception to magnitude determination all of the biasing effects are known to be present in this plot. For example significant numbers of aftershock earthquakes located by the NEMC from sparse network localities occurred in 2 areas in 2005. These zones being Bala, near Ankara with 291 events and Seferhisar, south of Izmir with 616 events. These 2 zones alone constitute 25% of the 2005 NEMC catalog being used in this study. Anomalous values seen in Figure 3 have epicenters in areas of sparse or no network. For example for magnitudes 3.7 to 3.8, 4.2, 4.5, 4.7 to 5.9 over 85% of these events are located either offshore Turkey to the west and south or in southeastern Turkey near the Iranian border. During the missed magnitude 5.9 event in Seferhisar (Oct. 20, 2140) EW's data server was down with virus problems. Some catalog biasing can be avoided if the EW auto-location threshold reliabilities are evaluated regionally.

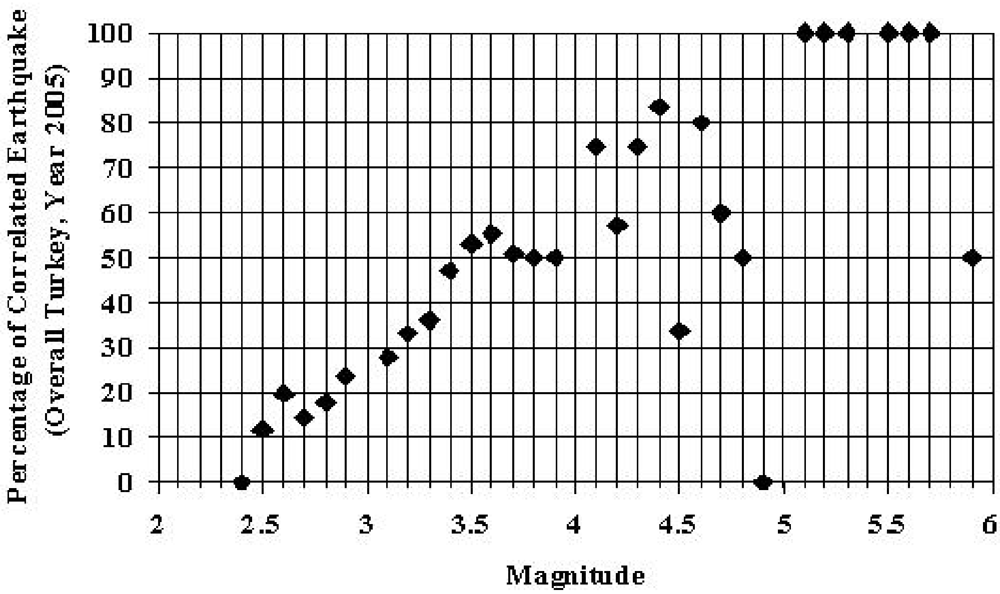

Figure 3. Based upon year 2005 EW and NEMC catalogs this plot shows the percentage of catalog correlated events (with respect to total events located by NEMC). Criteria used in the catalog correlation are <5s origin time and <50km epicentral differences. Linear extrapolation of non outlying data points above magnitude 3 give an estimated nationwide EW 90% auto-location reliability threshold of approximately magnitude 4.6. Data from 2004 using the same procedure gives a similar threshold magnitude of 4.4.

It has already been pointed out that seismic network performance is not homogeneous. A closer analysis was made of the Marmara region in northwestern Turkey. This area is home to more than 25% of Turkey's population, Turkey's largest city, Istanbul, and a major share of the Turkey's industrial strength. In addition, this area is exposed to considerable threat of a major earthquake which has and likely will be linked to activity associated with the major east-west striking North Anatolian Transform Fault. Figure 4 shows an EW 90% reliable auto-location magnitude threshold of approximately 3.1 for the Marmara Region. During the anomalous magnitude 4.1 event (Nov., 4 2012 UTC) shown in Figure 4 the EW data acquisition and real-time server was not functioning due to a system virus. The uncorrelated magnitude 3.6 event was located by EW's event associater but then killed due to one or more spurious picks.

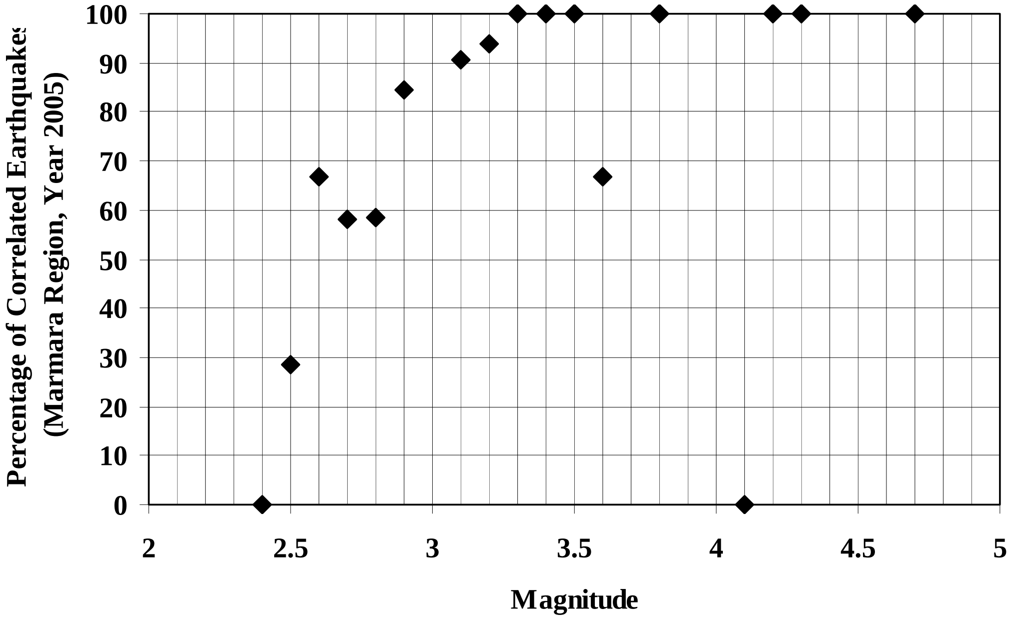

Figure 4. Based upon year 2005 EW and NEMC catalogs this plot shows the percentage of catalog correlated events within the Marmara Region of northwestern Turkey (with respect to total Marmara Region events located by NEMC). This plot shows clearly an estimated Marmara Region EW 90% auto-location reliability threshold of magnitude 3.1. Criteria used in the catalog correlation are <5s origin time and <50km epicentral differences. Events considered lie within the latitude range of 39.7 to 41.2 N and longitude range of 26.8 to 30.2 E.

3.5. A PILOT STUDY ON UNCORRELATED AUTO-LOCATED EVENTS

As Table 4 shows large numbers of uncorrelated events are found in both the EW and NEMC catalogs. We know that the NEMC uncorrelated events are earthquakes and have already discussed reasons why some of these earthquakes were not detected by the EW system. So what is the nature of the uncorrelated EW events? To find out a detailed look at uncorrelated EW auto-located events from April of 2005 was undertaken. First the April events were viewed and categorized as either seismic event or noise. The seismic events were then correlated with the NEMC April 2005 catalog. The EW catalog earthquakes that did not correlate with the NEMC April 2005 catalog were then timed and re-located manually and then correlated for a second time with the original NEMC April catalog. The numerical results of this analysis are shown in Table 5 below. Remarkably on the second correlation attempt only 14 or 12% of the total 133 manually re-located EW seismic events correlated with the April 2005 NEMC catalog. To be sure these EW auto-located events were not later discovered in the formation of NEMC's final catalog the same events were correlated with the final April 2005 NEMC catalog giving no difference in the result. Of the 119 uncorrelated EW seismic events 82% locate in northwestern Turkey which includes the seismically active Marmara Region (Lat. range 39.0 – 41.0 N, Long. Range 27.0 – 30.0 E). As shown previously the EW system's detection sensitivity is high for this area. A summary of the results are shown in the last row of Table 5. For April of 2005 the combining of both automatic and manual earthquake location methods would have increased the number of real-time detected seismic events by nearly 30%.

TABLE 5. Pilot study for April 2005 data showing results from the re-location of uncorrelated EW auto-located earthquakes.

Description	Results
Number of original events from each catalog for April of 2005	EW 388, NEMC 285
Number of seismic and noise events manually found from viewing the EW catalog's associated auto-event files	251 Seismic events, 137 Noise events
Result of 251 EW seismic events cross correlated with NEMC's April catalog with a criteria of <5s origin time difference and <50km epicentral offset.	84 Correlated, 167 Uncorrelated
Results of manual locations of 167 uncorrelated EW seismic events.	133 located , 7 teleseisms, 27 not locatable (magnitude too small, not enough stations etc.).
Location details of the 133 manually located EW auto-detected seismic events	Avg. azimuthal gap 208 degrees (58 events <200) Avg. number of picks per event 8.1 Avg. number of stations per event 5.8 Avg. RMS 133 events 0.83
The 133 events manually located EW were again correlated with the Apr 2005 NEMC catalog with a criteria of <5s origin time difference and <50km epicentral offset.	14 Correlated, 111 Uncorrelated
Summary of Results There were a combined number of 438 seismic events. Numbers to the right give the percentage in each group.	Only NEMC located 43%
	Only EW located 27%
	Jointly located by EW and NEMC 22%
	Other 8%

4. Re-design and Expansion of KOERI's Digital Broadband Seismic Station Network

4.1. INTRODUCTION

Experience in the Broadband Group gained from 3 years of managing, modifying, troubleshooting and monitoring seismic data quality from KORTASDPS prompted a shift in efforts toward modernizing the aging analog seismic station network which feeds KORTASDPS. In March of 2003 a 3 year institute level project was created whose goal was to re-design and expand KOERI's digital broadband seismic network which at that time consisted of four operational stations. Since the initiation of this project the digital broadband seismic network has increased to a total of 33 stations (December, 2005) with an additional 10 international stations arriving in real-time via the Internet (Figure 5). Since 2004 the NEMC has carried on the task of installing and maintaining the most recent broadband stations however a significant number of broadband stations continue to be managed by the Broadband Group

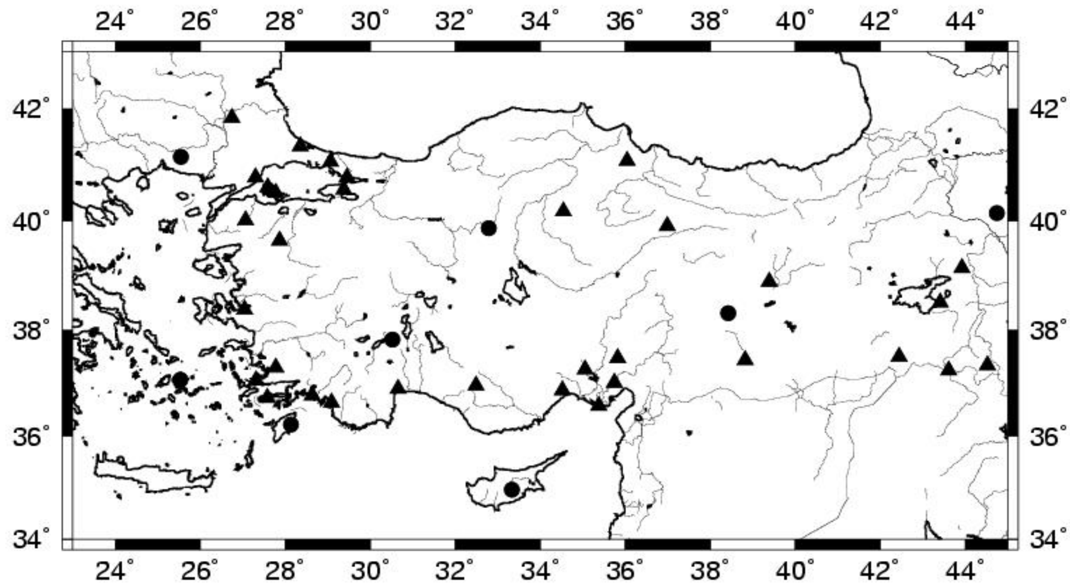

Figure 5. The KOERI real-time broadband station map, December of 2005. Thirty three KOERI operated stations are shown as black triangles and 10 international real-time data exchange stations from FDSN network codes: GE, HL and IU are shown as black circles. Note since March of 2003 there has been greater than a 7 fold increase in permanent KOERI digital broadband stations alone.

4.2. GENERAL OVERVIEW OF RE-DESIGNED BROADBAND STATION

All new broadband stations are equipped with a grounding array and a 220 VAC and phone line voltage surge protection units. Each station has enough backup power to run autonomously for approximately 1 week. Sensor vaults are designed to be thermally isolated and an attempt is made to select secure and quiet sites which are also near enough to some form of data communication link. Several data telemetry methods are being used currently. These include: digital lease line, Internet, analog lease line, digital radio, and satellite. The new broadband station design has proven to be inexpensive and robust. Many of the stations installed in 2003 and early 2004 have been in continuous operation since their installation despite the fact that they have not received any maintenance visits. The largest problem to date has centered on the poor service provided by the telecommunications organization.

5. Real-Time Data Exchange and Archiving

5.1. REAL-TIME SEISMIC DATA EXCHANGE

The rapid increase in high-quality broadband seismic data and improvements in the data collection and processing infrastructure at KOERI has made its position in the international seismic community as a provider of data products much more attractive and attainable. In 2003 the Broadband Group, in cooperation with the ORFEUS Data Center located in the Netherlands, established a first ever real-time sharing of data from KOERI owned broadband stations across the internet using the Seiscomp software suite (Hanka, et. al. 2000). Real-time international seismic data exchange is currently ongoing with the following partners: The National Observatory of Athens (NOA - Athens, Greece), The National Research Centre for Geosciences (GFZ - Potsdam, Germany), The Albuquerque Seismology Laboratory (Albuquerque, USA), The Observatories and Research Facilities for European Seismology (ORFEUS - De Bilt, Netherlands). Such "cross-border" sharing of information is a necessity for most countries interested in earthquakes just outside their borders and helps to create strong international working relationships which are valuable to the scientific community as a whole.

5.2. SEISMIC DATA ARCHIVING

Two separate semi-redundant seismic data archive systems are being operated within KOERI as a crucial component of the KORTASDPS. The primary system run by the NEMC and the secondary or backup system run by the Broadband Group. Comparisons of both systems are summarized below in Table 6.

TABLE 6. Comparison of archiving system capabilities for the NEMC and the Broadband Group

Description	**NEMC Archive**	**Broadband Group Archive**
Capacity	3 Terabytes	1 Terabyte
Data Format	SAC	SAC
Data Products	Continuous data all stations since Manually extracted event data	Continuous broadband data Manually extracted event data EW auto-event data
Data Accessibility	Public internet access to all waveform data	Data used internally for research. System is a secondary backup to the primary NEMC archive.
Long Term Storage	Data backed up monthly to stable media	Data backed up monthly to stable media

5.3. FUTURE DEVELOPMENTS IN DIGITAL BROADBAND SEISMOLOGY AT KOERI

Kandilli Observatory has a project scheduled to begin in 2006 which will provide for the expansion of the permanent broadband digital network to approximately 55 stations nationwide along with the creation of a 52 broadband instrument pool which will be managed by the Geophysics Dept. Also plans exist to increase the number of seismic data and information exchange partners both internationally and nationally thereby stimulating cooperative seismological research and more efficient use of high-quality data gathering resources for all.

6. Conclusions

Since 2000 there have been rapid improvements to the seismic data collecting, processing and archiving infrastructure at the Kandilli Observatory and Earthquake research Institute, Bogaziçi University. The establishment of the complex but robust Kandilli Observatory Real-Time Automated Seismic Data Processing System initiated in 2000-2001 has become the centerpiece of day to day earthquake monitoring operations conducted by the NEMC and has provided easy access to important data products used by the public, decision makers and researchers. Several years of operation and information collection has enabled the quantitative performance evaluation of the earthquake auto-detection and location core of KORTASDPS which uses the EW software suite.

EW's ability to auto-detect and properly locate events is, directly dependent on the earthquakes magnitude, its epicentral distance with respect to the first 4 nearby functioning seismic stations, station azimuthal coverage, and station sensitivity. For magnitudes ranging from 4.0 to 5.5 EW locates nearly 100% of the events with exception to distant events locating offshore to the west and south. For magnitudes ranging from 3.0 to 3.9 EW's auto-event location performs moderately well throughout mainland Turkey. Exceptions are the high performance in the northwest Marmara region and the low performance offshore to the west and south. For magnitudes ranging from 2.0 to 2.9 EW performs well in northwestern Turkey where station density and sensitivity are relatively high. The four proposed primary reasons for EW performance deficit are that the EW auto-picks late if at all emergent arrivals, S phases are not used in the location solution, EW is configured to a 4 station minimum as compared to 3 used by the NEMC and data comes from a low density "effective" seismic network (11634 km^2/station for 2005) composed of a large percentage of low sensitivity stations. Reduction of the hypocenter solution station minimum to 3 will probably cause large increases in spurious locations and noise events. Efforts should therefore be focused on one or more of the 3 remaining problem areas in order to improve EW's auto-detection and location accuracy. Network expansion and upgrade, already underway, has proven effective by increasing the auto-located seismic/noise event ratio thereby lowering the magnitude auto-detection threshold.

Based upon catalog correlation results quantitative analysis of years 2004 and 2005 shows that EW has nationwide a 90% auto-event detection and location reliability lower magnitude threshold with respect to the NEMC catalog between 4.4 – 4.6. Similar analysis for the high seismic risk Marmara Region in northwestern Turkey shows a 90% auto-event detection and location reliability lower magnitude threshold of 3.1. Auto-located earthquake above these magnitudes thresholds could be used as part of a pilot web page based rapid earthquake notification system.

Large percentages of known EW auto-located seismic events remain uncorrelated. The April 2005 pilot study shows that nearly one third of the April of 2005 earthquakes combined from the NEMC and EW catalogs can evade manual detection methods used by the NEMC. The review of auto-locations by NEMC analysts would therefore improve the completeness of real-time earthquake monitoring operations.

Recent expansion and design improvements of KOERI's seismic network including a 7 fold expansion of the digital broadband network in the last 2 years and the planned continued expansion will certainly lower the minimum magnitude threshold for automatic earthquake detection and locations produced by KORTASDP. The now open availability of this new high quality seismic data both in real-time and offline will provide an endless source of fuel for future seismological investigations in Turkey.

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